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EVALUATION OF SPACE STATION SOLAR ARRAY TECHNOLOGY AND RECOMMENDED ADVANCED DEVELOPMENT PROGRAMS

Lockheed Missiles and Space Company
Space Systems Division
Sunnyvale, California

December 1970

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FIRST TOPICAL REPORT

EVALUATION OF SPACE STATION SOLAR ARRAY TECHNOLOGY AND RECOMMENDED ADVANCED DEVELOPMENT PROGRAMS

Contract NAS9-11039

Prepared for
Manned Spacecraft Center,
Houston, Texas
by
Space Systems Division Power Systems

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28 December 1970

To: Space Station Solar Array Technology Evaluation Report Recipients

The enclosed report, which constitutes the First Topical Report under Contract NAS9-11039, represents the final documentation of the Technology Evaluation phase of the Program. The data and evaluation herein will serve as a basis for the design/analysis and test phases which follow. It is hoped that much of this data will be of general use to all space power system designers.

In all, in addition to the sources acknowledged in the bibliography, over 100 specialists in NASA, the Air Force and industry were personally contacted and have made significant contributions to this effort in one way or another. Accordingly, because of the extent of this participation, no effort was made to acknolwedge each individual contribution.

In order to take further advantage of potential technical contributions from the specialists on distribution for this report, we have designed the format in such a way as to provide convenient updating capability. The loose-leaf binder and the methods of tabulation were selected with this in mind. Should any of you have any corrections, additions, or conclusions which you feel should be incorporated, please forward them to:

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Appropriate pages will be corrected or added to and each person on distribution will receive new pages for incorporation into his copy of the report.

Again let me express my appreciation to the many specialists who have contributed their knowledge, time and energy to this report.

L.G. Chidester

L.G. Chidester, Program Manager
Space Station Solar Array
Technology Evaluation Program

LGC:od

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Section 1
INTRODUCTION

This is the first of four topical reports which will document the results of the major phases of the Space Station Solar Array Technology Evaluation Program This program is being conducted under NASA contract NAS 9-11039 with the Manned Spacecraft Center (MSC), Houston, Texas. The purpose of the program is to determine whether technology and analytical techniques are adequate to support the development of a solar power system for a large Space Station. The goals of the program are to

(1) Establish design requirements which are typical of space station missions.

(2) Perform technology evaluation of existing techniques for meeting such requirements.

(3) Identify specific areas where technology advancement is needed.

(4) Prepare a plan for development of the technology defined in item (3).

(5) Design components capable of meeting requirements imposed by a representative space station.

(6) Verify, by test, that the technology for item (5) is available — or establish the problems and deficiencies therewith — and that the analytical tools used in such design are adequate.

(7) Prepare representative system development plan(s) for system and mission evaluations.

(8) Develop a design handbook of parametric data based on the analyses and tests above.

This report documents the results of the Technology Evaluation Phase and satisfies goals (1) through (4) above. To accomplish the goals in items (3) and (4), it is necessary to define the current planning related to Space Station development and use.

Figure 1-1 shows that planning and indicates that a state of technology readiness must be achieved by June of 1972. Technology readiness is defined as the attainment of a

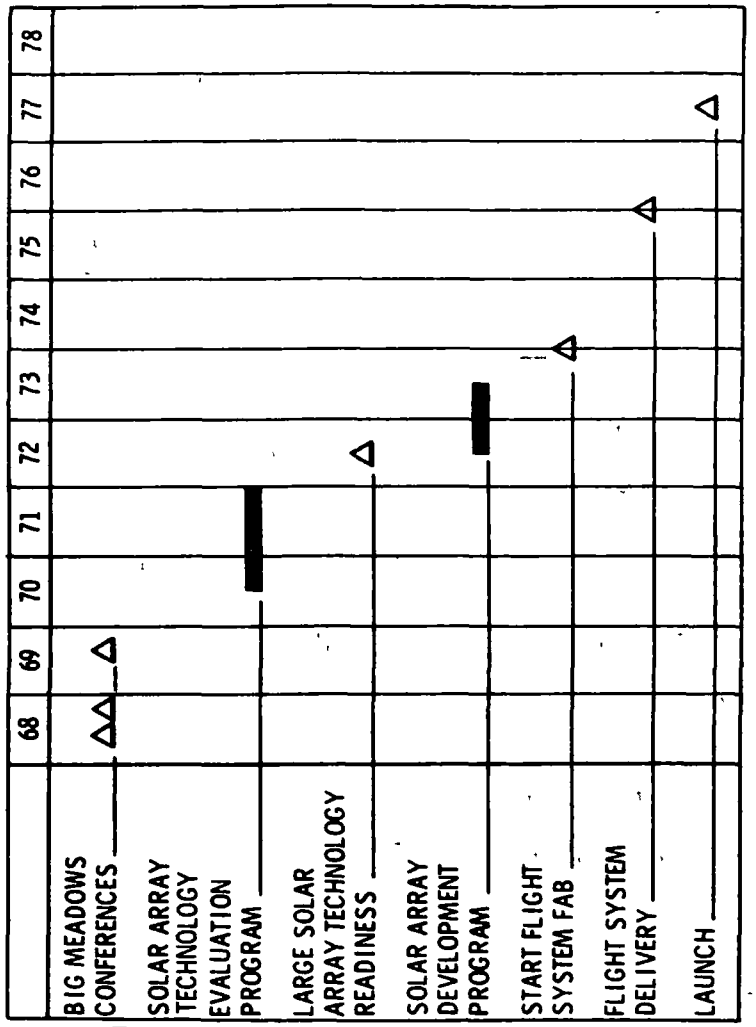


Fig. 1-1 Large Solar Array Development Program

high level of confidence that remaining problems can be solved by reasonable engineering solutions in a development and qualification program of approximately 42 months

The main sections of this report are as follows

2 Summary of Results – Discussion of degree of applicability of present technology to the Space Station Solar Array and a descriptive list of recommended projects.

3 Study Methodology and Data Source Review – Description of data collection and evaluation methods and review of data sources

4 Technology Evaluation – Presentation, in matrix format, of available technology and discussion of that technology for Space Station application.

5 Recommended Technical Projects – Summary and plans for recommended projects. These projects are listed by the following categories

Category I Projects planned under the MSC Space Station solar array contract.

Category II. Additional projects required to insure technology readiness.

Category III. Additional projects for significant downstream improvement.

6. Bibliography – Listing in alphabetical order of documents used for reference in compiling this report. There are two major sections: (1) Solar Array and Structure report and (2) Orientation and Power Transfer Reports.

Section 2
SUMMARY OF RESULTS

Evaluation of the data presented in this report indicates that much of the basic technology needed to develop a Space Station solar array is available; however, a number of unanswered questions have emerged with respect to applicability of this basic technology and these questions stem almost completely from the following three unique Space Station Solar Array requirements

- Ten-year lifetime goal (over 58,000 day/night cycles) in low earth orbit.
- The 10,000 square foot size – forty times larger than the largest experimental flexible solar array.
- On-orbit loads of up to 1g – ten times larger than the most severe previously known design requirement.

To objectively consider those unique requirements and determine how applicable the available technology is, it was necessary to "box in" the predicted mechanical loads and environmental extremes. This was done and the available data in each area are discussed with respect to those requirements.

The bulk of the report is contained in Section 4, Technology Evaluation, however, an important part of the task was to define the technical effort required between now and June 1972 to ensure technology readiness Therefore, the work accomplished is summarized below in two parts (1) a discussion of the available technology applicable to the Space Station array development task, and (2) the recommended additional effort that must be undertaken to qualify that technology for direct application to the Space Station Solar Array.

2 1 APPLICABLE TECHNOLOGY SUMMARY

2 1.1 Solar Array Structures

Mechanisms and structures for deploying rigid solar arrays have been used on flight systems which were operational for up to two and a half years and mechanisms and structures for array areas up to 1200 ft^2 have been developed and qualified It is not

practical to scale these rigid systems up to areas of 10,000 ft^2 because they result in excessive storage volumes and weights. On the other hand, flexible substrate array components have scale-up potential to space station requirements, but have not been flight proven and will not be until the Hughes Aircraft Company array is flown on the LMSC/Air Force SESP Program Deployable structures such as the reel-stored tubular beam have flight experience but not in the size necessary to support a large solar array in an artificial-g mode This technology can be sized up, but limitations in beam material fabrication coupled with the allowable diameter/thickness ratios dictate the maximum producible size, which is presently about 6 inches in diameter for a 2-element boom Truss booms, the most appealing from a stiffness to weight ratio, have no recorded flight experience

Ultra-lightweight trusses up to 100 ft long have been developed for specific antenna applications and will be qualified within two years Other technology is available in extendible trusses and folding beam trusses that have been developed and successfully operated for ground applications Here evaluation and modification will be necessary to qualify them for remote retraction and flight environment capabilities

2 1 2 Flexible Substrate Assemblies

The three major flexible array programs currently being qualified for flight are the Hughes roll-up flexible array, that will fly on the Air Force SESP program in mid 1971, the General Electric roll-up flexible array, that was developed for interplanetary probes, and the Lockheed fold-up flexible array, that was designed for a classified low earth orbit mission The flexible substrate and solar cell assembly techniques, the flexible array packaging techniques, the extension techniques, and the sheet tensioning mechanism are all applicable to the Space Station solar array Extended temperature cycle lifetime and increased sheet tension requirements, however, will require additional design and development effort and careful evaluation of this technology for Space Station use

2 1.3 Orientation Drive System

Motor technology is adequate and directly applicable to Space Station use Most prevalent motors used for drive have been DC brush type, DC stepper, and AC and DC servo. Lubricating bearings and brushes to satisfy ten-year life requirements, however, presents a major design task The ATM roll axis drive system is 10 feet in diameter, provides 150 degrees of rotation and provides power transfer through flex cables. This is actually larger than the drive anticipated for this application and, although the system is not completely qualified, the design and components developed for use must be considered applicable The largest bearing flown to date was a 9-inch outside diameter bearing flown on the BAPTA TACCOM SAT Spacecraft built by Hughes, however, bearings in excess of four feet have been built and used extensively for ground applications Hayden Engineering Corp., Rotek Inc., and Messinger Bearings Inc. have all made bearings with bores in excess of five-foot diameter.

Predominant types of lubricants used were greases and oils (F-50 oil, G300 grease, Bray Oil NPT-4, KK949B grease plots, and liquid VAC KOTE), however, bearings with dry film lubricant have been successfully used in array drive applications of one-year lifetime. Lubrication technology is available Methods of application and retention for 10-year lifetime must be designed and evaluated

2 1.4 Power Transfer

Slip rings are the most universally used transfer devices across rotary joints. That technology was highly advanced from experience gained with high altitude aircraft during World War II, and was adopted when the need arose for space applications. Current densities used in flight programs are normally 75 to 300 amp per square inch of brush area This technology in terms of power capability is adequate and directly applicable to the Space Station Orbiting Solar Observatory (OSO) III has operated successfully using slip ring power transfer for three and a half years and is still performing normally. Tradeoffs will have to be made between maintainability

and power transfer efficiency for ten-year lifetimes In a survey of slip ring manufacturers, seven companies stated that they have the necessary capability to fabricate power-type slip rings that would satisfy all Space Station requirements except the ten-year lifetime

Other methods of power transfer are available and will be studied The flexible cable technology developed for ATM can be directly applicable to this program if continuous rotation in both axes is not required. Rotary transformer technology is available to satisfy Space Station requirements, however, in all past studies, the rotary transfer losses in the final tradeoffs because of high weight and low efficiency A second consideration is that conversion to AC must be accomplished on the array side Other power transfer concepts, such as the power clutch and liquid metal slip rings, can be considered if that technology is developed and tested prior to the technology readiness deadline.

2 2 SUMMARY OF RECOMMENDED TECHNICAL PROJECTS

Technology breakthroughs are not required, however, additional advanced development is required in virtually every major hardware category to prove the feasibility of evaluating and meeting the ten-year lifetime goal and to evaluate problems associated with the forty-fold scale-up in size for the largest flexible solar array in existence today. A major effort will be to determine the applicability of the vast amount of available flexible array technology where no flight experience exists.

As a result of the Technology Evaluation, studies or test programs have been recommended in the following three categories

- Category I – Projects which will be accomplished under the Space Station Solar Array Technology Evaluation Program
- Category II – Additional projects that must be accomplished to ensure technology readiness
- Category III – Additional projects that, if accomplished, will provide significant downstream improvements

Following is a list of the recommended projects in each category Detailed plans and scheduling for each of the projects are contained in Section 5

Category I

- Space Station Shading Study
- Basic Substrate Materials Evaluation
- Substrate Packaging Evaluation
- Deployable Structure Test and Evaluation
- Deployment Drive and Tensioning Mechanism Evaluation
- Full-Scale Array Assembly Testing
- Lubrication Tests
- Drive Motor Evaluation
- Full-Scale Drive System Evaluation
- Maintainability Study – Bearings, Brushes, Motors
- Tracking System Duty Cycle Analysis
- Slip Ring Material Evaluation
- Flexible Cable Evaluation
- Full-Scale Power Transfer Tests

Category II

- Temperature Cycling Program
- Flexible Interconnect Development
- Solderless Joining Techniques
- Ultraviolet and Irradiation Tests of Flexible Substrates
- Flexible Substrate Solar Array Thermal Properties Determination
- Storage and Life Testing of Erection/Retraction Components
- Array/Station Interaction Study
- Testing of Alternate Large Bearing System
- Extended Life Testing of Orientation and Drive System
- Environmental Life Tests, Power Transfer Assembly

Category III

- Teflon Cover Evaluation
- Integral Solar Cell Covers
- Improvement of End-of-Life Solar Cell Efficiency
- Wrap-around Contact Solar Cells
- Standardization of Solar Cell Specifications
- Cost Effective Cell and Cover Procurement Study
- Integrated Power Modules With On-Array Electronics
- Optical Filter Evaluation
- Composite Structure Material and Joining Technique
- Test and Evaluation of Alternate Power Transfer Device

Section 3
STUDY METHODS AND DATA SOURCE DISCUSSION

To conduct a comprehensive review of the technology potentially applicable to space station solar arrays, several data acquisition/extraction methods were used. At the outset of the program the services of the Lockheed Technical Information Center (TIC) staff was arranged so that professionals would be involved in performing data acquisition. In like manner, the library staff at Ball Brothers Research Corporation (BBRC) was used to assist in data gathering rather than involving program personnel. The TIC activity was concentrated initially in conducting computer surveys using descriptors which were representative of the data desired, such as extendible structure, slip ring, flex cable, flexible array, etc. These searches were augmented by personal contact with the major government and industry centers listed in Table 3-1. These contacts served to supplement and clarify the published data, and were of particular value in assessing technology gaps and listing testing capabilities. Another method of published data augmentation was to correspond via mail or telecon with those engineers who have been or are still active in the applicable associated disciplines.

Figure 3-1 outlines the literature search and evaluation methods employed. In addition to the initial searches, TIC also has conducted daily surveillance since contract start-up The major items of review in this activity have been technical and scientific abstracts distributed periodically Also reviewed as received are technical journals, technical paper title/author listings, and regularly received reports Similar to the outputs from the computer search, summary lists were submitted to program engineering as depicted in Fig. 3-2, and pertinent reports were ordered. In all, over 1000 reports were reviewed.

The data accumulated and categorized have been used extensively in this topical report and will be of great value in continuing contract tasks In addition to the employment of specific data from the references in the various topical sections of this report, each reference was listed in the bibliography along with an indication of the subject matter covered and its applicability to the Space Station Solar Array design problems

Table 3-1

TECHNOLOGY REVIEWS

Industry		Government Centers		
Company	Area of Specialty	Division	Agency	Area of Specialty
NAR	Space Station Configuration	NASA	JPL	Sponsoring Center on 20 w/lb Rigid and 30 w/lb Flexible Arrays
Boeing	Lightweight Rigid Arrays/CdS Tests		MSFC	ATM and OWS Large Deployable Arrays
TRW	Flexible Folding Array		GSFC	Kapton and ADHS, Evaluation Temperature Cycle Testing
GE	Flexible Rollup Array		LeRC	CdS Cells/FEP Cell Covers/Temperature Cycle Testing
F-H	Flexible Rollup Array Deployable Structures Dynamic Analysis		LRC	Structural/Dynamic Analysis
Hughes	Flexible Rollup Array		MSC	Space Station Solar Array
Martin	Large-Scale Solar Array Tests	Air Force	AFAPL	Sponsor of Hughes FRUSCA/Array/Cell Testing and Radiation Hardening
Astraomast	Deployable Structures		SAMSO	Air Force Satellite Electrical Power
Spar	Deployable Booms	Private	COMSAT	Solar Cell and Array Technology
OCLI	Solar Cell Covers	Navy	NRL	Radiation Testing
ION Physics	Integral Cell Covers			
Heliotek	Solar Cells			
Centralab	Solar Cells			
Clevite	CdS Cells			
SJI	Solar Panel Fabrication			
EOS	Solar Panel Fabrication			
Mit-Lincoln Labs	Module Temperature Cycle Tests			

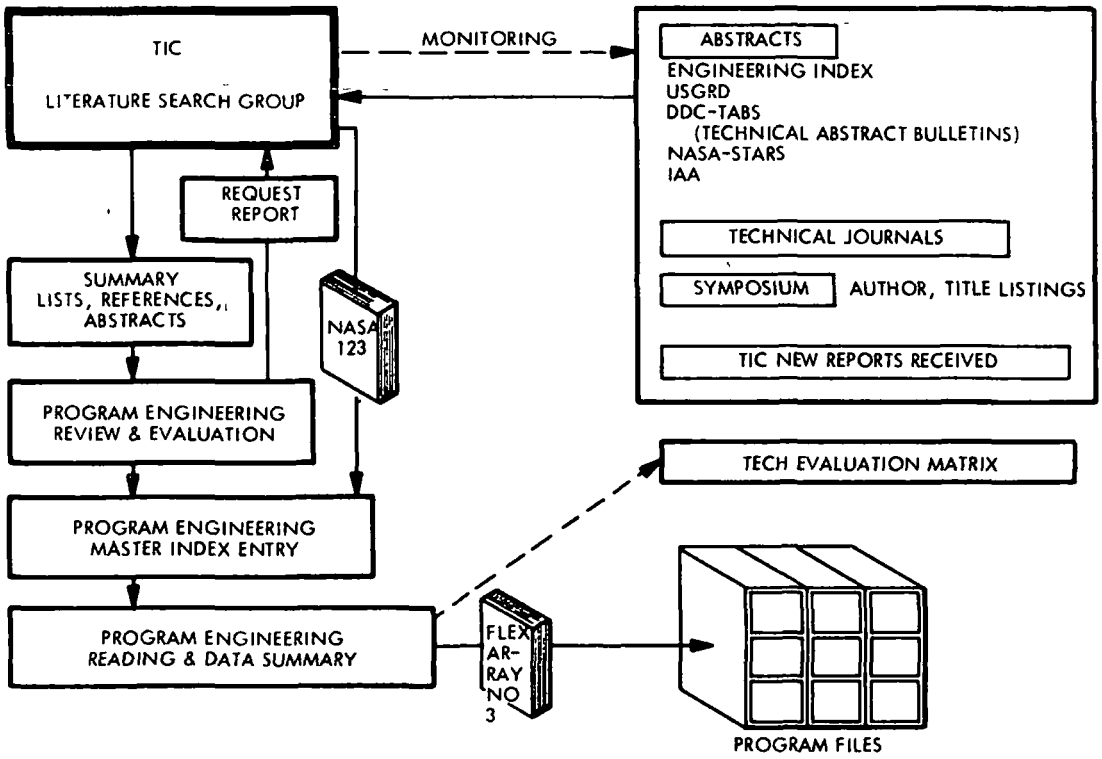


Fig 3-1 Technology Evaluation Data Sources, Daily Surveillance

FUNCTION	TOOL	SOURCE	OUTPUT	
			CATEGORY	TYPE
COMPUTER SEARCH	DESCRIPTORS	LOCKHEED-TIC FILM CATALOG INDEX TECHNICAL INFORMATION CENTER PALO ALTO & SUNNYVALE CALIF.	UNCLASSIFIED CLASSIFIED SRD	REPORT NO, TITLE AND ABSTRACT
	DESCRIPTORS	NASA-SCIENTIFIC AND TECHNICAL INFORMATION FACILITY COLLEGE PARK, MD	UNCLASSIFIED CLASSIFIED	REPORT LISTING
	DESCRIPTORS (REGISTER CONTRACT NO.)	DDC DEFENSE DOCUMENTATION CENTER ALEXANDRIA, VA.	UNCLASSIFIED CLASSIFIED SRD	REPORT BIBLIOGRAPHY
	DESCRIPTORS	USGRD-GOVERNMENT RESEARCH & DEVELOPMENT REPORTS	UNCLASSIFIED OPEN LITERATURE	REPORT LISTING
	DESCRIPTORS	AEROSPACE RESEARCH APPLICATIONS CENTER BLOOMINGTON, INDIANA	UNCLASSIFIED	REPORT LISTING
MANUAL BACKUP	CATALOG LISTING	NASA-CFSTI CLEARINGHOUSE FOR FEDERAL, SCIENTIFIC, AND TECHNICAL INFORMATION SPRINGFIELD, VA	UNCLASSIFIED	NASA REPORT LISTING INTERNATIONAL AEROSPACE ABSTRACTS REPORTS MICROFISCHE
	MICROFILM INDEX	TIC-PREVIOUS ABSTRACTS		

Fig 3-2 Technology Evaluation Data Sources, Initial Search

Section 4

EVALUATION OF AVAILABLE TECHNOLOGY

All data and information derived from the solar array technology search are presented in this section. The material was reviewed and tabulated by subject title and a liberal use has been made of tabs to aid the reader in referring to the topical sections.

4.1 Solar Array and Structure

4.1.1 Flexible Array Systems
4.1.2 Solar Array Structures
4.1.3 Solar Array Substrate Assemblies

4.2 Orientation Drive and Power Transfer Systems

4.2.1 Review of Flight Proven Systems
4.2.2 Drive Assemblies
4.2.3 Power Transfer Devices
4.2.4 Lubrication
4.2.5 Continuous Drive vs Reset Systems for LSSSA

It was intended that this section of the report be as much like a handbook as possible in order to maximize its utility. Therefore, wherever possible technical information was condensed into tabulated charts for easy reference and use, and narrative was held to a minimum. These charts are identified differently in the two major subject divisions as follows

Section 4.1 Solar Array and Structure

Charts are identified with a single letter A, B, C, etc. There may be more than one page to each chart, however, all charts on the same subject will be identified with the same letter. Items in the charts are numbered consecutively. A reference to Chart A-7 would indicate item 7 on Chart A.

Section 4.2 Orientation and Power Transfer

Charts are identified with double letters AA, BB, CC, etc. Items in the charts are numbered consecutively as in par. 4.1. A reference to Chart BB-9 would indicate item 9 in Chart BB.

In each subject section, a discussion and evaluation of information available on that subject is included. Gaps or "holes" in the technology are indicated in each section. Based on these evaluations, recommended supplemental technology effort is described in Section 5.

4.1 SOLAR ARRAY AND STRUCTURE

The material in this section includes the structural, mechanical, electrical, and material data pertinent to design of the flexible solar array substrate and deployable structure components of the Space Station Solar Array system.

The technology is discussed in three sections

- Flexible Array Systems (4.1.1) – Lessons learned from integrated flexible array systems developed to date.
- Solar Array Structures (4.1.2) – Basic structural approaches and technology applicable to deployment, retraction, and packaging hardware.
- Solar Array Assemblies (4.1.3) – Technology applicable to electrical, mechanical, and thermal design of the power-producing flexible module assembly.

The first two sections, 4.1.1 and 4.1.2, constituted the most difficult areas to evaluate in this entire study since the extremely large structural scale-up associated with the Space Station Solar Array results in only conceptual fallout in the overall structural design area. In the substrate assembly area (4.1.3), by contrast, a wealth of directly applicable data is available.

4 1 1 Existing Flexible Array Systems

Some of the most fruitful sources of flexible array design information are the flexible array development programs listed in Chart A at the end of section 4 1.1.1.

The earliest flexible array program was that sponsored by NASA-GSFC with Fairchild-Hiller for application of a spin-stabilized satellite. Shortly thereafter in 1965, Ryan started flexible array work under JPL sponsorship and Hughes started similar activities for the Air Force All the early flexible array designs incorporated drums as the stowage device

Even though lightweight flexible arrays have yet to be flown, in less than a decade ten companies have, with or without specific contract impetus, recognized the reduced volume, weight savings, and growth potential associated with flexible arrays and have conducted significant development programs.

This section discusses and evaluates the information available from these flexible array development programs including overall design characteristics (4.1 1 1), test experience (4 1.1 2), and dynamic analysis techniques (4 1 1 3) One of the areas where lessons learned can be applied directly to Space Station systems is in solar array packaging.

The three basic packaging design approaches employed to date - drum roll-up, flat spindle, and flat pack - are evaluated in 4.1 1 4 as to their potential application to the Space Station solar array.

4 1 1 1 Design Characteristics of Existing Flexible Arrays

The ten companies involved in the design and development of solar arrays using a flexible substrate are evenly divided in their selection of stowage approaches Five designs (GE, Fairchild-Hiller, Hughes, Ryan, BAC) utilize a drum roller stowage approach and five designs (Boeing, TRW, LMSC, RAE, Messerschmidt-Bolkow-Blohm) use the flat fold-out Lockheed has also built and tested a flat spindle design

Chart A, General Description of Current Flexible Arrays, lists the following evaluation factors to review and compare the flexible array design configurations for applicability to the LSSSA The chart also briefly describes the solar array systems and is followed by photographs of the hardware used in their development and test.

- Packaging (See also Section 4.1.1.4)
  - Stowage method
  - Padding for cell protection during launch and ground handling (Techniques and material)
  - End supports
  - Power transfer
- Tie-down and release
- Deployment/retraction capabilities
- Tensioning method after deployment
- Deployed area
- Stowage volume
- Weight summary

A brief discussion on each of the these factors follows.

4.1.1.1.1 Packaging

Stowage Method

Drum Roller. Flexible panels (solar cells, substrates, coverglass, and interconnects), are wrapped around a drum roller, similar to that of a window shade. The panels are rolled on the drum so that the solar cells are on the outside faces of the consecutive layers

The drum diameters used range from 5 to 12 in with size selection based primarily on engineering judgement Length of the drums is from 1 ft 8 in. to 9 ft The length and diameter selection was made to satisfy a definite area requirement The Hughes design had two sets of panels interwound around a single drum so that when deployed they were 180 deg from each other One of the Fairchild-Hiller configurations has two back-to-back panels each on its own 1 5 ft diameter drum, with the deployment mechanism centered between them This was a spinning vehicle design and is therefore not applicable to the Space Station.

Flat Spindle. In the Lockheed flat spindle, panels are wrapped around a spindle, similar to that of a bolt of fabric The layer sequence is such that the cell area of each wrap lies on the flat surface of the spindle. There are no cells where the panels form a fold at the bend area The panels are wrapped on the spindle so that the solar cells are on the outside faces of the consecutive layers A 0 50 in thick bv 9 in wide by 67 in long spindle was fabricated and used in a concept feasibility demonstration model

Flat Fold-out Panels lay Z-folded on a pallet with the cells surfaces of every other fold facing each other There are no cells at the bend areas of the panels TRW's design was based on 250 ft^2 with a pallet area of 28 in. by 86 in. LMSC's design, based on 90 ft^2 with capability to increase its length 2 5 times, has a pallet area of 18 in by 72 in The Royal Aircraft Establishment design has an area of 39 ft^2 and the pallet size is 2.5 in. by 36 in The Boeing periphery frame design has five main panels Each of the outer four main panels has a pair of auxiliary panels hinged to the side member of its frame When stowing, the auxiliary panels fold inward 180 deg to lie on its respective main panel The four panel assemblies (main and auxiliary) and the inboard main panel then fold (Z-shaped) into a compact package Messerschmitt-Bolkow-Blohm subpanels with inflatable periphery foil hoses are first Z-folded onto the main panels The main panel and subpanel assemblies are then either wrapped around the vehicle structure or are Z-folded into a neat stack

Padding Technique and Material

Drum Roller. Both the GE and Ryan designs used foam buttons bonded to the rear surface at the corners of the cells. Fairchild-Hiller uses foam strips bonded to the rear surface in a lengthwise direction with magnesium strips bonded 90 deg to the foam strips Hughes and British Aircraft Corporation use embossed Kapton and a thin foam sheet respectively, which are interwound with the wrapped panels Each has its own take-up reel.

Flat Spindle This Lockheed design utilized foam buttons bonded to the rear surface

Flat Fold-out. TRW uses small rectangular foam pads bonded to the cell side of the panels LMSC and Messerschmitt use a fold size cushioning sheet inserted between cell-to-cell surfaces Boeing's design requires no padding. The rigid framework and substrate tension prevent the panels from coming in contact when folded together

End Supports

Drum Roller/Flat Spindle. All designs except one are end supported and require bearings, end caps, axles, etc. The one exception (General Electric) is end-supported during launch only. Prior to panel deployment the outboard end supports are released and, once released, the two drums are cantilevered from the center support This approach was feasible because of the low tension load requirements in the deployed array

Flat Fold-out. This technique does not require end supports

Support Structure

Drum Roller/Flat Spindle. Drum Roller/Flat Spindle systems are limited to attachment patterns at the ends only Any load variations must be taken into account prior to initial design and may require significant changes for multiple usage.

Flat Fold-out. Attachment patterns can be modified with very few design changes for multiple usage applications.

Power Transfer

Drum Roller/Flat Spindle. Either slip ring assemblies or coiled harnesses are used

Flat Fold-out None required.

4 1 1 1 2 Tie-down and Release

Lockheed, General Electric, Boeing, and Royal Aircraft Establishment use pyrotechnic devices such as a preloaded pin puller, explosive bolt, nut, or guillotine Fairchild-Hiller employs a solenoid that disconnects a lock device A pin puller can also be used, and is an alternate design Ryan uses two electric motors (one to deploy, the other to retract) connected to a gear train on the drum roller The system is locked in place as long as no current is available Information on the Hughes, BAC, TRW, and Messerschmitt designs was not available at the time of this survey

4.1.1.1 3 Deployment/Retraction

Seven of the design approaches use a reel-stored extendible tubular device to perform deployment and retraction. Fairchild-Hiller uses a folding arm linkage system. Boeing's design incorporates a tie-down system that, when released, starts two motors to deploy the main panels. The pair of four auxiliary panels sequentially unlatch and deploy by torsion springs. Messerschmitt employs a block and tackle arrangement to deploy the main panels. Once fully deployed, the framework (foil hoses) of the subpanels are pneumatically inflated and are rigidized by a gelatine glass fiber laminate. Ten to twenty hours are needed to achieve complete rigidity under environmental conditions. This design once deployed and rigidized in space cannot be retracted.

4.1.1.1.4 Tensioning Methods

General Electric, Hughes, and British Aircraft Corporation use the reel-stored extendible tubular device driven out by electric motors and reacted by a negator motor Fairchild-Hiller employs the folding arm linkage which, during the final half revolution, is counteracted by a torsion spring that provides a retracting or tensioning force. Ryan uses two electric motors (deploying and retracting) that work in unison through an electronic sensing system. The retracting motor imposes a drag on the drum, resulting in the proper panel tension Motors lock when current is off Lockheed uses the reel-stored extendible tubular device, counteracted by springs which can be adjusted to maintain proper panel tensions In the Boeing design the frame is used to pre-tension the flexible substrate of the panels. Messerschmitt

applies tension to the subpanels during deployment by pneumatically inflating the frame The main panels are rigid and do not require tension. Information for the TRW and RAE designs was not available for this survey Extended array tension forces for all these systems range from 0 55 to 1 6 lb/ft of substrate width, considerably less than the 40 lb per foot estimated for the artificial-g mode of the Space Station Solar Array

4.1.1 1 5 Deployed Area/Stowage Volume

In the area and volume columns of Chart A, six design approaches were normalized to establish a deployed area and stowage volume comparison Two of the designs were scaled-up (Hughes and LMSC) and one was scaled-down (Ryan) to give an equivalent area of 250 ft^2 for comparison purposes. Stowage volume was normalized on the basis of this deployed solar array size. Hughes and LMSC actual areas are 166 ft^2 and 90 ft^2, respectively, and both have the capability to be easily scaled up to 250 ft^2 without a significant increase in stowage volume The Ryan design has a deployed area of 280 ft^2 because its outermost panel is a protective blanket. Here again the change in stowed volume is insignificant The Boeing, RAE, and Messerschmitt designs were not considered because they were for a specific requirement and could not be extrapolated objectively

The stowage volume requirement is an important consideration for Space Station solar array design. For ease of comparison of available flexible arrays the normalized volume data is summarized below:

Company	Stowage Method	Volume (ft^3)
TRW	Flat fold-out	1.90
LMSC	Flat fold-out	1.95
F-H	Drum roller	2.03
Hughes	Drum roller	2.30
GE	Drum roller	3.54
Ryan	Drum roller	6.30

GENERAL DESCRIPTION OF CURRENT FLEXIBLE SOLAR ARRAY SYSTEMS

SOURCE	STOWAGE METHOD	DESCRIPTION	ILLUSTRATION	PADDING FOR CELL PROTECTION DURING LAUNCH AND GROUND HANDLING		END SUPPORTS	ATTACHMENT TO STRUCTURE	POWER TRANSFER	TIE-DOWN AND RELEASE	DEPLOYMENT/RETRACTION CAPABILITIES	TENSIONING METHOD	CELL AR (FT²)
				TECHNIQUE	MATERIAL							
GENERAL ELECTRIC	DRUM ROLLER 1	STOWAGE IS ON TWO IDENTICAL 8 0 IN DIA x 47 0 IN LONG CYLINDRICAL DRUMS WHICH STRADDLE A SINGLE 81 STEM BOOM ACTUATOR THE DRUM MATERIAL IS CROSS-ROLLED BERYLLIUM SHEETS IN ADDITION TO STOWING THE PANEL THE DRUM HOUSES THE BEARINGS A CONSTANT TORQUE SPRING MOTOR AND SLIP RINGS REMOVABLE END CAPS ALLOW EASY ACCESSIBILITY		CUSHIONING BUTTONS ARE PLACED ON THE REAR SURFACE OF THE PANELS (ARRAY BLANKET) AND AT THE CORNERS OF EACH SOLAR CELL BUTTONS SUPPLY THE INTERLAYING CUSHION ING IN THE STOWED CONFIGURATION; AS THE PANELS ARE WOUND AROUND THE DRUM THE BUTTONS OF THE NEXT WRAP LAY AGAINST THE CELL SURFACE OF THE PREVIOUS WRAP DURING ROLL-UP, TENSION IS APPLIED TO THE PANELS SO AS TO OBTAIN A TIGHT WRAP ON THE DRUM. WHEN THE ROLL-UP IS COMPLETE, THE CELL SUR FACE OF THE FINAL WRAP IS EXPOSED	FORMED RTV 560 (ROOM TEMPERATURE VULCANI ZER) CUSHIONING BUT TONS 0 250 DIA x 0 040 THICK	BOTH STORAGE DRUMS ARE MOUNTED TO A CENTER SUPPORT; ATTACHMENT IS BY A SHAFT WITH A PRELOADED PAIR OF BALL BEARINGS ON THE INBOARD END OF THE STORAGE DRUM IN THE STOWED (LAUNCH) POSITION THE OUTBOARD END IS SUP PORTED BY AN ARM WHICH IS MOUNTED TO THE VEHICLE STRUCTURE THIS OUTBOARD END SUPPORT PREVENTS THE DRUM FROM ROTATING ABOUT ITS OWN AXIS AND SUPPORTS THE OUTBOARD ENDS OF THE LEADING EDGE MEMBER WHEN THE ARRAY DEPLOYS THE OUT BOARD END SUPPORTS RELEASE AND EACH DRUM IS CANTI-LEVERED FROM THE CENTER SUP PORT STRUCTURE	IN THE STOWED (LAUNCH) POSITION THE SOLAR ARRAY ASSEMBLY IS ATTACHED TO THE VEHICLE FROM THE CENTER SUPPORT STRUCTURE AND THE DRUM OUTBOARD END SUPPORT ARMS. IN THE DEPLOYED CON DITION THE OUTBOARD END SUPPORT ARMS ARE RELEASED AND THE DRUMS ARE CANTI LEVERED FROM THE CENTER SUP PORT STRUCTURE	METHOD IS BY SLIP RING ASSEMBLY WHICH IS HOUSED IN SIDE THE PANEL STORAGE DRUM THE SLIP RING ASSEMBLY IS DESIGNED AND DEVELOPED BY POLY-SCIENTIFIC DIVISION OF LITTON PRECISION PRODUCTS INC	THE MOVABLE END SUPPORT TIES DOWN THE LEADING EDGE MEMBER (LEM) DRUM AND THE SOLAR ARRAY IN A LOCK CONDITION TO RELEASE THIS LOCK CONDITION A BOLT THAT PREVENTS THE ROTATION OF THE MOVABLE END SUPPORT UNDER PRELOADED CONDITION IS RELEASED BY AN ELECTRO-EXPLOSIVE SEPARA TION NUT WHEN THE SEPARATION NUT IS ACTUATED THE HINGED ARM ROTATES AWAY FROM THE DRUM AND THE LEM THROUGH THE ACTION OF A TORSION SPRING ONCE THE SUPPORT ARM PIVOTS OUT OF THE WAY THE DRUM IS FREE TO ROTATE ABOUT ITS OWN AXIS AND THE LEM IS FREE TO MOVE OUTWARD WHEN THE BOOM IS DEPLOYED	A SINGLE 1-3/8 IN DIA 81-STEM BOOM ACTUA TOR CENTERED AND ATTACHED BETWEEN TWO DRUMS AT THE BASE AND CONNECTED TO THE PANEL AT THE OUTBOARD SIDE BY THE LEADING EDGE MEMBER DEPLOY AND RETRACT THE PANELS A CONSTANT TORQUE SPRING MOTOR WHICH ACTS AS A BRAKE MAINTAINS PROPER TENSION ON THE PANELS DURING DEPLOY MENT AND RETRACTION WHEN RETRACTING THE ROLL-UP TENSION RESULTS IN A TIGHT WRAP AROUND THE DRUM THIS TIGHTNESS IS DEPENDENT UPON ITS TENSIONING SYSTEM AND CANNOT BE INDEPENDENTLY VARIABLE EACH DRUM IS ALSO 1 0 IN WIDER THAN THE PANEL ON EACH EDGE OVERHANG IS NECES SARY FOR PANEL TRACKING WHEN RETRACTING	DEPLOYED ARRAY WITH A RESON ANT FREQUENCY ABOVE 0 099 Hz REQUIRES A PRELOAD OF 0 55 LB/FT IN EACH ARRAY BLANKET THIS IS ACCOMPLISHED BY MOUNTING A NEGATOR CONSTANT TORQUE SPRING MOTOR IN EACH DRUM WHICH COUNTERACTS THE FORCE OF THE 81 STEM BOOM	250
FAIRCHILD-HILLER	DRUM ROLLER 2	STOWAGE IS ON A 5 0 IN DIA x 9-FT LONG THIN-WALLED GRAPHITE/EPOXY CYLINDRICAL DRUM ENDS ARE STABI-LIZED BY ALUMINUM CAPS THAT ARE MACHINED AND THEN CHEMICALLY MILLED TO OBTAIN VERY THIN WALLS THE END CAPS AND DRUM ARE THEN RIVETED TOGETHER AN ALUMINUM SPROCKET IS ATTACHED WITH SCREWS TO ONE OF THE END PLATES		CUSHIONING STRIPS ARE PLACED AND BONDED IN A LENGTHWISE DIRECTION AND COVER APPROXIMATELY 25% OF THE REAR SURFACE OF THE PANEL THESE STRIPS ARE THE CUSHIONING LAYERS IN THE STOWED CONFIGURATION IN ADDITION THERE ARE A NUMBER OF EQUALLY SPACE MAGNESIUM STRIPS BONDED 90-DEG TO THE CUSHIONING STRIPS AND THEY ADD LATERAL STIFFNESS TO THE PANELS AS THE PANELS ARE WOUND AROUND THE DRUM, THE STRIPS OF THE NEXT WRAP LAY AGAINST THE CELL SURFACE OF THE PREVIOUS WRAP ALSO TENSION IS APPLIED TO THE PANELS TO OBTAIN A TIGHT WRAP ON THE DRUM WHEN THE ROLL IS COMPLETE, THE CELL SURFACE OF THE FINAL WRAP IS EXPOSED	STRIPS RUNNING LENGTH-WISE ARE MADE OF 0 021 IN THICK x 0 312 IN WIDE POLYURETHANE FOAM LATERAL STIFF-ENERS ARE MADE OF 0 023 IN THICK BY 0 188 IN WIDE MAG NESIUM STRIPS	INDEPENDENT SHAFTS, MOUNT ED IN THE BEARINGS OF EACH END PLATE ARE USED TO SUP-PORT THE ROLLER AT ITS RES-PECTIVE HUB EACH SHAFT HAS A THREADED END WHICH IS SCREWED INTO THE HUB AND IS LOCKED TO THE ROLLER BY MEANS OF A SELF-LOCKING PLATE NUT AFFIXED TO THE HUB	END PLATES PROVIDE SUPPORT FOR THE SOLAR ARRAY ASSEM BLY AND TIE IT TO THE VEHI-CLE STRUCTURE PROVISIONS ARE MADE ON THE END PLATES TO SUPPORT THE ROLLER DRIVE SYSTEM, SPREADER BAR AND PULLEYS A BRACKET HOUS ING THE BEARINGS THAT SUP-PORTS THE ROLLER IS MOUNT-ED ON THE END PLATE AS IS A FITTING FOR SUPPORTING ELE-MENTS OF THE DRIVE SYSTEM PULLEY GUIDES AND SNUBBERS ARE MOUNTED ON THE END BRACKETS TO POSITION PULLEYS AND TRANSFER THE FOLDING ARM SYSTEM INERTIA LOADS TO THE BASE STRUCTURE	METHOD IS BY SLIP RINGS WHICH ARE MOUNTED ON ONE END OF THE PANEL STORAGE DRUM	THE SPREADER BAR HOLDS THE LINKAGE ASSEMBLY ARRAY PANELS AND ITS ROLLER IN A LATCHED CONDITION TO THE PRIMARY STRUC TURE OF THE SPACECRAFT TO RELEASE THE SYS-TEM, TWO METHODS WERE CONSIDERED ONE METHOD EMPLOYS A SOLENOID THE OTHER AN EXPLOSIVE BOLT FUNCTIONALLY BOTH SYS TEMS ATTAIN THE SAME RESULTS — RESTRAINING THE SPREADER BAR THE SOLENOID METHOD USES A MECHANICAL LATCH AND LINK AND HAS RELATCHING CAPABILITY THE EXPLOSIVE BOLT METHOD REQUIRES ONLY A TIE-PLATE WHICH SEPARATES UPON RELEASE BUT DOES NOT HAVE RELATCHING CAPABILITY THE RELEASE OF THE SPREADER BAR FROM THE END PLATE ACTUATES THE ELECTRIC MOTOR WHICH DEPLOYS THE COM BINATION OF FOLDING ARMS PULLEYS AND CABLES FOR EXTENDING THE SOLAR ARRAY	FOLDING ARM LINKAGE SYSTEM INTEGRATES WITH THE DRUM ROLLER BY TWO DRIVE TRAINS OPERATIONAL POWER IS PROVIDED BY A SMALL TURE OF THE SPACECRAFT TO RELEASE THE SYS-TEM, TWO METHODS WERE CONSIDERED ONE METHOD EMPLOYS A SOLENOID THE OTHER AN EXPLOSIVE BOLT FUNCTIONALLY BOTH SYS TEMS ATTAIN THE SAME RESULTS — RESTRAINING THE SPREADER BAR THE SOLENOID METHOD USES A MECHANICAL LATCH AND LINK AND HAS RELATCHING CAPABILITY THE EXPLOSIVE BOLT METHOD REQUIRES ONLY A TIE-PLATE WHICH SEPARATES UPON RELEASE BUT DOES NOT HAVE RELATCHING CAPABILITY THE RELEASE OF THE SPREADER BAR FROM THE END PLATE ACTUATES THE ELECTRIC MOTOR WHICH DEPLOYS THE COM BINATION OF FOLDING ARMS PULLEYS AND CABLES FOR EXTENDING THE SOLAR ARRAY	FRICTION DRAG BRAKE CREATES TENSION WHILE DEPLOYING DUR ING THE LAST HALF-REVOLUTION BY MEANS OF ENGAGING A TOR SION SPRING THIS MAINTAINS A TENSION OF 1 2 LB/FT IN THE SUBSTRATE AFTER DEACTI VATION OF THE DRIVE SYSTEM LOADING AND POWER REQUIRE MENTS TO THE DRIVE SYSTEM ARE MINIMIZED DURING THE DEPLOYMENT PHASE.	250
FAIRCHILD-HILLER	DRUM ROLLER 3	TWO ARRAYS ARE STOWED BACK TO BACK, WOUND ON SEPARATE 1 5 IN DIA DRUMS WITH THE COMMON OUTBOARD END ATTACHED TO THE DEPLOYMENT MECHAN-ISM. THE PANELS ARE BONDED TO THE DRUMS USING PRIMACEL 18 THERMOSETTING ADHESIVE.		A THIN FOAM BACKING SHEET COVERS THE ENTIRE REAR SURFACE OF THE PANEL TO PRE-VENT SCUFFING AND BREAKING OF THE SOLAR CELLS IN THE STOWED CONDITION IN ADDI-TION MAGNESIUM STRIPS ARE BONDED INTER-MITTENTLY ACROSS THE WIDTH OF THE PANELS BETWEEN THE PANELS AND FOAM BACKING SHEET THIS ADDS LATERAL STIFFNESS TEN SION IS APPLIED TO THE PANELS DURING ROLL UP SO AS TO OBTAIN A TIGHT WRAP ON THE DRUM WHEN THE ROLL IS COMPLETE THE CELL SURFACE IS EXPOSED	0.020-IN THICK POLY-URETHANE FOAM SHEET BONDED TO REAR SUR-FACE OF THE PANEL WITH RTV 108 AND 102 CEMENTS, LATERAL STIFFENERS ARE MAGNESIUM STRIPS	INDEPENDENT SHAFTS ATTACHED TO THE ROLLER AND MOUNTED IN THE BEARING AND END CAPS WHICH IS ALSO THE SPROCKET THESE ARE ALL ATTACHED TO THE CONTAINER-LIKE SUPPORT STRUCTURE	THE SUPPORT STRUCTURE PRO-VIDES A SOUND BASE FROM WHICH TO MOUNT THE LINK-AGE ARRAY AND RELEASE MECHANISM IT IS SHAPED SOMEWHAT LIKE A CON-TAINER AND SUPPLIES HAND LING AND SHIPPING PRO-TECTION IN ITS STOWED (LAUNCH) POSITION THE CON-TAINED SOLAR ARRAY ASSEM-BLY IS BOLTED DIRECTLY TO THE PRIMARY STRUCTURE OF THE SPACECRAFT	AN ELECTRICAL CABLE ROUTING STARTS AT THE OUTBOARD END OF THE PANELS ALONG THE LINKAGE SYSTEM AND IS CONNECTED TO THE SPACECRAFT	THE RELEASE MECHANISM FOR THE ARRAY SYS TEM CONSISTS OF A GEAR TRAIN LOCK ATTACHED TO THE SLIDING CAM WHICH IS PART OF THE SOLENOID ARMATURE WHEN THE SOLENOID IS ACTIVATED A FORCE OF 15 POUNDS DEVELOPS ON THE SLIDING CAM WHICH DISCONNECTS THE GEAR TRAIN LOCK FROM THE ROLLER ARRAY GEAR TRAIN ALLOW-ING THE ARRAYS TO START DEPLOYMENT AND DISPLACES THE PUSH ROD TO START RELEASE OF THE EXTENSION LINKAGE THE PUSH ROD IS AN ALUMINUM TUBE HAVING A LOCKING BLOCK ON EACH END WHICH PROTRUDES THROUGH THE END PLACES AND IS SUPPORTED AT ITS CENTER BY A FITTING THE BLOCKS PROVIDE A POSITIVE (NTERFERENCE LOCK FOR THE RESTRAINT LEVERS MOUNTED ON THE SIDE PLATES. THESE LEVERS WHEN FREED ALLOW THE CLAMPING ARMS TO RELEASE THE FRONT PLATE RELEASE OF THE FRONT PLATE ALLOWS THE SCREW JACK ASSEMBLY TO DEPLOY THE EXTENSION LINKAGES AND THE SOLAR ARRAY A PROTOTYPE HAS BEEN BUILT AND DEPLOYED ABOUT 40 TIMES WITH NO PROBLEMS	THIS SYSTEM IS DESIGNED TO BE DEPLOYED ONLY SINCE RETRACTION IS NOT A REQUIRE-MENT NO INFORMATION IS AVAILABLE DEPLOYMENT IS ACHIEVED BY A SCISSORS-TYPE LINKAGE MOUNTED ON A SCREW JACK SYSTEM WHICH IS DRIVEN BY A SPRING MOTOR A SYNCHRONOUS GEAR TRAIN ROTATES THE ROLLERS AND IS INTEGRATED WITH THE LINK AGE WHEN DEPLOYMENT STARTS, A CEN-TRIFUGAL BRAKE ATTACHED TO THE ROLLER MAINTAINS PROPER PANEL TENSION	SPIN VEHICLE, TENSION APPLIED BY CENTRIFUGAL FORCE	
HUGHES	DRUM ROLLER 4	PANELS ARE STOWED ON A 6 5 IN DIA x 50 75-IN LONG TUBE WALL THICKNESS OF 0 058 IN THE MATERIAL IS 6061-T4 ALUMINUM ALLOY TWO PANEL ASSEMBLIES ARE STOWED ON THIS COMMON DRUM (TUBE) AND DEPLOY IN OPPOSITE DIRECTIONS THEY ARE MECH-ANICALLY ATTACHED TO THE DRUM IN ADDITION BEARINGS ARE FITTED TO THE INSIDE OF THE DRUM AND INTERNAL RING GEARS ON EACH END		A THIN FLEXIBLE FOAM CUSHION SHEET IS INTERWOUND WITH THE PANELS, AND PRO VIDES THE PROTECTIVE PADDING FOR THE CELLS IN THE STOWED CONFIGURATION IN ADDI TION TO REDUCE SURFACE FRICTION OF THE CELLS TO THE FOAM CUSHION THE CUSHION IS COVERED WITH A POLYETHYLENE FILM SHEET TENSION ON THE CUSHIONING SHEET IS PRO-VIDED BY THE TAKE-UP ROLLER BRAKE TO ASSURE PROPER COMPRESSION ON THE PANELS SO AS TO HAVE A TIGHT WRAP AROUND THE DRUM. AFTER PANEL WRAPPING IS COMPLETE THE CUSHIONING SHEET CONTINUES FOR ONE MORE REVOLUTION TO PROVIDE A PROTECTIVE COVER ON THE PANELS	FLEXIBLE FOAM CUSHION-ING SHEET 0.080-IN THICK TYPE OF CUSH-IONING NOT KNOWN THE FRICTION-PREVENTION MATERIAL IS A POLY-ETHYLENE FILM	TUBULAR STRUCTURAL SPAR FIXED TO BOTH BULKHEAD ENDS THESE SUPPORT THE STORAGE DRUM THROUGH TWO PLAIN RING BEARINGS INTERNAL RING GEARS ATTACHED TO EACH END OF THE DRUM ARE CON-NECTED TO THE EXTENDER MECH-ANISM TO SYNCHRONIZE BOOM EXTENSION AND DRUM ROTATION	THE INBOARD END OF THE SPAR BISTEM BOOM ACTUATOR IS ATTACHED TO THE ORIENTATION LINKAGE FACE PLATE THE OUTBOARD END IS ATTACHED TO A SUPPORT ARM BOTH OF THESE ATTACH TO THE VEHICLE AND THEY SUPPORT THE SOLAR ARRAY ASSEMBLY IN THE STOWED (LAUNCH) POSITION IN THIS POSITION THE ARRAY ASSEMBLY IS NEARLY PARALLEL TO THE X-AXIS OF THE SPACE-CRAFT THE OUTBOARD END SUPPORT ARM RELEASES AND THE ASSEMBLY PIVOTS AT THE ORIENTATION LINKAGE FACE PLATE UNTIL THE ARRAY ASSEMBLY IS 90° TO THE X AXIS THE PANELS CAN NOW BE DEPLOYED	FLEXIBLE FLAT CABLE INSERTED BETWEEN THE FIXED SPAR AND THE PANEL STORAGE DRUM ONE END CONNECTED TO THE DRUM AND THE OTHER TO THE SPAR AS THE DRUM TURNS THE FLAT CABLE UNWINDS FROM THE DRUM AND WINDS AROUND THE SPAR	DATA NOT AVAILABLE	DEPLOYMENT IS BY TWO SETS OF STEM DEVICES EACH OF WHICH HAVE TWO EXTENDIBLE BOOMS ORIENTED TO DEPLOY IN OPPOSITE DIRECTIONS THE BOOMS STRADDLE THE PANELS IN ADDI TION TWO FOAM CUSHIONING SHEETS INTER LAY WITH THE PANELS WHEN THEY ARE WOUND ON THE ROLLER THE SHEETS ATTACH TO THE ROLLER AND ITS RESPECTIVE TAKE-UP ROLLER POWER IS FURNISHED BY A SYNCHRONOUSLY OPERATED DC MOTOR THROUGH A CHAIN DRIVE AND ROTATING FLEXIBLE SHAFT WHICH EXTEND THE BOOMS THEY ARE CONNECTED TO A TIE BAR WHICH SUPPORTS THE PANELS RETRACTION IS BY ANOTHER DC MOTOR WHICH IS GEARED TO THE DRUM ROLLER WHEN DEPLOYING, A CONSTANT VOLTAGE IS APPLIED TO THE STEM MOTOR TO OBTAIN A CONSTANT EXTENSION RATE A SMALL CURRENT IS APPLIED TO THE DRUM ROLLER MOTOR PROVIDING A WEAK REVERSE TORQUE TO MAINTAIN PANEL TENSION AT FULL DEPLOYMENT BOTH MOTORS ARE LOCKED SIMULTANEOUSLY THE TAKE-UP ROLLER WITH ITS TORSION SPRING REEL ON THE SHEET TO RETRACT THE PANELS THE PRO CEDURE IS REVERSED THERE IS NO EVIDENCE OF ANY PANEL TRACKING PROBLEMS	TO CONTROL THE TENSION ON THE SOLAR ARRAY A NORMAL VOLTAGE TO THE STEM MOTOR IS APPLIED TO GIVE A CONSTANT BOOM EXTENSION RATE WHILE A SMALL AMOUNT OF POWER TO THE DRUM MOTOR PROVIDES A WEAK REVERSE TORQUE OR DRAG UPON REACHING FULL DEPLOYMENT BOTH THE STEM MOTOR AND THE DRUM MOTOR ARE LOCKED TO PREVENT ANY DRIFT AND RESULTANT SAGGING OF THE UNRUBBED ARRAYS FOR RETRACTION OPER ATION THE ABOVE PROCEDURE IS REVERSED TENSION LOADING ON SUBSTRATES RANGE BETWEEN 0 9 AND 1 42 LB/FT	250

FOLDOUT FRAME 1

FOLDOUT FRAME 2

GENERAL DESCRIPTION OF CURRENT FLEXIBLE SOLAR ARRAY SYSTEMS

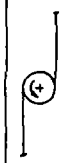
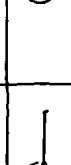
A

ANSFER	TIE-DOWN AND RELEASE	DEPLOYMENT/RETRACTION CAPABILITIES	TENSIONING METHOD	CELL AREA (FT^2)	STOWED VOL (FT^3)	WEIGHT SUMMARY: STRUCT (LB)	WEIGHT SUMMARY: SOLAR PANEL (LB)	WEIGHT SUMMARY: STRUCT + SOLAR PANEL (LB)	WEIGHT SUMMARY: STRUCT WT/AREA (LB/FT^2)	POWER/AREA ($WATTS/FT^2$)	POWER/WT (WATTS/LB)	BIBLIO NO
'RING IS HOUSED IN ORAGE DRUM EMBLY IS VELOPED BY DIVISION OF PRODUCTS	THE MOVABLE END SUPPORT TIES DOWN THE LEADING EDGE MEMBER (LEM) DRUM AND THE SOLAR ARRAY IN A LOCK CONDITION TO RELEASE THIS LOCK CONDITION, A BOLT THAT PREVENTS THE ROTATION OF THE MOVABLE END SUPPORT UNDER PRELOADED CONDITION IS RELEASED BY AN ELECTRO-EXPLOSIVE SEPARATION NUT WHEN THE SEPARATION NUT IS ACTUATED THE HINGED ARM ROTATES AWAY FROM THE DRUM AND THE LEM THROUGH THE ACTION OF A TORSION SPRING ONCE THE SUPPORT ARM PIVOTS OUT OF THE WAY THE DRUM IS FREE TO ROTATE ABOUT ITS OWN AXIS AND THE LEM IS FREE TO MOVE OUTWARD WHEN THE BOOM IS DEPLOYED	A SINGLE 1-3/8 IN DIA BI-STEM BOOM ACTUATOR CENTERED AND ATTACHED BETWEEN TWO DRUMS AT THE BASE AND CONNECTED TO THE PANEL AT THE OUTBOARD SIDE BY THE LEADING EDGE MEMBER DEPLOY AND RETRACT THE PANELS A CONSTANT TORQUE SPRING MOTOR WHICH ACTS AS A BRAKE MAINTAINS PROPER TENSION ON THE PANELS DURING DEPLOYMENT AND RETRACTION WHEN RETRACTING THE ROLL-UP TENSION RESULTS IN A TIGHT WRAP AROUND THE DRUM THIS TIGHTNESS IS DEPENDENT UPON ITS TENSIONING SYSTEM AND CANNOT BE INDEPENDENTLY VARIABLE EACH DRUM IS ALSO 1 0 IN WIDER THAN THE PANEL ON EACH EDGE OVERHANG IS NECESSARY FOR PANEL TRACKING WHEN RETRACTING	DEPLOYED ARRAY WITH A RESONANT FREQUENCY ABOVE 0 099 Hz REQUIRES A PRELOAD OF 0 55 LB/FT IN EACH ARRAY BLANKET THIS IS ACCOMPLISHED BY MOUNTING A NEGATOR CONSTANT TORQUE SPRING MOTOR IN EACH DRUM WHICH COUNTERACTS THE FORCE OF THE BI STEM BOOM	250	3 54	34 4	50 0	84 4	0 138	11	32 5	G 2-1 THRU -4 G 2-3 THRU -9 & 13
RINGS WHICH ONE END OF E DRUM	THE SPREADER BAR HOLDS THE LINKAGE ASSEMBLY ARRAY PANELS AND ITS ROLLER IN A LATCHED CONDITION TO THE PRIMARY STRUCTURE OF THE SPACECRAFT TO RELEASE THE SYSTEM, TWO METHODS WERE CONSIDERED ONE METHOD EMPLOYS A SOLENOID THE OTHER AN EXPLOSIVE BOLT FUNCTIONALLY BOTH SYSTEMS ATTAIN THE SAME RESULTS — RESTRAINING THE SPREADER BAR THE SOLENOID METHOD USES A MECHANICAL LATCH AND LINK AND HAS RELATCHING CAPABILITY THE EXPLOSIVE BOLT METHOD REQUIRES ONLY A TIE-PLATE WHICH SEPARATES UPON RELEASE BUT DOES NOT HAVE RELATCHING CAPABILITIES THE RELEASE OF THE SPREADER BAR FROM THE END PLATE ACTUATES THE ELECTRIC MOTOR WHICH DEPLOYS THE COMBINATION OF FOLDING ARMS PULLEYS AND CABLES FOR EXTENDING THE SOLAR ARRAY	FOLDING ARM LINKAGE SYSTEM INTEGRATES WITH THE DRUM ROLLER BY TWO DRIVE TRAINS OPERATIONAL POWER IS PROVIDED BY A SMALL DC GEARMOTOR ONE DRIVE TRAIN OPERATES THE FOLDING ARM LINKAGE TO DEPLOY AND RETRACT THE PANEL THE OTHER APPLIES TORQUE TO THE DRUM ROLLER DURING RETRACTION WHEN DEPLOYING THE ROLLER IS AT A FREE STATE AND THE FOLDING ARM LINKAGE IS CENTERED ON THE REAR SURFACE OF THE PANEL TENSION IN THE PANEL IS APPLIED BY A DRAG BRAKE ATTACHED TO THE ROLLER WHEN FULLY DEPLOYED TENSION IS BY A TORSION SPRING WHICH TENDS TO RETRACT THE ROLLER AFTER DEACTIVATION OF THE LINKAGE DRIVE TRAIN CABLES AND PULLEYS CONNECTED TO THE FOLDING ARM ASSEMBLY KEEP THE PANEL FULLY DEPLOYED TENSION IN THE CABLES PUSH AGAINST A BUILT-IN STOP AT THE JOINTS THERE IS NO POSITIVE LOCK TO OFFSET COLUMN LOADING IN THE FOLDING ARMS TO RETRACT BRAKE RESISTANCE IS REMOVED THE TORSION SPRING STARTS ROLLER RETRACTION AND THE GEARMOTOR DRIVE IS REVERSED THE ROLLER DRIVE TRAIN IS ACTIVATED AND THE PANELS ARE REWOUND AROUND THE ROLLER. PROPER PANEL TENSION IS FURNISHED BY THE RESISTANCE AT THE JOINTS OF THE FOLDING ARMS THIS DEPLOYMENT/RETRACTION SYSTEM EXPERIENCED SERIOUS PROBLEMS IN PANEL TRACKING DURING RETRACTION NO INFORMATION IS AVAILABLE FOR SOLVING AT THIS TIME. NOTE: PROBLEM MAY NOT NECESSARILY BE IN THE SYSTEM. MAY BE A RATIO OF DRUM ROLLER DIA (5.0 IN.) TO LENGTH OF ROLLER (9 FT) CE DID NOT EXPERIENCE ANY PROBLEMS EVEN WITH A 10 IN. TIP DEFLECTION. THEIR DRUM DIA IS 8 IN AND A LENGTH OF 3 FT 11 IN	FRICTION DRAG BRAKE CREATES TENSION WHILE DEPLOYING DURING THE LAST HALF-REVOLUTION BY MEANS OF ENGAGING A TORSION SPRING THIS MAINTAINS A TENSION OF 1 2 LB/FT IN THE SUBSTRATE AFTER DEACTIVATION OF THE DRIVE SYSTEM LOADING AND POWER REQUIREMENTS TO THE DRIVE SYSTEM ARE MINIMIZED DURING THE DEPLOYMENT PHASE.	250	2 03	28 02	50 0	78 0	0 112	11	35 2	F 1-1 THRU -4
BLE ROUTING BOARD END OF O THE LINKAGE NNECTED TO	THE RELEASE MECHANISM FOR THE ARRAY SYSTEM CONSISTS OF A GEAR TRAIN LOCK ATTACHED TO THE SLIDING CAM WHICH IS PART OF THE SOLENOID ARMATURE WHEN THE SOLENOID IS ACTIVATED A FORCE OF 15 POUNDS DEVELOPS ON THE SLIDING CAM WHICH DISCONNECTS THE GEAR TRAIN LOCK FROM THE ROLLER ARRAY GEAR TRAIN ALLOWING THE ARRAYS TO START DEPLOYMENT AND DISPLACES THE PUSH ROD TO START RELEASE OF THE EXTENSION LINKAGE THE PUSH ROD IS AN ALUMINUM TUBE HAVING A LOCKING BLOCK ON EACH END WHICH PROTRUDES THROUGH THE END PLACES AND IS SUPPORTED AT ITS CENTER BY A FITTING THE BLOCKS PROVIDE A POSITIVE INTERFERENCE LOCK FOR THE RESTRAINT LEVERS MOUNTED ON THE SIDE PLATES THESE LEVERS WHEN FREED ALLOW THE CLAMPING ARMS TO RELEASE THE FRONT PLATE RELEASE OF THE FRONT PLATE ALLOWS THE SCREW JACK ASSEMBLY TO DEPLOY THE EXTENSION LINKAGES AND THE SOLAR ARRAY A PROTOTYPE HAS BEEN BUILT AND DEPLOYED ABOUT 40 TIMES WITH NO PROBLEMS	THIS SYSTEM IS DESIGNED TO BE DEPLOYED ONLY SINCE RETRACTION IS NOT A REQUIREMENT NO INFORMATION IS AVAILABLE DEPLOYMENT IS ACHIEVED BY A SCISSORS TYPE LINKAGE MOUNTED ON A SCREW JACK SYSTEM WHICH IS DRIVEN BY A SPRING MOTOR A SYNCHRONOUS GEAR TRAIN ROTATES THE ROLLERS AND IS INTEGRATED WITH THE LINKAGE WHEN DEPLOYMENT STARTS A CENTRIFUGAL BRAKE ATTACHED TO THE ROLLER MAINTAINS PROPER PANEL TENSION	SPIN VEHICLE: TENSION APPLIED BY CENTRIFUGAL FORCE	CONCEPT NOT APPLICABLE TO SPACE STATION							F 1-6 T BU -7
E INSERTED SPAR AND THE BUM, ONE END E DRUM AND BAR AS THE LAT CABLE E DRUM AND E SPAR	DATA NOT AVAILABLE.	DEPLOYMENT IS BY TWO SETS OF STEM DEVICES EACH OF WHICH HAVE TWO EXTENDIBLE BOOMS ORIENTED TO DEPLOY IN OPPOSITE DIRECTIONS THE BOOMS STRADDLE THE PANELS IN ADDITION TWO FOAM CUSHIONING SHEETS INTERLAY IN FRONT THE PANELS WHEN THEY ARE WOUND ON THE ROLLER THE SHEETS ATTACH TO THE ROLLER AND ITS RESPECTIVE TAKE-UP ROLLER POWER IS FURNISHED BY A SYNCHRONOUSLY OPERATED DC MOTOR THROUGH A CHAIN DRIVE AND ROTATING FLEXIBLE SHAFT WHICH EXTEND THE BOOMS THEY ARE CONNECTED TO A TIE BAR WHICH SUPPORTS THE PANELS RETRACTION IS BY ANOTHER DC MOTOR WHICH IS GEARED TO THE DRUM ROLLER WHEN DEPLOYING A CONSTANT VOLTAGE IS APPLIED TO THE STEM MOTOR TO OBTAIN A CONSTANT EXTENSION RATE A SMALL CURRENT IS APPLIED TO THE DRUM ROLLER MOTOR PROVIDING A WEAK REVERSE TORQUE TO MAINTAIN PANEL TENSION AT FULL DEPLOYMENT BOTH MOTORS ARE LOCKED SIMULTANEOUSLY THE TAKE-UP ROLLER WITH ITS TORSION SPRING REEL IN THE SHEET TO RETRACT THE PANELS THE PROCEDURE IS REVERSED THERE IS NO EVIDENCE OF ANY PANEL TRACKING PROBLEMS	TO CONTROL THE TENSION ON THE SOLAR ARRAY A NORMAL VOLTAGE TO THE STEM MOTOR IS APPLIED TO GIVE A CONSTANT BOOM EXTENSION RATE WHILE A SMALL AMOUNT OF POWER TO THE DRUM MOTOR PROVIDES A WEAK REVERSE TORQUE OR DRAG UPON REACHING FULL DEPLOYMENT BOTH THE STEM MOTOR AND THE DRUM MOTOR ARE LOCKED TO PREVENT ANY DRIFT AND RESULTANT SAGGING OF THE UNFURLED ARRAYS FOR RETRACTION OPERATION THE ABOVE PROCEDURE IS REVERSED TENSION LOADING ON SUBSTRATES RANGE BETWEEN 0 9 AND 1 42 LB/FT	250	2 3	29 4	50	79 4	0 118	11	34 '	H 6 1 THRU -6

FOLDOUT FRAME 2

FOLDOUT FRAME 3

GENERAL DESCRIPTION OF CURRENT FLEXIBLE SOLAR ARRAY SYSTEMS

SOURCE	STOWAGE METHOD	DESCRIPTION	ILLUSTRATION	PADDING FOR CELL PROTECTION DURING LAUNCH AND GROUND HANDLING: TECHNIQUE	PADDING FOR CELL PROTECTION DURING LAUNCH AND GROUND HANDLING: MATERIAL	END SUPPORTS	ATTACHMENT TO STRUCTURE	POWER TRANSFER	TIE-DOWN AND RELEASE	DEPLOYMENT/RETRACTION CAPABILITIES	TENSIONING METHOD	CELL ARI (FT²)
HUGHES	DRUM ROLLER 5	PANELS ARE STOWED ON AN 8 0 IN DIA x 30 75-IN LONG DRUM, MADE FROM CHEMICALLY MILLED MAGNESIUM. TWO PANEL ASSEMBLIES ARE STOWED ON THIS COMMON DRUM AND DEPLOY IN OPPOSITE DIRECTIONS. THEY ARE MECHANICALLY ATTACHED TO THE DRUM IN ADDITION BEARINGS ARE FITTED TO THE INSIDE DIAMETER OF THE DRUM FOR STABILITY END PLATES ARE PROVIDED THAT ARE MADE FROM ALUMINUM SAND WICHES PLATES		SAME AS DRUM ROLLER 4 EXCEPT THE CUSHONING SHEET AND THE POLY ETHYLENE FILM IS REPLACED BY AN EMBOSSED KAPTON SHEET ALSO, THE TAKE-UP ROLLER BRAKE IS REPLACED BY A NEGATOR MOTOR THE RANGE IS BETWEEN 0 40 LB (FULL) TO 1 25 LB (EMPTY)	EMBOSSED KAPTON SHEET 2 MIL THICK EMBOSSMENTS ARE FROM 0 010 TO 0 045 HIGH	TORQUE TUBE MOUNTS INTO THE DRUM END BEARINGS THAT ARE HOUSED IN THE STORAGE DRUM ENDS THE INBOARD PAIR OF BEARINGS CARRY THE TOTAL LOAD OUTBOARD BEARINGS CARRY ONLY RADIAL LOAD THIS IS DUE TO THERMAL EXPANSION THE TORQUE TUBE ALSO ATTACHES TO THE SPAR BI-STEM BOOM ACTUATOR UNITS	SAME AS DRUM ROLLER 4	SAME AS DRUM ROLLER 4	DATA NOT AVAILABLE	DEPLOYMENT OF THE PANELS IS BY TWO SETS OF SPAR STEM DEVICES EACH OF WHICH HAVE TWO EXTENDIBLE BOOMS OPPOSING EACH OTHER THE STEM DEVICES ARE CONNECTED BY A TORQUE TUBE THAT ATTACHES TO A SINGLE AC MOTOR THE MOTOR EXTEND ALL FOUR BOOMS A CONTOURED NEGATOR MOTOR ATTACHED TO THE DRUM END MAINTAINS PROPER PANEL TENSION DURING AND AFTER DEPLOYMENT THE INTERLAYING CUSHION ING SHEETS STILL ATTACH TO ITS RESPECTIVE TAKE-UP ROLLERS IT IS DRIVEN BY A NEGATOR MOTOR AND IS INDEPENDENT FROM THE DRIVE MOTOR REVERSING THE DRIVE SYSTEM STARTS RETRACTION IN ADDITION, THERE IS A BOOM LENGTH COMPENSATOR SPREADER BAR THAT IS INTEGRATED INTO THE SYSTEM IT ELIMINATES THE BOOM SYNCHRONIZATION PROBLEM WHEN RETRACTING THERE IS NO EVIDENCE OF PANEL TRACKING PROBLEM	SAME AS DRUM ROLLER 4	
RYAN	DRUM ROLLER 6	PANELS ARE STOWED ON 12 0 IN DIA x 43 1 IN LONG DRUM, MADE FROM 0 025 SHEET MAGNESIUM SKIN APPROX 30% OF THE SURFACE AREA IS REMOVED AS LIGHTENING HOLES THE PANEL ASSEMBLY IS MECHANICALLY ATTACHED TO THE DRUM BY A HINGE SYSTEM. THERE IS A SERIES OF SUBPANEL ASSEMBLIES AND EACH END IS HINGED DRUM ENDS FABRICATED FROM HONEY-COMB SANDWICH AND FLANGED AT THE O.D PROVIDE RIVET ATTACHMENT TO THE DRUM MACHINED MAGNESIUM HUB MOUNTED AT THE CENTER OF THE ENDS SUPPORTS THE STATIC AND DYNAMIC LOADS OF THE ASSEMBLY THE SUBSTRATE WIDTH OF THE SOLAR PANEL IS EXTENDED TO PROVIDE AN OVERLAP ON THE TWO EXTENDIBLE LENTICULAR BOOMS (BEAMS) FLAT SURFACE FOR USE IN ATTACHING DIRECTLY TO THE BOOM STEP THE BOOMS AND THE PANEL ASSEMBLY ARE STOWED TOGETHER ON THE DRUM.		THE BACK SURFACE OF THE PANELS CONTAIN SILICON FOAM BUTTONS (PADS) THIS IS THE INTERLAYING CUSHIONING IN THE STOWED CONFIGURATION WHICH ROTATES THE SOLAR CELLS IN ADDITION THE BUTTONS ARE FACED WITH A THIN TEFLON SHEET TO REDUCE SURFACE FRICTION WHEN THE PANEL IS DEPLOYED THE TWO BOOMS AND THE PANEL ARE WOUND AROUND THE DRUM AS A UNIT DURING ROLL-UP THE DIFFERENT DIAMETERS BETWEEN THE BOOMS AND THE PANEL CAUSE A LATERAL TENSIGN IN THE PANELS IN THE STOWED CONFIGURATION AFTER COMPLETION OF THE ROLL-UP THE CELL SURFACE IS EXPOSED	BUTTONS ARE MADE FROM 0 50 DIA SILICON FOAM PADS AND ARE FACED WITH 3 MIL THICK TEFLON SHEET	ON BOTH ENDS THE BALL BEAR INGS ARE HOUSED IN THE STORAGE DRUM END CAPS AND MOUNTED ON TWO SEPARATE END AXLES WHICH ATTACH TO THE END ASSEMBLY SUPPORT STRUCTURE IN ADDITION ONE END ALSO HAS PROVISIONS TO MOUNT THE DRIVEN GEAR TO THE DRUM END CAP	THE ROLLER ARRAY ASSEMBLY WITH ITS LENTICULAR BOOMS ARE ATTACHED TO THE END SUPPORT STRUCTURES BOTH STRUCTURES ARE STABILIZED TOGETHER BY TWO TIE BARS THIS COMPLETE UNIT IS MOUNTED ON THE SPACECRAFT	FLEXIBLE FLAT CABLE IS INSERTED INSIDE PANEL STORAGE DRUM.	DATA NOT AVAILABLE	TWO LENTICULAR BOOMS STRADDLE THE PANEL AND ATTACH TO THE DRUM AND SIDE EDGES OF THE PANEL. THE TWO BOOMS AND PANEL WRAP AROUND THE ROLLER POWER IS SUPPLIED BY A DC DRIVE MOTOR THROUGH AN INTEGRAL PLANETARY GEAR REDUCTION GAGE WHICH ATTACHES TO A PINION GEAR, ROTATING THE DRUM ROLLER SPUR GEAR. THE RESULT IS ROLLER ROTATION OF 1 41 RPM AND LENTICULAR BOOM EXTENSION OF 4 43 FT/MIN A SPREADER BAR AT THE TIP ATTACHES TO THE BOOMS AND SUPPORTS THE PANEL A SILICON RUBBER SPACER STEP IS BONDED TO THE REAR SURFACE OF THE BOOM PROVIDING A CONTROL SPACE BETWEEN PANEL LAYERS AS THEY WRAP ON THE DRUM. WHEN RETRACTING, PANEL TRACKING IS NOT A PROBLEM BECAUSE THEY ATTACH TO THE BOOM, GUIDED BY THE END ASSEMBLY SUPPORT STRUCTURE. MAXIMUM IN AND OUT POSITION OF THE BOOM IS SENSED BY A LIMIT SWITCH WHICH ALLOWS THE DRUM TO ROTATE 1990 DEG	SAME AS DRUM ROLLER 7	30
RYAN	DRUM ROLLER 7	STOWAGE OF THE PANELS IS ON A 12 0 IN DIA x 7 FT 1 IN LONG CYLINDER WITH LIGHTENING HOLES MADE FROM 0 032 IN THICK MAGNESIUM SHEET THE PANEL ASSEMBLY IS MECHANICALLY ATTACHED TO THE DRUM BY A HINGE SYSTEM. THERE IS A SERIES OF SUBPANEL ASSEMBLIES AND EACH END IS HINGED THE DRUM IS STIFFENED INTERNALLY WITH NINE EQUALLY SPACED MAG-NESIUM RINGS ENDS CONTAIN AN ADHESIVE BONDED ALUMINUM HONEY-COMB SANDWICH BULKHEAD TO WHICH AXEL HUBS OF MACHINED MAGNESIUM ALLOY ARE FASTENED THE SUBSTRATE WIDTH OF THE SOLAR PANEL IS EX-TENDED TO PROVIDE AN OVERLAP ON THE TWO EXTENDIBLE LENTICULAR BOOMS (BEAMS) FLAT SURFACE FOR USE IN ATTACHING DIRECTLY TO THE BOOM STEP THE BOOMS AND THE PANEL ASSEMBLY ARE STOWED TOGETHER ON THE DRUM.		SAME AS DRUM ROLLER 6 EXCEPT SILICON FOAM BUTTONS ARE REPLACED BY POLY URETHANE FOAM DAMPER PADS BONDED TO THE REAR SURFACE PADS ARE ARRANGED DECREASINGLY DENSE FROM DRUM TO THE TIP OF THE PANEL IN ADDITION, A PROTECTIVE BLANKET IS ADDED TO THE PANEL LEADING EDGE AND IT BECOMES THE FINAL WRAP WHICH ELIMINATES EXPOSURE OF THE CELLS	DAMPER PADS ARE MADE FROM POLYURETHANE FOAM	THE PANEL AND DEPLOYABLE BOOM STORAGE DRUM IS SUPPORTED AT EACH END OF THE DRUM AXLE BY MACHINED MAGNESIUM HUBS THEY ATTACH TO A MAGNESIUM SHEET METAL BOX SECTION THAT SUPPORTS AND POSITIONS THE DEPLOYABLE BOOMS WITH GLASS REINFORCED TEFLON GUIDES DRUM AXLE BEARINGS ARE CAGED IN A MAGNESIUM GUIDE AND ARE CONTAINED IN A MACHINED MOUNTING TRACK THIS COMPLETE UNIT IS RETAINED AGAINST PINION EXTENSION GEARS BY TENSION SPRINGS THUS MAINTAINING ALIGNMENT OF THE DRUM BOOM TAGENCY WITH BOOM SUPPORT GUIDES.	THE BOX SECTION SUPPORTING THE BOOM GUIDES ALSO HAS MOUNTING PROVISIONS FOR THE EXTENSION MOTOR PINION GEAR, AND DRIVE SHAFT IN ADDITION THE BOOM GUIDES ATTACH TO THE BOX STRUCTURE IN A MANNER WHICH ALLOWS LATERAL FREE-DOM FOR POSSIBLE SUBSTRATE THERMAL CONTRACTION THIS COMPLETE UNIT IS HOUSED IN THE DRUM SUPPORT ASSEMBLY AND IT MOUNTS TO THE VEHI-CLE STRUCTURE AT ONE END THE ATTACHMENT IS FIXED THE OTHER END HAS A SLIDING FIT TO ALLOW FOR THERMAL EXPANSION AND CONTRACTION	UTILIZES A SLIP RING ASSEMBLY THAT ATTACHES TO ONE HUB OF THE PANEL STORAGE DRUM.	THE LOCKING DEVICE EMPLOYED ON RYAN'S EXTENSION BOOM IN A DEPLOYED OR A PACKAGED CON-DITION IS CONTROLLED BY TWO ELECTRIC MOTORS WHEN CUR-RENT IS CUT OFF THE MOTORS LOCK INTO POSITION, AND PRE-VENTS THE MOVEMENT OF THE DRUM AND THE CORRUGATED BOOM	MAGNESIUM PINION GEARS AT EACH END OF A MAGNESIUM DRIVE SHAFT ENGAGE THE COR RUGATED BOOM DRIVE STRIP TO SYNCHRONIZE THE RELATIVE POSITIONS OF THE BOOM. DEPLOYMENT DRIVE POWER IS BY A GEAR BOX SYSTEM ATTACHED TO A DRIVE SHAFT DOUBLE MOTORS THROUGH A DIFFERENTIAL GEAR BOX PROVIDE REDUNDANCY A RETRACTION IS FUR-NISHED BY A MOTOR ATTACHED TO THE DRUM END HUB PROPER TENSION IS BY DRAG OF THE RETRACTION MOTOR AT DEPLOYMENT PROCEDURE IS REVERSED WHEN RETRACTING LIMIT SWITCH SHUT-OFF POWER AT FULL DE-PLOYMENT AND RETRACTION DURING RE-TRACTION BOTH BOOMS AND THE PANEL WRAP AROUND THE DRUM, AND THERE ARE NO PANEL TRACKING PROBLEMS ATTACHMENT OF THE PANEL TO THE BOOMS ELIMINATES THIS THEY ARE GUIDED BY THE CORRUGATED BOOM DRIVE STRIP	THE DEPLOYMENT AND RETRACTION MOTORS WORK IN UNISON ON BOTH DEPLOYMENT AND RETRACTION CYCLES THROUGH AN ELECTRONIC SENSING SYSTEM THAT CON-TROLS POWER TO EACH MOTOR THIS SYS TEM IS DESIGNED SO THAT, WHEN DEPLOY-MENT IS COMMANDED BOTH DEPLOYMENT AND RETRACTION MOTORS ARE ENERGIZED BY ADJUSTMENT OF CURRENT INPUT THE DE-PLOYMENT MOTOR IS THE SUPERIOR FORCE AND BEAM AND SUBSTRATE DEPLOYMENT TAKES PLACE WITH THE RETRACTION MOTOR IMPOSING A DRAG ON THE DRUM, WHICH ENSURES A TENSION LOAD BETWEEN BEAM AND DRUM DURING RETRACTION MODE THE SYS-TEM REVERSES CAUSING THE DEPLOYMENT MOTOR TO LAG THE RETRACTION MOTOR THE MOTORS ACT AS LOCKING DEVICES WHEN CURRENT IS OFF NO DATA ARE AVAILABLE ON TENSION LOADS.	250
BRITISH AIRCRAFT CORP	DRUM ROLLER 8	PANELS ARE STOWED ON A 30 CM (7 874 IN.) DIA x 50 CM (19 IN APPROX) LONG DRUM. INBOARD END OF THE PANEL IS HELD TO THE DRUM WITH CLAMPS. DRUM IS SUPPORTED BY END PLATES THAT HOUSE THE BEARINGS. A CENTRAL SHORT SHAFT GOES THROUGH THE BEARINGS AND THE DRUM SUPPORT BRACKET		THE PANELS ARE INTERFOLIND WITH A CUSHIONING MATERIAL SIMILAR TO THE HUGHES DESIGN TO PROVIDE PROTECTION OF THE CELLS IN THE STOWED CONFIGURATION TENSION IS APPLIED TO THE PROTECTIVE SHEET AND THE PANELS BY TENSATOR S SPRING MOTORS TO OBTAIN A TIGHT WRAP AROUND THE DRUM. AFTER COMPLETION OF THE ROLL-UP, THE CELLS OF THE FINAL WRAP ARE EXPOSED	CUSHIONING SHEET IS MADE FROM PLASTOZATE AND IS NOT SATISFAC-TORY PRESENTLY CON-SIDERING POLYURETHANE FOAM SHEET	THE STORAGE DRUM IS SUP-PORTED BY A LONG TUBULAR CENTRAL SHAFT GOING THROUGH BALL BEARINGS HOUSED IN THE DRUM END PLATES. THE SHAFT ALSO SUP-PORTS THE STRUT (STOW BOOM) STORAGE DRUM THAT IS KEYED TO THE SHAFT THE END PLATES ARE MOUNTED TO THE DRUM SUPPORT BRACKET	THE COMPLETE SOLAR ARRAY ASSEMBLY IS ATTACHED TO THE DRUM SUPPORT BRACKETS. THE BRACKETS ARE STABILIZED AS A UNIT BY THREE TIE BARS THE COMPLETE UNIT MOUNTS TO THE SPACECRAFT	THE UNIT HAS PROVISIONS FOR USING EITHER FLEXIBLE FLAT CABLE OR A SLIP RING ASSEM-BLY BOTH INTERCHANGEABLE. MOUNTING IS ON THE PANEL STORAGE DRUM BRACKET ASSEMBLY	DATA NOT AVAILABLE	POWER IS PROVIDED BY A MAGNETIC DC MOTOR DRIVE. IT IS COUPLED TO THE CON-TRAL SHAFT THROUGH A REDUCTION GEAR BOX IT ROTATES THE (STRUT) STOW-AGE DRUM THAT DEPLOYS THE BOOMS STRAD-DLING THE PANELS A FOAM CUSHIONING SHEET IS INTERFOLIND WITH THE PANEL WHEN STOWED THE SPREADER BAR ATTACHES TO THE BOOMS AND SUPPORTS THE PANEL, AND THE CUSHIONING SHEET ATTACHES TO A TAKE-UP ROLLER. AS THE BOOMS DEPLOY THE SPREADER BAR RAISES THE PANELS AND A TENSATOR S MOTOR, ATTACHED TO THE SHAFT AND THE ROLLER END PLATE, PROVIDES PROPER PANEL TENSION IT ALSO COMPENSATES FOR DIF-FERENCES IN ROLL-OFF RATE BETWEEN THE PANEL AND BOOMS ANOTHER TENSATOR S MOTOR OPERATES THE CUSHIONING SHEET TAKE-UP ROLLER WHEN RETRACTING THE MOTOR IS REVERSED THE ROLLER TENSATOR MOTOR ROLLS UP THE PANEL AND CUSHION-ING SHEET AND THE TAKE-UP ROLLER TENSA TOR MOTOR ACTS AS A BRAKE TO MAINTAIN PROPER PANEL TENSION	NO TENSION LOAD DATA AVAILABLE	8 1
LMSC	FLAT SPINDLE 1	PANELS ARE STOWED ON A FLAT THICK PLYWOOD SPINDLE 0.30 IN x 9 0 IN. WIDE x 67 0 IN LONG THEY ARE TAPED TO THE SPINDLE TWO SHORT SHAFTS ARE PROVIDED ON EACH END AND ARE CONNECTED TO THE END SUP-PORTS DURING RETRACTION THE CELL AREA LAYS ON THE FLAT SURFACE OF THE SPINDLE CONSEQUENTLY THE DISTANCE BETWEEN SUBPANELS IN CREASES BY CONSECUTIVE INCREMENTS TO MAKE UP FOR THE CHANGE IN THICKNESS AROUND THE BEND AREA. CREEP OF THE SUBSTRATE MATERIAL SHALL BE CONSIDERED		FOAM CUSHION BUTTONS ARE PLACED ON THE REAR SURFACE OF THE PANEL TO PROTECT THE CELLS IN THE STOWED CONFIGURATION TEN-SION IS APPLIED TO THE PANELS DURING ROLL-UP TO OBTAIN A TIGHT WRAP AROUND THE SPINDLE AFTER COMPLETION OF THE ROLL-UP, THE CELL SURFACE OF THE FINAL WRAP IS EXPOSED	BUTTONS ARE MADE OF 0 50-IN DIA FOAM CUSHION	SPINDLE IS SUPPORTED BY SHORT SHAFTS ATTACHED ON THE ENDS SHAFT GOES THROUGH JOURNAL BEARINGS HOUSED INSIDE THE END FITTINGS OF THE SPINDLE SUPPORT STRUCTURE	THE SOLAR ARRAY ASSEMBLY IS ATTACHED TO THE SPINDLE SUPPORT STRUCTURE THIS STRUCTURE MOUNTS TO THE SPACECRAFT FIXED ON ONE END AND A SLIDE FIT ON THE OTHER END TO ALLOW FOR THERMAL EXPANSION AND CONTRACTION	FLEXIBLE FLAT CABLE IS ATTACHED TO THE SUBSTRATE AND WRAPPED AROUND THE SPINDLE	DATA NOT AVAILABLE	DATA NOT AVAILABLE	DATA NOT AVAILABLE	30

FOLDOUT FRAME 1

FOLDOUT FRAME 2

ENERAL DESCRIPTION OF CURRENT FLEXIBLE SOLAR ARRAY SYSTEMS

A

	TIE-DOWN AND RELEASE	DEPLOYMENT/RETRACTION CAPABILITIES	TENSIONING METHOD	CELL AREA (FT^2)	STOWED VOL (FT^3)	WEIGHT SUMMARY: STRUCT (LB)	SOLAR PANEL (LB)	STRUCT SOLAR PANEL (LB)	STRUCT WT/AREA (LB/FT^2)	POWER AREA ($WATTS/FT^2$)	POWER/WT (WATTS/LB)	BIBLIO NO
	DATA NOT AVAILABLE	DEPLOYMENT OF THE PANELS IS BY TWO SETS OF SPAR STEM DEVICES EACH OF WHICH HAVE TWO EXTENDIBLE BOOMS OPPOSING EACH OTHER THE STEM DEVICES ARE CONNECTED BY A TORQUE TUBE THAT ATTACHES TO A SINGLE AC MOTOR THE MOTOR EXTEND ALL FOUR BOOMS A CONTOURED NEGATOR MOTOR ATTACHED TO THE DRUM END MAINTAINS PROPER PANEL TENSION DURING AND AFTER DEPLOYMENT THE INTERLAYING CUSHIONING SHEETS STILL ATTACH TO ITS RESPECTIVE TAKE-UP ROLLERS IT IS DRIVEN BY A NEGATOR MOTOR AND IS INDEPENDENT FROM THE DRIVE MOTOR REVERSING THE DRIVE SYSTEM STARTS RETRACTION IN ADDITION, THERE IS A BOOM LENGTH COMPENSATOR SPREADER BAR THAT IS INTEGRATED INTO THE SYSTEM IT ELIMINATES THE BOOM SYNCHRONIZATION PROBLEM WHEN RETRACTING THERE IS NO EVIDENCE OF PANEL TRACKING PROBLEM	SAME AS DRUM ROLLER 4					SAME AS DRUM ROLLER 4				H.6-7 THRU -13 H 4 17 & 18
	DATA NOT AVAILABLE	TWO LENTICULAR BOOMS STRADDLE THE PANEL AND ATTACH TO THE DRUM AND SIDE EDGES OF THE PANEL THE TWO BOOMS AND PANEL WRAP AROUND THE ROLLER POWER IS SUPPLIED BY A DC DRIVE MOTOR THROUGH AN INTEGRAL PLANETARY GEAR REDUCTION GAGE WHICH ATTACHES TO A PINION GEAR, ROTATING THE DRUM ROLLER SPUR GEAR THE RESULT IS ROLLER ROTATION OF 1 41 RPM AND LENTICULAR BOOM EXTENSION OF 4 43 FT/MIN A SPREADER BAR AT THE TIP ATTACHES TO THE BOOMS AND SUPPORTS THE PANEL A SILICON RUBBER SPACER STRIP IS BONDED TO THE REAR SURFACE OF THE BOOM PROVIDING A CONTROL SPACE BETWEEN PANEL LAYERS AS THEY WRAP ON THE DRUM WHEN RETRACTING, PANEL TRACKING IS NOT A PROBLEM BECAUSE THEY ATTACH TO THE BOOM, GUIDED BY THE END ASSEMBLY SUPPORT STRUCTURE. MAXIMUM IN AND OUT POSITION OF THE BOOM IS SENSED BY A LIMIT SWITCH WHICH ALLOWS THE DRUM TO ROTATE 1990 DEG	SAME AS DRUM ROLLER 7	50	2 65				DEMONSTRATION MODEL ONLY, NOT OPTIMIZED FOR STRUCTURAL WEIGHT				B.4-1 THRU -4
EMBLY HUB OF M	THE LOCKING DEVICE EMPLOYED ON RYAN'S EXTENSION BOOM IN A DEPLOYED OR A PACKAGED CONDITION IS CONTROLLED BY TWO ELECTRIC MOTORS WHEN CURRENT IS CUT OFF THE MOTORS LOCK INTO POSITION AND PREVENTS THE MOVEMENT OF THE DRUM AND THE CORRUGATED BOOM.	MAGNESIUM PINION GEARS AT EACH END OF A MAGNESIUM DRIVE SHAFT ENGAGE THE CORRUGATED BOOM DRIVE STRIP TO SYNCHRONIZE THE RELATIVE POSITIONS OF THE BOOM. DEPLOYMENT DRIVE POWER IS BY A GEAR BOX SYSTEM ATTACHED TO A DRIVE SHAFT DOUBLE MOTORS THROUGH A DIFFERENTIAL GEAR BOX PROVIDE REDUNDANCY RETRACTION IS FURNISHED BY A MOTOR ATTACHED TO THE DRUM END HUB PROVID TENSION IS BY DRAG OF THE RETRACTION MOTOR AT DEPLOYMENT PROCEDURE IS REVERSED WHEN RETRACTING LIMIT SWITCH SHUT-OFF POWER AT FULL DEPLOYMENT AND RETRACTION DURING RETRACTION BOTH BOOMS AND THE PANEL WRAP AROUND THE DRUM, AND THERE ARE NO PANEL TRACKING PROBLEMS ATTACHMENT OF THE PANEL TO THE BOOMS ELIMINATES THIS. THEY ARE GUIDED BY THE CORRUGATED BOOM DRIVE STRIP	THE DEPLOYMENT AND RETRACTION MOTORS WORK IN UNISON ON BOTH DEPLOYMENT AND RETRACTION CYCLES THROUGH AN ELECTRONIC SENSING SYSTEM THAT CONTROLS POWER TO EACH MOTOR THIS SYSTEM IS DESIGNED SO THAT WHEN DEPLOYMENT IS COMMANDED BOTH DEPLOYMENT AND RETRACTION MOTORS ARE ENERGIZED BY ADJUSTMENT OF CURRENT INPUT THE DEPLOYMENT MOTOR IS THE SUPERIOR FORCE AND BEAM AND SUBSTRATE DEPLOYMENT TAKES PLACE WITH THE RETRACTION MOTOR IMPOSING A DRAG ON THE DRUM, WHICH INSURES A TENSION LOAD BETWEEN BEAM AND DRUM DURING RETRACTION MODE THE SYSTEM REVERSES CAUSING THE DEPLOYMENT MOTOR TO LAG THE RETRACTION MOTOR THE MOTORS ACT AS LOCKING DEVICES WHEN CURRENT IS OFF NO DATA ARE AVAILABLE ON TENSION LOADS.	230	6 30	39 06	50	89 06	0 154	11	30 9	B.4-5 THRU -8
S FOR AT EEM-ABLE ANEL	DATA NOT AVAILABLE	POWER IS PROVIDED BY A MAGNETIC DC MOTOR DRIVE. IT IS COUPLED TO THE CENTRAL SHAFT THROUGH A REDUCTION GEAR BOX. IT ROTATES THE BOOM (STRUT) STOWAGE DRUM THAT DEPLOY THE BOOMS STRADDLING THE PANELS A FOAM CUSHIONING SHEET IS INTERWOUND WITH THE PANEL WHEN STOWED THE SPREADER BAR ATTACHES TO THE BOOMS AND SUPPORT THE PANEL, AND THE CUSHIONING SHEET ATTACHES TO A TAKE-UP ROLLER. AS THE BOOMS DEPLOY THE SPREADER BAR RAISES THE PANELS AND A TENSATOR B MOTOR, ATTACHED TO THE SHAFT AND THE ROLLER END PLATE, PROVIDES PROPER PANEL TENSION IT ALSO COMPENSATES FOR DIFFERENCES IN ROLL-OFF RATE BETWEEN THE PANEL AND BOOMS ANOTHER TENSATOR B MOTOR OPERATES THE CUSHIONING SHEET TAKE-UP ROLLER WHEN RETRACTING THE MOTOR IS REVERSED THE ROLLER TENSATOR MOTOR ROLLS UP THE PANEL AND CUSHIONING SHEET AND THE TAKE-UP ROLLER TENSATOR MOTOR ACTS AS A BRAKE TO MAINTAIN PROPER PANEL TENSION	NO TENSION LOAD DATA AVAILABLE	8.1	0 61	7 7	1 95	1 65	0 96	11	8 4	B 2-1
ATE HE	DATA NOT AVAILABLE	DATA NOT AVAILABLE	DATA NOT AVAILABLE	50	0.61	DEMONSTRATION MODEL ONLY NOT OPTIMIZED FOR STRUCTURAL WEIGHT						

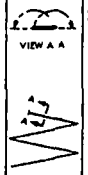
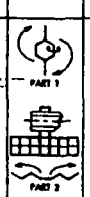
2

FOLDOUT FRAME

3

FOLDOUT FRAME

GENERAL DESCRIPTION OF CURRENT FLEXIBLE SOLAR ARRAY SYSTEMS

SOURCE	STOWAGE METHOD	DESCRIPTION	ILLUSTRATION	PADDING FOR CELL PROTECTION DURING LAUNCH AND GROUND HANDLING		END SUPPORTS	ATTACHMENT TO STRUCTURE	POWER TRANSFER	TIE-DOWN AND RELEASE	DEPLOYMENT/RETRACTION CAPABILITIES	TENSIONING METHOD	CELL AREA (FT²)
				TECHNIQUE	MATERIAL							
BOEING	FLAT PACK 1	FLEXIBLE SOLAR PANELS ARE PRETENSIONED AND FASTENED TO A RECTANGULAR SEMI-RIGID BERYLLIUM FRAME CENTER PORTIONS OF THE PANELS ARE SUPPORTED BY AN OPEN MATRIX ATTACHED TO THE RECTANGULAR FRAME. WHEN STOWED THE PANELS FOLD ON TOP OF EACH OTHER	 VIEW A A	PADDING PER SE IS NOT REQUIRED THE SEMI-RIGID FRAMEWORK PROVIDES A MINIMUM DISTANCE BETWEEN CELL SURFACES OF 0 75 INCH, PRECLUDING ANY NEED FOR PADS IN ADDITION A 12 LB/IN TENSION IS APPLIED TO THE PANELS NORMAL TO ITS EDGES	NONE REQUIRED	NONE	THE INBOARD PANEL DESIGN IS UNIQUE FROM THE OTHERS IN THAT IT PROVIDES THE STRUCTURAL BACKBONE FOR THE REMAINING STOWED PANEL ASSEMBLY IT IS ATTACHED TO THE VEHICLE BY THREE HINGES THE CENTER ONE HELD FIRMLY AND THE OTHER TWO ALLOWED TO MOVE FOR THERMAL EXPANSION AND CONTRACTION THE OTHER END OF THE PANEL IS HELD IN PLACE BY THE TIE-DOWN SYSTEM AND UPON RELEASE ROTATES 90° THE REMAINING PANELS UNFOLD FROM IT	FLEXIBLE FLAT CABLE IS ROUTED ALONG THE FRAMEWORK TO THE VEHICLE	THE TIE-DOWN OF THE FOUR SOLAR ARRAY ASSEMBLIES TO THE SPACECRAFT CENTER-LINE REQUIRES SIX PRETENSIONED CIRCUMFERENTIAL CABLES IN A "COTTON BALE" TYPE TECHNIQUE THIS FORMS A FOUR SIDED BOX WHICH IS ATTACHED AT 12 PLACES TO THE SPACECRAFT BY THE MAIN INTERFACE HINGES STRUCTURAL SHEAR TIE FITTINGS BETWEEN EACH OF THE 13 STOWED SUBPANELS PROVIDES SHEAR CONTINUITY FROM OUTBOARD SUBPANEL TO INBOARD SUBPANEL TO RELEASE THE SYSTEM, THE CABLES ARE CUT WITH ORDNANCE-DRIVEN GUILLOTINE CUTTERS AND THE CABLES THEN ARE JETTISONED FROM CORNER FITTINGS BY A PRETENSION FLAT SPRING THE CABLES ARE THEN DRAWN AWAY LEAVING THE SOLAR ARRAY CLEAN OF CABLE DEBRIS AND ALLOWING THE DEPLOYMENT SYSTEM (CONSISTING OF A MOTOR/CABLE-DRUM, CABLE AND QUADRANTS) TO OPERATE	DEPLOYMENT IS BY REDUNDANT MOTORS RELEASING THE PANEL ASSEMBLY THROUGH SEQUENTIALLY OPERATED MECHANICAL DEVICES UPON FULL DEPLOYMENT THEY ARE LOCKED IN PLACE FOLLOWING ARE THE THREE SEPARATE FUNCTIONS RELEASE OF THE TIE-DOWN SYSTEM DEPLOYMENT OF 5 MAIN PANELS AND DEPLOYMENT OF 8 AUXILIARY PANELS AFTER THE TIE-DOWN SYSTEM RELEASES, THE MOTORS THROUGH TWO HARMONIC DRIVES ROTATE THE CABLE DRUM AT 0 265 RPM TO PRODUCE A CABLE RATE OF 2 IN./MIN TO DEPLOY THE 5 MAIN PANELS AS SUBSEQUENT MAIN PANELS DEPLOY THE PREVIOUS 8 AUXILIARY PANELS HINGED ON THE SIDE OF THE MAIN ONES ARE SEQUENTIALLY UNLATCHED AND DEPLOYED BY TORSION SPRINGS RATE OF DEPLOYMENT NEAR THE LATCHING POSITION IS BY A ROTARY DAMPER WHEN THE PANELS REACH FULL DEPLOYMENT AN OVER-CENTER LATCH SNAPS INTO PLACE LOCKING THE PANELS IN A FLAT PLANE THIS SYSTEM DOES NOT HAVE RETRACTION CAPABILITIES	FIBERGLASS TAPE IS PRETENSIONED AND THEN FUSED TO FORM A PICTURE-FRAME TYPE OF PANEL CONNECTED TO THE STRUCTURAL FRAME THE PROGRAMS INVOLVED IN MAINTAINING THE POSITION OF PRE TENSIONED TAPE INTERCONNECTIONS RELATIVE TO FRAME MEMBERS ARE UNSOLVED	1424
TRW	FLAT PACK 2	PANELS ARE STOWED IN A FIREHOSE FOLD ("Z" SHAPED) ON TOP OF A CUSHION-BACKED RIGID PLATFORM. THEY ARE RETAINED BY A CUSHION-BACKED, SPLIT, RIGID COVER COMPLETE ASSEMBLY IS DIRECTLY ATTACHED TO THE SPACECRAFT		PANELS ARE Z FOLDED AND COMPRESSED BETWEEN A FOAM-BACKED RIGID PLATFORM AND SPLIT COVER SMALL SIZE RECTANGULAR FOAM CUSHIONS ARE PLACED ON THE CELL SIDE OF THE PANEL TO PREVENT CELL-TO-CELL CONTACT AND PROTECT AGAINST CELL BREAKAGE IN THE STOWED CONFIGURATION A TIE-DOWN SYSTEM CONNECTING THE PLATFORM AND THE COVER PROVIDES A MEANS OF APPLYING A COMPRESSIVE PRELOAD TO THE FOLDED PANELS THUS PREVENTING MOVEMENT BETWEEN THEM THE PANELS ARE NOT EXPOSED TO THE ENVIRONMENT	SMALL RECTANGULAR PADS ARE MADE OF 0 060 IN THICK SILICON FOAM RUBBER PADS	NONE	THE INBOARD RIGID RETAINER, WHICH SUPPORTS THE STOWED SOLAR ARRAY ASSEMBLY AND HAS A CUTOUT TO PROVIDE INSTALLATION OF THE BI-STEM BOOM ACTUATOR, MOUNTS DIRECTLY TO THE SPACECRAFT PORTION OF THE ACTUATOR IS INSIDE THE VEHICLE	FLEXIBLE FLAT HARNESS IS ATTACHED TO ONE EDGE OF THE SUBSTRATE	DATA NOT AVAILABLE	DEPLOYMENT AND RETRACTION IS BY A BI-STEM BOOM ACTUATOR CENTERED BETWEEN TWO PANEL ASSEMBLIES A SINGLE LEADING EDGE TIE BAR SUPPORT THE TWO PANELS AND CONNECTS TO THE EXTENDING BOOM OF THE BI-STEM DEVICE INTERMEDIATE TUBULAR STIFFENERS MADE FROM THE PANEL S SUBSTRATE MATERIAL ARE ATTACHED AT THE FOLD LINES OF EACH SUBPANEL THEY ARE PREVENTED FROM GOING OVER CENTER BY ADJACENT STIFFENERS PLACED ON OPPOSITE SIDES OF THE BOOM, THEREBY ALLOWING RETRACTION A FEASIBILITY MODEL WAS BUILT AND TESTED AND RESULTS WERE EXCELLENT	DATA NOT AVAILABLE	250
ROYAL AIRCRAFT ESTABLISHMENT	FLAT PACK 3	PANELS ARE STOWED IN A FIREHOSE FOLD ("Z" SHAPED) ON TOP OF A CUSHION-BACKED RIGID PLATFORM THEY ARE RETAINED BY A CUSHION BACKED SPLIT RIGID COVER COMPLETE ASSEMBLY IS DIRECTLY ATTACHED		PANELS ARE Z FOLDED AND COMPRESSED BETWEEN THE BOTTOM OF A HONEYCOMB COMPARTMENT AND THE TOP CROSS-MEMBER (COVER) WHICH IS ATTACHED TO THE TELESCOPIC MAST THE BOTTOM AND CROSS-MEMBER ARE FOAM-BACKED INTERMEDIATE FOAM-BACKED HONEYCOMB CROSS-MEMBERS ATTACH TO THE FORWARD END OF EACH MAST AND ARE APPROX 2 5 INCHES APART IN THE STOWED CONFIGURATION THE PANELS FOLD 13 TIMES BETWEEN EACH CROSS-MEMBER AND CAPTIVE PLASTIC INTERLEAVES ARE BETWEEN EACH FOLD ELIMINATING CELL-TO-CELL CONTACT A DOWNWARD FORCE ON THE COVER APPLIES A COMPRESSIVE PRELOAD TO THE FOLDED PANELS TO PREVENT MOVEMENT BETWEEN THEM AND BREAKAGE OF CELLS PANELS ARE COMPLETELY ENCLOSED	CROSS-MEMBERS ARE FOAM CUSHION-BACKED ALUMINUM HONEYCOMB STRUCTURES THE INTERLEAVED ARE OF THIN PLASTIC FILM	NONE	THE COMPLETE SOLAR ARRAY ASSEMBLY IS INSTALLED IN A CONTAINER-LIKE SUPPORT STRUCTURE. THIS STRUCTURE MOUNTS DIRECTLY TO THE SPACECRAFT	FLEXIBLE FLAT HARNESS IS ATTACHED TO ONE EDGE OF THE SUBSTRATE	DATA NOT AVAILABLE	THIS SYSTEM IS DESIGNED TO DEPLOY ONLY IT UTILIZES A GAS-CONTROL OPERATED TELESCOPIC MAST WITH THE INNERMOST MAST ALSO SERVING AS THE GAS BOTTLE. THE MAST SYSTEM IS CENTERED BETWEEN TWO PANEL ASSEMBLIES THE TOP CROSSMEMBER ATTACHES TO THE TOP-MOST MAST AND THE LEADING EDGE OF THE PANELS THIS CROSSMEMBER IS ALSO THE COVER TO DEPLOY THE TIE-DOWN SYSTEM RELEASES A SPRING PUSHES OFF A SLEEVE ON A CENTRAL SPINDLE AND UNCOVERS A SMALL PORT GAS PASSES THROUGH THE PORT AT A CONTROLLED RATE INTO A RELEASE CHAMBER WHICH INITIATES DEPLOYMENT SEALS ON THE OUTSIDE OF EACH MAST IMPART A PISTON ACTION FIRST TO THE INNERMOST MAST AND SO ON UNTIL FULL DEPLOYMENT IS REACHED A CHECK VALVE RELEASES ANY EXCESS GAS IN THE SYSTEM KEYS, PADS, SEALS, ETC. PREVENT ROTATION AND KEEP THE MAST CONCENTRIC	DATA NOT AVAILABLE	39
LMSC	FLAT PACK 4	PANELS ARE STOWED IN A FIREHOSE FOLD ("Z" SHAPED) ON TOP OF A CUSHION-BACKED RIGID PLATFORM. THEY ARE RETAINED BY A CUSHION BACKED, SPLIT RIGID COVER, COMPLETE ASSEMBLY IS DIRECTLY ATTACHED		PANELS ARE Z FOLDED AND COMPRESSED IN A CONTAINER BETWEEN A HONEYCOMB FOAM BACKED PALLET AND RIGID SPLIT COVER FOAM SHEETS ARE INSERTED BETWEEN FOLDS WHERE CELLS ARE FACE-TO-FACE. A TIE-DOWN SYSTEM, WHICH APPLIED A COMPRESSION PRELOAD ON THE SPLIT COVERS AND THE FOLDED PANELS, PREVENTS MOVEMENT BETWEEN THEM AND BREAKAGE OF CELLS PANELS ARE COMPLETELY ENCLOSED AND ARE PROTECTED FROM THE ENVIRONMENT	SPLIT COVERS AND PALLET ARE ALUMINUM HONEYCOMB STRUCTURE BACKED BY FOAM CUSHION THE PANEL SEPARATIONS ARE 0.125-INCH THICK FOAM SHEETS	NONE	SAME AS FLAT PACK 3 EXCEPT A PORTION OF BI-STEM BOOM ACTUATOR IS INSIDE THE VEHICLE.	FLEXIBLE FLAT HARNESS IS ATTACHED TO ONE EDGE OF THE SUBSTRATE.	THE HOLD-DOWN/RELEASE SYSTEM EMPLOYED BY LMSC CONSISTS OF A SERIES OF PULLEYS AND CABLES CONNECTED AT ONE END TO THE SPRING-LOADED "HOLD-DOWN WHEEL" WHICH RESTRAINS THE SOLAR ARRAY COVERS, AT THE OTHER END TO TWO PYRO PIN-PULLERS WHICH IS A REDUNDANT SAFETY FEATURE A TURNBUCKLE IS PROVIDED FOR EACH CABLE SO THAT EQUAL TENSION CAN BE APPLIED TO EACH HOLD DOWN POINT FIRING EITHER ONE OF THE PIN-PULLERS WILL RELEASE THE CABLE TENSIONS ALLOWING THE "HOLD-DOWN WHEEL" AND THE SOLAR ARRAY COVERS TO PIVOT OUT OF THE WAY THEN THE SOLAR ARRAYS ARE FREE TO DEPLOY THIS SYSTEM OF OPERATION ELIMINATES A SERIES OF PYRO PIN-PULLERS AND A HIGH DEGREE OF RELIABILITY AND WEIGHT SAVING CAN BE ATTAINED	SAME AS FLAT PACK 2 DESIGN EXCEPT THAT TUBULAR STIFFENERS ARE REPLACED BY HINGE PINS WHICH DO NOT EXTEND PAST THE EXTENDING BOOM, THEREBY PRECLUDING RETRACTION	MOTOR DRIVEN BI-STEM BOOM AND ATTACHING SPREADER BAR DEPLOYS FLEXIBLE SOLAR ARRAY DURING THE DEPLOYMENT PHASE NO TENSION LOADS ARE APPLIED BECAUSE OF THE SLACK IN THE PANEL AFTER FULL DEPLOYMENT, TENSION LOADS BETWEEN A FOLD HONEYCOMB PLATFORM AND SPREADER BAR AMOUNTS TO 90 LB	250
MESSERSCHMITT - BOLKOW - BLOHM	FLAT PACK 5	A POLYAMID FOIL (SUPPORTING TUBES) FORM THE FRAMEWORK THAT SUPPORTS THE SUBPANELS THEY ARE FIRST Z" FOLDED ON TO THE MAIN PANELS (A LOW-WEIGHT MAGNESIUM FRAMEWORK). THE ASSEMBLY SUBPANEL (AND MAIN PANEL) ARE THEN EITHER WRAPPED AROUND THE VEHICLE OR Z" FOLDED	 PART 1 PART 2	FOAM LAYERS ARE INSERTED BETWEEN CELL-TO-CELL SURFACES WHEN FOLDING THE SUBPANELS	FOAM LAYERS (TYPE NOT REPORTED) WITH A DENSITY OF 2 5 LB/FT³	NONE	THE RIGID SURFACES THE SO-CALLED MAIN PANELS CONSIST OF LIGHT STRUCTURAL FRAMES HAVING SEVERAL SECTIONS THESE FRAMES ARE HINGED TOGETHER AND ARE ATTACHED TO THE BODY OF THE SPACECRAFT ACCORDING TO ITS CONFIGURATION EITHER IN A ZIG ZAG MANNER (LIKE BOEING) OR IN A POLYGON ARRANGEMENT A TABLE ARRANGEMENT AND ITS RELEASE DEVICE (NOT REPORTED) TIE DOWN THE STOWED ASSEMBLY TO THE VEHICLE	FLEXIBLE FLAT CABLE IS ROUTED ALONG THE FRAMEWORK TO THE VEHICLE	TIE DOWN IS BY A PYROTECHNIC DEVICE IN CONJUNCTION WITH SPRINGS AND A TACKLE ARRANGEMENT	RELEASE DEVICE THROUGH A TACKLE ARRANGEMENT INITIATES FULL DEPLOYMENT OF THE MAIN PANELS WHICH ARE FIXED IN POSITION BY SPRING LOCKS UPON FULL DEPLOYMENT OF THE MAIN PANELS THE SUBPANEL FRAMEWORKS ARE THEN PRESSURIZED BY A GELATINE GLASS-FIBER LAMINATE, WHICH INFLATES THE FRAMEWORK AS WELL AS DEPLOYS THE SUBPANELS TEN TO TWENTY HOURS ARE REQUIRED TO COMPLETE RIGIDITY OF THE FRAMEWORK UNDER ENVIRONMENTAL CONDITIONS THIS SYSTEM DOES NOT RETRACT	TENSION REQUIRED ON SUBPANELS ONLY AS THE FRAMEWORK IS INFLATED THE DISTANCE BETWEEN PANEL ATTACHMENTS IN CREASE THEREBY RESULTING IN TENSION TO THE PANELS	1390

FOLDOUT FRAME 1

FOLDOUT FRAME 2

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GENERAL DESCRIPTION OF CURRENT FLEXIBLE SOLAR ARRAY SYSTEMS

A

ANSFER	TIE-DOWN AND RELEASE	DEPLOYMENT/RETRACTION CAPABILITIES	TENSIONING METHOD	CELL AREA (FT²)	STOWED VOL (FT³)	WEIGHT SUMMARY: STRUCT (LB)	SOLAR PANEL (LB)	STRUCT + SOLAR PANEL (LB)	STRUCT WT/AREA (LB/FT²)	POWER AREA (WATTS/FT²)	POWER/WT (WATTS/LB)	BIBLIO NO
ABLE IS ROUTED AMEWORK TO	THE TIE-DOWN OF THE FOUR SOLAR ARRAY ASSEMBLIES TO THE SPACECRAFT CENTER-LINE REQUIRES SIX PRETENSIONED CIRCUMFERENTIAL CABLES IN A COTTON BALE TYPE TECHNIQUE THIS FORMS A FOUR-SIDED BOX WHICH IS ATTACHED AT 12 PLACES TO THE SPACECRAFT BY THE MAIN INTERFACE HINGES STRUCTURAL SHEAR TIE FITTINGS BETWEEN EACH OF THE 12 STOWED SUBPANELS PROVIDES SHEAR CONTINUITY FROM OUTBOARD SUBPANEL TO INBOARD SUBPANEL TO RELEASE THE SYSTEM, THE CABLES ARE CUT WITH ORDNANCE-DRIVEN GUILLOTINE CUTTERS AND THE CABLES THEN ARE JETTISONED FROM CORNER FITTINGS BY A PRETENSION FLAT SPRING THE CABLES ARE THEN DRAWN AWAY LEAVING THE SOLAR ARRAY CLEAN OF CABLE DEBRIS AND ALLOWING THE DEPLOYMENT SYSTEM (CONSISTING OF A MOTOR/CABLE DRUM, CABLE AND QUADRANTS) TO OPERATE	DEPLOYMENT IS BY REDUNDANT MOTORS RELEASING THE PANEL ASSEMBLY THROUGH SEQUENTIALLY OPERATED MECHANICAL DEVICES UPON FULL DEPLOYMENT THEY ARE LOCKED IN PLACE FOLLOWING ARE THE THREE SEPARATE FUNCTIONS RELEASE OF THE TIE-DOWN SYSTEM DEPLOYMENT OF 3 MAIN PANELS AND DEPLOYMENT OF 8 AUXILIARY PANELS AFTER THE TIE-DOWN SYSTEM RELEASES, THE MOTORS THROUGH TWO HARMONIC DRIVES, ROTATE THE CABLE DRUM AT 0 265 RPM TO PRODUCE A CABLE RATE OF 2 IN./MIN TO DEPLOY THE 3 MAIN PANELS AS SUBSEQUENT MAIN PANELS DEPLOY THE PREVIOUS 8 AUXILIARY PANELS HINGED ON THE SIDE OF THE MAIN ONES ARE SEQUENTIALLY UNLATCHED AND DEPLOYED BY TORSION SPRINGS RATE OF DEPLOYMENT NEAR THE LATCHING POSITION IS BY A ROTARY DAMPER WHEN THE PANELS REACH FULL DEPLOYMENT, AN OVER-CENTER LATCH SNAPS INTO PLACE LOCKING THE PANELS IN A FLAT PLANE THIS SYSTEM DOES NOT HAVE RETRACTION CAPABILITIES	FIBERGLASS TAPE IS PRETENSIONED AND THEN FUSED TO FORM A PICTURE-FRAME TYPE OF PANEL CONNECTED TO THE STRUCTURAL FRAME THE PROGRAMS INVOLVED IN MAINTAINING THE POSITION OF PRETENSIONED TAPE INTERCONNECTIONS RELATIVE TO FRAME MEMBERS ARE UNSOLVED	1424	155	523	342	865	0 366	11	19 2	B 3 1 THRU -6 B 3-12 & -18
ARNESS IS NE EDGE OF	DATA NOT AVAILABLE	DEPLOYMENT AND RETRACTION IS BY A BI STEM BOOM ACTUATOR CENTERED BETWEEN TWO PANEL ASSEMBLIES A SINGLE LEADING EDGE TIE BAR SUPPORT THE TWO PANELS AND CONNECTS TO THE EXTENDING BOOM OF THE BI-STEM DEVICE INTERMEDIATE TUBULAR STIFFENERS MADE FROM THE PANEL S SUBSTRATE MATERIAL ARE ATTACHED AT THE FOLD LINES OF EACH SUBPANEL THEY ARE PREVENTED FROM GOING OVER CENTER BY ADJACENT STIFFENERS PLACED ON OPPOSITE SIDES OF THE BOOM, THEREBY ALLOWING RETRACTION A FEASIBILITY MODEL WAS BUILT AND TESTED AND RESULTS WERE EXCELLENT	DATA NOT AVAILABLE	250	1 9	23 34	50	73 34	0 093	11	37 6	T 3-19
ARNESS IS NE EDGE OF	DATA NOT AVAILABLE	THIS SYSTEM IS DESIGNED TO DEPLOY ONLY IT UTILIZES A GAS-CONTROL OPERATED TELESCOPIC MAST WITH THE INNERMOST MAST ALSO SERVING AS THE GAS BOTTLE. THE MAST SYSTEM IS CENTERED BETWEEN TWO PANEL ASSEMBLIES THE TOP CROSSMEMBER ATTACHES TO THE TOP-MOST MAST AND THE LEADING EDGE OF THE PANELS THIS CROSSMEMBER IS ALSO THE COVER TO DEPLOY THE TIE-DOWN SYSTEM RELEASES A SPRING PUSHES OFF A SLEEVE ON A CENTRAL SPINDLE AND UNCOVERS A SMALL PORT GAS PASSES THROUGH THE PORT AT A CONTROLLED RATE INTO A RELEASE CHAMBER WHICH INITIATES DEPLOYMENT SEALS ON THE OUTSIDE OF EACH MAST IMPART A PISTON ACTION FIRST TO THE INNERMOST MAST AND SO ON UNTIL FULL DEPLOYMENT IS REACHED A CHECK VALVE RELEASES ANY EXCESS GAS IN THE SYSTEM. KEYS, PADS, SEALS, ETC., PREVENT ROTATION AND KEEP THE MAST CONCENTRIC	DATA NOT AVAILABLE	38	62 0	12 6	9 37	21 97	0 323	11	34 1	B 3-4 & -9
ARNESS IS NE EDGE OF	THE HOLD-DOWN/RELEASE SYSTEM EMPLOYED BY LMSC CONSISTS OF A SERIES OF PULLEYS AND CABLES CONNECTED AT ONE END TO THE SPRING-LOADED HOLD-DOWN WHEEL WHICH RESTRAINS THE SOLAR ARRAY COVERS, AT THE OTHER END TO TWO PYRO PIN-PULLERS WHICH IS A REDUNDANT SAFETY FEATURE. A TURNBUCKLE IS PROVIDED FOR EACH CABLE SO THAT EQUAL TENSION CAN BE APPLIED TO EACH HOLD DOWN POINT FIRING EITHER ONE OF THE PIN-PULLERS WILL RELEASE THE CABLE TENSIONS ALLOWING THE HOLD-DOWN WHEEL AND THE SOLAR ARRAY COVERS TO PIVOT OUT OF THE WAY; THEN THE SOLAR ARRAYS ARE FREE TO DEPLOY THIS SYSTEM OF OPERATION ELIMINATES A SERIES OF PYRO PIN-PULLERS AND A HIGH DEGREE OF RELIABILITY AND WEIGHT SAVING CAN BE ATTAINED	SAME AS FLAT PACK 2 DESIGN EXCEPT THAT TUBULAR STIFFENERS ARE REPLACED BY HINGE PINS WHICH DO NOT EXTEND PAST THE EXTENDING BOOM, THEREBY PRECLUDING RETRACTION	MOTOR DRIVEN BI-STEM BOOM AND ATTACHING SPREADER BAR DEPLOYS FLEXIBLE SOLAR ARRAY DURING THE DEPLOYMENT PHASE NO TENSION LOADS ARE APPLIED BECAUSE OF THE SLACK IN THE PANEL. AFTER FULL DEPLOYMENT, TENSION LOADS BETWEEN A FIXED HONEYCOMB PLATFORM AND SPREADER BAR AMOUNTS TO 10 LB	250	1 95	37 7	30	77 7	0 108	11	35 3	L 4-9 -16, 17 & -19
ABLE IS ROUTED AMEWORK TO	TIE DOWN IS BY A PYROTECHNIC DEVICE IN CONJUNCTION WITH SPRINGS AND A TACKLE ARRANGEMENT	RELEASE DEVICE THROUGH A TACKLE ARRANGEMENT, INITIATES FULL DEPLOYMENT OF THE MAIN PANELS WHICH ARE FOLED IN POSITION BY SPRING LOCKS UPON FULL DEPLOYMENT OF THE MAIN PANELS THE SUB PANEL FRAMEWORKS ARE THEN PRESSURIZED BY A GELATINE GLASS-FIBER LAMINATE, WHICH INFLATES THE FRAMWORK AS WELL AS DEPLOYS THE SUBPANELS TEN TO TWENTY HOURS ARE REQUIRED TO COMPLETE RIGIDITY OF THE FRAMEWORK UNDER ENVIRONMENTAL CONDITIONS THIS SYSTEM DOES NOT RETRACT	TENSION REQUIRED ON SUBPANELS ONLY AS THE FRAMEWORK IS INFLATED THE DISTANCE BETWEEN PANEL ATTACHMENTS INCREASE THEREBY RESULTING IN TENSION TO THE PANELS	1290	905	139	258	397	0 108	11	35 8	M, 3-1

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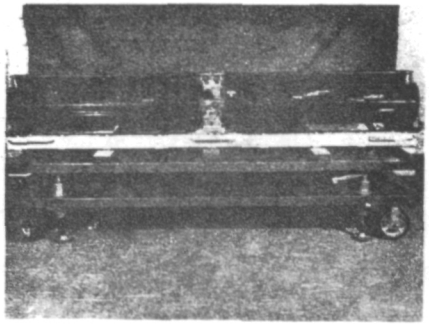
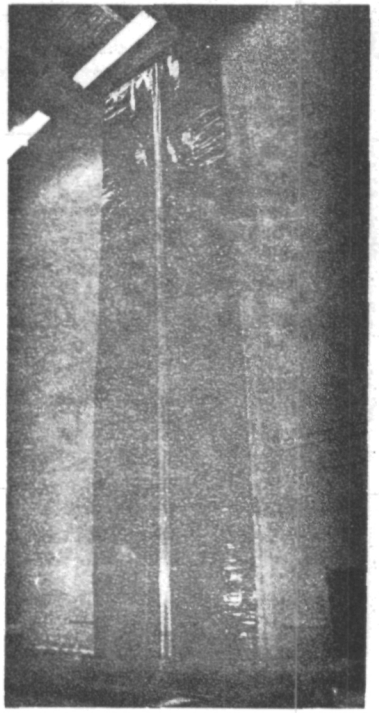


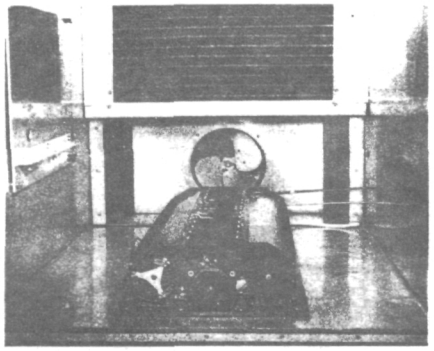
(Stowed)



(Deployed)

Flexible Solar Array, 250-ft^2 Model (General Electric, Space Division, Valley Force, Pa.

Current Flexible Solar Array Systems



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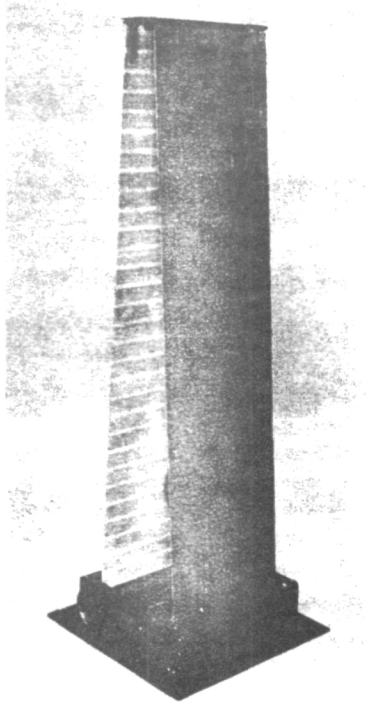
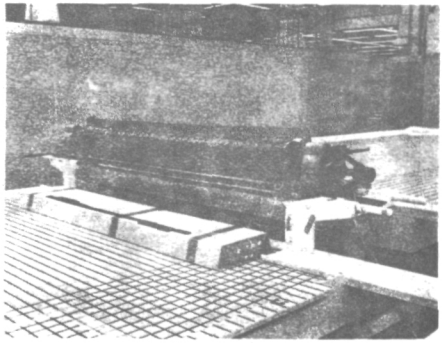


(Deployed)

Fairchild-Hiller
Germantown, Md.

Current Flexible Solar Array Systems (Cont.)



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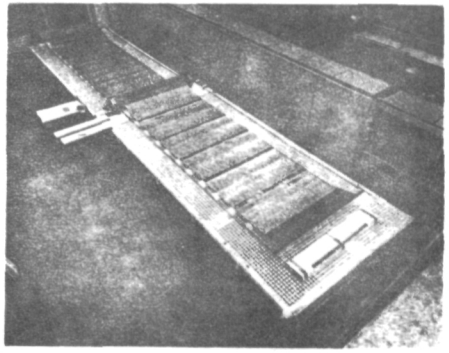
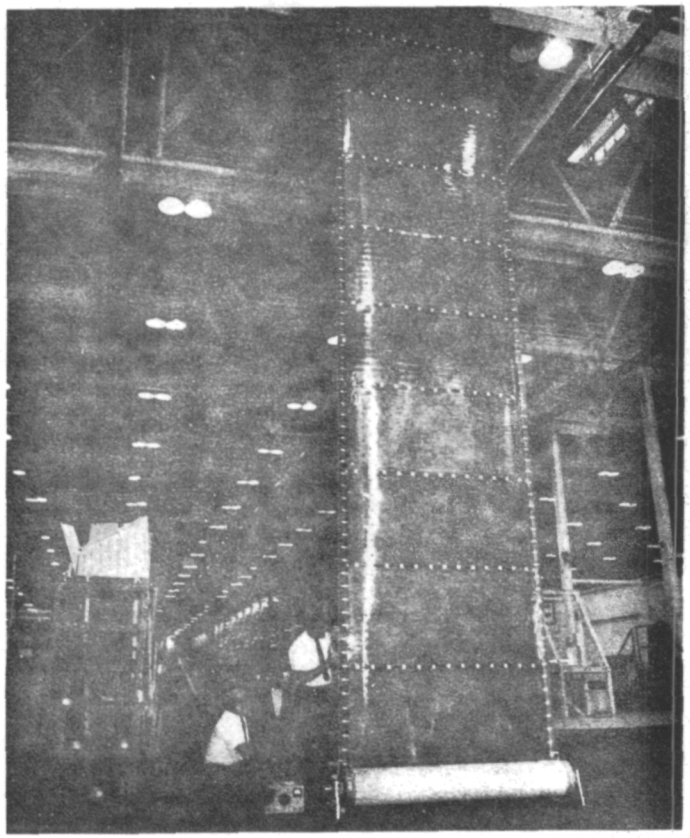


(Deployed)

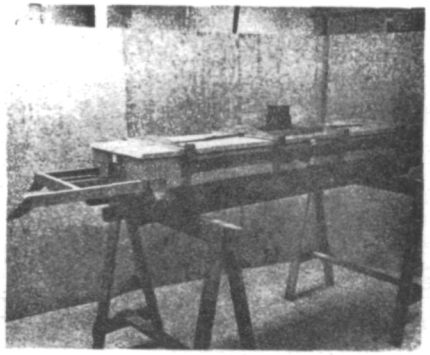
Hughes Aircraft Company
El Segundo, Calif.

Current Flexible Solar Array Systems (Cont.)



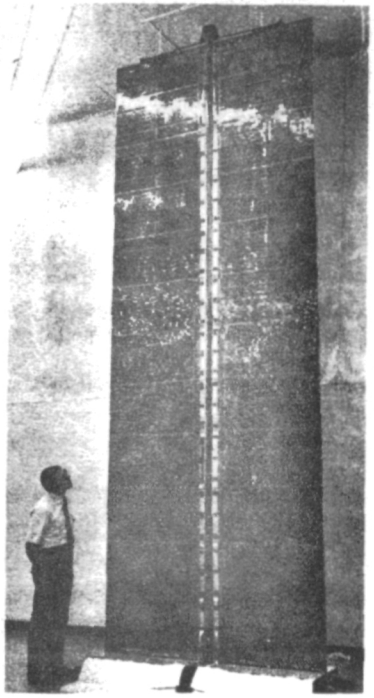
Flexible Solar Array – Back Surface of 250-ft^2 Model
(Ryan Aeronautical Company, San Diego, Calif.)

Current Flexible Solar Array Systems (Cont.)



(Stowed)

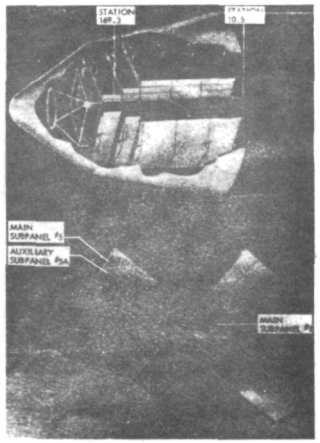
Lockheed Missiles & Space Company, Sunnyvale, Calif.



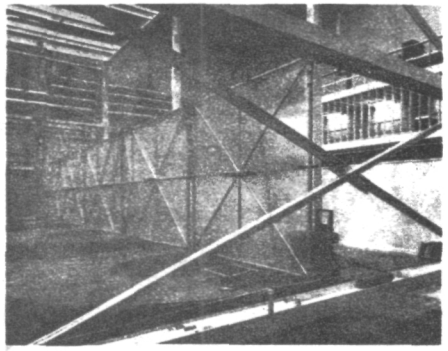
(Deployed)

Flexible Solar Array, 100-ft^2 Model

Current Flexible Solar Array Systems (Cont.)

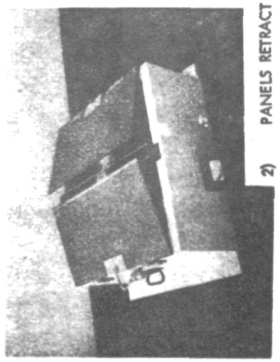


Artist's Conception of Stowed and Deployed Configurations

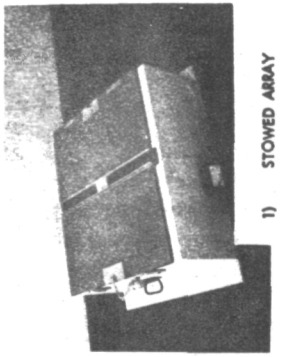


Deployed Configuration of Five Main Panels on Test Fixture (The Boeing Company, Seattle, Washington

Current Flexible Solar Array Systems (Cont.)

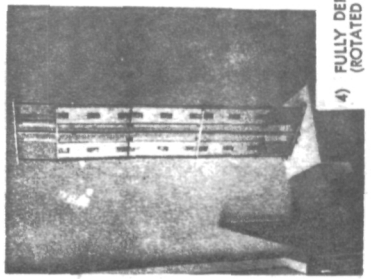


2) PANELS RETRACT

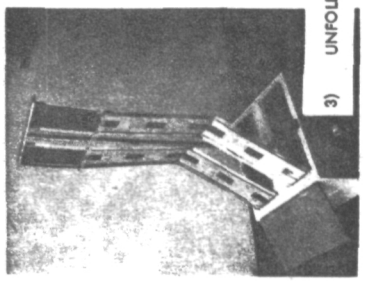


1) STOWED ARRAY

TRW



4) FULLY DEPLOYED WING (ROTATED 40°)



3) UNFOLDING PANELS

Flexible Solar Array, 12-ft^2 Model (TRW System Group, Redondo Beach, Calif.)

Current Flexible Solar Array Systems (Cont.)

4.1.1.2 Testing Performed on Flexible Array Systems

A review of the testing accomplished in the field of flexible solar arrays was made to determine which of the significant or unique test methods could be applied to large space station solar arrays (LSSSA).

The review covered the 10 major contractors who have developed, fabricated, and tested flexible substrate solar arrays. The Structure Environmental Test Chart, Chart B at the end of this section, reveals that much thermal, structural, and dynamic testing has occurred on the various flexible solar array configurations. None of these arrays were of comparable size to the LSSSA; in fact, all those on which significant testing was performed were 280 square feet or less in area, approximately one-fortieth of the space station solar array area. This large scale-up in dimensions places severe restriction on the degree to which test results previously obtained may be applied to the LSSSA. The testing did point out the important problem areas, and developed some unique test methods.

All flex array systems were tested for deployment capabilities and most were tested for retraction. In the flat fold category, the TRW system was the only remote retraction system. The others, because of configuration or program requirements, were capable of deployment only and manual aids were necessary for retraction. The overhead support techniques for deployment/retraction testing which have been used appear feasible for scale-up to the LSSSA size without any unsurmountable problems.

Panel alignment tests were conducted to evaluate retraction capabilities or aerodynamic characteristics. Here it is important to note that Fairchild-Hiller experienced problems in keeping the substrate on the drum during retraction. They attributed this to lateral displacement of the outer panel support by the folding beam. Also, their drum length/diameter is in the range of 20/1, where the other drum concepts were 7/1 or less, which may have an effect on retraction. Local panel wrinkling was experienced, but this was eliminated with the application of cells to the substrate. Solar panel wrinkling will be apparent in all but the frame systems during ground deployment tests without aids to reduce panel support deflections to near zero. The systems may be fully satisfactory for zero-g applications, but in one-g applications the tensioning systems would require extreme over-design, penalizing both support structure and tensioning system.

The most unique and comprehensive dynamic testing was done at G.E., including heavily instrumented sine, random, and acoustic tests of their 250 square foot rollup array, in the stowed condition. They also conducted a modal test of the deployed array in both atmospheric air and a vacuum, and a modal test of the stowed system.

Findings of the G.E. deployed modal test are of significance to LSSSA, inasmuch as they indicate the following:

- Analytical out-of-plane predictions of the lower frequencies, using a finite element technique and treating the array as a membrane, are very close to the true values in a 1-g field directed from the roller towards the array tip. It is, therefore, very reasonable to suppose that analytical predictions of the lower natural frequencies, using the same technique, for the zero-g condition will be good approximations to the truth,
- The higher modes are sensitive to the bending stiffness of the array and also to the uniformity, or lack of uniformity, of tension across the width of the array,
- The structural damping of the array is very high when measured in air compared to its value (the true value) when measured in vacuum. The measured damping coefficient for out-of-plane oscillatory motion of the array was 25 times higher in air than in vacuum. Further testing is being conducted to resolve the problem correlating in-plane vibration analysis with in-plane vibration of the deployed configuration.

Despite the discrepancy in size between the two arrays, there is no reason why the G.E./JPL findings should not be applicable to the larger LSSSA. In fact, the increase in size for very little change in substrate thickness between the two arrays should make the assumption that the array acts as a membrane even more valid, and hence should render possible for the accurate computation of higher modes using this assumption, than was possible for the G.E. array. Therefore, experimental determination of array modes will not be necessary, provided that adequate stiffness data for the boom are obtained, either analytically or by static test, and the boom is a reasonably linear structure with little or no "slop". A test of an array of this size in vacuum to determine structural damping would be prohibitively expensive if, indeed, possible. The value for structural damping derived by G.E. was 0.004 for the lower modes and a higher value for the higher ones. The value of 0.004 is undoubtedly conservative (low) for the space station array since for the type of boom which will be necessary for the LSSSA (heavily built-up truss or tubular structure) the structural damping should be greater than this. Also, the G.E. test specimen did not incorporate the metal

interconnects between adjacent cells which, especially in the higher modes where bending of the array takes place, will increase damping.

Boom damping data for the lower modes on the LSSA can be estimated during the boom static deflection tests by releasing the boom suddenly from a deflected position and measuring the resultant decay. It is not expected that air damping will be significant as long as the boom used has a low drag area/mass ratio. Sine, random, acoustic and shock testing of stowed configurations was quite comprehensive. The most significant problem here was encountered by G.E., when they found that during vibration testing of their drum roll-up system the successive wraps tightened around the core, leaving the outer wraps to flap, resulting in damage to cells. Further testing is being conducted to resolve the problem and arrive at the proper stowed tension levels for the array by increasing the tensions on the substrate while the array is being stowed.

Static tests were performed on some systems, but the results are generally peculiar to the structure being used. The boom design for the LSSSA will be much larger in size and will be subjected to artificial-g loads that are proportionally much larger than the smaller arrays were designed for. Therefore, the data from these tests will not be applicable. Static tests of the extensible boom in combined axial and bending modes will provide information on the load-carrying behavior of the boom and, if carried to destruction, the ultimate capability and failure mode. In addition, this test will yield essential information on the boom stiffness for use in the dynamic analysis.

The angular velocity associated with the artificial-g portion of the mission creates a component of centrifugal force along the span of the array at right angles to the Space Station longitudinal axis, and an orthogonal component along the chord parallel to the Space Station longitudinal axis. This latter component will cause buckling or sagging of the substrate that can only be eliminated by pre-tensioning. The appropriate ratio between chordwise and spanwise centrifugal force may be produced in a 1-g field by suspending an appropriately weighted panel of the array with its chord in a vertical plane and its spanwise axis tilted at a predetermined angle to the horizontal. The amount of pretension required to avoid sagging of the blanket may then be determined experimentally for the ratio between chordwise and spanwise forces appropriate to this angle.

The substrate tests conducted by Lockheed indicated that substrate flatness can be reasonably controlled by the support techniques which are employed in either zero-g or 1-g environments, but not both without aids. The aids would, of course, be applied during the ground tests. The aids must be designed to allow realistic deflections in the substrate to occur so that retraction effects are accurately simulated.

Some system thermal testing has been accomplished on solar arrays. However, the large size of the LSSSA, together with the fact that system temperature distribution and resulting structural distortions are so very dependent on the individual structural details, that to render meaningful extrapolation of test results from one system to predict those of another system, even if it is somewhat similar, is very questionable. Ascent thermal conditions can generally be controlled by shroud or fairing internal insulations. Orbital thermal environments of ±200°F for 58,000 cycles are much more severe and much more detrimental to system operation. Extension, retraction, and operation phases are all affected. Thermal environment effects during operation of the solar array, on both the extensible boom and the substrate, will have a bearing on their design criteria. Thermal deflection tests are planned for the selected baseline boom and substrate, and the test data will be applied to the system configuration to determine their effects.

In addition to the test summary presented in Chart B, a brief summary of the testing conducted by each solar array contractor is included in the following Structural Test Program Survey to indicate the problems which were revealed and the solutions planned or accomplished.

STRUCTURAL TEST PROGRAM SURVEY

1. General Electric – 50-ft^2 Flex Array Feasibility Model (Ref. Bibliography G.2-1 through -4)

- Bi-stem Boom Deployment Test

  Vertical upward, unaided, extension of boom with 4-inch wide 1-mil Kapton strips to simulate panels. Full extension of 33.5 ft with no apparent problems. Repeat test with 480 cells mounted on one strip and 480 glass blanks on the other adding 1.4 lb to boom tip load. Boom stalled at 30 ft. Back-wound tape caused by excessive column load as the boom approached full extension. Replaced tape, with no further problems.

- Bearing and Lubrication Considerations
  - Three Constraints

    Capability of withstanding static (non-rotating) radial and thrust loads of launch.

    Retention of lubrication properties in space environment.

    Low starting torque after prolonged idle periods in space.
  - Lubrication Considerations

    Dry film – two types commonly used.

    Transfer film – reinforced Teflon.

    Dry film – Molybdenum disulfide.
  - Bearing and Retainer Used

Bearing Type:	Instrument size ball bearing
Case and Ball Material:	440c Stainless steel
Container Material:	Rulon C (reinforced Teflon)

  NOTES: Low speed application; bearing should first be run at 500 to 1000 RPM at light load (1/4 pound approximately) for 1 hour to assure transfer of film from retainer. Bearing must be supplied without oil lubrication.

- Vibration per GE Drawing 47E214524:
  - Sinusoidal along 3 mutually perpendicular axes.
  - Random along 3 mutually perpendicular axes.
- Acceleration per GE Drawing 47E214524:

  ±13 g ±0.7 g at cg along 3 mutually perpendicular axes and varying across the component by not more than 1.3 g from the specific 13 g.

2. General Electric – 250-ft^2 Flex-Array Prototype (Ref. Bibliography G.2-5 through -8)

- Bi-stem Thermal Motion Test

  Two tests conducted in a vacuum chamber to investigate boom thermal motion behavior. The chamber consists of a vertical cylinder approximately 1-ft in diameter by 13-ft high, incorporating a liquid N_2 shroud, and with solar simulation that provides an intensity conformity of better than ±5 percent. One test allowed unrestrained motion (rotation) between the bi-steam elements, the other test restrains motion between the elements at the tip. This is the GE design, where the tip plug is attached to both elements. The relative motion of the elements with respect to rotation was noted when the heat source was turned on and off.

  Results: Tip deflections were repeatable for the non-attached configuration. The attached configuration had slight variations when selective points were checked. One point selected was considered to be unstable and could result in thermal flutter. (Ref. Bibliograph G.2-8, Pages 2-39 to 2-40). For extrapolation, derivation and discussion of results see Bibliography G.2-8, Pages 2-40 to 2-45.

- Array Structure Load Deflection Test

  (For load-deflection testing of the drums and end support in the stowed configuration, see complete test summary, Bibliograph G.2-8, Pages 2-48 to 2-64).

- Bi-stem Component Vibration Test

  Spar bi-stem actuator unit subjected to vibration levels per GE Specification SVS 7552. Tests performed were sinusoidal and random (Bibliograph G.2-8, Page 2-63).

- AiResearch Motor/Gearhead Test

  Test to determine capability of operation of motor/gear assembly to retract the solar array for the required duty cycle without overheating when in a vacuum. Previously it was determined that it would operate under rated conditions in vacuum. Ratings are 120 oz-in. load one minute on, five minutes off. This test was to determine if it would handle maximum expected load of 20 oz-in. with a duty time of five minutes on. (Bibliography G.2-8, Pages 2-66 to 2-71).

- Systems Test (Bibliography G.2-8, Pages 2-72 to 2-87)

  - Deployed Model Test. Applied base displacements in the form of sinusoidal excitations from 0.1 to 2.0 Hz. Array extended vertically with leading end down, drum up in a vacuum chamber. The primary objectives were to obtain natural frequencies and mode shape of array in vacuum and 1-g field and compare the results to analysis, and to measure the damping characteristics in vacuum and standard atmospheric conditions. Reports and discussions have indicated that correlation of analysis and test were successful in the out-of-plane mode of excitation. In-plane modes did not correlate and further study will be accomplished in a follow-on program. In vacuum damping coefficient established by test was 0.004 and in one atmosphere was 0.1.

  - Stowed Modal Test. Sinusoidal excitation applied to the stowed array from 10 to 2000 Hz. The primary objectives are to (1) correlate analysis with test results; (2) measure damping characteristics in ambient environment; and (3) evaluate modes of vibration peculiar to blankets. Testing revealed a tightening of blanket inner layers and a loosening of outer layers which produced cell damage. Follow-on testing will involve higher substrate tensions provided by ground aids during the retraction process. Testing not concluded at this time.

- GSE and Test Experiment (Ref. Bibliography G.2-8, Pages 2-88 to 2-95/96)

  - Holding fixture developed for ground handling of drum assembly.
  - Deployment aids for upward extension of array successfully developed and demonstrated.
  - Deployed model test equipment developed and demonstrated for flexible array systems

3. Fairchild-Hiller – 250 ft^2 Flex-Array Feasibility Model (Ref. Bibliography F.1-1 through -4)

- Counterbalance weights were attached through a system of overhead pulleys and cables to simulate vertical, upward deployment of the folding arm system, and the sub-array panel. Counterbalancing weights were used for configuring varying weights of the array panel as it is deployed off the drum. The deployment/retraction tests were conducted to establish the operational characteristics of the deployment/retraction mechanism. See Bibliograph F.1-4, Table 2.5.3-1, Page 2-79 for cable rigging tensions. This test was conducted to determine the system loading capabilities. Significant factors uncovered are as follows:

  - Tracking of panels during roll-up. Difficulty was experienced in keeping the substrate on the drum. Problem not resolved.
  - Random wrinkling occurred during retraction – problem disappeared when panels were covered with solar cells.
  - Folding arm cable rigging tension effects:
    - Cable Pre-Load. Cable tension rigged to such magnitude that the active cables would develop only the load required to perform its function without permitting its companion cable to go slack.
    - Cable Pre-Stress. Pre-stretch the cable to give it permanent set, thereby preventing subsequent stretching and tension relaxation in folding arm system.
  - In-plane shear stability and rigidity of the array panel. Small lateral motion of spreader bar during extension/retraction affected tracking. Problem unresolved, needs further investigation.

4. Fairchild-Hiller – 16-ft^2 Spinning Satellite Flex-Array (Ref. Bibliography F.1-5 through -7)

- Vertical Upward Deployment. Increase linkage force with additional springs to actuate array panels to overcome force of gravity for ground testing.
- Humidity. Test was conducted in Tenny Altitude Chamber for 24 hours at 86° ±2°F at relative humidity of 95 ±5 percent. Corrosion problems due to dissimilar metals. Proper preparation and choice of material could eliminate these problems.
- Vibration. Test included a three-axis sinusoidal and random shake (see Bibliography, F.1-6, page 3-17 to page 3-24).
- Spin Deployment. To verify structural integrity and proper mechanical functioning of the array. Test was to simulate flight condition, deploying two arrays and spinning at 160 RPM (16.75 radians/sec). Calculated and actual deployment times are shown in Bibliography F.1-6, Fig. 3.20, page 3-24.

5. Hughes – 166-ft^2 Flex-Array Prototype (Ref. Bibliograph H.1-1 through -6)

- Array Wrapping

  Various tests were conducted to develop techniques that utilize the force in the compressed foam layers to protect the solar cells from vibration. (Ref. Bibliography H.1-3, pages 13 to 15)
- Mechanical Model Tests (Ref. Bibliography H.1-5, pages 7 to 14)
  - Stem device deployment demonstrates retraction to verify capability
  - Active area decrease – Rate of substrate coming off the rolled up layers compared to the rate of stem tube deployment required adjustment of leading edge thus reducing the active area. This problem was resolved in a follow-on program by replacing gearing system with a negator motor.
  - Substrate sag prevalent during all "G" deployments.
  - Failure and rework of stem devices as a result of exceeding design loads.
  - Inter-panel pressure tests to assess the effects of varying the panel restraining loads for ascent.
  - Environmental tests (not completed in this contract).

    Thermal shock – three continuous shock cycles +85°C to -48°C

    Mechanical shock – 6 millisecond sawtooth

Fore g	Aft g	Lateral g
30 ±3	30 ±3	30 ±3

Acceleration – 1 minute

Fore g	Aft g	Lateral g
6.6	2.0	0.5

Vibration – Sine Acceleration

Frequency	Acceleration
5 - 10	0.2 inch double amplitude
10 - 18	1-g acceleration peak
18 - 56	0.06 inch double amplitude
56 - 2000	10 g acceleration peak

Random Vibration Levels

100 - 1000	0.06g^2/cps (9.3 g-rms)
100 - 50	Down 6 db/octave
1000 - 2000	Down 6 db/octave

6. Hughes – Follow-On Testing (Same Unit) (Ref. Bibliography H.6-7 through -13)

- Development test of boom length compensation (Bibliograph H.6-8, pages 17 and 18).
- Room temperature test of drum drive negators (Bibliography H.6-8, pages 11 and 12).
- Vibration test of panels and cushion. Room temperature life test on contoured drum negators (Bibliography H.6-10, pages 13 to 15).
- Completion of vibration test of panels and cushion. Bearing and negator development tests. Boom actuation unit development test (Bibliography H.6-11, pages 15 to 20).

7. Ryan – 280-ft^2 Flex-Array Prototype (Ref. Bibliography R.4-5 through -8)

- Investigations of extension and retraction torque required for the beam held radially against the wrap drum. The minimum torques required were determined when the radial forces were such that the wrapped beam was held against the wrapped drum with no deformation from the wrapped drum curvature between the radial points. The radial forces were provided by 3/8-in. diameter rollers held against the flattened beam by a tension spring each side of the beam. The test was conducted by recording the force, at a given crank arm (torque), to extend and retract the beam. (See Bibliography R.4-4, Test Results, page 186, Fig. 11-2.)
- For theoretical torque calculations, see R.4-4, page 187 to page 190.
- Beam bending test was conducted to determine the vertical plane bending capability of the cantilevered deployable beam.

- See R.4-4, page 192, Fig. 11-4 for test results. For calculated comparison, see pages 191-199.
- The deployment/retraction test of the array showed that clips attached to array panel and bi-stem came loose resulting in tear of substrates. Problem has not been resolved.

8. British Aircraft Corporation – 8.1-ft^2 Flex-Array Prototype (Ref. Bibliography B.2-1 through B.2-3)

- Static Load 15g, Two Array Axes
  - Longitudinal – normal to direction of deployment.
  - Lateral
- Harmonic Vibration

Frequency	Two Array Axes
10 - 50 Hz	3 g
50 - 500 Hz	10 g
500 - 3000 Hz	10 g

Scanning speed: 2 octave/minute

- Random Vibration

Frequency	PSD	Amplitude	Duration
20 - 2000 Hz	0.07 g^2/Hz	11.5 g - rms	4 minutes

- Flexibility

  Deployment/retraction: 20 cycles in normal room temperature
- Depressurization (Roll-up Array)

  10^{-1} in 5 minutes

9. Lockheed Missiles & Space Co. – 50-ft^2 Feasibility Model – Spindle (Ref. Bibliography L.4-3)

- Flat Spindle Deployment/Retraction Capability Test

  Rate of extension erratic because of moment arm change. Retraction rate was uniform. Problem solvable by use of cams but details not worked out.

10. Lockheed Missiles & Space Company – 90 ft^2 Flex-Array Prototype Flat Fold (Ref. Bibliography L.4-19)

- Hold Down/Release System Test
  - Cable tension for redundant pin pullers
  - Proper pre-load (1/2 lb/in.^{2})

- Deployment/Retraction – Vertically Upward
  - SPAR unit only – alignment checks for offset, rotation and repeatability
- Tension Test on Complete Panel Assembly
  - Effect on pallet width
  - Uniform tension distribution
  - Higher edge tension distribution proved to be best support technique
  - Edge curl not apparent in tests with proper support
- Systems Capability
  - Hold down/release and deployment test, 20 cycles at room temperature.
- Vibration Test
  - Acoustic – octave band sound pressure level, 124-139.5 db at frequencies from 63-8000 Hz.
  - Shock synthesis, X-axis only

Acceleration	Frequency
10 g	15 - 25 Hz
14 g	25 - 35 Hz
25 g	35 - 450 Hz

  - Random sine search for resonance

    Frequency: 35 Hz
    Amplitude: 1

11. Boeing – 1424-ft^2 Flex Substrate/Rigid Frame Prototype – Flat Fold (Ref. Bibliography B.3-1 through -8)

Lead weights were added to a deployment model (MTA-3) for simulating the mass, center of gravity, and mass moment of inertia of the flight prototype subpanel units. For the effects of this test see Bibliography B.3-8, page 5-4, Table V-1.

Comparison of bending frequency attained at ambient temperature to suspending a model in a deployment fixture simulating a structure in space (see B.3-8, Fig. Fig. 5-2).

- Tests Performed
  - Mechanisms functional testing

    Deployment drive – electric motor drum assembly
    Quadrant assembly
    Main hinge assembly

- Simulated Zero-Gravity Deployment System

  Mechanical System – With fixture to allow deployment of multiple folding solar array panel with minimum gravity effects. Fixtures consist of mechanical interface, cables and quadrant, air sled, air track and overhead suspension lines.

- Test Method and Observation
  - Zero Initial Velocity Tests. Test to obtain time-history and other data for a given deployment swing starting with zero velocity and zero cable tension. Deployment is initiated by turning on the deployment motor and allowing the panels to proceed through approximately 177 degrees. Test provided data for comparison and definition of parameters.
  - Controlled Starting Condition Tests. Obtained time history and other data for a given deployment wing as influenced by the closing velocity of the previous swings.
  - Aerodynamic Test. Test conducted same as above, except a plastic membrane was attached to the array frame to simulate aerodynamic drag. Comparison of time history for test run showed no consistent differences that could be attributed to aerodynamic membrane.
  - Sigma Resistance Tests. Evaluate the sum of all resistance on each deployment swing. Resistances arose from hinges, latch link, GSE instrumentation frictions, air-bearing track, and ambient air effects.
  - Deflected Panel Tests. Determined the effects on deployment of a pressured deflection of a panel due to differential heating of the sunside and the darkside. A 50°F steady-state differential was actually shown by analysis based on a test run.

The testing of the MTA-3 showed that fabrication and assembly required closer tolerances and more refined tooling. Misalignment of the holes in the hinge plates caused interference with other mechanical parts during deployment. Several areas of mechanical interference were discovered during assembly of the MTA-3. These were generally minor in nature and were corrected by providing reliefs or adjusting the location of the interfering parts.

12. TRW – 12 ft^2 Feasibility Model (Ref. Bibliography T.3-19)
    - Stowage Method
      - Cell Fracture Load Test. Determine ascent preload pressures.

        Cushion placed in different positions on 18 $in.^2$ cell area.
        Individual cells loaded as simply supported beam.
        Result – in all cases cells fractured at 8 lb.

- Face-to-face Cell Vibration Three different configurations with pressure bag on top and silicon pad on bottom. Vibration with retention pressure levels of 6, 2, and 0.5 psig, sine sweeping from 25 to 120 cps in 2 minutes each at g-levels of 5, 12, and 17.5-g. There were 27 tests per configuration. Same panels used for all 27 tests, and upon removal and inspection damage was negligible.

  Pads after every fold
  Pads on backside of panels only
  No pads

- Total Systems Demonstration Test – 12-ft^2 Model, 200 cycles

  Stowage
  Deployment/retraction
  Articulation for suntracking

13. Royal Aircraft Establishment – 39 ft^2 Prototype Model (Ref. Bibliography R.3-10)
    - Vibration and Acceleration Test. Dummy glass-covered cells and patches of live cells in the stowed condition. Levels not available.
    - Repeated deployment and restowing and mechanical tests in the fully deployed state. Deployment test to be conducted vertically to minimize gravitational effects and facilitate panel stowage. No apparent problems reported.

14. Messerschmitt-Bolkow-Blohm GMBH – 1290 ft^2 Inflatable Flex-Array Prototype – Flat Fold (Ref. Bibliography M.3-1)

A comprehensive test program on component, subsystem, and system level was carried out in 1969 and 1970. The tests on the complete panel comprised:

- Laboratory (3 months) and thermal storage (-20°C to +60°C at 60 percent humidity).
- Sinusoidal vibration 10-g (6 mm double amplitude) in thrust vector direction. 6-g (4 mm double amplitude) normal to thrust vector direction 5 to 2000 Hz.
- Random noise vibration: 0.06 g^2/Hz, 15 to 2100 Hz
- Mechanical shock: 150-g, 5 to 10 ms
- Pressure reduction (launch simulation). Pressure reduction to 10^{-5} Torr within 12 - 15 min.
- Space environment simulation, $p < 10^{-5}$ Torr, cold wall cooled by liquid N_2 panel stowed (launch phase)

  Solar Radiation Intensity: $1/\pi \cdot$ solar constant (spinning rocket stage)
- Deployment duration: 30 to 45 minutes at 1 solar constant.
- Rigidizing and operational tests – temperature shock: (switching off solar radiation simulator for 30 min).

The same test procedures were applied in general in the component tests. In the dynamic tests an additional factor of 1.5 was applied to take into account increases in amplitude due to resonance.

With critical components radiation tests were also performed. For example, the gelatine-glass fiber laminate was subjected to ultraviolet (UV) and particle irradiation.

Strength degradation of unprotected samples was as follows:

With simulated solar radiation (UV) under vacuum conditions: 20 percent after 3500 hours.

With electrons irradiation (10^{16}, 1 MeV, electrons per cm^2): 15 percent

The very high safety factor considered in dimensioning the supporting tubes, due to fabrication technical reasons, will therefore ensure a lifetime of several years.

STRUCTURE ENVIRONMENTAL TEST HISTORY B

| TEST / STOWAGE METHOD | | |

4.1.1.3 Techniques Used in Flexible Array Dynamic Analysis

The techniques employed by several contractors for analyzing flexible solar arrays were reviewed and the results summarized. The review revealed several techniques that were used to dynamically analyze flexible solar arrays. Structural and thermodynamic methods were the routinely used state-of-the-art techniques. However, the most significant feature of the review was, as in the testing, the comprehensive membrane analysis and analysis techniques by JPL and G. E. Further basic work is being done by these organizations in the area of modeling in-plane motions. Modeling techniques developed and verified by test under this program will be used as a basis for Space Station Solar Array dynamic models used in the Langley/Fairchild-Hiller Solar Array Interaction Study, contract NAS1-10155.

4.1.1.3.1 Review of General Analysis Methods. For purposes of ensuring that specified natural frequency restrictions on the solar array are met, and also for determining the dynamic properties of the array for use in control equations, accurate analytical prediction of the natural frequencies and mode shapes of the array are necessary. The four basic procedures for achieving this end are: (1) exact analysis; (2) Rayleigh-Ritz energy method; (3) lumped parameter or string method; and (4) finite element procedures. These four methods are described below.

Exact Method. If the array itself is considered to be a stretched membrane (i.e., capable of resisting in-plane tensile forces only) the equations of motion for the membrane, the booms (as cantilever beams), and the stretcher beam may be written. By incorporating natural and geometric boundary conditions, it may be possible to obtain a closed form solution for the natural frequencies and mode shapes of the system. For the simplest cases this procedure would be fairly straight-forward. The case of a rectangular stretched membrane supported on all four edges is readily dealt with in "Vibration Problems in Engineering," by S. Timoshenko. However, as soon as two edges are freed (as is the case with most contemporary flex array designs) the problem of satisfying the free edge boundary conditions becomes very complex. The additional factor of the cantilever boom coupled with the membrane leads to further complication and to the conclusion that though a closed form solution to (at least) the simpler configurations may be possible, the use of numerical methods is more practical in terms of time and effort required to obtain a solution of acceptable accuracy.

Rayleigh-Ritz Energy Method. The basic procedure of this very powerful method of determining natural frequencies is to equate the strain energy of the system at its maximum displacement (i.e., zero velocity for simple harmonic motion) to the kinetic energy at zero displacement (i.e., maximum velocity). It is necessary to assume a mode shape to apply this method, but by expressing the mode shape in infinite series form and using other opportune classical dynamic principles, it is possible to obtain fairly accurate solutions for both mode shapes and frequencies. As with the exact methods, the greatest drawback of this method is the difficulty of satisfying all of the boundary conditions for some configurations. General Electric used this method (Ref. Bibliography G. 2-6) to obtain solutions for a membrane with two free edges and two fixed edges, and the resulting computations were quite complex.

Lumped Parameter Method. This is a numerical procedure in which an elastic structure is broken down into a series of lump masses (with or without rotary inertia), connected together by springs. Depending on the modes of interest, this could include any combination of shear, moment, and torsion springs. By solving the equations of motion for each lump simultaneously, the relative displacements of each lump (mode shape) and the associated modal frequencies are obtained. Usually, the equations of motion are written in matrix form to facilitate computer solution.

The most convenient lumped parameter method for flex array analysis is the so-called string method, in which the membrane portion of the solar array is replaced by a system of elastic strings with lumped masses, representing the mass of the array, disposed at various positions on the strings. Members having bending stiffness are represented as lumped systems that have both shear and bending springs associated with them. A typical roll-up solar array and one of the many string dynamic models that could be used to represent it are shown in Figs. 4-1 and 4-2.

In the case illustrated the array is divided into six equal parts per wing, as shown by the dotted lines in Fig. 4-1, and the mass of each one of these parts is lumped at its cg as shown in Fig. 4-2(b). The boom is split into three equal length rigid bars and its bending stiffness is simulated by shear and moment springs joining the rigid bars together and to the center body. The strongback is considered to be a rigid bar pinned

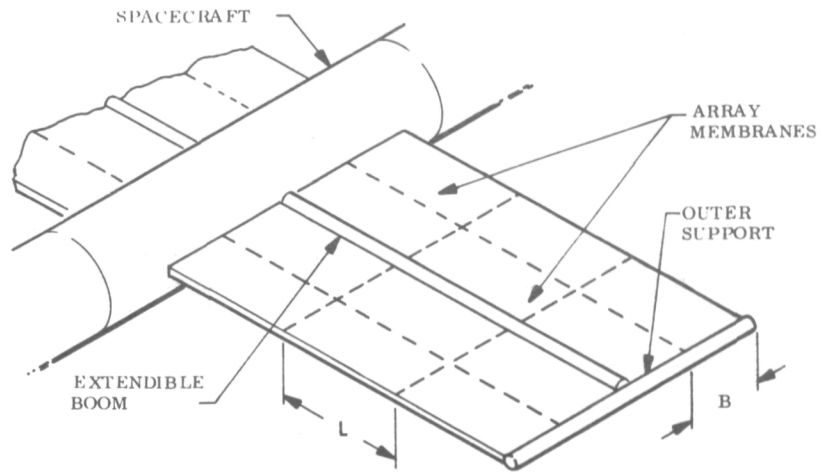


Fig. 4-1 Typical Flexible Array Structure

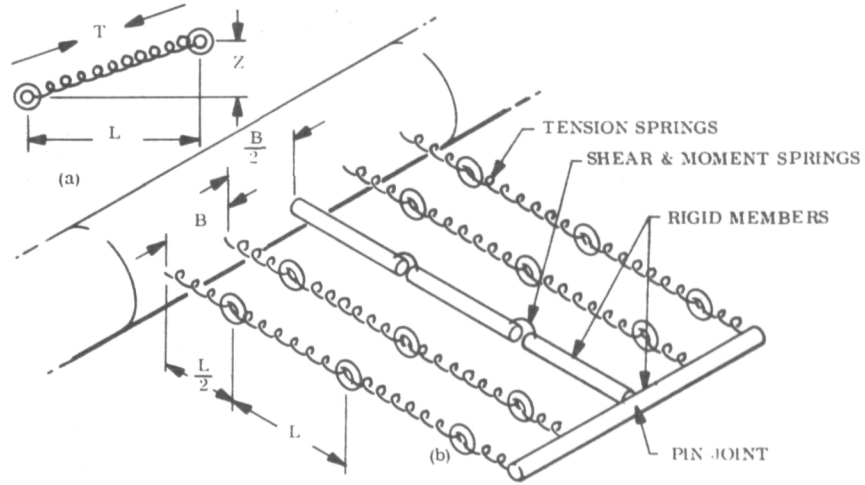


Fig. 4-2 Lump Spring (or String) Model of Structure in Fig. 4-1

to the boom end. However, if desired, this too may be given an elastic representation similar to that of the boom.

The model of Fig. 4-2 may be used to determine longitudinal (in-plane) modes and, to a lesser degree of accuracy, in-plane bending modes. The solar array representation is somewhat inadequate for this case because of the lack of any chord-wise members to give coupling between adjacent strings. Further work on modeling methods for in-plane modes is currently under way at G. E., under the direction of JPL.

Generally, the in-plane modes have frequencies beyond the usual range of interest, so the most important case is that of out-of-plane motion. In this case, the springs joining adjacent array lumps provide out-of-plane shear forces by virtue of the relative out-of-plane motion between adjacent lumps. Fig. 4-2(a) shows this situation. If the tension (T) in the spring is assumed to remain constant during the deformation, the shear stiffness is given by $\frac{T}{L}$.

Modes and frequencies for the model of Fig. 4-2, or any other string model, may be determined by any one of the many existing eigenvalue-solver computer programs. At LMSC the "Wong-Choleski" or "Calvert-Choleski" program would be used.

Finite Element Methods. This method is essentially similar to the lump method, but a more accurate representation of the structure is possible. Instead of being broken down into lumps and springs, the structure is broken down into a series of structural elements, each of which has a stress distribution associated with it. Continuity of displacements between adjoining elements is maintained in contrast to the lump method, in which step changes of displacement occur. The basic finite element program at LMSC is the REXBAT (revised expanded BATDORF) program.

4.1.1.3.2 Review of Significant Dynamic Analysis Methods Employed in Flexible Array Programs – General Electric (Ref. Bibliography G. 2-6 and -7). The work done by G. E. was by far the most comprehensive of all those surveyed. The array they considered had one central extendible boom and a stretcher bar with the array disposed symmetrically on each side of it, with an area of 250 ft^2. The rolled-up configuration was analyzed using a lump-spring model of the drum, stowed array, and support system.

The deployed configuration dynamic analysis was performed using a finite element approach considering the boom and stretcher bar as a series of beam elements, with the effect of end load due to sheet tension taken into account. The array structure was broken down into a series of rectangular membrane elements.

An attempt was made by G. E. (Ref. Bibliography G. 2-6) to obtain a closed form solution for the membrane modes by assuming X, Y, Z displacement functions of the form:

$$u = \sum a\, u\,(x\ ,\ y) e^{i\omega t}$$

and using Rayleigh-Ritz techniques. The resulting analysis was quite complex and did not incorporate the boom effects. Accordingly, their recommendation was that the finite element procedure be pursued further, possibly taking account of the bending stiffness of the array also.

Frequencies calculated for out-of-plane motion varied from 0.077 Hz for the first mode to 0.29 Hz for the sixth in zero-g conditions and 0.18 Hz for first mode to 0.65 Hz for sixth mode in a one-g field directed from the roller toward the stretcher bar.

If the total axial load on the boom was no greater than one-quarter of the boom buckling load, the end load had negligible effect on the frequency of the first mode. For higher loads there was a significant drop in first mode frequency.

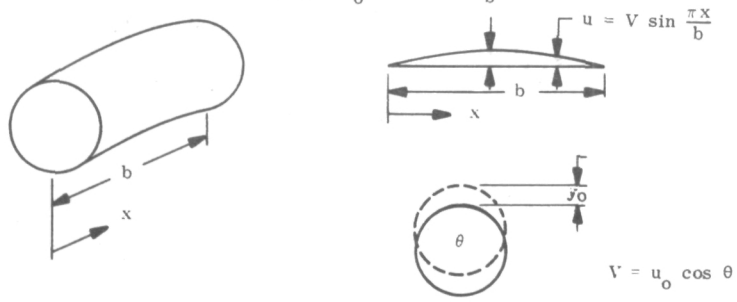
Reduction of the number of chord-wise elements (into which each subpanel was divided) to less than two will cause some loss of essential modal information. Reduction of the spanwise elements from ten to five had little effect on the first five modal frequencies.

In addition to the analysis, the array was subjected to random, acoustic, and sinusoidal vibration, and a modal test of the deployed array was conducted in vacuum and in air (Ref. Bibliography G. 2-20). Results of the modal test indicated excellent

agreement with analytical frequencies and also showed a measured first-mode damping coefficient of 0.004 in vacuum compared to 0.10 in air.

Ryan (Ref. Bibliography R.4-4 and R.4-7). This company placed greatest emphasis on dynamic analysis of the stowed array. They used a Rayleigh-Ritz technique, assuming a combined longitudinal and circumferential mode shape given by:

$$u(x, \theta) = u_o \cos\theta \sin\frac{\pi x}{b}$$



Because the deployed array had two edge members, no pre-tension of the array was employed. Hence, unlike the pre-tensioned arrays, the assumption that tension remains essentially constant during array deformation cannot be made. Further, because of the assumed displacement form and the essential slack in the system, the tension is not a linear function of displacement.

For the deployed 300 square foot array natural frequencies of 0.04 Hz for first bending and 0.438 Hz for first torsion were derived using calculated boom inertia and geometric properties and a standard formula from "Mechanical Vibrations" by D. Hartog.

$$\omega_N = {}^{3}H\sqrt{\frac{EI}{\mu_L^{\frac{1}{4}}}}$$

Hughes (Ref. Bibliography H.6-6). This company analyzed a 50 square foot and a 500 square foot array, representing the array by a single continuous string and the boom by a uniform cantilever beam. The stretcher bar was assumed to be rigid, and no torsional motor was permitted. The exact equations of motion for the string and boom were solved in conjunction with appropriate boundary conditions to evaluate the natural frequencies and mode shapes of the string-boom combination.

4.1.1.4 Evaluation of the Three Basic Flexible Array Packaging Techniques for Space Station Use

In section 4.1.1.1, data on ten flexible array designs, whose areas varied from 8.1 ft^2 to 250 ft^2, were discussed and compared. In this section, the three basic flexible array packaging concepts (drum roller, flat spindle, and flat fold) are evaluated in terms of their adaptability to the 10,000 ft^2 Space Station array requirement. Chart C lists the three concepts and discusses the advantages and disadvantages of each in the major categories of Packaging Characteristics, Ground Handling Capabilities, Ascent Capabilities, Tiedown Release and Tensioning Mechanism Operation, Stowage Volume, and Predicted Reliability. Comments are subjective in many cases because data or test results to support conclusions are not available. Supporting data and general conclusions in each of the categories are included in the following discussions to help clarify the comparisons.

4.1.1.4.1 Packaging Characteristics. Foam in thin sheets, placed between layers of substrate, or in button or strip configurations, bonded directly to the flexible substrate, are the most commonly used padding configurations. One new idea in this area is especially interesting for the Space Station application. This is the use of Fluorinated Ethylene Propylene (FEP) sheets employed in a double use as cell covers and as protective padding material.

FEP cell covers are currently being tested and, if successful, could replace conventional covers. If the test program were expanded to include cell-to-cell vibration tests of FEP covered wrap-around solar cells, the feasibility of using FEP as a combined cover and padding may be demonstrated. Embossed Kapton material bonded to the rear surface of the panels also appears to be a reasonable approach for either the drum or spindle designs. However, this approach may lower the backside radiation capabilities. The flat fold could also use this material, but protection may be required only in the phases prior to first deployment. Should the panels be retracted, dynamic loads during shuttle resupply may not be severe enough to require the protective padding between the cells.

During extension and retraction the end supports of the rotating drum and flat spindle concepts are points of concentrated loading and may also be subject to thermal distortion. The flat folding concept does not require end supports so the obvious advantages are: weight saving, elimination of concentrated load points, and also elimination of a power transfer device at that rotating interface.

4.1.1.4.2 Manufacturing, Test and Storage Handling. From manufacturing handling considerations, the maximum width of the solar panel should probably not exceed 6 feet. Kapton, a good substrate material is made in a standard off-the-shelf width of 5 feet. Manufacturers of Kapton are not inclined to increase the width because it would require major capital outlay for the equipment. Furthermore, the maximum suggested width of a panel laid out flat on a table should only be 6 feet to allow manufacturing personnel to reach their work from both sides with ease during assembly operations.

The container for the flat fold and spindle designs protects the solar panels at all times during ground tests, including removal and replacement handling of the unit, and also during performance of tests. Present drum designs do not incorporate a closed container in the package design and therefore will require ground handling protection.

Long term storage appears to have a serious effect on the cushioning pads, requiring readjustment of the panel restraining force. In the drum design for example, it may not be desirable to maintain a tight wrap on the drum during storage, and then have to remove and reapply tensions to it prior to launch. Tension readjustment cannot be done in its rolled-up state. Roll-up forces can also cause substrate edge curl. In the flat fold and spindle designs, however, the restraining force is a compressive load and is easily removed or reapplied without excessive handling of the panels.

4.1.1.4.3 Ascent Capabilities. Since ascent and ground handling requirements for the solar arrays are similar, design features should be considered that satisfy both needs.

The discussion in Chart C is based on load and dynamic effects including acceleration and acoustic/random vibration. It also includes discussion of thermal effects in the packaged condition along with the possibility of exposure of the array minus the protective shroud for a six day orbit period. This could result in approximately 100 thermal cycles and extreme temperature changes due to "greenhouse" effects in the stowed array.

4.1.1.4.4 Tie Down, Release and Tensioning Mechanism Operation. A release system is normally initiated by pyrotechnic devices such as squibs, explosive nuts or bolts, or linear shape charges. Assuming the drum design incorporates a releasable lock to prevent ascent pre-rotation, no concept has an advantage over the others in this regard.

Increased tensions must be applied to the panel substrates during the artificial-g experiment. The same tensioning system can be used for the outboard force in all three stowage concepts; however, the restraining force that must be applied at the array root presents problems in the roll-up concepts. The drum design, for example, employs a releasable lock to prevent drum rotation which is the opposing inboard force of the tensioning system. This force is a function of the wrapped drum radius and results in the highest restraining torque. The spindle also employs a releasable lock that is indexed to stop with the spindle width parallel to the deployed panels. The resulting lower restraining torque is a function of half the thickness of the wrapped spindle.

Even with releasable locks the rotating versions may impose unacceptable loads on the cell assemblies as tension is increased. Also, a change in length by creep and/or thermal expansion or contraction can change the fold area location on the flat spindle so that the retraction indexing would be impossible.

4.1.1.5 Stowage Volume. Section 4.1.1.1 presented a comparison of stowage volume requirements for present flexible array design concepts after they were normalized to 250 ft^2. Experience on those flexible array programs has shown that where there are specific design envelope requirements, the available stowage volume and an L/D ratio that is compatible with proper retraction tracking (substrate wrapping on drum) will determine the drum diameter. For instance, in their Space Station solar array studies for NAR, G.E. selected a drum diameter of 25 inches.

In order to make a gross evaluation of packaging concepts for Space Station application, three drum diameters were chosen based on the G.E. selection in their study. Those selected were: 1.5-ft diameter, 2.0-ft diameter, and 2.5-ft diameter. For each of the above drum diameters, three arbitrary flat-fold widths were selected to compare stowage volumes. Those were: the fold width equals the drum diameter, the fold width equals one-half the drum circumference, and the flat fold width equals the drum circumference. The groundrules used in the comparison for baseline array design were:

(1) There are four solar panel assemblies (quadrants) of 2,520 ft^2 each, for a total array area of 10,080 ft^2.

(2) The aspect ratio of each quadrant (2,520 ft^2) is approximately three to one.

(3) There are six, 5-ft wide solar panel strips 84 ft long in each quadrant.

Using the above groundrules, the comparison of stowage volume required for each of the three concepts (drum roller, flat fold, and flat spindle) is tabulated on the next page.

VOLUME COMPARISON

	Size					Circumference of Drum Equal Two Flat Folds				Circumference of Drum Equal One Flat Fold				One Fold Equals Drum Diameter			
	Diameter (ft)		Length (ft)	Volume (ft^3)		Length (ft)	Width (ft)	Stacked Height (ft)	Volume (ft^3)	Length (ft)	Width (ft)	Stacked Height (ft)	Volume (ft^3)	Length (ft)	Width (ft)	Stacked Height (ft)	Volume (ft^3)
	Drum	Final															
Drum Roller	1.50	1.70	5.00	11.35	Flat Fold	5.00	2.35	.281	3.30	5.00	4.71	.182	4.29	5.00	1.50	.391	2.93
	2.00	2.14	5.00	18.00		5.00	3.14	.226	3.55	5.00	6.28	.154	4.84	5.00	2.00	.314	3.14
	2.50	2.62	5.00	27.00		5.00	3.91	.198	3.92	5.00	7.86	.143	5.61	5.00	2.50	.270	3.37
					Spindle	5.00	2.99	.365	5.46	5.00	5.35	.265	7.09	5.00	2.14	.474	5.07
						5.00	3.78	.315	5.95	5.00	6.92	.238	8.23	5.00	2.64	.397	5.24
						5.00	4.55	.287	6.52	5.00	8.50	.227	9.65	5.00	3.14	.353	5.54

4.1.1.4.6 Reliability. Chart C contains only a stacking of the three packaging concepts based on qualitative evaluation of design complexity. Comparison was based on design simplicity and number of anticipated failure modes.

Comments concerning the reliability rating in each category are as follows:

- Stowage Methods

  Drum Roller. The solar cells and interconnects are subjected to some bending stress due to the circular shape of the drum.

  Flat Spindle and Flat Fold. Solar cells and interconnects are stowed on the flat surface only. No cells appear in the area of the fold (bend) lines. However, the feeder harnesses are subjected to a small radius bend, but as shown on two existing designs, the effect was negligible. With respect to reliability, the flat spindle and flat fold designs were considered to be better.

- Protective Padding. No advantage was identified in this category. Although the techniques are different between the flat fold and drum and/or spindle, reliability is not affected.

- Deployment/Retraction

  Drum Roller. Partial deployment during artificial-g has two problem areas, namely the need for a releaseable lock (brake) to prevent drum rotation, and introduction of added bending stress to the solar cells due to applied panel tensions.

  Flat Spindle. Partial deployment during artificial-g requires a releaseable lock (brake) to prevent drum rotation as in the drum design, but no bending stresses are introduced to the solar cells. Critical panel indexing problem (no cell area can meet edge of spindle) during retraction. Uneven (jerky) rate of deployment due to changing moment arm may be corrected with a cam mechanism.

  Flat Fold. Partially deployed during artificial-g, the unfinished panel folds utilize a hollow rod that is held in place by a pyrotechnic device; also, there are no moving parts.

The drum and spindle are rated equal in deployment reliability, since both require releasable brakes. The drum has increased bending of the stowed cells during the artificial-g mode. The spindle has indexing problems during retraction along with uneven deployment motion.

From the viewpoint of reliability, the flat fold appears to be the outstanding deployment technique, since no moving parts are required.

- Method of End Support

  Drum Roller. This design employs bearings and shafts (axles), well established and considered very reliable.

  Flat Spindle. Same as above except it requires a greater distance between the mounting base and axis of rotating spindle.

  Flat Fold. No requirement.

- Power Transfer

  Drum Roller/Flat Spindle. Utilizes slip rings or flex cable where possible. Problems may occur such as lubrication/contamination: has moving parts.

  Flat Fold. Uses conventional transfer at the base attach point. No moving parts, therefore, inherently more reliable.

- Tension Method

  Drum Roller. Requires a releasable lock (brake) which means a number of moving parts. Also has most restraining torque. For artificial-g requires a releasable indexing lock (brake) to assure the spindle will stop with its width parallel to the deployed panels, resulting in a smaller restraining torque. In this case more moving parts are necessary.

  Flat Fold. A hollow rod attached to the panels and held in place by a pyrotechnic device. No moving parts, pre-set prior to launch and again more reliable.

NO.	STOWAGE METHOD	ILLUSTRATION	PACKAGING				
			PROTECTIVE PADDING FOR SOLAR CELLS DURING FLIGHT AND GROUND HANDLING	DEPLOYMENT/RETRACTION	DRUM/SPINDLE END SUPPORT	ATTACHMENT TO STRUCTURE	POWER TRANSI
1	DRUM ROLLER		PRESENT STATE-OF-THE-ART METHODS ARE APPLICABLE; BECAUSE OF LARGE DEPLOYED AREA MANUFACTURING PROBLEMS, COST, ETC. ARE INCREASED. CONSIDER OTHER POSSIBILITIES. BOND SHEET OF EMBOSSED KAPTON TO ENTIRE REAR SURFACE. FEP COVER SHEET BESIDES RADIATION PROTECTOR, COULD REPLACE EXISTING CUSHIONING MAT'L TESTS IN PROGRESS—SHOULD INCLUDE VIBRATION. DRUM CURVATURE MAY REQUIRE USE OF CUSHIONING MATERIAL.	VERY GOOD FOR ROLLING UP LARGE SURFACE AREAS. IF PARTIALLY DEPLOYED DURING ARTIFICIAL "G" 1. DRUM MUST BE RESTRAINED TO PREVENT ROTATION 2. INCREASED PANEL TENSION RESULT IN INCREASED BENDING OF STOWED CELLS AND DAMAGE MAY OCCUR.	END SUPPORTED USING PRESENT STATE-OF-THE-ART METHODS. SUPPORTS ARE CRITICAL STRESS AND THERMAL AREA. ADVERSE CONDITIONS WILL NOT INTERFERE WITH POSITIVE DEPLOYMENT/RETRACTION.	ATTACHMENT IS IN THE AREA OF END SUPPORT. RESULTS IN CONCENTRATED SYSTEM LOADING REMOVAL OF UNDESIRABLE RESONANT FREQUENCIES BY STRUCTURAL CHANGES DIFFICULT TO ACHIEVE.	PRESENT STATE-OF-THE-ODS ARE APPLICABLE. I TRANSFER EQUIPMENT C ELIMINATED BY DEPLOY BUT ALSO RESULTS IN H LOAD.
2	FLAT SPINDLE		SAME AS ABOVE EXCEPT FEP COVERS AND THE SPINDLE FLAT SURFACE COULD ELIMINATE USING CUSHION MATERIAL. POTENTIALLY APPEAR TO BE VERY FEASIBLE.	SAME AS ABOVE EXCEPT INCREASED TENSION DOES NOT AFFECT STOWED CELLS. INDEXING OF PANEL BEND AREA TO SPINDLE IS CRITICAL PROBLEM DURING RETRACTION. UNEVEN (JERKY) RATE OF DEPLOYMENT DUE TO CHANGING MOMENT ARM.	SAME AS ABOVE EXCEPT SUPPORT HEIGHT FROM THE BASE TO THE ℄ IS GREATER.	SAME AS ABOVE.	SAME AS ABOVE.
3	FLAT PACK		SAME AS ABOVE EXCEPT CUSHION MAT'L MUST BE ON CELL SIDE OF EVERY OTHER PANEL. CELL AREA IS DECREASED IF CUSHIONING BUTTONS, STRIPS, OR WINDOW FRAME SECTIONS ARE USED. REMOVABLE CUSHIONING SHEET BETWEEN CELL-TO-CELL FOLD FOR HANDLING AND ASCENT PROTECTION ONLY.	IF PARTIALLY DEPLOYED DURING ARTIFICIAL "G," A HOLD-DOWN FRAMEWORK DEVICE KEEP STOWED PANELS IN PLACE. INCREASED TENSION DOES NOT AFFECT STOWED CELLS. AS PROVEN BY TRW RETRACTION IS FEASIBLE.	NONE REQUIRED.	MOUNTING HOLES DISTRIBUTED AS REQUIRED. EASY TO REMOVE UNDESIRABLE RESONANT FREQUENCIES. (ADD MORE ATTACHMENTS)	NONE REQUIRED.

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

EVALUATION OF EXISTING SOLAR ARRAY PACKAGING METHODS

		GROUND HANDLING CAPABILITIES				ASCENT C
	POWER TRANSFER	MANUFACTURING HANDLING	GROUND TEST HANDLING	EFFECT OF LONG TERM STORAGE	PROTECTION FROM CONTAMINATION AND DAMAGE	LOADS AND DYNAMIC EFFECTS
NT	PRESENT STATE-OF-THE-ART METHODS ARE APPLICABLE. POWER TRANSFER EQUIPMENT CAN BE ELIMINATED BY DEPLOYING DRUM, BUT ALSO RESULTS IN HIGH TIP LOAD.	EASY TO STORE SOLAR PANEL WITH MINIMUM NUMBER OF PERSONNEL. TENSION FOR TIGHT PANEL WRAP IS NOT ADJUSTABLE AND ANY CHANGE REQUIRES RE-EXTENSION. VULNERABLE TO DAMAGE, SO A PROTECTIVE CONTAINER MUST BE PROVIDED	VULNERABLE TO DAMAGE ONCE OUT OF CONTAINER. DIFFICULT TO INSTALL INSTRUMENTATION ON DRUM. DURING AND AFTER VIBRATION TEST: 1. REQUIRES RE-EXTENSION OF PANELS TO CHANGE TIGHTNESS OF WRAP. 2. DIFFICULT TO VERIFY SMALL ROTATIONAL MOVEMENT BETWEEN PANEL WRAPS. 3. REQUIRES EXTENSION TO VISUALLY CHECK FOR DAMAGE TO CELLS, INTERCONNECTS, ETC.	SLIGHT EFFECT ON INTERCONNECTS AND CELLS DUE TO CURVATURE. TIGHT WRAP MAY BE AN UNDESIRABLE CONDITION. 1. COULD RESULT IN A "SET" OF CUSHIONING PAD CAUSING A CHANGE IN THE RESTRAINING FORCE 2. CAUSES UNDUE BENDING STRESSES ON THE SOLAR CELLS 3. FOR LARGE ASPECT RATIO SECTIONS, ROLL-UP FORCES AROUND THE DRUM HAS THE TENDENCY TO CAUSE SUBSTRATE EDGE CURL.	PROTECTIVE BLANKET CAN BE ADDED TO THE PANEL FOR THE FINAL WRAP ON THE DRUM. ADDS LENGTH TO THE EXTENDED ARRAY. EXPOSED DURING TEST. NO PROTECTION FROM FALLING OBJECTS.	POSSIBLE DRUM PRE-ROTATION IF NOT LOCKED. IF LAUNCH AXIS IS PARALLEL TO DRUM ℄, WRAPPED PANELS COULD "FUNNEL" DURING ASCENT.
	SAME AS ABOVE.	EASY TO STORE SOLAR PANEL WITH MINIMUM NO. OF PERSONNEL. ADJUSTABLE PANEL RESTRAINING FORCE. PANELS CONTAINED IN BOX, ALWAYS PROTECTED.	PANELS ARE CONTAINED-PROTECTED DURING TEST. DIFFICULT TO INSTALL INSTRUMENTATION ON SPINDLE IF NEEDED. PANEL RESTRAINING FORCE EASILY ADJUSTED DURING TEST. REQUIRE EXTENSION TO VISUALLY CHECK FOR DAMAGE TO CELLS, INTERCONNECTS, ETC.	NO EFFECT ON INTERCONNECTS OR CELLS, STOWED ON FLAT SURFACE. PANEL RESTRAINING FORCE EASILY REMOVED, REAPPLIED, AND READJUSTED.	PANELS ARE CONTAINED IN A BOX. ALWAYS PROTECTED.	PANELS ARE CONTAINED IN A BOX 1. SPINDLE HELD IN PLACE 2. EASY TO READJUST RESTRAINING FORCE (ASCENT PRE-LOAD)
S	NONE REQUIRED.	ADDITIONAL PERSONNEL REQUIRED TO FOLD PANELS. ADJUSTABLE PANEL RESTRAINING FORCE. PANELS CONTAINED IN A BOX, ALWAYS PROTECTED PANELS CAN BE CHECKED AND/OR REPLACED WITHOUT EXTENDING	SAME AS ABOVE EXCEPT NO DIFFICULTY TO INSTALL INSTRUMENTATION. EASY TO VISUALLY CHECK FOR DAMAGE TO CELLS, INTERCONNECTS, ETC. WITHOUT EXTENDING PANELS.	SAME AS ABOVE IN ADDITION SHARP BENDS IN FEEDER HARNESS WILL RESULT IN "KINKS" WHEN EXTENDED, DISAPPEARING IN TIME.	SAME AS ABOVE.	PANELS ARE CONTAINED IN A BOX EASY TO READJUST RESTRAINING FORCE (ASCENT PRE-LOAD). MINIMUM NUMBER MOVING PARTS.

FOLDOUT FRAME

FOLDOUT FRAME

THODS

ASCENT CAPABILITIES		TIE-DOWN AND RELEASE	TENSION METHOD	STOWAGE VOLUME (FT^3)			RELIABILITY	GEN
LOADS AND DYNAMIC EFFECTS	THERMAL							
POSSIBLE DRUM PRE-ROTATION IF NOT LOCKED. IF LAUNCH AXIS IS PARALLEL TO DRUM ℄, WRAPPED PANELS COULD "FUNNEL" DURING ASCENT.	UNLESS THERMALLY PROTECTED, 1. TEMP. GRADIENT BETWEEN THE INNERMOST TO THE OUTERMOST PANEL WRAPS. 2. POSSIBLE OUTGASSING OF LUB, SEALS, ETC. 3. THERMAL DISTORTION OF MOVING PARTS MAY OCCUR.	DRUM PRE-ROTATION MAY OCCUR DURING LAUNCH AND ASCENT-SHOULD HAVE A RELEASABLE LOCK. EXISTING STATE-OF-THE-ART METHODS ARE APPLICABLE.	IF PARTIALLY DEPLOYED DURING ARTIFICIAL "G," RELEASABLE LOCK (DRUM BRAKE) REACTS PANEL TENSION. RESULT IN HIGHEST RESTRAINING TORQUE (FUNCTION OF THE WRAPPED DRUM RADIUS-LARGEST MOMENT ARM).	DIAMETER (FT)	1.50	11.35	RATED NO. 2	UNCERTAINTIES OF AC ADJACENT WRAPS MAK THE AMOUNT OF TENS DAMAGE DUE TO ASCE RESTRAIN THE PANEL IS TO CHANGE. UNDESI TO REMOVE. THE END AREA AND IT MUST WIT LOADING AND THERM MENT. LOADING ON THE MINIMUM DRUM T REQUIREMENT.
					2.00	18.00		
					2.50	27.00		
PANELS ARE CONTAINED IN A BOX 1. SPINDLE HELD IN PLACE 2. EASY TO READJUST RESTRAINING FORCE (ASCENT PRE-LOAD)	PANELS CONTAINED IN BOX. UNLESS THERMALLY PROTECTED 1. POSSIBLE OUTGASSING OF LUB, SEALS, ETC. 2. THERMAL DISTORTION OF MOVING PARTS MAY OCCUR.	PRIOR TO PANEL DEPLOYMENT CONTAINER BASE ROTATE 180°. EXISTING STATE-OF-THE-ART METHODS APPLY.	IF PARTIALLY DEPLOYED DURING ARTIFICIAL "G" AND SPINDLE PARALLEL TO PARTIALLY EXTENDED PANPANELS (SMALLEST MOMENT ARM), RELEASABLE LOCK (SPINDLE BRAKE) REACT PANEL TENSION. RESULT IN LOWEST RESTRAINING TORQUE.	CIRCUMFERENCE OF DRUM EQUAL	TWO FOLDS	5.46 5.95 6.52	RATED NO. 3	UNDESIRABLE RESONA END SUPPORTS ARE CO MUST WITHSTAND ADV THERMAL DISTORTION OF SUBSTRATE MATERI AREA MUST BE KEPT WI INDEXING PROGRAM. TION AND HIGH TENS PROBLEM.
					ONE FOLD	7.09 8.23 9.65		
				DIAMETER EQUAL	ONE FOLD	5.07 5.24 5.54		
PANELS ARE CONTAINED IN A BOX. EASY TO READJUST RESTRAINING FORCE (ASCENT PRE-LOAD). MINIMUM NUMBER MOVING PARTS.	PANELS ARE CONTAINED IN A BOX. ALWAYS PROTECTED.	SAME AS ABOVE EXCEPT CONTAINER BASE IS STATIONARY.	PANEL TENSIONS ARE NOT PRESENT DURING DEPLOYMENT. IF PARTIALLY DEPLOYED DURING ARTIFICIAL "G" A CUSHION BACKED FRAMEWORK HOLDDOWN THE REMAINING STOWED PANELS. NO MOVING PARTS AND ITS PRESET PRIOR TO LAUNCH	CIRCUMFERENCE OF DRUM EQUAL	TWO FOLDS	3.30 3.55 3.92	RATED NO. 1 (BEST)	UNDESIRABLE RESONA SIMPLE STRUCTURAL C BOLTS. CONTAINER B THE PANEL SUPPORT (C ARE ASSEMBLED, IT BE ARE THIN SECTIONS A AND ONLY SERVE AS CAN BE HINGED SO T RECTANGULAR SECTIO CAN BE DONE WITHO
					ONE FOLD	4.29 4.84 5.61		
				DIAMETER EQUAL	ONE FOLD	2.93 3.14 3.37		

FOLDOUT FRAME 4

FOLDOUT FRAME 5

FOLDOUT 6

C

I AND RELEASE	TENSION METHOD	STOWAGE VOLUME (FT^3)			RELIABILITY	GENERAL DESIGN COMMENTS
ATION MAY OCCUR CH AND ASCENT- A RELEASABLE LOCK. E-OF-THE-ART APPLICABLE.	IF PARTIALLY DEPLOYED DURING ARTIFICIAL "G," RELEASABLE LOCK (DRUM BRAKE) REACTS PANEL TENSION. RESULT IN HIGHEST RESTRAINING TORQUE (FUNCTION OF THE WRAPPED DRUM RADIUS-LARGEST MOMENT ARM).	DIAMETER (FT)	1.50	11.35	RATED NO. 2	UNCERTAINTIES OF ACTUAL FRICTION COEFFICIENTS BETWEEN ADJACENT WRAPS MAKE IT VERY DIFFICULT TO RELIABLY ESTIMATE THE AMOUNT OF TENSION REQUIRED ON THE PANELS TO PREVENT DAMAGE DUE TO ASCENT VIBRATION. THE TENSION REQUIRED TO RESTRAIN THE PANEL IS NOT ADJUSTABLE AND IS VERY DIFFICULT TO CHANGE. UNDESIRABLE RESONANT FREQUENCIES ARE DIFFICULT TO REMOVE. THE END SUPPORTS ARE CONSIDERED TO BE A CRITICAL AREA AND IT MUST WITHSTAND ADVERSE CONDITIONS (ASCENT LOADING AND THERMAL DISTORTION TO ASSURE POSITIVE DEPLOYMENT. LOADING ON THE DRUM IS SMALL AND IT CAN BE LIGHT. THE MINIMUM DRUM THICKNESS SHALL BE DETERMINED BY STIFFNESS REQUIREMENT.
			2.00	18.00		
			2.50	27.00		
L DEPLOYMENT SE ROTATE 180°. E-OF-THE-ART Y.	IF PARTIALLY DEPLOYED DURING ARTIFICIAL "G" AND SPINDLE PARALLEL TO PARTIALLY EXTENDED PANPANELS (SMALLEST MOMENT ARM), RELEASABLE LOCK (SPINDLE BRAKE) REACT PANEL TENSION. RESULT IN LOWEST RESTRAINING TORQUE.	CIRCUMFERENCE OF DRUM EQUAL	TWO FOLDS	5.46 5.95 6.52	RATED NO. 3	UNDESIRABLE RESONANT FREQUENCIES ARE DIFFICULT TO REMOVE. END SUPPORTS ARE CONSIDERED TO BE A CRITICAL AREA AND IT MUST WITHSTAND ADVERSE CONDITIONS (ASCENT LOADING AND THERMAL DISTORTION TO ASSURE POSITIVE DEPLOYMENT. CREEP OF SUBSTRATE MATERIAL AND CHANGING WIDTHS OF THE BEND AREA MUST BE KEPT WITHIN A TOLERABLE RANGE TO MINIMIZE INDEXING PROGRAM. HOWEVER, THERMAL EXPANSION/CONTRACTION AND HIGH TENSIONS DURING ARTIFICIAL "G" INCREASE THE PROBLEM.
			ONE FOLD	7.09 8.23 9.65		
		DIAMETER EQUAL	ONE FOLD	5.07 5.24 5.54		
E EXCEPT CONTAIN- IONARY.	PANEL TENSIONS ARE NOT PRESENT DURING DEPLOYMENT. IF PARTIALLY DEPLOYED DURING ARTIFICIAL "G" A CUSHION BACKED FRAMEWORK HOLDDOWN THE REMAINING STOWED PANELS. NO MOVING PARTS AND ITS PRESET PRIOR TO LAUNCH	CIRCUMFERENCE OF DRUM EQUAL	TWO FOLDS	3.30 3.55 3.92	RATED NO. 1 (BEST)	UNDESIRABLE RESONANT FREQUENCIES CAN BE ELIMINATED BY SIMPLE STRUCTURAL CHANGES SUCH AS ADDING MORE MOUNTING BOLTS. CONTAINER BY ITSELF IS VERY FLIMSY, HOWEVER WHEN THE PANEL SUPPORT (CONTAINER BOTTOM), PANELS, AND COVER ARE ASSEMBLED, IT BECOMES VERY RIGID. SIDE AND END MEMBERS ARE THIN SECTIONS AND ARE CONSIDERED TO BE NON-STRUCTURAL AND ONLY SERVE AS ENVIRONMENTAL PROTECTORS. FOLD LINES CAN BE HINGED SO THAT EACH FOLDED PANEL IS AN INDIVIDUAL RECTANGULAR SECTION. REPAIR AND REPLACEMENT OF PANELS CAN BE DONE WITHOUT EXTENSION.
			ONE FOLD	4.29 4.84 5.61		
		DIAMETER EQUAL	ONE FOLD	2.93 3.14 3.37		

FOLDOUT FRAME 5

FOLDOUT FRAME 6

4.1.2 Solar Array Structures

The basic load carrying element in the Space Station Solar Array is the extendible structure or boom. This component is of singular importance for the following reasons:

- Based on preliminary evaluation, it will comprise at least 20 percent of the system weight.
- It represents the pacing packaging envelope problem.
- It represents the most difficult portion of the retraction problem.

For these reasons a broad evaluation has been made of structural materials (4.1.2.1) on basic boom designs (4.1.2.2). Candidate boom configuration material combinations were then evaluated against nine potential Space Station array configurations in Section 4.1.2.3 in order to avoid selection pitfalls associated with a point design. It is anticipated that this evaluation will form a parametric base for boom selection for a variety of possible space station configurations.

4.1.2.1 Structural Material Candidates for LSSSA

Material selection for Space Station solar array applications involves consideration of many environmental and fabrication aspects. The materials used in these applications must be capable of withstanding the environments of ground handling phases as components during fabrication and assembly and as systems during various test phases; boost phases where the materials will experience primarily compression, tension, shear, bending, and fast changes in pressure; and orbital phase which will subject the materials not only to compression, tension, shear, and bending but additional factors such as fatigue, large temperature variations, temperature cycling and exposure to high vacuum and radiation for up to 10 years. In addition to the environmental factors, the material costs, development status, and producibility must be considered to assure that a cost and time-effective design is produced.

These considerations leading toward a low cost, easily producible, lightweight, high strength and high modulus material demand a constant search for new materials and development of their fabrication techniques.

Chart D lists the most commonly used materials and includes some new materials being considered for spacecraft applications. The chart reviews the material ambient physical properties (with the exception of vapor pressure) and includes present costs, predicted costs, and a producibility rating. In general, the composites look very promising as structural materials for Space Station applications, especially the graphite/epoxy. They are lighter than aluminum, 2-1/3 times as strong and 5 times as stiff. The stiffness-to-weight ratio is the best of the materials considered and since the major design criterion in the solar array is stiffness for configuration stability during extension/retraction, the material is very promising. These composites have a directional coefficient of linear expansion approaching zero (-0.5×10^{-6} in./in./^{o}F) which would minimize the thermal bending effects in structures. In addition, they can be fabricated with the techniques presently developed for the epoxy/fiberglass materials. They are the most cost-effective advanced composites and are presently being applied to many structural components in the aircraft industry. Unfortunately, the space environment physical characteristics data of these materials are limited. The only apparent space application work is being done

by Goodyear in antenna applications and by Lockheed in a small independent development effort to evaluate design applications. The Space Station designs will require that work be done in thin sections (2 to 3 mil) applications, whereas present work has been limited to pre-preg thicknesses of 5 to 6 mils. Joint designs must be investigated that would take up to 58,000 thermal cycles for temperature ranges from $-200^{\circ}F$ to $+200^{\circ}F$ without failures in bearing or delamination. The long time effects of radiation on the material properties must be established. The surface optical properties for thermal control surfaces and the potential for applying various thermal control surfaces must be investigated.

Repeatable and reliable data are not available at this time on graphite/epoxy and graphite/aluminum vapor pressure (which is important from the sublimation standpoint), because if the vapor pressure is low, the resulting sublimination could seriously degrade the optical surfaces on the Space Station. Thermo-gravimetric analysis performed on specimens of graphite/epoxy and graphite/polyimide advanced composites at LMSC indicate very low weight loss (less than 1/2 percent) at elevated temperatures when the cured composite has been properly post cured at elevated temperatures and reduced pressures for several hours. The volatiles, evolved during the tests showed no significant degradation to cold optical surfaces. Use of these composites for Space Station applications will be determined by further evaluation of their properties in the space environment, cost reduction, and producibility experience over the next few years. One problem in applying this material is in joint applications where large variations may occur.

The cost and time requirements of this contract will require the use of readily available materials with fully developed fabrication techniques (aluminum, magnesium, steel and developed non-metallics). Improvements obtainable by the use of the more advanced materials will be evaluated during the design analysis phase of this program.

AEROSPACE MATERIALS

D

	ρ DENSITY (lb/in^3)	F_{tu} (ksi)	F_{cu} (ksi)	E_t (x 10^6 psi)	E_c (x 10^6 psi)	E_t/ρ (x 10^6 $\frac{psi}{lbs/in^3}$)	COEF OF THERMAL EXPANSION 10^{-6} IN/IN/°F LONG	TRANSV	VAPOR PRESS AT 10^{-8} MILL. OF Hg, KELVIN	MATERIAL COST/LB 1970	1972	COST/IN^3 1970	1972	PRODUCIBILITY RATING COMPARISON MATRIX (1) GOOD, (10) POOR
ALUMINUM 7178-T6 2024-T3	.102 .100	88 64	78 64	10.4 10.5	10.5 10.7	102 105	13.0 13.0	13.0 13.0	950 (LIQUID) 950 (LIQUID)	1 1	1 1	1.02 1.00	1.02 1.00	1 1
MAGNESIUM AS31B-H24	.064	42	26	6.3	6.5	102	14.0	14.0	460	1	1	.64	.64	3-4
CRES 301	.286	141	141	26	26	91	9.0	9.0	1150	1.5	1.5	4.3	4.3	1
TITANIUM Ti 13V-11Cr-3AL Pure	.175 .163	125 50	120 42	14.5 15.5	* 16	83 95	4.8 5.3	4.8 5.3	* 1330	14 14	14 14	24.5 22.8	24.5 22.8	5 5
LOCKALLOY 62-38 AL	.076	57	42	28	28	370	8	8	950	200	200	152.0	152.0	7-8
BERYLLIUM	.067	78	53	42	42	627	6.4	6.4	970	200	200	134.0	134.0	10
EPOXY-FIBERGLASS**	.065	45	45	3.5	3.5	54	5.5	6.7	*	2	2	1.3	1.3	2
GRAPHITE/EPOXY**	.058	186	144	40	40	800	-.5	16	*	98	50	57	29	2.5
BORON/EPOXY**	.070	200	200	30	30	430	2.75	16.0	1650	250-425	150	236.0	150.0	5
BORON/ALUMINUM	.096	165	165	33	33	344	2.0	13.0	950	1000	125	960	120	7

* RELIABLE NUMBERS NOT AVAILABLE
** 60% FIBER VALUES

4.1.2.2 Deployment/Retraction Structures

This section summarizes the evaluation of current extensible structures technology. The work was directed mainly toward a study of deployable space structures; however, concepts and designs not yet used in space were reviewed for ideas applicable to the Space Station.

The purpose of the evaluation was to investigate and summarize the current technology of extensible structures and deployment/retraction systems. The section is presented in a fashion to facilitate trade-off and systems selection. Six charts are employed for this purpose:

- Beam Basic Cross-Section Forms (Chart E)
- Beam and Beam Member Cross Section Variations (Chart F)
- Truss Configuration Variations (Chart G)
- Basic Stowage Methods and Variations (Chart H)
- Extension/Retraction Methods (Chart I)
- Deployable Structures Survey (Chart J)

To evaluate all possible boom configurations would involve consideration of combinations of beam cross-section, truss configuration (if employed), packaging method, and drive method which, in total, number in the thousands.

The alternative is to classify the building block forms with respect to their basic characteristics so that fundamental differences can be isolated and evaluated. With this approach all boom types can be compared with respect to their worst fundamental characteristics, and many approaches can be reasonably compared. This is the approach chosen for this evaluation. Charts E and F present characteristics of basic candidate member shapes, any one or combination of which may be used in a given deployable structure design. Chart G presents several common truss shapes which might employ one or more of the basic shapes shown in Charts E and F.

A second basic design parameter is stowage method, six basic forms of which are discussed in Chart H. Chart I synthesizes practical combinations of basic shapes and

stowage methods with applicable types of prime mover to complete the basic classification and evaluation of deployable boom design approaches. Chart J presents and evaluates twenty combinations of these basic design approaches which have actually been designed and, in some cases, developed. Using combinations of these charts, variations on these twenty boom types can be readily evaluated with respect to basic advantages and disadvantages. The following sections discuss these charts in further detail.

4.1.2.2.1 Basic Structure Forms. The Beam Basic Cross-Section Forms, Chart E, show the common forms of beams and beam members in use. Each member has advantages, as indicated, and the selection of one over another involves trade-off by weight, strength, cost, availability, and fabricability.

Beams and Beam Member Cross-Section Variations are illustrated in Chart F. The form variations shown are generally the results of a functional consideration and not purely structural; i.e., the tubular variations result from the requirements that the member be flattened for stowage and/or extension and/or retraction, and the solid variations result from efficiency considerations. The structural characteristics of the members vary considerably from those of their basic form.

A form often used is the curved solid, the first example on the chart. It is most familiar as the steel measuring tape, from six to twelve feet long. The curved stock is available in a variety of materials and has often been used in space as deployable antenna elements. Continuation of the curvature will ultimately produce a section commonly used in tubular extensible beams. Most solid or tubular beams become inefficient as load carrying members when the length approaches 50 feet.

Trusses are defined as a combination of members so arranged and joined as to form a rigid framework. The framework is generally triangulated and loaded at the joints so that the stresses in the members are essentially simple tensions or compressions. Chart G shows truss configuration variations used as beams in deployable masts. Truss-configured beams can be designed for a specific load bias or combination. Therefore, they are the most efficient structures studied in terms of stiffeners, weight, and material economy. Combinations of truss configurations are sometimes used to

develop the geometry required to allow the beam to be folded, and yet be strong, stiff, and lightweight when extended.

4.1.2.2.2 Structures Stowage Methods. The three basic stowage methods and their variations are illustrated in Chart H.

Folding is the method most used for stowing beams and beam members. It is mechanically the simplest and most versatile stowage method. In hinged designs, the structural characteristics of the extended beam are sometimes compromised by bearing/journal clearance. A trade-off can be made between the structural characteristics and weight. The bearing/journal can incorporate features that eliminate clearance.

Folding is used as a basic method for stowing some beams that do not have hinges, such as:

- Inflatables
- Lenticular tubes (modified cross-section)
- Curved plates (tapes)

Inflatables have the most advantageous stowed/extended length ratio and potentially the greatest stiffness/weight ratio of the beams investigated. However, the extremely thin walls required severely limits the strength available.

Combined folding methods and devices are used for stowing beams. For example, two joined sets of folding beams form the widely used lazy tongs, and three sets of lazy tongs joined to three lenticular columns form the tri-extender truss.

Rolling beams on or in drums is a clever solution to some stowage problems. The beam occupies little volume when stowed in relation to it's extended size. It is a method that can be used in stowing beams of a variety of cross-sectional forms. The technique of rolling on or coiling in a drum, stresses the material so that the thickness is quite limited. This limits the strength of the beam.

Telescoping beams for stowage is a relatively common method. It is used in sizes from pocket pointers (extends from 6 to 18 inches) to natural gas storage tanks. Their stowage efficiency-ratio of stowed to extended height is low in the designs investigated. However, increasing the number of telescoping segments improves the ratio. (Increasing the number of joints also increases weight and/or decreases beam strength/stiffness.) Another way used to improve the stowed/extended height ratio is combining the telescoping and folding methods. Using this combination, the segmented beam is telescoped to its minimum height and folded 90-degrees about a hinge joint at its base.

4.1.2.2.3 Structures Deployment Methods. The extension/retraction methods shown in Chart I are actually used in the beam designs studied. The prime movers can be exchanged in accordance with design constraints. It is conceivable that pneumatic or hydraulic motors could be interchanged with electric motors to produce rotary motion, but they cannot be reversed. The most effective or available energy source and the motion required determine the method or energy/motion transducer used.

The term hydraulic actuator, as applied to most spacecraft actuators, is a misnomer. They generally are mechanical spring actuators incorporating hydraulic damping.

4.1.2.2.4 Deployable Structure Survey. The survey considers twenty unique extendible structures (Chart J). Most of the structures are available from several sources.

The structures are separated in the chart by stowage method, telescoping, folding, and reel roll-up. Further separation is achieved by structural differences, i.e., truss vs. solid, interlocking vs. overlapping, etc. The chart displays general characteristics, uses and experiences, known fabricators, and reference material on each structure.

A section of photographs of the structures follows Chart J, and are numbered (1a, 1b, etc.) to relate to the structure number in the chart. The photographs were selected to clarify extension techniques and to illustrate the state-of-the-art. Photographs No. 3a and 3b (Mobile Aerial Towers) illustrate the incorporation of good engineering fundamentals. Most obvious is the simplicity of design and few moving parts. To achieve that simplicity, the design utilizes the available stowage space very well, which allows the structure elements to be of maximum size and minimum in number.

The industry survey revealed a variety of designs in an advanced state of development and use. Many designs have fundamental similarities; the features of each system exhibit dominance of some primary consideration such as stiffness, strength, weight, economy, stowage, deployment, and retraction.

BASIC BEAM CROSS SECTION FORMS

E

STRUCTURE	FORM	STRUCTURAL CHARACTERISTICS	COMMENTS
SOLID		GOOD TENSION MEMBER, MOMENT OF INERTIA CHANGES IN ORTHOGONAL DIRECTIONS	ECONOMICAL MATERIAL SECTION, FLAT SURFACES FACILITATE FABRICATION OF TRUSS STRUCTURES
		FAT SECTION SUITABLE FOR HIGH SHEAR LOADS	PRIMARILY USED IN MECHANISMS; HOWEVER USEFUL FOR SHORT BEAMS OR STRUTS
		FAT SECTION SUITABLE FOR HIGH SHEAR LOADS, CONSTANT MOMENT OF INERTIA	ECONOMICAL MAT'L SECTION, BEAM END FITINGS FABRICATED WITH SIMPLE DRILLED HOLES
		MOMENT OF INERTIA CHANGES IN ORTHOGONAL DIRECTIONS	USUALLY A FORGED SHAPE;USED EXTENSIVELY AS A SIMPLE BEAM
TUBES		TORSIONALLY GOOD, PROVIDES DIFFERENT MOMENT OF INERTIA IN ORTHOGONAL AXIS	WIDELY USED IN ANTENNA STRUCTURES WHEREIN WAVEGUIDE SERVES ITS NORMAL MICROWAVE FUNCTION AS WELL AS STRUCTURAL SUPPORT
		TORSIONALLY GOOD, PROVIDES EQUAL MOMENT OF INERTIA IN ORTHOGONAL AXIS	USED IN STRUCTURES WHERE FLAT SURFACES FOR MOUNTING OR FABRICATION ARE DESIRED
		TORSIONALLY STIFFEST TO WEIGHT FORM AVAILABLE, CONSTANT MOMENT OF INERTIA	ECONOMICAL, WIDELY USED FORM COMMERCIALLY AVAILABE IN A BROAD SELECTION OF MATERIALS AND ALLOYS
		TORSIONALLY GOOD, PROVIDES DIFFERENT MOMENT OF INERTIA IN ORTHOGONAL AXIS	USUALLY PRODUCED IN FABRICATION SHOP BY FLATTENING A ROUND TUBE
TRUSS BEAMS		TORSIONALLY GOOD, PROVIDES DIFFERENT MOMENT OF INERTIA IN ORTHOGONAL AXIS	COMMONLY USED IN BRIDGE TRUSSES OR ANY TRUSS WITH UNSYMMETRICAL LOADING
		TORSIONALLY GOOD, PROVIDES EQUAL MOMENT OF INERTIA IN ORTHOGONAL AXIS	COMMONLY USED WHERE LOADS ARE SYMMETRICAL SUCH AS RADIO TOWERS
		TORSIONALLY GOOD, MOMENT OF INERTIA MAY BE VARIED IN ANY OF THREE DIRECTIONS	GENERALLY USED FOR SYMMETRICAL LOADS, HOWEVER CAN BE MADE ASYMMETRICAL FOR SPECIAL CONDITIONS

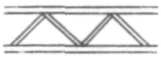
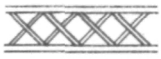
BEAM AND BEAM MEMBER CROSS SECTION VARIATIONS

F

BEAM FORM	VARIATION	COMMENTS
OPEN SECTIONS		LOW OUT OF PLANE STIFFNESS LIMIT THIS TO LOW BENDING AND TORSIONAL LOAD APPLICATIONS.
		LOW TORSIONAL STIFFNESS, HIGH DYNAMIC DAMPING, EVEN WHEN MADE TO OVERLAP. WIDELY USED AS SMALL DIAME.ER, LONG MEMBERS FOR ELECTROMAGNETIC ANTENNA. SEVERE THERMAL BENDING PROBLEMS.
		BROAD RANGE OF SIZES AND MATERIALS AVAILABLE. SUITABLE FOR STIFFENERS OR COMPONENT PARTS OF A BUILT-UP BEAM OR COLUMN.
		SIMILAR TO ABOVE WITH SLIGHTLY IMPROVED BENDING STRENGTH.
		WIDELY USED AS STRUCTURAL BEAMS. IDEAL FOR HIGH BENDING LOADS ABOUT THE MAJOR PRINCIPAL AXIS
		AS ABOVE EXCEPT HIGHER FLANGE BUCKLING HAZARD. SHEAR CENTER NOT COINCIDENT WITH C.G.
ROUND TUBE		APPROACHES THE STRUCTURAL CHARACTERISTICS OF A THIN WALLED TUBE. EXACT MECHANICAL PROPERTIES DEPEND UPON INDIVIDUAL DESIGN. USUALLY <6 IN DIA AND WITH APPROX 250:1 DIAMETER TO THICKNESS RATIO. CRITICAL REVIEW OR APPLICATIONS ARE REQUIRED TO MINIMIZE THERMAL BENDING PROBLEMS.
FLATTENED TUBE		USUALLY IN THIN WALLED SECTIONS. BENDING LOAD CAPACITY VARIES WITH LATERAL CURVATURES. TEST DATA LIMITED, ANALYSIS METHOD NOT DEVELOP FOR BEAM WITH SEALED EDGES. CENTER PIECE HELPS STABILIZE SHAPE, HENCE INCREASES STRENGTH AND STIFFNESS. HOWEVER INCREASED DRUM WEIGHT SHOULD BE STUDIED IN A TRADE-OFF.
TUBULAR DELTA		USUALLY IN THIN WALLED SECTIONS AND LIMITED IN SIZE TO 6 INCHES PER SIDE.

TRUSS CONFIGURATION VARIATIONS

G

CONFIGURATION	COMMENTS
1	DIAGONALS AND BATTENS BOTH SUBJECTED TO COMPRESION AND TENSION LOADS.
2	SAME AS ABOVE
3 	DIAGONAL MEMBERS SUBJECTED TO BOTH COMPRESSION AND TENSION. CONSEQUENTLY MEMBERS MUST BE HEAVY ENOUGH TO RESIST COLUMN BUCKLING.
4 	REDUNDANT DIAGONALS SUBJECTED TO BOTH COMPRESSION AND TENSION. OFTEN USED WHEN TRUSS IS TO BE FOLDED.
5	LIGHTWEIGHT DESIGN, SHORT BATTENS SUBJECTED TO COMPRESSION LOADS LONG DIAGONALS SUBJECTED TO TENSION LOADS.

FIGURES 1,2, AND 3 HAVE APPROXIMATELY THE SAME STRENGTH AND WEIGHT.
THE COMBINATION OF FIGURES 4 AND 5 TRUSS FORMS MAKES A FEASIBLE STRUCTURE.

BASIC STOWAGE METHODS AND VARIATIONS

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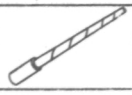
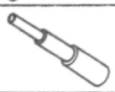
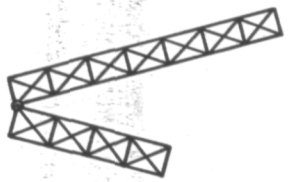
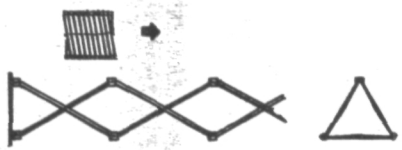
METHOD	VARIATIONS	CHARACTERISTICS	COMMENTS
FOLDED		STOWS BY DISPLACEMENT ONLY, STOW VOLUME IS APPROX. EQUAL TO EXTENDED VOLUME.	SIMPLE, EFFECTIVE, AND WIDELY USED, LIGHT WEIGHT FOR MORE HEAVILY LOADED SYSTEMS.
		STOWS VERY COMPACT, REQUIRES LATCHES TO DEVELOP RIGIDITY. EXCELLENT DEPLOYMENT DEVICE	MULTIPLE HINGE JOINTS REQUIRE PRUDENT DESIGN TO MINIMIZE LOOSENESS. USUALLY SPRING LOADED AGAINST A DAMPER MECHANISM.
		STOWAGE CAPABILITY DEPENDS UPON THE MATERIAL ALLOWABLE STRESS AND THICKNESS. INFLATIBLES USING METAL FOILS STOW VERY COMPACTLY	NO JOINTS OR LATCHES REQUIRED TO PROVIDE A RIGID STRUCTURE. COLUMN STRENGTH IS LIMITED BY MATERIAL THICKNESS, STOWED CONFIGURATION, AND ALLOWABLE STRESS. NO REMOTE RETRACTION.
ROLLED		BEAM IS WRAPPED AROUND A REEL AND ITSELF. REQUIRES A SECTION OF THE BEAM REMAIN EXTENDED BUT STOWS COMPACTLY. CAN BE SELF EXTENDING BUT USUALLY MOTOR DRIVEN	USUALLY CAPABLE OF MANY EXTENSIONS AND RETRACTIONS WITHOUT DEGRADING PERFORMANCE, DEVELOPS FULL STRENGTH AT PARTIAL EXTENSION. COLUMN STRENGTH IS LIMITED BY MAT'L THICKNESS STOW CONFIG. & STRESS
		USUALLY SELF EXTENDING BY STORED SPRING ENERGY, ALTHOUGH SOME MOTOR DRIVEN MODELS HAVE BEEN USED	CAPABLE OF MANY EXTENSIONS OR RETRACTIONS WITHOUT DEGRADING PERFORMANCE. COLUMN STRENGTH IS VERY LIMITED.
TELESCOPED		STOWED VOLUME FROM 20 TO 50 PERCENT OF EXTENDED VOLUME. DESIGNS READILY ADAPT TO DEVELOP ALL USABLE STRENGTH OR INDIVIDUAL MEMBERS	SIMPLE, FEW PARTS, MAKE DESIGN VERY RELIABLE. MAY BE TRUSSES, TUBES OR COMBINATIONS OF THE TWO

EXTENSION/RETRACTION METHODS

PRIME MOVER	STOWAGE METHOD	BEAM SECTION FORM	CHARACTERISTICS
ELECTRIC MOTOR	REEL STORED		REMOTE ACTUATION, CAPABLE OF MULTIPLE EXTENSIONS AND RETRACTIONS. SOME MODELS INCORPORATE TWO STORAGE REELS THAT ARE INTERCONNECTED AND DRIVEN BY A COMMON MOTOR.
			REMOTE ACTUATION, CAPABLE OF MULTIPLE EXTENSIONS AND RETRACTIONS. USES THREE STORAGE REELS INTERCONNECTED AND DRIVEN BY A COMMON MOTOR.
			REMOTE ACTUATION, CAPABLE OF MULTIPLE EXTENSIONS AND RETRACTIONS. A SINGLE STORAGE REEL IS DRIVEN BY THE MOTOR.
			WIRE TRUSS IS FOLDED AND ROLLED UP ON A SINGLE, MOTOR DRIVEN REEL.
	TELESCOPING		REMOTE EXTENSION MAY BE ACCOMPLISHED BY MOTOR DRIVEN WINCH ACTION OR A MOTOR DRIVEN HYDRAULIC SYSTEM. BEAM SECTIONS MAY BE SOLID OR TRUSS.
	FOLDING	VARIOUS	REMOTE EXTENSION MAY BE ACCOMPLISHED BY MOTOR DRIVEN WINCH ACTION OR BY A MOTOR DRIVEN SCREW JACK (USUALLY IN CONJUCTION WITH MECHANICAL SPRINGS).

EXTENSION/RETRACTION METHODS

PRIME MOVER	STOWAGE METHOD	BEAM SECTION FORM	CHARACTERISTICS
MECHANICAL SPRINGS	REEL STORED	SAME BEAM SECTION USED AS ELECT. MOTOR CONFIG.	SPRING MOTOR POWERS EXTENSION ONLY, MANUAL RETRACTION REWINDS MOTOR.
	TELESCOPING		SPRINGS OR SPRING MOTOR POWERS EXTENSION ONLY, REQUIRES MANUAL RETRACTION. GENERALLY USED WITH A DAMPER TO CONTROL EXTENSION DYNAMICS.
	FOLDING	VARIOUS	SPRINGS AT EACH JOINT EXTEND STRUCTURE, MANUAL RETRACTION REQD. MAY BE USED IN CONJUNCTION WITH AN ELECTRICAL MOTOR THAT WILL ASSIST IN EXTENSION AND CONTROL EXTENSION DYNAMICS.
PNEUMATIC (STORED GAS)	TELESCOPING		SLIDING SEALS MAKE TELESCOPIC MAST GAS TIGHT, GAS PRESSURE EXTENDS CYLINDERS. MANUAL RETRACTION REQD.
	FOLDING	VARIOUS	SEALED TUBES INFLATED WITH GAS PRESSURE, MANUAL RETRACTION REQD PNEUMATIC ACTUATORS MAY BE EMPLOYED TO ERECT HINGED JOINTS, AGAIN MUST BE RETRACTED MANUALLY.

NO. & NAME OF EXTENDIBLE STRUCTURE	ILLUSTRATION	DESCRIPTION & OPERATION OF STRUCTURE & MECHANISM (RETRACTION CAPABILITIES)	FLIGHT EXPERIENCE	SOURCE	DEVE
1 TELESCOPING TRIANGULAR TRUSS		CONCENTRIC TRIANGULAR TRUSS SECTIONS SUPPORTED BY ROLLERS. SECTIONS ARE EXTENDED AND LATCH IN THE FULL EXTENDED POSITION. CAN BE UNLATCHED AND RETRACTED	FLIGHT EXPERIENCE: NONE	TRI-EX TOWER CORP., VISALIA, CALIFORNIA	USED EXTENSIVELY IN EA PORTABLE ANTENNA TO QUITE ADAPTABLE TO SP
2 TELESCOPING CYLINDERS		CONCENTRIC SOLID TUBES IN GRADUATED DIAMETERS. SECTIONS ARE EXTENDED AND LATCH IN THE FULL EXTENDED POSITION. CAN BE UNLATCHED AND RETRACTED	FLIGHT EXPERIENCE: UNKNOWN FLIGHT EXPERIENCE UNKNOWN FLIGHT EXPERIENCE: NONE	SANDERS ASSOC. INC., NASHAU, N.H. ROYAL AIRCRAFT ESTABLISHMENT, FARNSBOROUGH, U.K. TRI-EX TOWER CORP., VISALIA, CALIFORNIA	TELESCOPING MAST WITI LATCHING AND RETRACT 21 FEET AND 30 FEET, HA INTERESTING ACTUATOR, TWO MODELS OF PNEUM 17-FT LONG TELESCOPIN USED EXTENSIVELY IN G "SKY NEEDLE TOWERS". CABLES SYSTEM FOR EXT
3 FOLDING BEAM		SECTIONS MAY BE TRUSS, TUBULAR, OR SOLID: HINGES ON EITHER END AND LATCHES AT FULL EXTENSION. USUALLY DEPLOYED BY A TENSION CABLE SYSTEM WITH PULLEYS AT EACH JOINT. CAN BE UNLATCHED AND RETRACTED.	USED FREQUENTLY IN SPACE FLIGHTS, USUALLY AS RELATIVELY SHORT MEMBERS. (LESS THAN 30 FT.)	BOEING CO., SEATTLE, WASHINGTON FAIRCHILD HILLER CORP., GERMANTOWN, MD. MOBILE AERIAL TOWERS INC., FT. WAYNE, IND.	BOEING DID DEVELOPME ARRAY THAT DEPLOYED I FAIRCHILD HILLER BUILT MANUFACTURE FOR GRC TOWERS TO ELEVATE ME 130 FT. SIMPLE CONSTR SPACE USAGES.
4 LAZY TONG		STRUCTURAL PANELS HINGED TOGETHER AND STABILIZED ATTACHMENT TO HINGED BEAMS AT THE EDGES. THE HINGED BEAMS ARE SOMEWHAT LONGER FROM PIVOT TO PIVOT THAN THE STRUCTURAL PANELS. THE PANELS ALIGN TO ACCEPT COLUMN LOADS. MAY BE LATCHED AT FULL EXTENSION, USUALLY NOT RETRACTABLE ONCE LATCHED. USUALLY SPRING-LOADED; MAY HAVE SCREW JACK ASSISTANCE. COULD USE A TENSION CABLE SYSTEM AS IN NO. 3 BUT THE NUMBER OF JOINTS IS USUALLY HIGH.	THIS CONFIGURATION USED EXTENSIVELY BY LOCKHEED TO DEPLOY SOLAR PANELS. THE PEGASUS SPACECRAFT DEPLOYED FLAT-PANELS 14 BY 48 FT (EACH WING) AS METEROID DETECTORS USING THIS SYSTEM.	LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA FAIRCHILD HILLER CORP., GERMANTOWN, MD.	A WORKING MODEL 8-1 TONG (NO FLAT PANEL FAIRCHILD HILLER
5 TRI AXIS PANTOGRAPH		THREE LAZY TONGS TIED AT THE NODES WITH U-SHAPED CLIPS. MAY BE LATCHED AT FULL EXTENSION. AS IN NO. 4, MOSTLY USED AS A SPRING-LOADED, NON-RETRACTING DEVICE INVOLVING ONLY LIGHT COLUMN LOADS. MAY USE A SCREW JACK ASSIST WHICH WILL CONTROL DEPLOYMENT.	FLIGHT EXPERIENCE: NONE	LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA	A SMALL 5-FT LONG DE BUILT BY LOCKHEED.

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

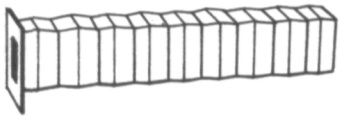
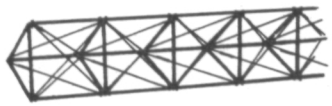
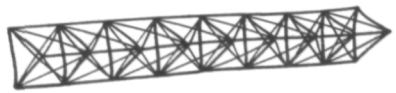
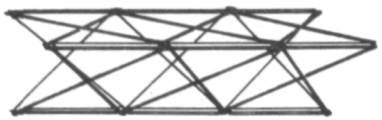
DEPLOYABLE STRUCTURES SURVEYED

	SOURCE	DEVELOPMENT WORK	GENERAL DESIGN COMMENTS	PRODUCIBILITY	GE E
	TRI-EX TOWER CORP., VISALIA, CALIFORNIA	USED EXTENSIVELY IN EARTH APPLICATIONS SUCH AS PORTABLE ANTENNA TOWERS. SIMPLE CONSTRUCTION IS QUITE ADAPTABLE TO SPACE USAGE	TRIANGULAR SHAPE PROVIDES EXCELLENT STIFFNESS-TO-WEIGHT CHARACTERISTICS. MEMBERS MAY BE SIZED-UP ACCORDING TO LOAD REQUIREMENTS AND PACKAGING ENVELOPE. VERY SIMPLE DESIGN ANALYSIS. AN EXTREMELY EFFICIENT BEAM IF THREE OR LESS TELESCOPIC SECTIONS ARE USED. LOOSENESS IN THE JOINTS WILL YIELD A NON-LINEAR SYSTEM AND MUST BE AVOIDED OR MINIMIZED. AN IDEAL BEAM FOR THERMAL BENDING WHEN USED WITH A CONSTANT SUN ANGLE, AS EXPOSURE TO SUNLIGHT CAN BE NEARLY EQUAL ON ALL LONGITUDIONAL MEMBERS. UNEVEN SIDE HEATING COULD PRODUCE DEFORMATION AND RESULT IN RETRACTION PROBLEMS.	SIMPLE PARTS SECURED BY CONVENTIONAL METHODS REQUIRES MINIMAL SPECIAL JIGS AND TOOLING. DESIGN WOULD ADAPT WELL TO USE COMPOSITE MATERIALS	RUGGED CC DEPLOYMEN FORMANCE REQUIRED F TESTING
	SANDERS ASSOC. INC., NASHAU, N.H. ROYAL AIRCRAFT ESTABLISHMENT, FARNSBOROUGH, U.K. TRI-EX TOWER CORP., VISALIA, CALIFORNIA	TELESCOPING MAST WITH INCREMENTAL EXTENSION; LATCHING AND RETRACTION UNLATCHING. TWO MODELS, 21 FEET AND 30 FEET, HAVE BEEN BUILT AND TESTED. VERY INTERESTING ACTUATOR/LATCH MECHANISM. TWO MODELS OF PNEUMATIC OPERATED 17-FT LONG TELESCOPING MAST USED EXTENSIVELY IN GROUND APPLICATIONS UP TO 100 FT, "SKY NEEDLE TOWERS". USES MOTORIZED WINCH AND CABLES SYSTEM FOR EXTENSION	COLUMN LOADED THIN WALL TUBES ARE BEST USED FOR INTERMEDIATE LENGTH BEAMS (LESS THAN 50 FT.). INCREASES IN LENGTH REQUIRE AN INCREASE IN TUBE DIAMETER TO MAINTAIN A MINIMUM SLENDERNESS RATIO. SIMULTANEOUSLY THE TUBE WALL THICKNESS MUST BE INCREASED TO MAINTAIN A LOW R/T RATIO TO AVOID LOCAL BUCKLING. CONSIDERABLE OVERLAP IS REQUIRED TO AVOID ROTATIONAL LOOSENESS. NONUNIFORM TEMPERATURES WILL CAUSE BENDING. CROSS-SECTION WILL NOT REMAIN CIRCULAR AND MUST BE ANALYZED FOR BINDING DURING RETRACTION. THERMAL CONTROL SURFACE MUST WITHSTAND SLIDING ABRASION DURING EXTENSION AND RETRACTION.	SIMPLE PARTS, PRUDENT DESIGN WILL PRECLUDE THE NEED FOR EXTENSIVE TOOLING. STRUCTURAL SHAPES COULD BE ADAPTED TO USE COMPOSITE MATERIAL	
, BERS.	BOEING CO., SEATTLE, WASHINGTON FAIRCHILD HILLER CORP., GERMANTOWN, MD. MOBILE AERIAL TOWERS INC., FT. WAYNE, IND.	BOEING DID DEVELOPMENT WORK ON A 63-FT LONG SOLAR ARRAY THAT DEPLOYED IN THIS MANNER. FAIRCHILD HILLER BUILT A WORKING MODEL 36-FT LONG MANUFACTURE FOR GROUND USE A LINE OF MOBILE AERIAL TOWERS TO ELEVATE MEN AND EQUIPMENT AS HIGH AS 130 FT. SIMPLE CONSTRUCTION IS QUITE ADAPTABLE TO SPACE USAGES.	CHARACTERISTICS ARE THOSE OF THE BASIC SECTION SELECTED; MAY BE VERY EFFICIENT, DEPENDING UPON THE DETAIL DESIGN. LOOSENESS IN THE JOINTS WILL RESULT IN A DYNAMICALLY NON-LINEAR SYSTEM AND MUST BE MINIMIZED. THERMAL BINDING IS UNLIKELY. ALL OTHER THINGS EQUAL, THIS BEAM GENERALLY REQUIRES MORE STORAGE SPACE THAN A TELESCOPING BEAM.	SIMPLE PARTS SECURED BY CONVENTIONAL METHODS REQUIRES MINIMAL SPECIAL JIGS AND FIXTURES FOR FABRICATION (SEE TESTING). PARTS OF THE STRUCTURE WILL BE ADAPTABLE TO COMPOSITE MATERIALS.	RUGGED CC REPEATED DE WITHOUT PE ZIG-ZAG DI EXTENSIVE F DEPLOYMEN
IVELY BY S. FLAT- METEROID	LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA FAIRCHILD HILLER CORP., GERMANTOWN, MD.	A WORKING MODEL 8-1/2-FT LONG OF ONLY THE LAZY TONG (NO FLAT PANELS) WAS BUILT AND TESTED BY FAIRCHILD HILLER	VERY COMPACT STOWAGE. THIS BEAM IS AN EFFECTIVE DEPLOYMENT DEVICE. PROPER LOCKING OF PANELS IS REQUIRED TO CHANGE THE DEVICE INTO A STRUCTURE. THE LARGE NUMBER OF JOINTS WILL PROBABLY LEAD TO A NON-LINEAR STRUCTURE, WHICH MAKES MEANINGFUL DYNAMIC ANALYSIS DIFFICULT.	A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. MINIMAL SPECIAL JIGS AND FIXTURES. HINGE AND LATCH BEARING LOADS REQUIRE METALLIC CHARACTERISTICS WHICH WILL REDUCE THE EFFECTIVENESS OF COMPOSITE MATERIALS; HOWEVER, THE USE OF BERYLLIUM AND MAGNESIUM SHOULD BE INVESTIGATED.	CONSTRUCT DEPLOYMEN PERFORMAN MULTIPLE JC CAUSING LC REQUIRED F TEST
	LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA	A SMALL 5-FT LONG DEMONSTRATION MODEL HAS BEEN BUILT BY LOCKHEED.	THIS IS A GOOD DEPLOYMENT DEVICE BUT A VERY POOR STRUCTURE, INHERENTLY NON-LINEAR WITH LOW LATERAL AND TORSIONAL STIFFNESS. COLUMN STRENGTH IS LIMITED BY THE EXTENSION MECHANISM; OR EVEN IF LATCHED IN THE EXTENDED POSITION, ALL OF THE STRUCTURAL MEMBERS ARE LOADED IN BENDING. THERMAL BENDING WILL BE SMALL IF BEAM SELF SHADING IS HELD TO A LOW VALUE. VERY COMPACT STOWAGE.	A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. MINIMAL SPECIAL JIGS AND FIXTURES. HINGE AND LATCH BEARING LOADS REQUIRE METALLIC CHARACTERISTICS WHICH WILL REDUCE THE EFFECTIVENESS OF COMPOSITE MATERIALS; HOWEVER, THE USE OF BERYLLIUM AND MAGNESIUM SHOULD BE INVESTIGATED.	

FOLDOUT FRAME 3

FOLDOUT FRAME 4

PRODUCIBILITY	TESTING & HANDLING: GROUND DEPLOYMENT DEMO ENVIRONMENTAL TESTING STATIC LOAD TEST	TESTING & HANDLING: INSTALLATION ON SPACECRAFT	BIBLIO AND VENDOR DATA *
SIMPLE PARTS SECURED BY CONVENTIONAL METHODS REQUIRES MINIMAL SPECIAL JIGS AND TOOLING. DESIGN WOULD ADAPT WELL TO USE COMPOSITE MATERIALS	RUGGED CONSTRUCTION ALLOWS REPEATED DEPLOYMENT/RETRACTIONS WITHOUT PERFORMANCE DEGRADATION. MINIMAL FIXTURES REQUIRED FOR ENVIRONMENT AND LOAD TESTING	USES LONG NARROW STOWAGE SPACE. NO SPECIAL HANDLING REQUIRED.	P.2-2, *
SIMPLE PARTS, PRUDENT DESIGN WILL PRECLUDE THE NEED FOR EXTENSIVE TOOLING. STRUCTURAL SHAPES COULD BE ADAPTED TO USE COMPOSITE MATERIAL	SAME AS NO. 1 (ABOVE)	SAME AS NO. 1 (ABOVE)	P.2-2, * R.3-11 P.2-2, *
SIMPLE PARTS SECURED BY CONVENTIONAL METHODS REQUIRES MINIMAL SPECIAL JIGS AND FIXTURES FOR FABRICATION (SEE TESTING). PARTS OF THE STRUCTURE WILL BE ADAPTABLE TO COMPOSITE MATERIALS.	RUGGED CONSTRUCTION ALLOWS REPEATED DEPLOYMENT/RETRACTIONS WITHOUT PERFORMANCE DEGRADATION. ZIG-ZAG DEPLOYMENT MAY REQUIRE EXTENSIVE FIXTURES FOR GROUND DEPLOYMENT	NO SPECIAL HANDLING REQUIRED; HOWEVER, DOES NOT STOW EFFICIENTLY. STOWAGE SHAPE MAY BE TAILORED SOMEWHAT BY CHANGING THE SECTION LENGTHS.	B.3-4, N.2-5, T.3-1 T.3-1, N.2-5, F.1-4 T.3-1, N.2-5
A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. MINIMAL SPECIAL JIGS AND FIXTURES. HINGE AND LATCH BEARING LOADS REQUIRE METALLIC CHARACTERISTICS WHICH WILL REDUCE THE EFFECTIVENESS OF COMPOSITE MATERIALS; HOWEVER, THE USE OF BERYLLIUM AND MAGNESIUM SHOULD BE INVESTIGATED.	CONSTRUCTION ALLOWS REPEATED DEPLOYMENT/RETRACTION WITHOUT PERFORMANCE DEGRADATION. HOWEVER MULTIPLE JOINTS AND LATCHES MAY WEAR, CAUSING LOOSENESS. MINIMAL FIXTURES REQUIRED FOR ENVIRONMENT AND LOADS TEST	NO SPECIAL HANDLING REQUIRED. STOWS VERY EFFICIENTLY	F.1-5 THRU -7, *
A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. MINIMAL SPECIAL JIGS AND FIXTURES. HINGE AND LATCH BEARING LOADS REQUIRE METALLIC CHARACTERISTICS WHICH WILL REDUCE THE EFFECTIVENESS OF COMPOSITE MATERIALS; HOWEVER, THE USE OF BERYLLIUM AND MAGNESIUM SHOULD BE INVESTIGATED.	SAME AS NO. 4 (ABOVE)	SAME AS NO. 4 (ABOVE)	NONE

NO. & NAME OF EXTENDIBLE STRUCTURE	ILLUSTRATION	DESCRIPTION & OPERATION OF STRUCTURE & MECHANISM (RETRACTION CAPABILITIES)	FLIGHT EXPERIENCE	SOURCE	D
6 EXTENSIBLE TRUSS (PROPOSAL BASELINE)		TWO LAZY TONGS CONNECTED WITH PANELS TO PRODUCE A RECTANGULAR TRUSS BEAM WHEN EXTENDED; PANELS ALIGN TO ACCEPT COLUMN LOADS. MAY BE LATCHED AT FULL EXTENSION: USUALLY NOT RETRACTABLE ONCE LATCHED. MAY USE A SCREW JACK ASSIST WHICH WILL CONTROL DEPLOYMENT.	FLIGHT EXPERIENCE: UNKNOWN	FAIRCHILD HILLER, SPACE AND ELECTRONICS SYSTEMS DIVISION, GERMANTOWN, MD.	A SMALL DEMONST FAIRCHILD HILLER, DIVISION. THIS C THE PRINCIPLES USE PEGASUS SPACECRA
7 BOX BELLOWS (JACK-IN-THE BOX)		FLAT RECTANGULAR PANELS JOINED LONGITUDINALLY BY HINGES, INCORPORATING TORSION SPRINGS AND SUPPORTED BY FLANGES. HINGES OPEN INWARD AND OUTWARD ON ALTERNATE PANELS. MAY BE LATCHED AT FULL EXTENSION, USUALLY NOT RETRACTABLE.	FLIGHT EXPERIENCE: UNKNOWN	LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA FAIRCHILD HILLER, SPACE & ELECTRONICS SYSTEMS DIVISION, GERMANTOWN, MD.	SMALL DEMONSTRA LOCKHEED AND FA COMPLETED A 90° T COMPACTLY.
8 ASTROMAST ARTICULATED LATTICE		TRIANGULAR SECTIONS ARE RIGID: THE LONGITUDINAL LINKS PIVOT AT EACH BAY. FOLDING IS ACHIEVED BY LOOSENING ONE TENSION MEMBER (WIRE ROPE) IN EACH BAY: THE TENSION MEMBERS ARE LOCKED AS EACH BAY IS EXTENDED. RETRACTABLE.	FLIGHT EXPERIENCE: UNKNOWN	ASTRO RESEARCH CORP., SANTA BARBARA, CALIFORNIA	MANY APPLICATIO BOTH CIVIL AND M BOOMS ARE MANU DEVELOPMENTAL U ACTUATED (ERECTIN DELIVERED TO THE STEEL IS USED FOR STELL WIRE ROPE FC
9 ASTROMAST COILABLE LATTICE		FIBERGLASS CONSTRUCTION WITH WIRE ROPE TENSION MEMBERS. LONGITUDINAL SECTIONS ARE CONTINUOUS; THE TRIANGULAR BAY SECTIONS ARE RIGID AND PIVOTED ON THE LONGITUDIONAL MEMBERS. RETRACTABLE. FIBERGLASS BATTENS (SIDES OF TRIANGULAR SECTION) ARE BUCKLED TO BEGIN COILING OPERATION.	FLIGHT EXPERIENCE: UNKNOWN	ASTRO RESEARCH CORP., SANTA BARBARA, CALIFORNIA	ONE FLIGHT UNIT DELIVERED TO NAS EXPERIMENT AS PA PERIMENT CANCEL MAST WILL BE DELI CORP. AS PART OF FREQUENCY RADIO
10 TRI EXTENDER LMSC		TRIANGULAR BOOM, PANTOGRAPH LINKS CONNECT THE LONGITUDIONAL MEMBERS. EACH LONGITUDIONAL MEMBER HAS A LENTICULAR SECTION BETWEEN THE LAZY TONG NODES SIMILAR TO EXT. STRUCTURE NO. 12. THE LENTICULAR SECTIONS ARE FLATTENED THEN BUCKLED ALTERNATELY INWARD/OUTWARD TO STOW. NOT RETRACTABLE	FLIGHT EXPERIENCE: NONE	LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA	TWO MODELS BUIL (5 BAYS HIGH) USE LENTICULAR CROS MEMBERS. THE SEC BAYS WHEN EXTEN IS MADE ENTIRELY WORK IS UNDERWA ALUMINUM LAZY T EPOXY COMPOSITE

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

DEPLOYABLE STRUCTURES SURVEYED

	SOURCE	DEVELOPMENT WORK	GENERAL DESIGN COMMENTS	PRODUCIBILITY	GROUN ENVI
	FAIRCHILD HILLER, SPACE AND ELECTRONICS SYSTEMS DIVISION, GERMANTOWN, MD.	A SMALL DEMONSTRATION MODEL HAS BEEN BUILT BY FAIRCHILD HILLER, SPACE AND ELECTRONICS SYSTEMS DIVISION. THIS CONFIGURATION IS AN EXTENSION OF THE PRINCIPLES USED TO DEPLOY THE SOLAR ARRAY IN THE PEGASUS SPACECRAFT.	VERY COMPACT STOWAGE. PRUDENT LATCH DESIGN WILL MAKE THIS A REASONABLY STIFF STRUCTURE. HOWEVER IT WILL INHERIT SOME LESS DESIREABLE STRUCTURAL QUALITIES SUCH AS NOW LINEARITY AND LOW TORSIONAL STIFFNESS. LATCHES MAKE RETRACTION MORE DIFFICULT, LESS RELIABLE. SELF SHADING MAY PRODUCE EXCESSIVE THERMAL BENDING AND MAY INDUCE BINDING IF RETRACTION IS ATTEMPTED. BEAM IS NOT RIGID UNLESS FULLY EXTENDED.	A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. MINIMAL SPECIAL JIGS AND FIXTURES. HINGE AND LATCH BEARING LOADS REQUIRE METALLIC CHARACTERISTICS WHICH WILL REDUCE THE EFFECTIVENESS OF COMPOSITE MATERIALS; HOWEVER, THE USE OF BERYLLIUM AND MAGNESIUM SHOULD BE INVESTIGATED.	CONSTRUCTIC MENT/RETRAC DEGRADATIOI AND LATCHES NESS. MINIM ENVIRONMEN
	LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA FAIRCHILD HILLER, SPACE & ELECTRONICS SYSTEMS DIVISION, GERMANTOWN, MD.	SMALL DEMONSTRATION MODELS HAVE BEEN BUILT BY LOCKHEED AND FAIRCHILD HILLER. LOCKHEED'S MODEL COMPLETED A 90° TURN WHEN DEPLOYED, YET FOLDS COMPACTLY.	VERY COMPACT STOWAGE. BASIC DESIGN PROVIDES GOOD TORSIONAL STIFFNESS. HOWEVER, THE HIGH L/B (SLENDERNESS RATIO) AND THE LOW B/T (LOCAL STIFFNESS) REQUIREMENT MAKE THIS STRUCTURE VERY INEFFICIENT FOR LONG BEAMS. HOLES, AT LEAST ON THE SUN SIDE, ARE PROBABLY REQUIRED TO MINIMIZE TEMPERATURE DIFFERENCES. EFFECT OF NONUNIFORM TEMPERATURES ON ABILITY TO REFOLD WOULD HAVE TO BE EVALUATED. BEAM IS NOT RIGID UNLESS FULLY EXTENDED.	A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. MINIMAL SPECIAL JIGS AND FIXTURES. HINGE AND LATCH BEARING LOADS REQUIRE METALLIC CHARACTERISTICS WHICH WILL REDUCE THE EFFECTIVENESS OF COMPOSITE MATERIALS; HOWEVER, THE USE OF BERYLLIUM AND MAGNESIUM SHOULD BE INVESTIGATED.	SA
	ASTRO RESEARCH CORP., SANTA BARBARA, CALIFORNIA	MANY APPLICATIONS ON EARTH FROM 30 TO 100 FT LONG; BOTH CIVIL AND MILITARY. EXCEPT FOR ONE CASE THE BOOMS ARE MANUALLY ERECTED AND RETRACTED. A DEVELOPMENTAL UNIT OF A 30-FT HIGH, REMOTELY ACTUATED (ERECTING AND RETRACTION) MODEL HAS BEEN DELIVERED TO THE US ARMY. ALUMINUM OR STAINLESS STEEL IS USED FOR THE RIGID MEMBERS AND STAINLESS STELL WIRE ROPE FOR THE TENSION MEMBERS.	COMPACT STOWAGE. THIS BEAM CAN BE MADE AS EFFICIENT AS THE BASIC TRIANGULAR TRUSS, WITH HIGH STIFFNESS TO WEIGHT RATIO. BEAM IS AT FULL STRENGTH AT ALL TIMES DURING DEPLOYMENT. REMOTE (AUTOMATIC) DEPLOYMENT MAY BE MORE COMPLICATED THAN REQUIRED FOR OTHER DEPLOYABLE STRUCTURES. UNIFORM SOLAR ILLUMINATION IS BEST ACHIEVED IN A TRIANGULAR OPEN TRUSS BEAM.	A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. PRODUCTION TOOLING AND TECHNIQUES ARE WELL DEFINED. SOME DEVELOPMENTAL TOOLING REQUIRED FOR THE REMOTE EXTENSION MECHANISM.	CONSTRUCTIC DEPLOYMENT/ DEGRADATIOI FIXTURES REQU LOADS TEST
	ASTRO RESEARCH CORP., SANTA BARBARA, CALIFORNIA	ONE FLIGHT UNIT OF A 10 INCH BY 100 FT MAST WAS DELIVERED TO NASA, HOUSTON FOR USE IN A LUNAR EXPERIMENT AS PART OF THE APOLLO PROGRAM (EXPERIMENT CANCELLED) A 6 INCH BY 13 FOOT COILABLE MAST WILL BE DELIVERED TO GOODYEAR AEROSPACE CORP. AS PART OF A SCALE MODEL OF THE LOFT (LOW FREQUENCY RADIO TELESCOPE)	COMPACT STOWAGE, LINEAR SYSTEM, HIGH STIFFNESS TO MASS RATIO. BEAM IS AT FULL STRENGTH AT ALL TIMES DURING DEPLOYMENT. HOWEVER, THIS BEAM IS LIMITED TO LOW LOAD APPLICATIONS. AS THE LOAD INCREASES, THE REQUIRED DIAMETER OF THE LONGERON INCREASES AND QUICKLY BECOMES TOO STIFF TO COIL IN A REASONABLE STORAGE AREA. LOW TEMPERATURE BENDING CHARACTERISTICS MAY BE A PROBLEM. THE LOW THERMAL CONDUCTIVITY OF FIBERGLASS WILL ACCENTUATE TEMPERATURE NONUNIFORMITY. PLASTIC WILL REQUIRE A PROTECTIVE – THERMAL COATING TO RESIST U.V. ETC. DAMAGE.	A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. PRODUCTION TOOLING AND TECHNIQUES ARE WELL DEFINED. SOME DEVELOPMENTAL TOOLING REQUIRED FOR THE REMOTE EXTENSION MECHANISM.	SA
	LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA	TWO MODELS BUILT, THE FIRST WITH 5-INCH BAYS (5 BAYS HIGH) USED LUFKINS TAPES (SEMI-LENTICULAR CROSS-SECTION) AS THE LONGITUDINAL MEMBERS. THE SECOND MODEL HAS 40-INCH SQUARE BAYS WHEN EXTENDED (3 BAYS OR 10-FEET TALL) AND IS MADE ENTIRELY OF ALUMINUM. DEVELOPMENTAL WORK IS UNDERWAY TO REPLACE SOME OF THE ALUMINUM LAZY TONG MEMBERS WITH A GRAPHITE-EPOXY COMPOSITE.	COMPACT STOWAGE, LINEAR SYSTEM. AN EXCELLENT STIFFNESS TO MASS RATIO IS ACHIEVED WITHOUT THE COMPLICATION OF LATCHES. THE LONGERONS BEND TO STOW BUT THE SECTION TO BE BENT IS FIRST FLATTENED WHICH LOWERS THE STRESSES SIGNIFICIENTLY. HOWEVER, THE BENDING WILL LIMIT THE COLUMN LOADING SOMEWHAT. BROAD LENTICULAR SECTIONS MAY CAUSE MORE SELF SHADING THAN CIRCULAR SECTIONS. THE BEAM IS NOT RIGID UNLESS FULLY EXTENDED. NO REASONABLE RETRACTION SYSTEM HAS BEEN PROPOSED FOR THIS BEAM.	A LARGE NUMBER OF SIMPLE PARTS REQUIRES ONE FORMING DIE FOR THE LENTICULAR SECTIONS AND OTHER MINIMAL TOOLING AND FIXTURES. ASSEMBLED WITH CONVENTIONAL METHODS AND TECHNIQUES. MAY PROVIDE LIMITED APPLICATIONS FOR EXOTIC MATERIALS.	CONSTRUCTIO DEPLOYMENT/ ANCE DEGRAD USED IN FLATT SECTIONS BEF FIXTURES REQU LOADS TEST

FOLDOUT FRAME

3

FOLDOUT F

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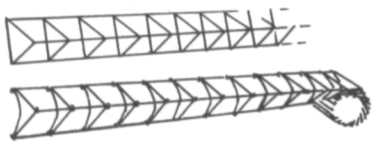
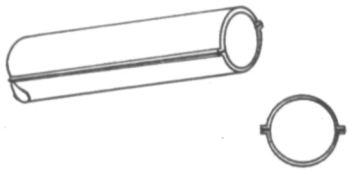
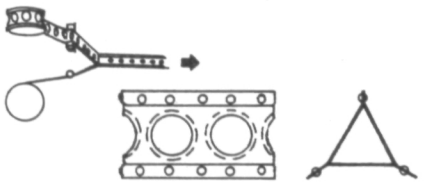
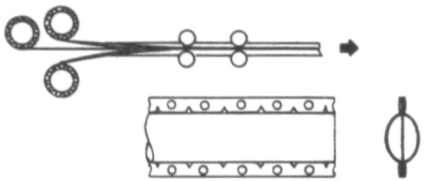
PRODUCIBILITY	TESTING & HANDLING: GROUND DEPLOYMENT DEMO ENVIRONMENTAL TESTING STATIC LOAD TEST	TESTING & HANDLING: INSTALLATION ON SPACECRAFT	BIBLIO AND VENDOR DATA *
A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. MINIMAL SPECIAL JIGS AND FIXTURES. HINGE AND LATCH BEARING LOADS REQUIRE METALLIC CHARACTERISTICS WHICH WILL REDUCE THE EFFECTIVENESS OF COMPOSITE MATERIALS; HOWEVER, THE USE OF BERYLLIUM AND MAGNESIUM SHOULD BE INVESTIGATED.	CONSTRUCTION ALLOWS REPEATED DEPLOYMENT/RETRACTION WITHOUT PERFORMANCE DEGRADATION. HOWEVER, MULTIPLE JOINTS AND LATCHES MAY WEAR CAUSING LOOSENESS. MINIMAL FIXTURES REQUIRED FOR ENVIRONMENTAL AND LOADS TEST.	NO SPECIAL HANDING REQUIRED, STOWS VERY EFFICIENTLY.	*
A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. MINIMAL SPECIAL JIGS AND FIXTURES. HINGE AND LATCH BEARING LOADS REQUIRE METALLIC CHARACTERISTICS WHICH WILL REDUCE THE EFFECTIVENESS OF COMPOSITE MATERIALS; HOWEVER, THE USE OF BERYLLIUM AND MAGNESIUM SHOULD BE INVESTIGATED.	SAME AS NO. 6 (ABOVE)	SAME AS NO. 6 (ABOVE)	*
A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. PRODUCTION TOOLING AND TECHNIQUES ARE WELL DEFINED. SOME DEVELOPMENTAL TOOLING REQUIRED FOR THE REMOTE EXTENSION MECHANISM.	CONSTRUCTION ALLOWS REPEATED DEPLOYMENT/RETRACTION WITHOUT DEGRADATION IN PERFORMANCE. MINIMAL FIXTURES REQUIRED FOR ENVIRONMENT AND LOADS TEST	CYLINDRICAL SECTION REQUIRED TO STOW; APPROXIMATELY 4 IN. LARGER THAN THE BEAM IN DIAMETER AND APPROXIMATELY (2) BAYS LONG. NO SPECIAL HANDLING REQUIRED.	R.2-1, *
A LARGE NUMBER OF IDENTICAL SIMPLE PARTS AND HINGE ASSEMBLIES. PRODUCTION TOOLING AND TECHNIQUES ARE WELL DEFINED. SOME DEVELOPMENTAL TOOLING REQUIRED FOR THE REMOTE EXTENSION MECHANISM.	SAME AS NO. 8 (ABOVE)	SAME AS NO. 8 (ABOVE)	*
A LARGE NUMBER OF SIMPLE PARTS REQUIRES ONE FORMING DIE FOR THE LENTICULAR SECTIONS AND OTHER MINIMAL TOOLING AND FIXTURES. ASSEMBLED WITH CONVENTIONAL METHODS AND TECHNIQUES. MAY PROVIDE LIMITED APPLICATIONS FOR EXOTIC MATERIALS.	CONSTRUCTION ALLOWS REPEATED DEPLOYMENT/RETRACTION WITHOUT PERFORMANCE DEGRADATION, IF REASONABLE CARE IS USED IN FLATTENING THE LENTICULAR SECTIONS BEFORE BENDING. MINIMAL FIXTURES REQUIRED FOR ENVIRONMENT AND LOADS TEST	STOWS IN A LARGE TRIANGULAR AREA. UNTRAINED PERSONNEL COULD DAMAGE THE THIN WALL LENTICULAR SECTIONS.	L.4-6 *

FOLDOUT FRAME 5

FOLDOUT FRAME 4

NO. & NAME OF EXTENDIBLE STRUCTURE	ILLUSTRATION	DESCRIPTION & OPERATION OF STRUCTURE & MECHANISM (RETRACTION CAPABILITIES)	FLIGHT EXPERIENCE	SOURCE	D
11 TRIANGULAR WIRE		SOLID SPRING WIRE CONSTRUCTION. TRIANGULAR SECTIONS WELDED TO LONGERONS. ONE LEG OF THE TRIANGULAR SECTION IS MADE TO FLEX (OR HINGED) SO THAT THE REMAINING 2 SIDES CAN BE BROUGHT TOGETHER. THE FOLDED BEAM CAN THEN BE ROLLED UP ON A REEL. REEL ROTATED BY ELECT. MOTOR & GEAR TRAIN, RETRACTION ACCOMPLISHED BY REVERSING MOTOR. IF RETRACTION IS NOT REQD, SPRING FORCE (OR MOTOR) MAY BE USED FOR EXTENSION.	FLIGHT EXPERIENCE UNKNOWN	MARTIN MARIETTA DENVER, COLO.	SOME DEVELOPMENT EXACT STATUS UNKN
12 LENTICULAR WELDED BEAM		TWO PIECES OF SPRING TAPES ARE PRE-FORMED TO APPROXIMATE A HAT SECTION. THE TWO TAPES ARE WELDED TOGETHER AT THE FLANGES. THE SECTION IS FLATTENED AND ROLLED UP ON A REEL FOR STOWAGE OR CAN BE LOCALLY FLATTENED AND BENT IN A FIRE HOSE FOLD. THE MOTOR DRIVEN REEL WOULD BE RETRACTABLE; THE FIRE HOSE FOLD WOULD NOT BE RETRACTABLE.	FLIGHT EXPERIENCE UNKNOWN	BOEING CO., KENT, WASH ASTRO RESEARCH CORP. SANTA BARBARA, CALIFORNIA	TRADE NAME MAST; D FABRICATED AND TEST A DEVELOPMENTAL M BEEN DELIVERED TO M RYAN AERONAUTICAL THIS BOOM AND MUC BEEN ASSUMED BY THI
13 TRIBEAM (LMSC)		BEAM COMPOSED OF 3 SPRING TAPES WITH EDGE FLANGES CONTAINING VELCRO TAPE AND SNAP FASTENERS. TAPES ROLL-UP ON REELS ARRANGED ABOUT THE BEAM CENTERLINE. REELS ARE INTERCONNECTED & ROTATED BY ELECT. MOTOR & GEAR TRAIN, RETRACTION ACCOMPLISHED BY REVERSING MOTOR.	NO FLIGHT EXPERIENCE	LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA	TWO GENERATIONS C BUILT AND DEMONST BEEN FABRICATED AN THERMAL TESTS.
14 INSTARECT (SANDERS)		3 PIECE BEAM, TWO OUTER PRE-FORMED SPRING TAPES ARE FLATTENED & ROLLED-UP ON REELS. THE CENTER (FLAT) SPRING TAPE WITH EDGE INDEX HOLES & SLOTS IS ALSO STORED ON A REEL. THE EDGES OF THE 3 TAPES INTERLOCK AS THE BEAM EXTENDS. REELS ARE INTERCONNECTED & ROTATED BY AN ELECT. MOTOR & GEAR TRAIN. RETRACTION ACCOMPLISHED BY REVERSING MOTOR.	FLIGHT EXPERIENCE UNKNOWN	SANDERS ASSOCIATES INC. NOSHAU, N.H.	TWO GENERATIONS C BUILT, TESTED AND D HARD 302 STAINLESS S 3 BY 4 INCHES CROSS
15 INTERLOCKING EXTENDIBLE REEL STORED		2 PIECES OF PRE-FORMED SPRING TAPES ARE FLATTENED & ROLLED-UP ON REELS. THE EDGES OF THE TAPES INTERLOCK AS THE BEAM EXTENDS. REELS ARE INTERCONNECTED & ROTATED BY AN ELECT. MOTOR & GEAR TRAIN. RETRACTION ACCOMPLISHED BY REVERSING MOTOR.	SIX UNITS (60 TO 120 FT LONG) WERE FLOWN ON NRL GRADIENT EXPERIMENT SATELLITES. FOUR (750 FT LONG) EDGELOCK TEES WERE USED ON RAE, 38 FT LONG HINGELOCK USED ON OGO AND FRENCH SATELLITE FR-2 EDLE.	SPAR AEROSPACE PRODUCTS LTD. ONTARIO, CANADA FAIRCHILD HILLER, GERMANTOWN, MD.	TRADE NAME INTERLC COMPLETED AND DEM AND LARGER DIA MO TRADE NAMES, EDGE INCH DIA MODEL CO TWO INCH MODEL IN COMPLETED FOR NAS CONDUCTORS.

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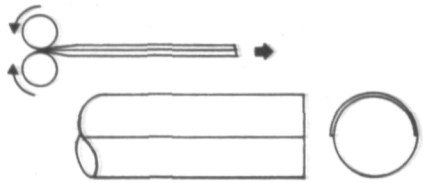
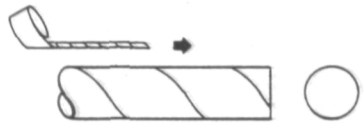
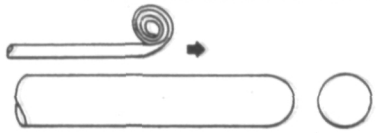
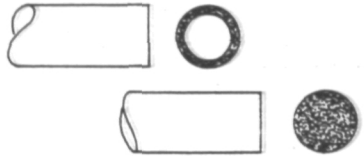
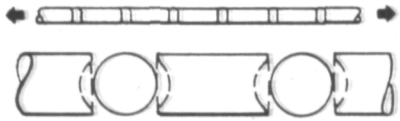
FOLDOUT FRAME 1

FOLDOUT FRAME 2

DEPLOYABLE STRUCTURES SURVEYED

	SOURCE	DEVELOPMENT WORK	GENERAL DESIGN COMMENTS	PRODUCIBILITY	GROUN ENVIR S
	MARTIN MARIETTA DENVER, COLO.	SOME DEVELOPMENT WORK DONE, EXACT STATUS UNKNOWN	REQUIRES DIAGONAL MEMBERS TO ACHIEVE REASONABLE TORSIONAL STIFFNESS. BENDING STRESSES IN LONGERONS DURING STOWAGE WILL LIMIT THEIR SIZE AND CONSEQUENT COLUMN LOADING CAPACITY. ANY THERMAL CONTROL SURFACES MUST RESIST ROLLING ABRASION AND FLEXING; HOWEVER, THIS IS AN EXCELLENT DESIGN TO MINIMIZE THERMAL DEFLECTIONS. MINIMUM DEPLOYMENT/RETRACTION PROBLEMS ARE ANTICIPATED. LINEAR DYNAMIC SYSTEM, FULL-BEAM STRENGTH COULD BE DEVELOPED AS THE BEAM EXTENDS. VERY COMPACT STOWAGE.	A LARGE NUMBER OF SIMPLE PARTS, MINIMAL JIGS AND FIXTURES. CONVENTIONAL FASTENING METHODS.	CONSTRUCTION DEPLOYMENT/RE PERFORMANCE D
	BOEING CO., KENT, WASH ASTRO RESEARCH CORP. SANTA BARBARA, CALIFORNIA	TRADE NAME MAST; DEVELOPMENTAL MODEL 20-FT LONG; FABRICATED AND TESTED BY BOEING. A DEVELOPMENTAL MODEL (20-FT LONG 2.3 IN. DIA) HAS BEEN DELIVERED TO MARTIN MARIETTA FOR EVALUATION. RYAN AERONAUTICAL CO. NO LONGER MANUFACTURES THIS BOOM AND MUCH OF THE RYAN TECHNOLOGY HAS BEEN ASSUMED BY THE ASTRO RESEARCH CORP.	LINEAR DYNAMIC SYSTEM, VERY COMPACT STOWAGE, BOOM, DEVELOPS FULL STRENGTH AS IT IS DEPLOYED. THIS BEAM IS GOOD FOR MEDIUM LENGTH APPLICATIONS (LESS THAN 50 FT). AS LENGTH INCREASES THE BEAM BECOMES INEFFICIENT FOR COLUMN LOADS. THE MOMENT OF INERTIA OF THE BEAM SECTION MAY BE INCREASED IN ONE DIRECTION WITH VERY LITTLE EFFECT ON STOWAGE VOLUME OR STRESSES. WELDED JOINTS SIMPLIFY THERMAL ANALYSIS. HOLE PATTERN PROBABLY REQUIRED, THERMAL COATINGS MUST WITHSTAND ROLLING ABRASION. THIS AND SIMILAR BEAMS COULD HAVE A THERMAL COMPENSATING CURVE BUILT IN.	FABRICATION AND ASSEMBLY TECHNIQUES WELL DEFINED. CONSTANT SECTION FACILITATES FORMING AND WELDING. TITANIUM HAS BEEN USED FOR DEMONSTRATION UNITS.	SAME
	LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA	TWO GENERATIONS OF ENGINEERING MODELS HAVE BEEN BUILT AND DEMONSTRATED. SEVERAL BEAM SECTIONS HAVE BEEN FABRICATED AND SUBJECTED TO STRUCTURAL AND THERMAL TESTS.	HIGH DYNAMIC DAMPING, FAIRLY COMPACT STOWAGE. FOR MEDIUM LENGTH THIS IS A GOOD SELECTION. AS THE LENGTH APPROACHES 50 FT THE TRIBEAM BECOMES INEFFICIENT FOR SIGNIFICANT COLUMN LOADS. REQUIRES HOLES TO MINIMIZE THERMAL DEFLECTION. INSIDE AND OUTSIDE REQUIRE ROLLING ABRASION RESISTANT THERMAL COATINGS. POOR THERMAL CONDUCTION THROUGH THE VELCRO TAPES SHOULD CAUSE NO MAJOR PROBLEMS, IF ADEQUATE HOLE PATTERN IS USED, ESPECIALLY WHEN USED WITH A CONSTANT SUN ANGLE.	FABRICATION AND ASSEMBLY TECHNIQUES WELL DEFINED. REQUIRES SIMPLE PROGRESSIVE PUNCH PRESS DIES FOR QUALITY PARTS. CONSTANT SECTION FACILITATES FORMING. CONVENTIONAL ASSEMBLY TECHNIQUES.	SAME
	SANDERS ASSOCIATES INC. NOSHAU, N.H.	TWO GENERATIONS OF ENGINEERING MODELS HAVE BEEN BUILT, TESTED AND DEMONSTRATED. BEAM MATERIAL FULL HARD 302 STAINLESS STEEL, 40 FT LONG BY APPROX. 3 BY 4 INCHES CROSS SECTION.	LINEAR DYNAMIC SYSTEM, FAIRLY COMPACT STOWAGE. AGAIN A MEDIUM-LENGTH BEAM CANDIDATE. HIGH R/T RATIOS IN THE CURVED SHEETS AND HIGH B/T RATIO ON FLAT SHEET LIMIT THE COLUMN LOAD CAPACITY. NOT LIKELY EFFICIENT IN LENGTHS GREATER THAN 50 FT. THE BEAM MOMENT OF INERTIA CAN BE INCREASED IN ONE DIRECTION WITH LITTLE EFFECT ON STOWAGE VOLUME OR STRESSES. SUBJECT TO LARGE THERMAL DEFLECTIONS IF CENTER IS SOLID. TEMPERATURE GRADIENTS DIFFICULT TO PREDICT BECAUSE OF UNCERTAINTY IN EDGE CONTACTS AND COMPLEX INNER STRUCTURE. HOLES MAY BE REQUIRED IN ALL THREE TAPES.	FABRICATION AND ASSEMBLY TECHNIQUES WELL DEFINED. REQUIRES SIMPLE PROGRESSIVE PUNCH PRESS DIES FOR QUALITY PARTS. CONSTANT SECTION FACILITATES FORMING. CONVENTIONAL ASSEMBLY TECHNIQUES.	CONSTRUCTION DEPLOYMENT/RE PERFORMANCE D TURES REQD FOR
OWN ITES. ERE USED EDLE.	SPAR AEROSPACE PRODUCTS LTD. ONTARIO, CANADA FAIRCHILD HILLER, GERMANTOWN, MD.	TRADE NAME INTERLOCKED BI STEM. TWO INCH DIA MODEL COMPLETED AND DEMONSTRATED. STUDIES IN MATERIAL AND LARGER DIA MODELS. TRADE NAMES, EDGELOCK AND HINGELOCK TEE. A SIX INCH DIA MODEL COMPLETED AND DEMONSTRATED. A TWO INCH MODEL IN NON-MAGNETIC STAINLESS STEEL COMPLETED FOR NASA, GODDARD CONTAINS 22 CONDUCTORS.	LINEAR DYNAMIC SYSTEM, VERY COMPACT STOWAGE. THIS BEAM (CONSIDERED AS A SOLID TUBE) IS GOOD FOR SHORT TO MEDIUM LENGTH APPLICATIONS (LESS THAN 50 FT). AS LENGTH INCREASES THE BEAM BECOMES INEFFICIENT FOR COLUMN LOADS. TEMPERATURE PREDICTION UNCERTAINTY IS INCREASED IF THE SUN DOES NOT SHINE SYMMETRICALLY ON THE INTERLOCKING LINE. HOLE PATTERN MAY BE REQUIRED TO OBTAIN REASONABLE THERMAL DEFLECTIONS. ROLL ABRASION RESISTANT THERMAL COATINGS ARE REQUIRED.	FABRICATION AND ASSEMBLY TECHNIQUES WELL DEFINED. REQUIRES SIMPLE PROGRESSIVE PUNCH PRESS DIES FOR QUALITY PARTS. CONSTANT SECTION FACILITATES FORMING. CONVENTIONAL ASSEMBLY TECHNIQUES.	SAME

PRODUCIBILITY	TESTING & HANDLING		BIBLIO AND VENDOR DATA *
	GROUND DEPLOYMENT DEMO ENVIRONMENTAL TESTING STATIC LOAD TEST	INSTALLATION ON SPACECRAFT	
A LARGE NUMBER OF SIMPLE PARTS, MINIMAL JIGS AND FIXTURES. CONVENTIONAL FASTENING METHODS.	CONSTRUCTION ALLOWS REPEATED DEPLOYMENT/RETRACTION WITHOUT PERFORMANCE DEGRADATION.	STORES ON A REEL WITH THE OUTBOARD END EXPOSED. THE EXPOSED SECTION SHOULD BE PROTECTED FROM UNTRAINED PERSONNEL.	NONE
FABRICATION AND ASSEMBLY TECHNIQUES WELL DEFINED. CONSTANT SECTION FACILITATES FORMING AND WELDING. TITANIUM HAS BEEN USED FOR DEMONSTRATION UNITS.	SAME AS NO. 11 (ABOVE)	SAME AS NO. 11 (ABOVE)	T.3-1, L.4-5, L.4-6, B.3-24, & * T.3-1, L.4-5, L.4-6, R.4-5, *
FABRICATION AND ASSEMBLY TECHNIQUES WELL DEFINED. REQUIRES SIMPLE PROGRESSIVE PUNCH PRESS DIES FOR QUALITY PARTS. CONSTANT SECTION FACILITATES FORMING. CONVENTIONAL ASSEMBLY TECHNIQUES.	SAME AS NO. 11 (ABOVE)	SAME AS NO. 11 (ABOVE)	T.3-1, L.4-5, L.4-7, L.4-23, L.4-24, *
FABRICATION AND ASSEMBLY TECHNIQUES WELL DEFINED. REQUIRES SIMPLE PROGRESSIVE PUNCH PRESS DIES FOR QUALITY PARTS. CONSTANT SECTION FACILITATES FORMING. CONVENTIONAL ASSEMBLY TECHNIQUES.	CONSTRUCTION ALLOWS REPEATED DEPLOYMENT/RETRACTION WITH MINIMUM PERFORMANCE DEGRADATION. MINIMAL FIXTURES REQD FOR ENVIRON AND LOADS TESTS.	STORES ON A REEL WITH THE OUTBOARD END EXPOSED. THE EXPOSED SECTION SHOULD BE PROTECTED FROM UNTRAINED PERSONNEL.	
FABRICATION AND ASSEMBLY TECHNIQUES WELL DEFINED. REQUIRES SIMPLE PROGRESSIVE PUNCH PRESS DIES FOR QUALITY PARTS. CONSTANT SECTION FACILITATES FORMING. CONVENTIONAL ASSEMBLY TECHNIQUES.	SAME AS NO. 14 (ABOVE)	SAME AS NO. 14 (ABOVE)	L.4-5, * L.4-5, F.1-10, *

NO. & NAME OF EXTENDIBLE STRUCTURE	ILLUSTRATION	DESCRIPTION & OPERATION OF STRUCTURE & MECHANISM (RETRACTION CAPABILITIES)	FLIGHT EXPERIENCE	SOURCE	
16 EXTENDIBLE REEL STORED		PRE-FORMED SPRING TAPE (OR TAPES) ARE FLATTENED AND ROLLED UP ON A REEL FOR STOWAGE. THESE ARE THE SIMPLEST OF THE REEL STORED BEAMS. THE REEL IS ROTATED BY AN ELECT. MOTOR & GEAR TRAIN. RETRACTION IS ACCOMPLISHED BY REVERSING MOTOR.	USED AS ANTENNA, GRAVITY GRADIENT BOOMS, ACTUATORS, ETC. APOLLO, ATS, DODGE, MARINER AND MANY MORE SPACECRAFT APPLICATIONS. USED AS ANTENNAS, GRAVITY GRADIENT BOOMS ETC. ON RAE, OGO, NIMBUS & OTHERS. UNKNOWN. UNKNOWN. UNKNOWN.	SPAR AEROSPACE PRODUCTS LTD. ONTARIO, CANADA FAIRCHILD HILLER GERMANTOWN, MD. GENERAL ELECTRIC CORP. MSD, VALLEY FORGE, PA. GENERAL DYNAMICS/CONVAIR DIV., SAN DIEGO, CA WESTINGHOUSE DEFENSE & SPACE CENTER, AEROSPACE DIV. BALTIMORE, MD.	TRADE NAME STEM, EXTENDIBLE MEMBEI IS STOWED BY COIL "JACK-IN-THE-BOX TRADE NAME TEE (T MODEL WITH A CRC FABRICATED AND D TRADE NAME MOLY TRADE NAME SCREE
17 SPRING HELIX		TUBE IS FORMED BY A HELICALLY PRE-STRESSED SPRING TAPE WHOSE OVERLAPPING COILS FORM A RIGID TUBE WHEN EXTENDED. MAY BE SELF-EXTENDING OR MOTOR DRIVEN. THE MOTOR DRIVE CONTROLS DEPLOYMENT SPEED AND PERMITS REMOTE RETRACTION.	USED TO ERECT FOIL SUNSHIELD OF CENTRAL CONTROL STATION ON APOLLO LUNAR SURFACE EXPERIMENTS PACKAGE.	AMETEK/HUNTER SPRING CO. HATFIELD PA.	TRADE NAME STACE USED TO EXTEND A APPROX. 9 FT.
18 INFLATABLES		GAS TIGHT TUBES (MYLAR, FOIL, MYLAR) ARE FLATTENED AND FOLDED FOR STORAGE; AN EXTERNAL GAS SUPPLY INFLATES AND ERECTS (AND REMOVES THE WRINKLES) THE TUBES. THE ALUM. FOIL SANDWICHED IN MYLAR THEN IS A THIN-WALLED TUBE AND LENDS ITSELF TO ANALYSIS. GAS PRESSURE IS RELIEVED WHEN THE SYSTEM REACHES EQUILIBRIUM. MAY BE USED AS A MULTIPLE-TUBE SYSTEM STIFFENED BY SPACERS AND GUY WIRES. ARE USUALLY NOT RETRACTABLE.	SEVERAL LOOP ANTENNAS, 6 TO 9 FT DIA, WERE FLOWN ON THE OGO SERIES (STANFORD UNIVERSITY EXPERIMENTS). ALL WERE SINGLE TUBES 1 TO 2 IN. DIA. A MECHANISM CONTAINING A COLUMN OF MULTIPLE TUBES 10 FT LONG WAS SUCCESSFULLY DEMONSTRATED ON CLASSIFIED MISSIONS.	LOCKHEED M.S.C. SUNNYVALE, CALIFORNIA	
19 RIGIDIZED INFLATABLES		TWO SYSTEMS ARE SHOWN: (A) A SOLID CORE OF RIGID FOAM IS FORMED INSIDE A FABRIC FORM WHILE RESTRAINED BY A DIE. THE PRESSURE OF THE FOAM FEEDS IN THE FABRIC FORM AS THE RIGID FOAM IS FORCED OUT THE OPPOSITE END; (B) PRE-TREATED GELATINE-GLASS FIBER LAMINATED TUBES MADE FLEXIBLE WITH A SOFTENING AGENT. THE TUBES ARE GAS-INFLATED IN SPACE AND THE SOFTENING AGENT EVAPORATES, LEAVING THE TUBES STIFF. COMPLETE RIGIDITY IS ACHIEVED IN 10 TO 20 HOURS. IS NOT RETRACTABLE.	FLIGHT EXPERIENCE UNKNOWN FLIGHT EXPERIENCE UNKNOWN FLIGHT EXPERIENCE UNKNOWN	GOODYEAR AEROSPACE CORP. AKRON, OHIO LOCKHEED M.S.C. SUNNYVALE, CALIFORNIA MESSERSCHMITT-BOLKOW-BLOHM GMBH, MUNICH, GERMANY	DEVELOPED A SERIE FOR AERO PROPULS DIZED BY EXPOSIN INFLATING SYSTEM DEVELOPED FOR N IMPREGNATED FIBE OF HEAT OR VACU DEVELOPED A RIGI SOLAR ARRAY. US SYSTEM EVAPORAT
20 FLEXIBLE TETHER		CYLINDRICAL SECTIONS WITH SPHERICAL SEATS ON EACH END, ALTERNATE WITH BALLS; ENTIRE ASSEMBLY HAS CENTER HOLE TO ACCEPT FLEXIBLE TENSION MEMBER. THE TENSION MEMBER IS FIXED TO ONE END; TENSION REACTED AGAINST THE OPPOSITE END CAUSES THE LOOSE PARTS TO ALIGN AND FORM A STRAIGHT COLUMN (THE SHORTEST LENGTH OF CABLE).	FLIGHT EXPERIENCE UNKNOWN FLIGHT EXPERIENCE UNKNOWN	GENERAL ELECTRIC MSD VALLEY FORGE, PA. ILLINOIS INSTITUTE OF TECHNOLOGY, MECHANICAL ENGINEERING DIV. CHICAGO, ILL.	WORKING MODELS GROUND AND UNI PROBLEMS. DEVELOPED A COLI PRINCIPLE.

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

DEPLOYABLE STRUCTURES SURVEYED

SOURCE	DEVELOPMENT WORK	GENERAL DESIGN COMMENTS	PRODUCIBILITY	GROUND DEPLO ENVIRONMENT STATIC LO
SPAR AEROSPACE PRODUCTS LTD. ONTARIO, CANADA FAIRCHILD HILLER GERMANTOWN, MD. GENERAL ELECTRIC CORP. MSD, VALLEY FORGE, PA. GENERAL DYNAMICS/CONVAIR DIV., SAN DIEGO, CA WESTINGHOUSE DEFENSE & SPACE CENTER, AEROSPACE DIV. BALTIMORE, MD.	TRADE NAME STEM AND BI STEM (STORABLE TUBULAR EXTENDIBLE MEMBER). SELF-ERECTING MODEL THAT IS STOWED BY COILING INSIDE A CYLINDER IS CALLED "JACK-IN-THE-BOX". TRADE NAME TEE (TUBULAR EXTENDIBLE ELEMENTS) A DOUBLE MODEL WITH A CROSS-SECTION RESEMBLING THE FIGURE 8 FABRICATED AND DEMONSTRATED. TRADE NAME MOLY ROD TRADE NAME SCREEN BOOM	LINEAR DYNAMIC SYSTEM, VERY COMPACT STOWAGE, LOW TORSIONAL STIFFNESS. AS ABOVE, INEFFICIENT IN LONGER LENGTHS. TEMPERATURE PREDICTION IS MORE DIFFICULT BECAUSE THE JOINT THERMAL CONDUCTANCE IS UNLIKELY TO BE REPEATABLE. HOLE PATTERN MAY BE REQUIRED TO OBTAIN REASONABLE THERMAL DEFLECTIONS. ROLL ABRASION RESISTANT THERMAL COATINGS REQUIRED.	FABRICATION AND ASSEMBLY REQUIREMENTS WELL DEFINED. CONSTANT SECTION FACILITATES FORMING. CONVENTIONAL ASSEMBLY TECHNIQUES.	CONSTRUCTION ALLOV DEPLOYMENT/RETRACT PERFORMANCE DEGRAI
AMETEK/HUNTER SPRING CO. HATFIELD PA.	TRADE NAME STACER, TWIN MOTOR-DRIVEN STACERS WERE USED TO EXTEND A NASA EXPERIMENTAL SOLAR ARRAY APPROX. 9 FT.	VERY COMPACT STOWAGE, VERY LOW AXIAL AND TORSIONAL STIFFNESS. COLUMN LOAD CAPACITY, LATERAL AND TORSIONAL STIFFNESS DEPEND ON FRICTIONAL FORCES EXISTING BETWEEN OVERLAPPING LAYERS. NO RELIABLE METHOD OF ANALYSIS HAS BEEN ESTABLISHED. STIFFNESS WILL BE DERIVED MAINLY BY TESTS. ROLL ABRASION-RESISTANT THERMAL COATINGS REQUIRED. MATERIAL CONTINUITY AND THE RESULTING SPIRAL THERMAL CONDUCTANCE PROBABLY RESULTS IN LOWER THERMAL DEFLECTIONS THAN A NON CONTINUOUS TUBE SECTION.	MINIMUM SPECIAL TOOLING REQUIRED. CONVENTIONAL ASSEMBLY TECHNIQUES.	SAME AS NO. 1
LOCKHEED M.S.C. SUNNYVALE, CALIFORNIA		HIGH DAMPING; PROBABLY A NON-LINEAR SYSTEM; VERY COMPACT STOWAGE. STRENGTH AND STIFFNESS VARY GREATLY AS THE STRUCTURE IS FOLDED MORE OR LESS, I.E., THE WRINKLED CONDITION OF THE FOIL. EMPIRICAL RESOLUTION MUST BE USED TO ESTABLISH FOLDING TECHNIQUES AND LIMITS. MYLAR DEGRADES WHEN EXPOSED TO U.V., SO A PROTECTIVE COATING MUST BE USED. LARGE FRONT-TO-BACK TEMP. GRADIENTS ARE LIKELY, PARTICULARLY IF MULTIPLE TUBE SYSTEM IS USED. ADHESION OF THERMAL CONTROL SURFACE TO THE MYLAR MAY BE DIFFICULT TO ACHIEVE.	MINIMUM TOOLING REQUIRED; HOWEVER, A GREAT AMOUNT OF HAND CRAFTSMANSHIP IS REQUIRED.	PERFORMANCE DEGRADES EACH DEPLOYMENT/RETRA HANDLING AND PRUDENT TESTING.
GOODYEAR AEROSPACE CORP. AKRON, OHIO LOCKHEED M.S.C. SUNNYVALE, CALIFORNIA MESSERSCHMITT-BOLKOW-BLOHM GMBH, MUNICH, GERMANY	DEVELOPED A SERIES OF INFLATABLE RIGIDIZED STRUCTURES FOR AERO PROPULSION LAB. USING DACRON FABRIC RIGIDIZED BY EXPOSING A URETHANE RESIN TO MOISTURE IN THE INFLATING SYSTEM. DEVELOPED FOR NASA AN ORBITAL ESCAPE DEVICE USING IMPREGNATED FIBERGLASS THAT HARDENED BY APPLICATION OF HEAT OR VACUUM. DEVELOPED A RIGIDIZED STRUCTURE TO SUPPORT A 215 SQ FT SOLAR ARRAY. USES GELETINE-GLASS TUBES AND INFLATION SYSTEM EVAPORATES THE SOFTENING AGENT.	HIGH DAMPING, LINEAR SYSTEM, CONVENIENT STOWAGE SYSTEM. FOAM MATERIALS HAVE A VERY LOW YOUNG'S MODULUS. TO MAKE UP THAT DEFICIENCY, A LARGE AMOUNT OF FOAM MUST BE PROVIDED, THEREIN DEFEATING THE ADVANTAGE OF USING A LOW DENSITY MATERIAL. LARGE FRONT-TO-BACK THERMAL GRADIENTS ARE LIKELY. THERMAL CONTROL SURFACE APPLICATION MAY BE A PROBLEM.	MINIMUM TOOLING REQUIRED; HOWEVER, A GREAT AMOUNT OF HAND CRAFTSMANSHIP IS REQUIRED.	NOT RETRACTABLE; DEPLO BE MADE ON FLIGHT HARI TESTS AND OTHER QUALIT MUST BE USED.
GENERAL ELECTRIC MSD VALLEY FORGE, PA. ILLINOIS INSTITUTE OF TECHNOLOGY, MECHANICAL ENGINEERING DIV. CHICAGO, ILL.	WORKING MODELS HAVE BEEN DEMONSTRATED ON THE GROUND AND UNDER WATER WITHOUT ANY REPORTED PROBLEMS. DEVELOPED A COLLAPSIBLE CANE THAT WORKS ON THIS PRINCIPLE.	POOR STORAGE CHARACTERISTICS (THE STOWED VOLUME IS EQUAL TO THE EXTENDED VOLUME). THE TETHER REQUIRES THE CONCENTRATION OF MASS TO BE NEAR THE CENTER OF THE BEAM, RESULTING IN A POOR STRUCTURE FOR STIFFNESS. THERMAL DEFLECTIONS ARE DEPENDENT UPON MATERIAL AND THICKNESS OF STRUCTURE.	DEPENDENT UPON DETAIL DESIGN; COULD EITHER BE VERY EASY OR NEARLY IMPOSSIBLE TO FABRICATE.	REPEATED DEPLOYMENTS CRACK THE WHIP IF ACTU

FOLDOUT FRAME 2

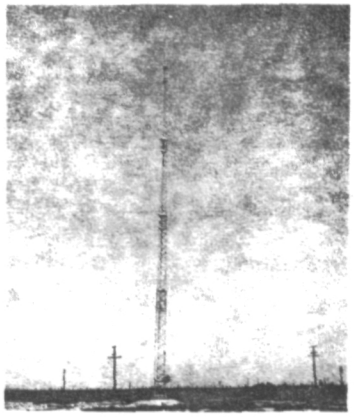
FOLDOUT FRAME 3

FOLDOUT FRAME 4

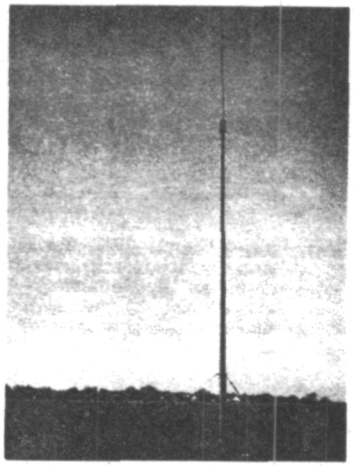
PRODUCIBILITY	TESTING & HANDLING		BIBLIO AND VENDOR DATA *
	GROUND DEPLOYMENT DEMO ENVIRONMENTAL TESTING STATIC LOAD TEST	INSTALLATION ON SPACECRAFT	
ABRICATION AND ASSEMBLY REQUIREMENTS 'ELL DEFINED. CONSTANT SECTION ACILITATES FORMING. CONVENTIONAL SSEMBLY TECHNIQUES.	CONSTRUCTION ALLOWS REPEATED DEPLOYMENT/RETRACTION WITHOUT PERFORMANCE DEGRADATION	STORES ON A REEL WITH THE OUTBOARD END EXPOSED. THE EXPOSED SECTION SHOULD BE PROTECTED FROM UNTRAINED PERSONNEL	L.4-5, J.2-6, N.2-14, S.4-1, P.2-2, J.2-3, A.6-1, & * L.4-5, N.2-14, P.2-2, J.2-3, A.6-1, F.1-10, * L.4-5, N.2-14, J.2-3, A.6-1 L.4-5, N.2-14, J.2-3, A.6-1 L.4-5, N.2-14, W.2-9, J.2-3, W.2-4, A.6-1
INIMUM SPECIAL TOOLING REQUIRED. ONVENTIONAL ASSEMBLY TECHNIQUES.	SAME AS NO. 16 (ABOVE)	SAME AS NO. 16 (ABOVE)	
INIMUM TOOLING REQUIRED; HOWEVER, GREAT AMOUNT OF HAND CRAFTSMANSHIP REQUIRED.	PERFORMANCE DEGRADES NOTICEABLY WITH EACH DEPLOYMENT/RETRACTION. CAREFUL HANDLING AND PRUDENT FIXTURES REQD FOR TESTING.	STORES WELL; MUST HAVE A GAS SUPPLY. VERY DELICATE; MUST BE PROTECTED FROM UNTRAINED PERSONNEL.	L.4-26
INIMUM TOOLING REQUIRED; HOWEVER, GREAT AMOUNT OF HAND CRAFTSMANSHIP REQUIRED.	NOT RETRACTABLE; DEPLOYMENT TESTS CAN NOT BE MADE ON FLIGHT HARDWARE. DEVELOPMENT TESTS AND OTHER QUALITY ASSURANCE TESTING MUST BE USED.	STORES WELL, BUT DOES REQUIRE ATTENDING PRESSURIZED CONTAINERS.	G.3-1 M.3-1
EPENDENT UPON DETAIL DESIGN; COULD THER BE VERY EASY OR NEARLY IMPOSSIBLE D FABRICATE.	REPEATED DEPLOYMENTS CAN BE MADE; MAY CRACK THE WHIP IF ACTUATED RAPIDLY.	EXTENSIVE DEVELOPMENT WORK REQUIRED TO OPTIMIZE PACKAGING/DEPLOYMENT TECHNIQUES.	NONE

FOLDOUT FRAME 4

FOLDOUT FRAME 5



1 – Telescoping Triangular Truss Tower Capable of Extending 70 Feet (Tri-Ex Tower Corp., Visalia, Calif.)



2A – Telescoping Cylinders Mast Capable of Extending 30 Feet (Sanders Associates, Inc., Nashua, New Hampshire)

2B – Telescoping Cylinders Sky Needle Tower (70 Feet) (Tri-(Tri-Ex Corp., Visalia, California)

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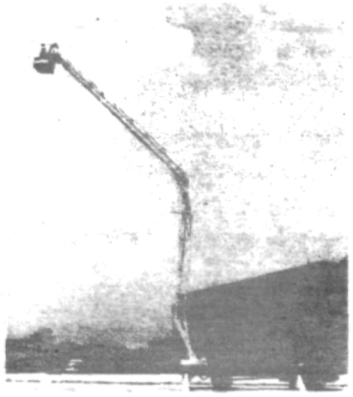
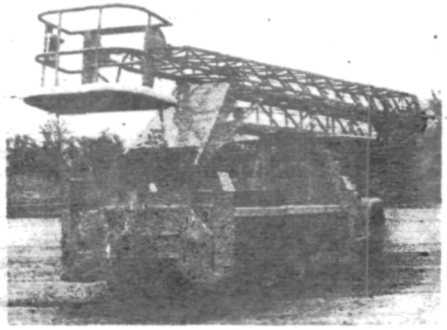
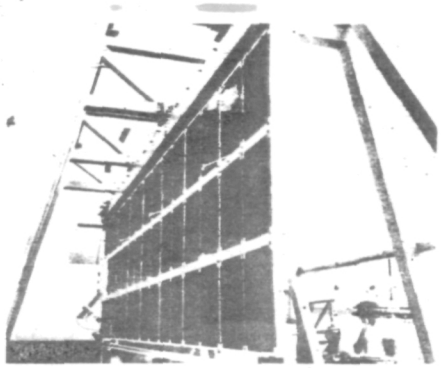


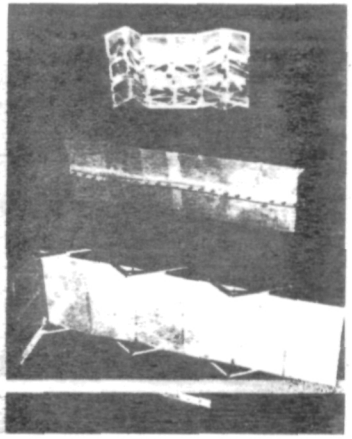
3A – Folding Beam, Mobile Aerial Tower Application, Heights up to 130 Feet (Mobile Aerial Towers, Inc., Fort Wayne, Indiana)



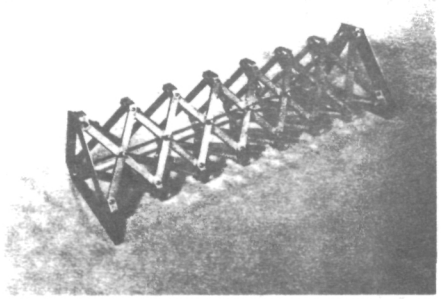
3B – Folding Beam (Mobile Aerial Towers, Inc., Fort Wayne, Indiana)



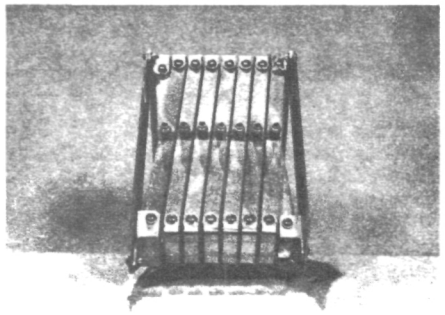
4 – Lazy Tong Model, Extends 20 Feet (Lockheed Missiles & Space Company, Sunnyvale, Calif.)



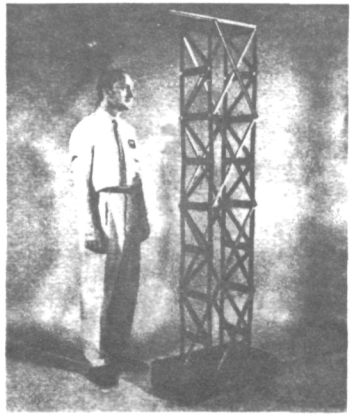
4A – Two-Foot Model of Lazy Tong, Plus a Small Model of Box Beam (No. 7) (Fairchild-Hiller, Germantown, Md.)



5A – Tri-Axis Lazy Tong (Deployed) (Lockheed Missiles & Space Company, Sunnyvale, Calif.)

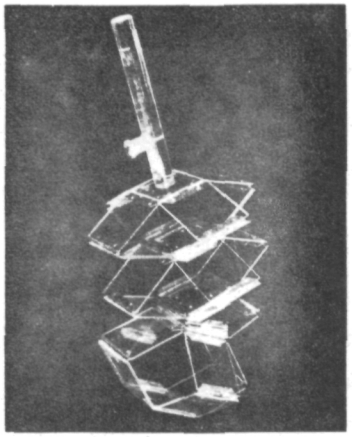


5B – Tri-Axis Lazy Tong (Stowed) (Lockheed Missiles & Space Company, Sunnyvale, Calif.)

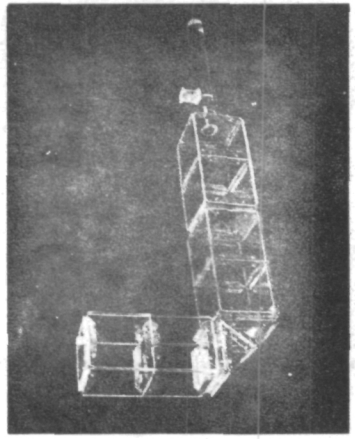


6 – Eight-Foot Model of Extensible Truss Beam (Fairchild-Hiller, Germantown, Md.)

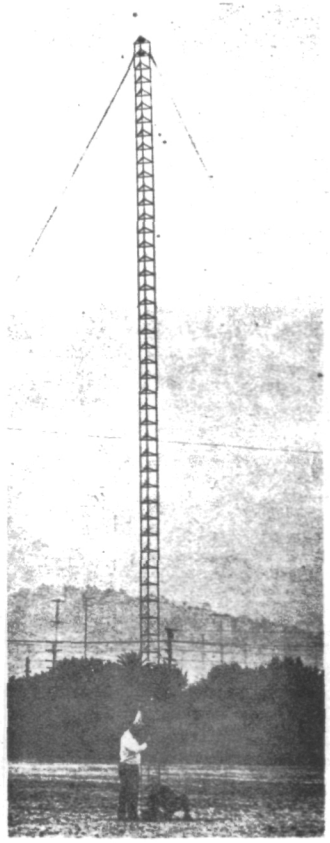
6A – Fully Retracted Eight-Foot Model of Extensible Truss Beam (Fairchild-Hiller, Germantown, Md.)

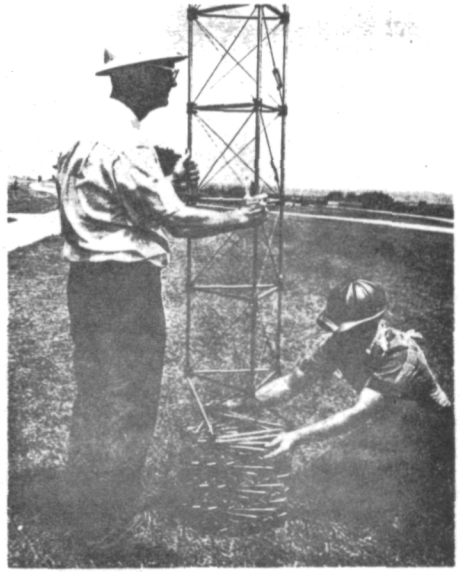


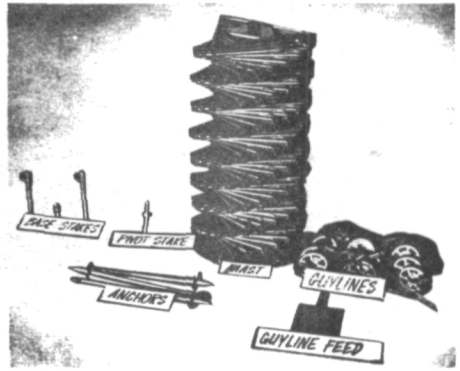
7A – Bellows (Jack-In-The-Box) Model Extends Two Feet (Lockheed Missiles & Space Company, Sunnyvale, Calif.)



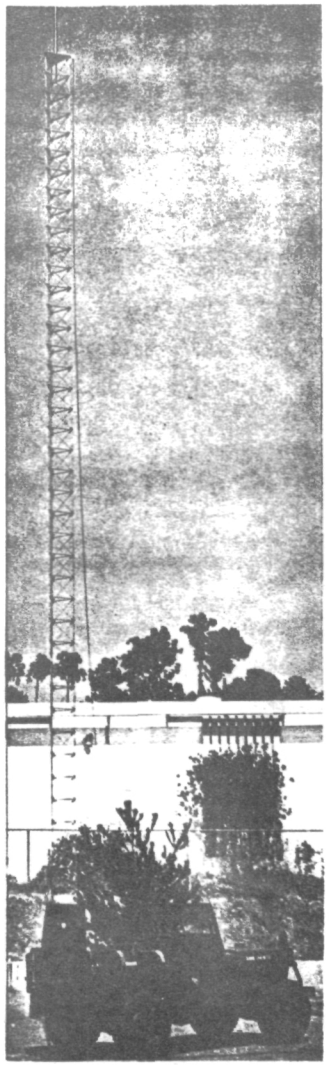
7B – Bellows (Jack-In-The-Box) (Lockheed Missiles & Space Company, Calif.)

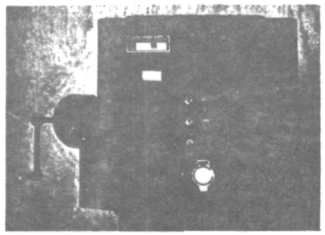


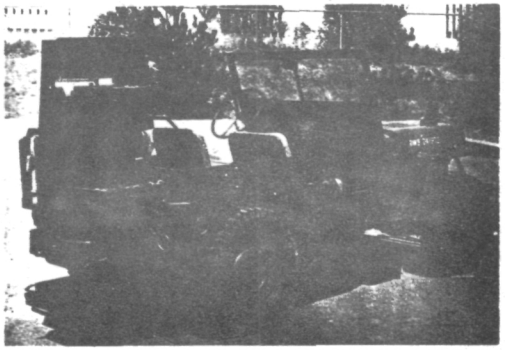




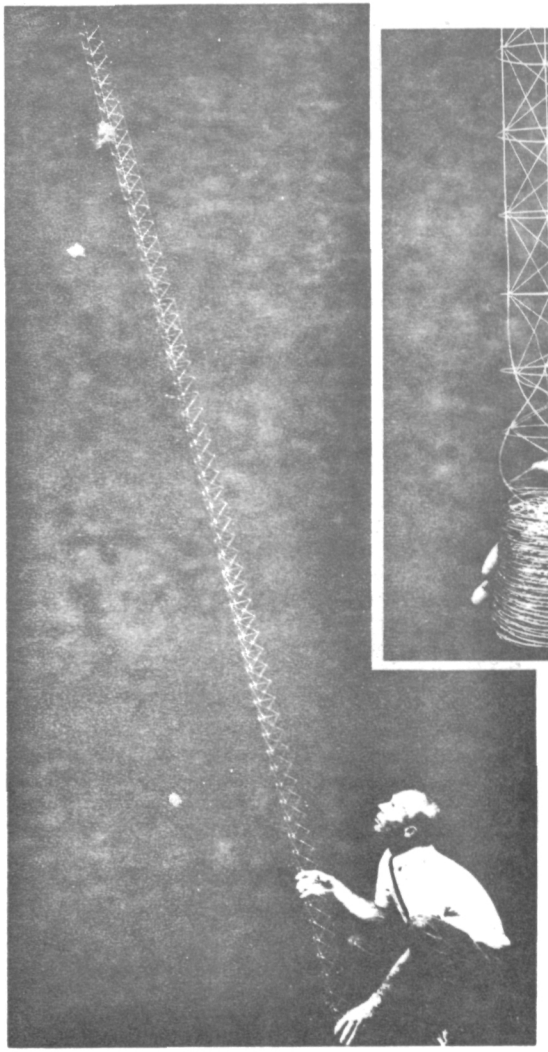
8A – Astromast Articulated Lattice (Series A15000) (Astro Research Corporation, Santa Barbara, Calif.)

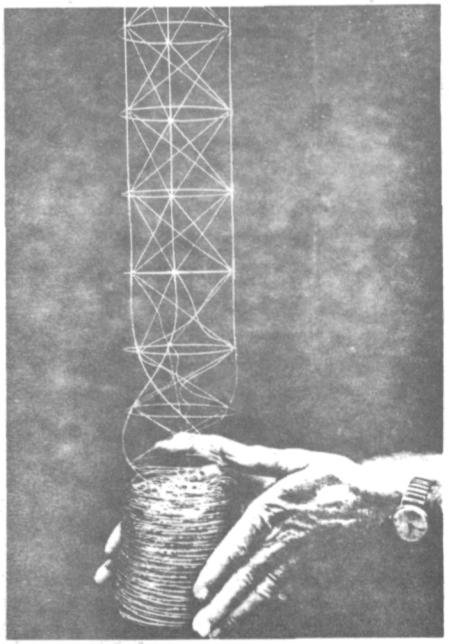




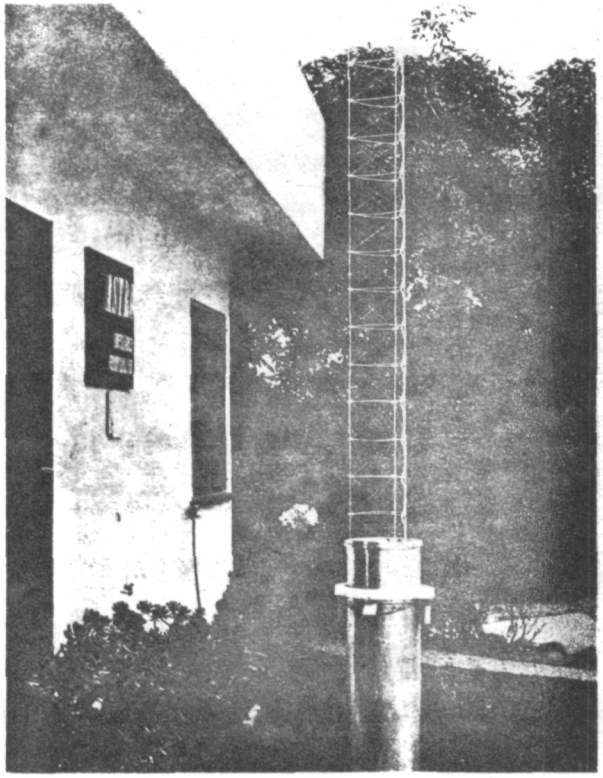


8B – Automatically Deployable Variable Height Tower
(Astro Research Corporation, Santa Barbara, Calif.)

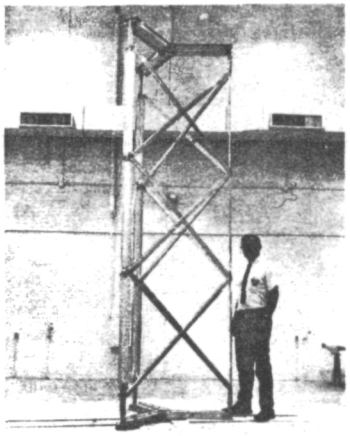




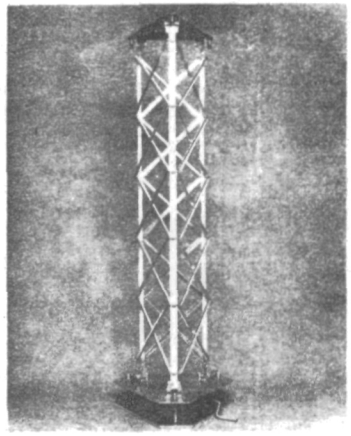
9A – Microweight Astromast (0.02 lb/ft)
(Astro Research Corporation, Santa Barbara, Calif.)



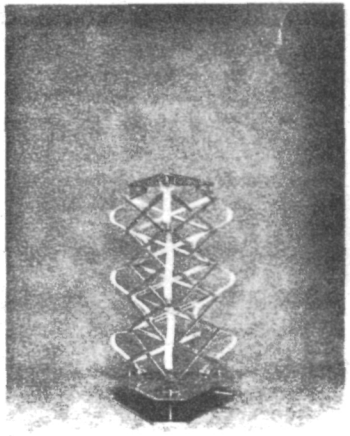
9B – Lunar Antenna Mast – Engineering Model
(Astro Research Corporation, Santa Barbara, Calif.)

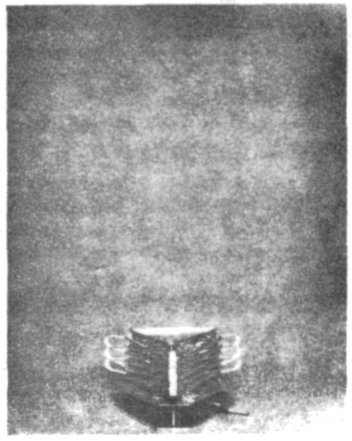


Extender Model Extends 12 Feet

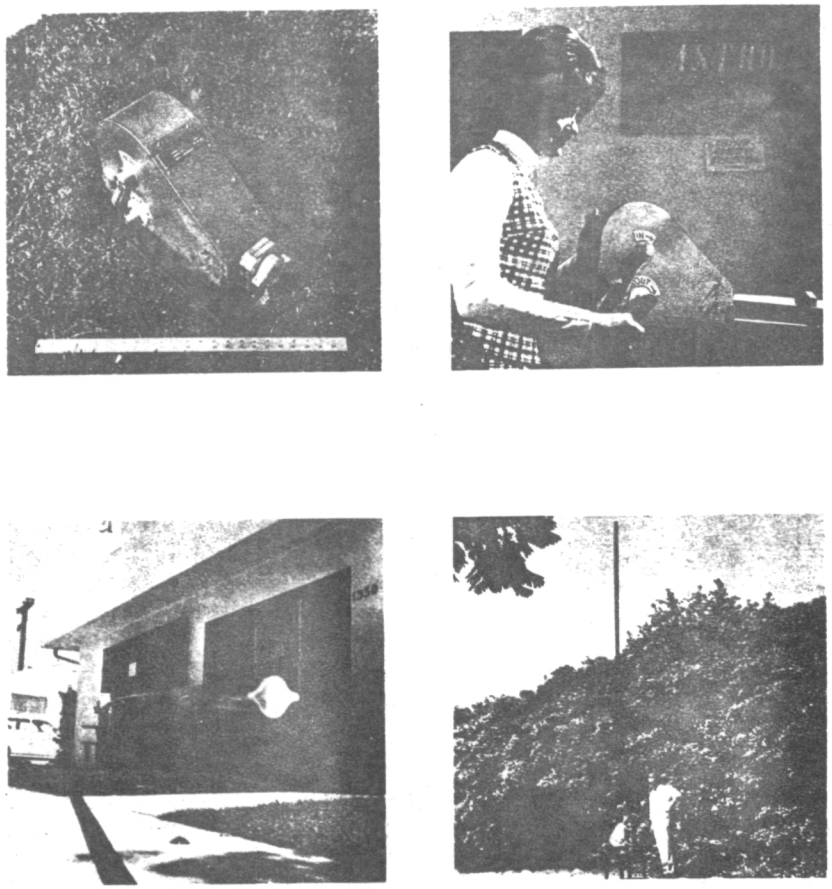


Extender Model Extends 3 Feet

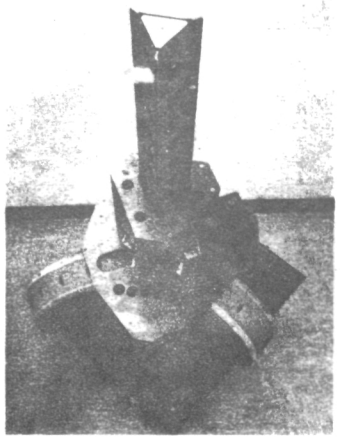




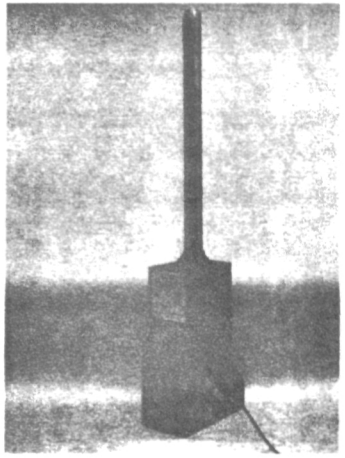
10 – Tri-Extender
(Lockheed Missiles & Space Company, Sunnyvale, Calif.)



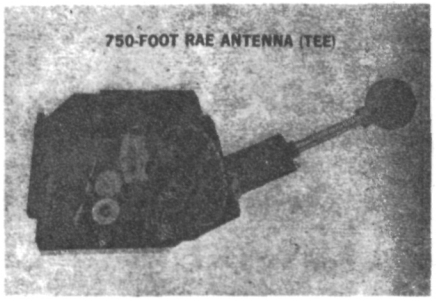
12 – Astro Tube Engineering Model for Viking Soil Sampler (Astro Research Corp., Santa Barbara, Calif.)



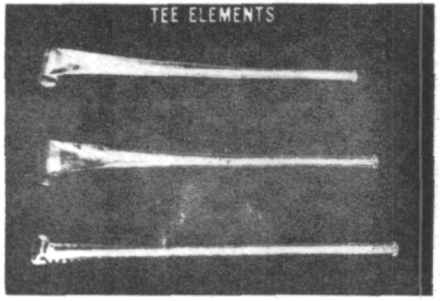
13 – Tri-Beam Model, Capable of Extending 40 Feet (Lockheed Missiles & Space Company, Sunnyvale, Calif.)



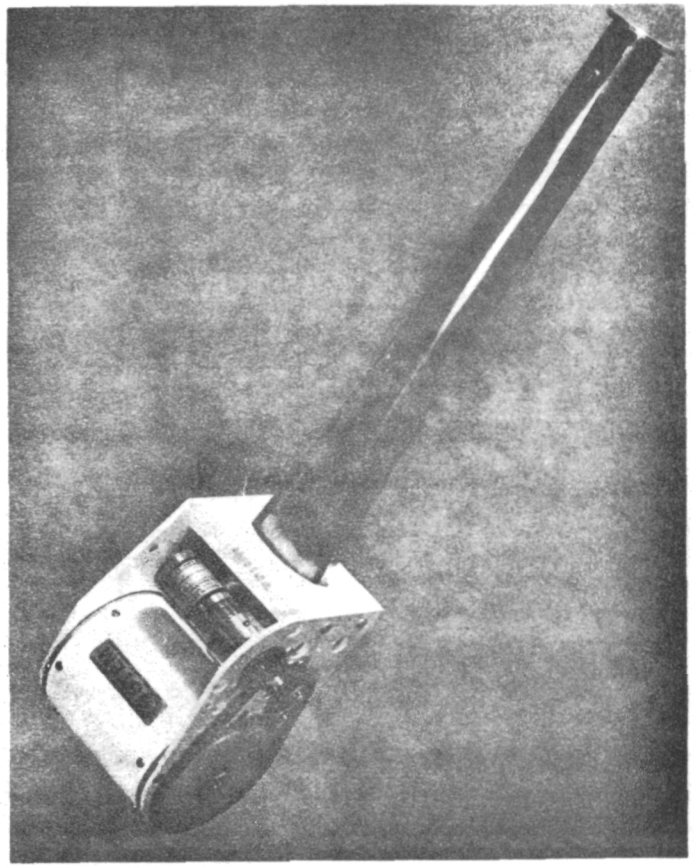
14 – Instarect Reel Stored Mast Model, Capable of Extending 40 Feet (Sanders Associates, Inc., Nashua, New Hampshire)



15A – Deployment Mechanism and 750-Foot Long Edgelock Tee (Fairchild-Hiller, Germantown, Md.)



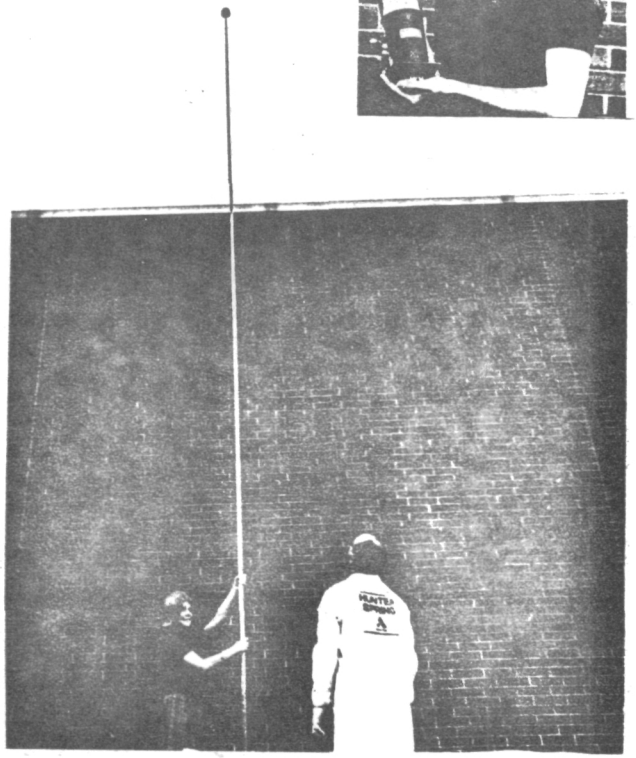
15B – Tubular Extendible Elements (Tee); Hingelock, Edgelock, and Overlapped (Fairchild-Hiller, Germantown, Md.)



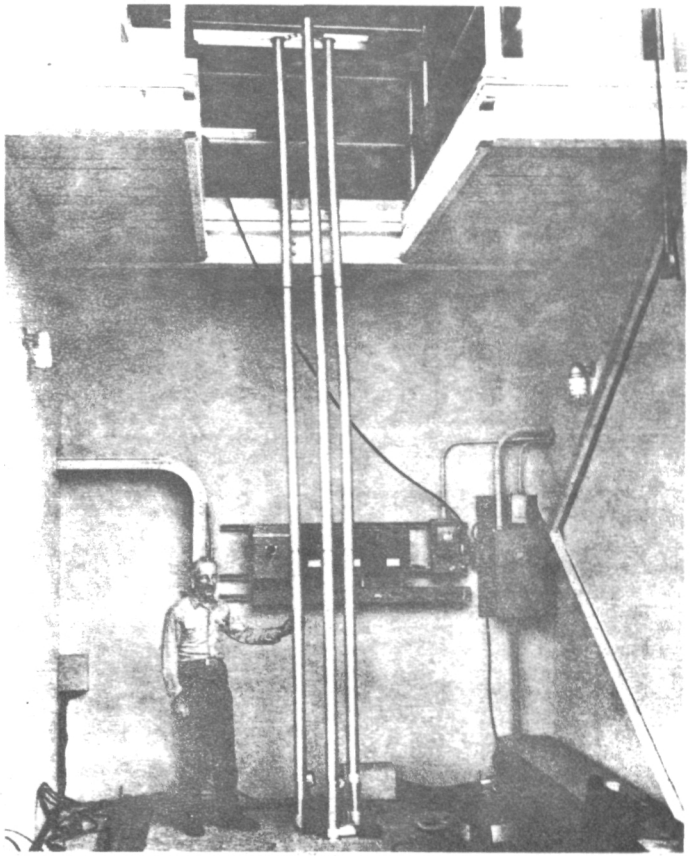
16 – Extendible Reel Stored; the Bi-Stem is Capable of Extending 120 Feet (SPAR Aerospace Products, Ltd., Toronto, Canada)

Boom Cannister Before a Boom is Released (Right)

Boom Extended to Its 21-Foot Length (Bottom)



17 – Spring Helix (Hunter Spring Div., Ametek, Inc., Hatfield, Pa.)



18 – Inflatables, Model Height 18 Feet
(Lockheed Missiles & Space Company, Sunnyvale, Calif.)

4.1.2.3 Evaluation of Deployable Structures

This section applies the extensible structure data from Sections 4.1.2.1 and 4.1.2.2 to the Space Station. The characteristics of extensible structures vary a great deal; therefore, their individual applicability to the Space Station depends largely upon how they function in the design. The method used to evaluate extendible structures was to define a series of configurations, one of which would be optimum for a specific type of extendible structure and all of which would satisfy the Space Station operational and packaging requirements. These configurations are shown in Chart K. Each type of extendible structure is then evaluated by analysis for use in one or more of the chosen configurations; the results are shown in Chart L. The beam loads are quite variable from one configuration to another (bending from zero to 16,000 ft-lb and column loading from 64 to 4,560 lb). This allows the beam to be studied as an independent variable with only stowage volume constraints. This method of evaluation will allow consideration of new extendible structures without repeating a complete structural analysis.

4.1.2.3.1 Solar Array Configurations (Chart K). This chart illustrates nine different ways the panels can be positioned. Configurations are varied through the range of complexity, from the simplest approach of 100-percent deployment at all times to complex pivoting and transversing full panels and panels with only partial (37.5 percent min.) deployment during the artificial gravity assessment. The objective of the chart is to provide a configuration that is near optimum for each type of beam, to provide a basis for evaluation of the overall structure system complexity and weight. The number and placement of extensible beams used in any configuration can readily be adjusted to optimize the design.

4.1.2.3.2 Structures and Mechanism Applicability to Space Station (Chart L). The loads determined for each solar array configuration were developed for the artificial gravity experiment, which represents the worst case (highest loads). This case assumed 4 rpm rotational speed from the beginning to the conclusion of the experiment.

Extensible beams Nos. 4, 5, 7, 9, 11, and 17 through 20 (Chart J) were not considered applicable to the Space Station for any of the nine configurations because of the high loads carried by the beams during artificial gravity. Also, the shock loads resulting from docking during zero gravity must be considered regardless of the artificial gravity assessment. These beams are not efficient extensible devices for high load applications.

The column, Extensible Structure Usable in This Configuration is used to eliminate highly unlikely beam candidates. The two reasons considered valid for elimination are when the configuration requires a function that the beam cannot normally perform; or when the loads make the beam so outsized that it is obviously beyond the state-of-the-art existing to fabricate the beam. Consider the following examples:

- A Functional Requirement. The Extensible Truss Beam No. 6, as used in Space Station Configuration No. 6 or No. 7, requires partial extension. The extensible truss does not develop any real load-carrying capabilities until it reaches full extension. It is conceivable that a design could be produced where one shortened extensible truss sets atop a second extensible truss, with sequenced extensions producing the configurations. The extra operations and complications reduce reliability and increase costs unnecessarily, especially when other beams adapt well to Space Station Configurations 6 and 7; therefore, beam No. 6 was eliminated in those configurations.
- An Outsized Beam Requirement. Consider the Interlocking Extendible Reel Stored Beam No. 15, as used in Configuration No. 1. Using stainless steel, the loads require a beam 0.07-in. thick by 17.5-in. diam; beam element weight is 1,430 lb. The largest size made to date is a short section of 6 in. dia. Scale-up to 17.5 in diam by 100 ft long would require tremendous expansion of technology and completely new fabrication facilities. Space Station Configurations Nos. 1, 2, and 3 do not favor the characteristics of beam No. 15; therefore consideration of beam 15 was eliminated in Configurations 1, 2, and 3.

The ancilliary structure and mechanism weights shown in the Applicability to Space Station Column of Chart L were estimated, as shown in the tabulations that follow. Weights are for total Space Station solar array structure. Materials considered are standard aluminum and stainless steel alloys.

Configuration 1, Baseline (Proposal)

Qty	Description	Weight (lb)
4	Outer panel support beams	160
2	Outboard cross arm (40 by 2 ft sq. folding, truss beam)	320
4	Containers, 32 by 2 by 3 ft, with cover and mounting frames	860
4	Guys, 150 ft by 5/64 in. dia with fittings	10
	Total Structure	1350
4	Cables (panel pull-out) 250 ft by 3/16 in. diam	78
As/Reqd	Pulleys and cable guides	8
2	Cable reel and motor	14
2 sets	Wiring and controls	4
	Total Mechanism	104
	Total Ancillary System	1454

Configuration 2, Baseline Mod. A

Qty	Description	Weight (lb)
2	Outboard cross arm (40 ft by 2 ft sq. folding truss beam)	215
4	Outer panel support beams	120
4	Containers, 32 by 2 by 3 ft, includes cover and mounting frames	780
4	Guys, 150 ft by 1/16 in. diam, with fittings	8
	Total Structure	1118
4	Cables (panel pull-out) 250 ft by 1/8 in diam	36
As/Reqd	Pulleys and cable guides	8
4	Cable reel and motor	20
2 sets	Wiring and controls	6
	Total Mechanism	70
	Total Ancillary System	1188

Configuration 3, Baseline Mod. B

(Same as Configuration No. 2)

Configuration 4, Symm. Dynamic Loads

Qty	Description	Weight (lb)
2	Outboard Cross arm (40 by 2 ft sq. folding truss beam)	200
4	Outer panel support beams	120
4	Containers 32 by 2 by 3 ft, includes cover and mounting frames	800
4	Guys 150 ft by 1/16 diam with fittings	8
	Total Structure	1128
4	Cables (panel pull-out) 250 ft by 1/8 in. diam	36
As/Reqd	Pulleys and cable guides	8
4	Cable reel and motor	20
2 sets	Wiring and controls	6
	Total Mechanism	70
	Total Ancillary System	1188

Configuration 5, Panels Tension Loaded

Qty	Description	Weight (lb)
2	Outboard cross arm 25 by 1.5 ft sq	60
6	Containers 24 by 2 by 3 ft, includes covers and mounting frames	880
2	Folding rail system	480
4	Extendible beams 3 in. diam by 89 ft long	660
2	Secondary outboard beam (folding truss 45 ft long)	120
	Total Structure	2200

Configuration 5, (Continued)

Qty	Description	Weight (lb)
2	Cable (panel pull-out 300 ft by 1/8 in. diam	20
As/Reqd	Pulleys and cable guides	6
2	Cable reel and motor	12
2 sets	Wiring and controls	8
2	Rail traversing drive mechanism	30
	Total Mechanism	76
	Total Ancillary System	2276

Configuration 6, Framed Assy

4	Outboard beams 32 by 1.5 ft	280
4	Containers 32 by 2 by 3 ft	800
	Total Ancillary Structure	1080

(No Ancillary Mechanisms Required)

Configuration 7, Symm. Partial Deploy

(Same as Configuration 2)

Configuration 8, Symm. Pivoted Panels

Qty	Description	Weight (lb)
4	Outboard beams (32 by 1.5 ft)	280
4	Containers	800
		1080

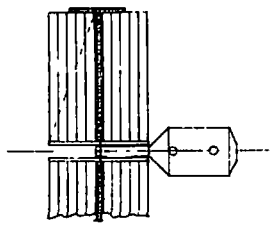
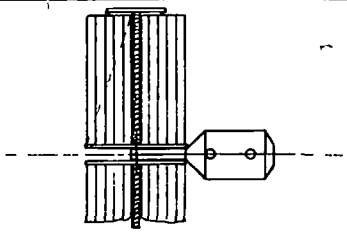
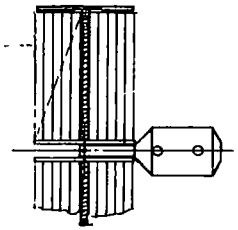
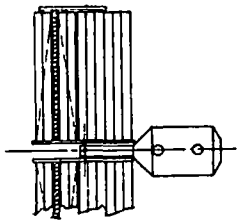
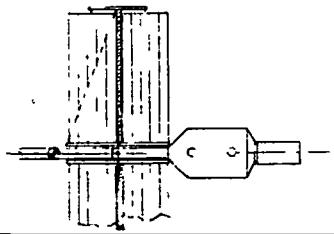
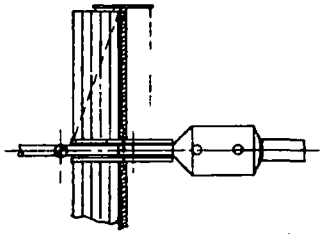
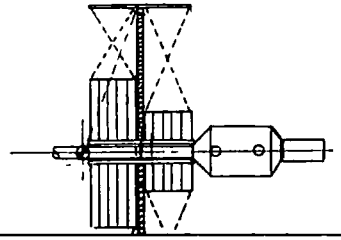
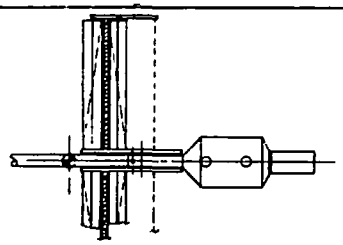
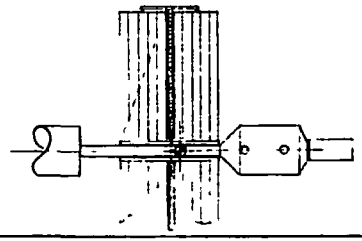
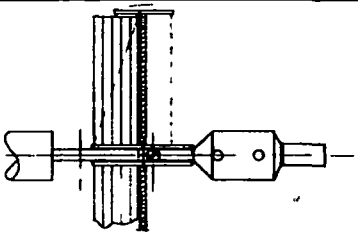
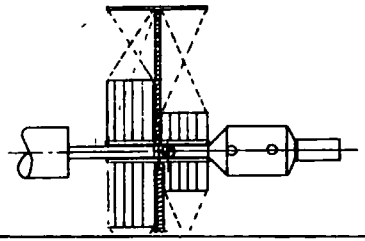
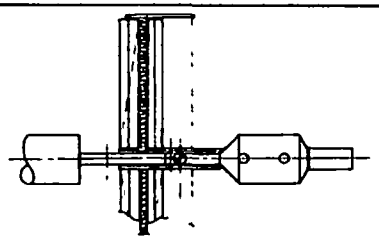
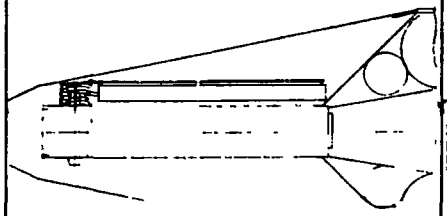
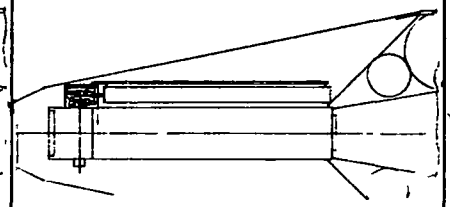
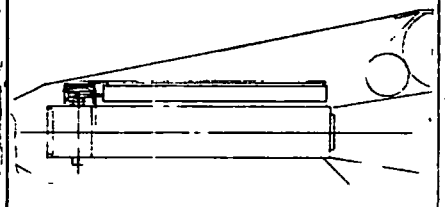
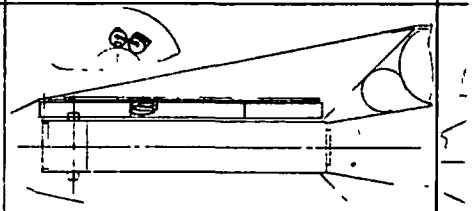
Configuration 9, Equilibrium Pivoted Panel

Qty	Description	Weight (lb)
2	Outboard cross arm, (40 by 1 ft folding truss beam)	130
4	Outer panel support beams	80
4	Containers 32 by 2 by 3 ft	780
2	Pivot mechanism structure	20
	Total Structure	1010
4	Cables (panel pull-up) 250 ft x 1/8 diam	36
As/Reqd	Pulleys and cables guides	8
4	Cable reel and motor	24
2 sets	Wiring and controls	6
	Total Mechanism	74
	Total Ancillary System	1084

4.1.2 3.3 Conclusions. A review of the applicability matrix will verify that only truss-type beams (Nos. 1, 3, 6, 8, and 10) are efficient (strength to weight) for the Space Station stress load levels. A review of the flight experience column of the technology survey will verify that no extensible structures have been used on spacecraft that approach the strength requirements of the Space Station. This lack of experience, combined with the obvious superiority of the truss beam, indicates the necessity for a development program.

The two chart system (configuration and applicability) is versatile and quite adaptable to change, either to consider a change in the basic requirements or to evaluate a new extensible structure. A change in the basic requirements will be reflected in the configuration chart and/or the loads column of the applicability chart.

Addition of a new extensible structure to be evaluated requires only that it follow the same general procedures used to evaluate the 20 existing beams, i.e., analyze and display the characteristics of the beam in terms similar to the technology survey matrix, and then evaluate those characteristics in the applicability matrix.

	1 BASELINE PROPOSAL	2 BASELINE MOD A	3 BASELINE MOD B	4 SYMMETRICAL DYNAMIC LOADS
ZERO G CONFIGURATION				
END OF ARTIFICIAL G CONFIGURATION				
INITIAL DEPLOYMENT AND START ARTIFICIAL G CONFIGURATION				
LAUNCH STOWAGE CONFIGURATION				
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SOLAR ARRAY CONFIGURATIONS

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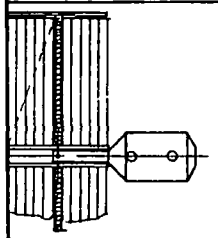
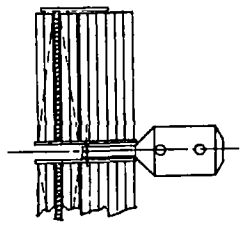
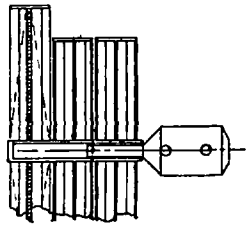
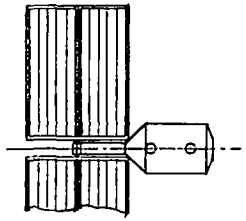
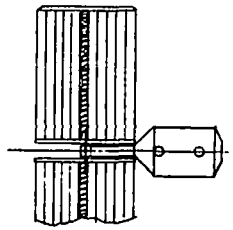
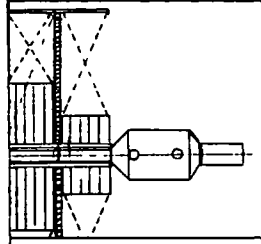
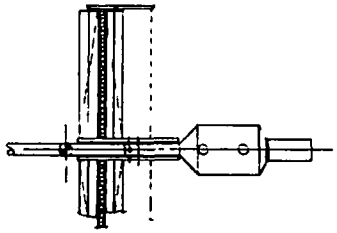
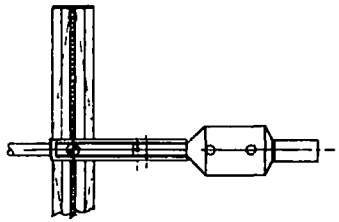
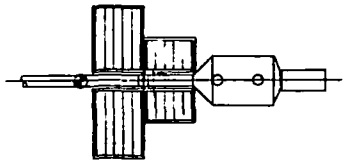
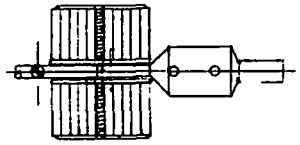
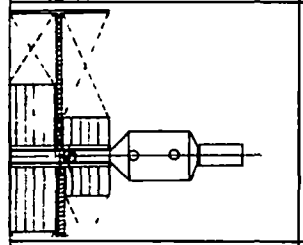
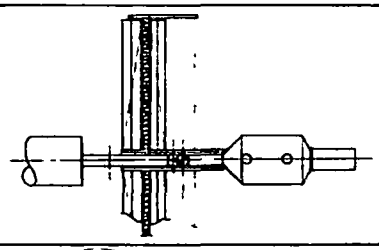
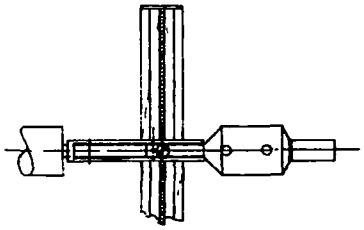
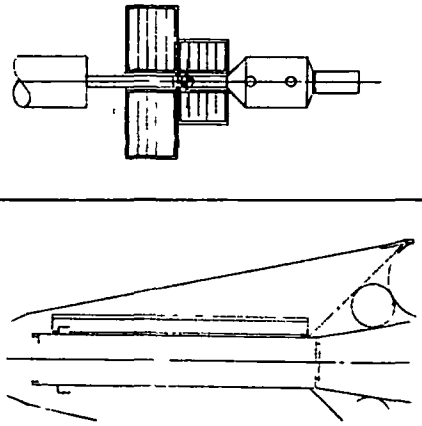
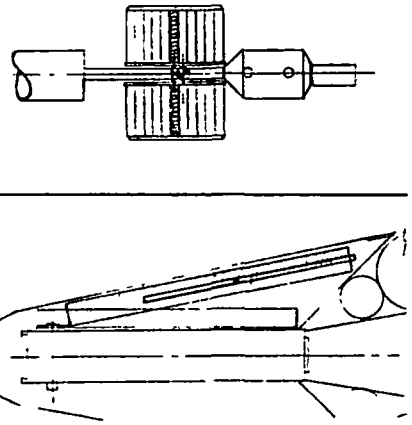
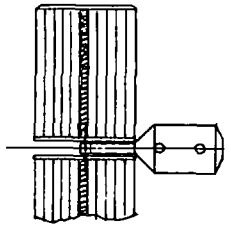
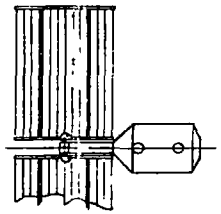
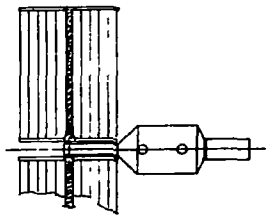
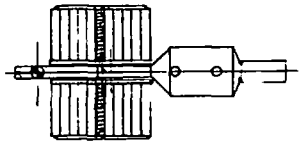
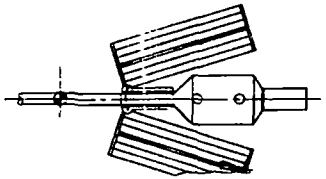
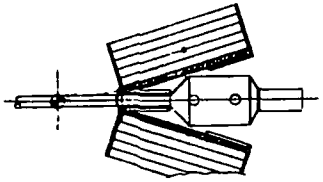
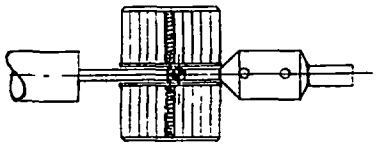
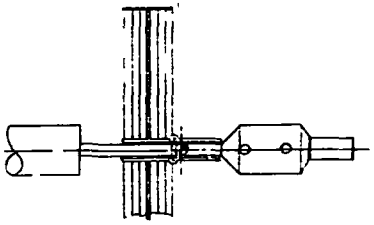
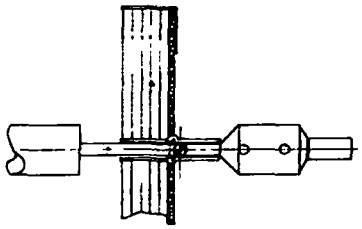
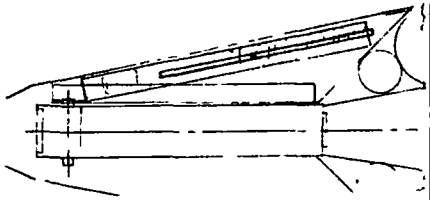
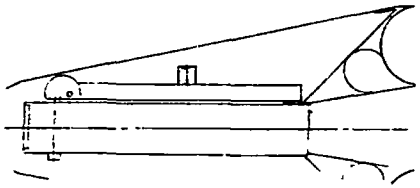
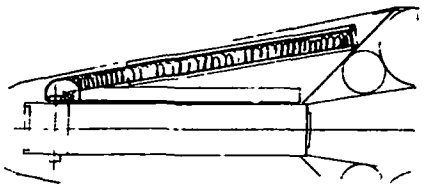
				
				
				
EXCEPT THAT THE FORWARD HALF WING IS DEPLOYED WING IS DEPLOYED 25% THROUGH THE ARTIFICIAL G ASTON MEMBERS ARE REQUIRED TO MAINTAIN SOLAR PARTIAL DEPLOYMENT AND CENTRIFUGAL LOADING.	BOOM LOCATED MID WAY BETWEEN THE EXTREME CENTERS OF ARTIFICIAL G ROTATION. TWO 40 BY 88 FT PANELS ARE DEPLOYED ON EACH SIDE OF THE BOOM THROUGH THE ARTIFICIAL G EXPERIMENT. SIX ADDITIONAL PANELS 40 BY 88 FT ARE DEPLOYED AFTER ARTIFICIAL G. THE AFT SIX PANELS ARE STOWED IN A CONTAINER (ALSO INBOARD BEAM) THAT IS AFFIXED TO THE GIMBAL. THE GIMBAL IS ROTATED TO ACQUIRE STOW POSITION. THE FORWARD PANELS STOW IN CONTAINERS THAT WITH THE BOOM BASE FORM THE FORWARD INBOARD BEAM. THE OUTBOARD CROSS ARM AND FORWARD INBOARD BEAM PIVOT 180° ON THE AFT INBOARD BEAM TO STOW	TWELVE PANELS 4 PANELS STOW IN EACH OF 3 CONTAINERS. THE PANELS IN CONTAINERS 1 AND 2 ARE 6 BY 66 FT AND DEPLOY AFTER THE ARTIFICIAL G. CONTAINER 1 IS AFFIXED TO THE GIMBAL AND STOWED BY GIMBAL ROTATION. CONTAINER 2 PIVOTS 180° ABOUT THE END OF CONTAINER 1 TO STOW. FOUR PANELS 16 BY 88 FT IN CONTAINER 3 ARE 40% OF THE WING AREA. A CENTER BOOM SUPPORTS THE PANELS. CONTAINER 3 IS MOUNTED ON A FOLDED RAIL SYSTEM THAT IS AFFIXED TO THE GIMBAL. CONTAINER 3 IS POSITIONED ON THE RAILS TO MAINTAIN THE CENTER BOOM COINCIDENT WITH THE ARTIFICIAL G SPIN CENTER. ARRAY LOCKS IN THE END OF ARTIFICIAL G CONFIGURATION.	SYMMETRICAL FRAMED HALF WINGS. STOW IN CONTAINERS THAT SERVE AS THE INBOARD BEAM OF THE FRAME. TWO BOOMS AND AN OUTBOARD BEAM COMPLETE EACH FRAME. THE AFT CONTAINER IS AFFIXED TO THE TURRET AND STOWED BY GIMBAL ROTATION. THE FORWARD ARRAY FRAME IS HINGED ON THE AFT FRAME AND ROTATES 180° TO STOW. THE FORWARD HALF WINGS DEPLOY 50%. THE AFT HALF WINGS DEPLOY 25% THROUGH THE ARTIFICIAL G EXPERIMENT.	SYMMETRICAL HALF WING SOLAR PANELS STOW IDENTICAL TO BASELINE. BOOM MAY BE STOWED BY COMPRESSING LENGTH AS BASELINE. FOLDED OR TELESCOPING BOOM SECTIONS MAY PIVOT AT THE BASE TO STOW INSIDE THE SHROUD. A 40 FT-LONG BOOM SECTION CAN BE ACCOMMODATED. EACH WING IS DEPLOYED 40% THROUGH THE ARTIFICIAL G EXPERIMENT. WING SIZE IS 60 BY 35 FT. WING SIZE FULLY DEPLOYED IS 60 BY 88 FT.

	7 SYMMETRICAL PARTIAL DEPLOYMENT	8 SYMMETRICAL PIVOTED PANEL	9 EQUILIBRIUM PIVOTED PANEL
			
			
			
			
S THAT SERVE OUTBOARD ED TO THE ARRAY FRAME THE FORWARD THROUGH THE	SYMMETRICAL HALF WING SOLAR PANELS STOW IDENTICAL TO BASELINE. BOOM MAY BE STOWED BY COMPRESSING LENGTH AS BASELINE; FOLDED OR TELESCOPING BOOM SECTIONS MAY PIVOT AT THE BASE TO STOW INSIDE THE SHROUD A 40 FT-LONG BOOM SECTION CAN BE ACCOMMODATED. EACH WING IS DEPLOYED 40% THROUGH THE ARTIFICIAL G EXPERIMENT WING SIZE IS 40 BY 35 FT WING SIZE FULLY DEPLOYED IS 40 BY 88 FT	SYMMETRICAL HALF WINGS. A CENTRAL BEAM IN EACH HALF WING EXTENDS THE PANELS. PANELS AND BEAMS ARE STOWED IN STRUCTURAL CONTAINERS INITIALLY THE FORWARD CONTAINER IS POSITIONED AND LOCKED AND THE FORWARD PANELS DEPLOYED A HINGE BETWEEN THE CONTAINERS IS UNLATCHED FOR ARTIFICIAL G AND CENTRIFUGAL FORCE WILL OVERCOME THE ERECTING SPRING FORCE AND THE FORWARD ASSEMBLY WILL PIVOT TO REDUCE PANEL AND BEAM LOADS. ARTIFICIAL G ENDED, THE ERECTING SPRINGS RETURN THE FORWARD ASSEMBLY ⊥ TO THE POWER BOOM AND THE HINGE IS LATCHED THE AFT ARRAY IS THEN DEPLOYED	PANELS AND STORAGE IDENTICAL TO NO 2 (BASELINE MOD A) EXCEPT THAT THE BOOM IS PIVOTED NEAR THE GIMBAL ATTACHMENT AND MAY BE STOWED WITH ONLY A PARTIAL REDUCTION IN LENGTH. A CONSTANT SMALL FORCE ERECTS AND LATCHES THE BOOM ⊥ TO THE SPACE STATION POWER BOOM. THE BOOM IS UNLATCHED DURING THE ARTIFICIAL G EXPERIMENT AND ALLOWED TO SEEK EQUILIBRIUM

FOLDOUT FRAME 4

FOLDOUT FRAME 5

STRUCTURES AND MECHANISMS APPLICABILITY TO

NO AND NAME OF EXTENDIBLE STRUCTURE	SPACE STATION CONFIGURATION NO	EXTENDIBLE STRUCTURE USABLE IN THIS CONFIGURATION	STOWAGE TO FIT WITHIN EXISTING SHROUD	DYNAMICS LOADS (EACH BEAM)			STRESS, 1 1 YIELD SAFETY MARGIN			
				WITHOUT GUYS FT LBS BENDING	WITH GUYS LBS COMPRESSION	COMPRESSION REACTING PANEL TENSION	BEAM ELEMENTS SIZED	BEAM WEIGHT	MECHANISM WEIGHT (LB)	TOTAL BEAM AND MECHANISM WEIGHT (LB)
1 TELESCOPING TRIANGULAR TRUSS	1	YES	YES, (STOW AS NO 7)	16,000	530	4030	AL ALLOY TUBULAR	694	15	(710 X 2 = 1420)
	2	YES	YES, (STOW AS NO 7)	4,800	160	1670		280	15	(295 X 2 = 590)
	3	YES	YES, (STOW AS NO 7)	5,200	173	416		90	15	(105 X 2 = 210)
	4	YES	YES, (STOW AS NO 7)	3,840	320	920		190	15	(205 X 2 = 410)
	5	YES	YES (STOW AS NO 7)	0	0	194		30	15	(45 X 2 = 90)
	6	NO, REQUIRES PARTIAL DEPLOYMENT		600 (FRONT) 350 (AFT)	–	103 (FRONT) 64 (AFT)			12 12	
	7	YES (ERECT STOWED LENGTH)	YES,	2,650	–	660		166	15	(181 X 2 = 362)
	8	YES	YES, (STOW AS NO 7)	4,800	–	1040		432	15	(447 X 4 = 1788)
	9	YES	YES,	4,800	–	834 (RESULTS IN 12,500 FT LB BEND)		1104	16	(1120 X 2 = 2240)
2 TELESCOPING CYLINDERS	1	YES	YES, (STOW AS NO 7)	16,000	530	4030		1716	16	(1732 X 2 = 3464)
	2	YES	YES (STOW AS NO 7)	4,800	160	1670		1260	15	(1275 X 2 = 2550)
	3	YES	YES, (STOW AS NO 7)	5,200	173	416		560	15	(575 X 2 = 1150)
	4	YES	YES (STOW AS NO 7)	3,840	320	920		876	15	(891 X 2 = 1782)
	5	YES	YES (STOW AS NO 7)	0	0	194		358	15	(373 X 2 = 746)
	6	NO, REQUIRES PARTIAL DEPLOYMENT		600 (FRONT) 350 (AFT)	–	103 (FRONT) 64 (AFT)		218 90	12 12	(230 X 4 = 920 (102 X 4 = 408 1328
	7	YES (ERECT STOWED LENGTH)	YES	2,650		660		425	15	(440 X 2 = 880)
	8	YES	YES (STOW AS NO 7)	4,800	–	1040		876	15	(891 X 4 = 3564)
	9	YES	YES	4,800	–	834 (RESULTS IN 12,500 FT LB BENDING)		1260	16	(1276 X 2 = 2552)
3 FOLDING BEAM	1	YES	YES (STOW AS NO 7)	16,000	530	4030		2160	18	(2178 X 2 = 4356)
	2	YES	YES, (STOW AS NO 7)	4,800	160	1670		1365	17	(1382 X 2 = 2764)
	3	YES	YES (STOW AS NO 7)	5,200	173	416		870	17	(887 X 2 = 1774)
	4	YES	YES, (STOW AS NO 7)	3,840	320	920		1103	17	(1120 X 2 = 2240)
	5	YES	YES, (STOW AS NO 7)	0	0	194		555	17	(572 X 2 = 1144)
	6	NO, REQUIRES PARTIAL DEPLOYMENT		600 (FRONT) 350 (AFT)	–	103 (FRONT) 64 (AFT)		218 140	14 14	(232 X 4 = 928 (154 X 4 = 616 1544
	7	NO REQUIRES PARTIAL DEPLOYMENT		2,650	–	660		488	17	(505 X 2 = 1010)
	8	YES	YES (STOW AS NO 7)	4 800	–	1040		1103	17	(1120 X 4 = 4480)
	9	YES	YES,	4,800	–	834 (RESULTS IN 12,500 FT LB BENDING)		1365	18	(1383 X 2 = 2766)

FOLDOUT FRAME

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FOLDOUT FRAME 2

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APPLICABILITY TO SPACE STATION

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1 1 YIELD SAFETY MARGIN

MECHANISM WEIGHT (LB)	TOTAL BEAM AND MECHANISM WEIGHT (LB)	NO OF BEAMS REQ'D	ANCILLARY STRUCTURE WEIGHT	ANCILLARY MECHANISM WEIGHT	WEIGHT SUMMARY	ANCILLARY MECHANISM COMMENTS EXPERIENCE, COMPLEXITY (EACH WING)	APPLICABILITY SUMMARY
15	(710 X 2 = 1420)	2	1350	104	2874	TWO SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE EACH TO EXTEND THE BEAM AND THE PANELS	EXTREMELY SIMPLE, BUT A BIT HEAVY, AND SOME PROBLEM AREAS IN RIGGING CABLES
15	(295 X 2 = 590)	2	1118	70	1778	THREE SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE FOR BEAM EXTENSION, TWO FOR PANEL PULL-OUT	SIMPLE DESIGN, A GOOD CANDIDATE TO REVIEW FOR WEIGHT REDUCTION AND CABLE RIGGING PROBLEMS
15	(105 X 2 = 210)	2	1118	70	1398	THREE SIMPLE, WIDELY USED MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE FOR BEAM EXTENSION TWO FOR PANEL PULL-OUT	LIGHT WEIGHT SYSTEM, REQUIRES CRITICAL REVIEW OF CABLE RIGGING
15	(205 X 2 = 410)	2	1128	70	1600	THREE SIMPLE, WIDELY USED MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE FOR BEAM EXTENSION, TWO FOR PANEL PULL-OUT	NOT APPLICABLE, SHORTENED STOWAGE LENGTH MAKES THIS CONFIGURATION LESS DESIRABLE THAN NOS 2 OR 7
15	(45 X 2 = 90)	2	2200	76	2366	TWO SIMPLE WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED FOR FORWARD ASSEMBLY TWO TO SIX DEPLOYABLE STRUCTURES AND MECHANISMS REQUIRED FOR AFT ASSEMBLY	NOT APPLICABLE
12 12		4 4	1080	–	–		IMPRACTICAL DUE TO PARTIAL EXTENSION
15	(181 X 2 = 362)	2	1118	70	1550	TWO SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE EACH TO EXTEND THE BEAM AND PANELS PRUDENT DESIGN MAY COMBINE FUNCTIONS AND USE ONLY ONE MECHANISM	LIGHT WEIGHT SYSTEM WITH MINIMUM CABLE RIGGING PROBLEMS A LIKELY CANDIDATE.
15	(447 X 4 = 1788)	4	1080	–	2876	FOUR SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED (TWO EACH FOR BEAM EXTENSION AND 2 EACH TO PULL OUT PANELS (MAY COMBINE FUNCTIONS) A PYROTECHNIC LOCK IS REQUIRED	NOT APPLICABLE; COMPLEX SYSTEM IS HEAVIER THAN OTHER SIMPLER CONFIGURATION
16	(1120 X 2 = 2240)	2	1010	74	3324	THREE SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED (ONE FOR BEAM EXTENSION, TWO FOR PANEL PULL-OUT A PYROTECHNIC LOCK IS REQUIRED	EXCESSIVE WEIGHT
16	(1732 X 2 = 3464)	2	1350	104	4918	TWO SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE EACH TO DEPLOY THE BEAM AND THE PANELS	
15	(1275 X 2 = 2550)	2	1118	70	3772	THREE SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED (ONE FOR BEAM EXTENSION, TWO FOR PANEL PULL-OUT	
15	(575 X 2 = 1150)	2	1128	70	2338	THREE SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE FOR BEAM EXTENSION, TWO FOR PANEL PULL-OUT	
15	(891 X 2 = 1782)	2	1128	70	2980	THREE SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE FOR BEAM EXTENSION, TWO FOR PANEL PULL-OUT	
15	(373 X 2 = 746)	2	2200	76	3022	TWO SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED FOR FORWARD ASSEMBLY TWO TO SIX DEPLOYABLE STRUCTURES AND MECHANISMS REQUIRED FOR AFT ASSEMBLY	NOT APPLICABLE AS THERE ARE NO ADVANTAGES OVER THE TELESCOPING TRUSS BEAM.
12 12	(230 X 4 = 920 (102 X 4 = 408 1328	4 4	1080	–	2408		
15	(440 X 2 = 880)	2	1118	70	2068	TWO SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE EACH TO EXTEND THE BEAM AND PANELS PRUDENT DESIGN MAY COMBINE FUNCTIONS AND USE ONLY ONE MECHANISM	
15	(891 X 4 = 3564)	4	1080	–	4644	FOUR SIMPLE, WIDELY USED MOTORIZED REEL AND CABLE SYSTEMS REQUIRED 2 EACH TO EXTEND THE BEAMS AND 2 EACH TO PULL OUT PANELS (MAY COMBINE FUNCTIONS) A PYROTECHNIC LOCK IS REQUIRED	
16	(1276 X 2 = 2552)	4 6	1010	74	3636	THREE SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE FOR BEAM EXTENSION, TWO FOR PANEL PULL-OUT A PYROTECHNIC LOCK IS REQUIRED	
18	(2178 X 2 = 4356)	2	1350	104	5810	TWO SIMPLE, WIDELY USED MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE EACH TO DEPLOY THE BEAM AND THE PANELS	EXCESSIVE WEIGHT
17	(1382 X 2 = 2764)	2	1118	70	3952	THREE SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE FOR BEAM EXTENSION, TWO FOR PANEL PULL-OUT	EXCESSIVE WEIGHT
17	(887 X 2 = 1774)	2	1118	70	2942	THREE SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE FOR BEAM EXTENSION TWO FOR PANEL PULL-OUT	HEAVY AND POTENTIAL CABLE RIGGING PROBLEMS A CANDIDATE BUT NOT VERY LIKELY
17	(1120 X 2 = 2240)	2	1128	70	3438	THREE SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE FOR BEAM EXTENSION TWO FOR PANEL PULL-OUT	EXCESSIVE WEIGHT
17	(572 X 2 = 1144)	2	2200	76	3420	TWO SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED FOR FORWARD ASSEMBLY TWO TO SIX DEPLOYABLE STRUCTURES AND MECHANISMS REQUIRED FOR AFT ASSEMBLY	NOT APPLICABLE. TOO COMPLEX
14 14	(232 X 4 = 928 (154 X 4 = 616 1544	4 4	1080	–	2624		IMPRACTICAL DUE TO PARTIAL EXTENSION
17	(505 X 2 = 1010)	2	1118	70	2760		IMPRACTICAL DUE TO PARTIAL EXTENSION
17	(1120 X 4 = 4480)	4	1080	–	5560	FOUR SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED 2 EACH TO EXTEND THE BEAM AND 2 EACH TO PULL-OUT PANELS (MAY COMBINE FUNCTIONS A PYROTECHNIC LOCK IS REQUIRED	EXCESSIVE WEIGHT
18	(1383 X 2 = 2766)	2	1010	74	3850	THREE SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEMS REQUIRED ONE TO EXTEND BEAM, TWO FOR PANEL PULL-OUT A PYROTECHNIC LOCK IS REQUIRED	EXCESSIVE WEIGHT

STRUCTURES AND MECHANISMS APPLICABILITY

NO AND NAME OF EXTENDIBLE STRUCTURE	SPACE STATION CONFIGURATION NO	EXTENDIBLE STRUCTURE USABLE IN THIS CONFIGURATION	STOWAGE TO FIT WITHIN EXISTING SHROUD	DYNAMICS LOADS (EACH BEAM) WITHOUT GUYS FT LBS BENDING	WITH GUYS LBS COMPRESSION	COMPRESSION REACTING PANEL TENSION	STRESS, 1 1 YIELD SAFETY MARGIN BEAM ELEMENTS SIZED	BEAM WEIGHT	MECHANISM WEIGHT (LB)	TOTAL BEAM AND MECHANISM WEIGHT (LB)
6 EXTENDIBLE TRUSS (PROPOSAL BASELINE)	1	YES	NO EXCESSIVE STOW HEIGHT	16,000	530	4030	(4) 1 IN SQ TUBES ON 23 IN CENTERS CROSS SECT AREA = 507 IN SQ EACH TUBE	448	14	(462 X 2 = 924)
	2	YES	NO EXCESSIVE STOW HEIGHT	4,800	160	1670	SEE ABOVE AREA = 203-2	179	14	(193 X 2 = 386)
	3	YES	NO EXCESSIVE STOW HEIGHT	5,200	173	416	SEE ABOVE AREA = 066-2	59	14	(73 X 2 = 146)
	4	YES	YES	3,840	320	920	SEE ABOVE AREA = 138-2	122	14	(136 X 2 = 272)
	5	YES	YES	0	0	194	SEE ABOVE AREA = 022-2	20	14	(34 X 2 = 68)
	6	NO UNSTABLE AT PARTIAL EXTENSION		600 (FRONT) 350 (AFT)	–	103 (FRONT) 64 (AFT)	SEE ABOVE AREA = 023-2 AREA = 012-2	21 11	12 12	(33 X 4 = 132) (23 X 4 = 92) 234
	7	NO, UNSTABLE AT PARTIAL EXTENSION		2,650	–	660	SEE ABOVE AREA = 160-2	142	14	(156 X 2 = 312)
	8	YES	YES	4 800	–	1040	SEE ABOVE AREA = 273-2	242	14	(256 X 4 = 1024)
	9	YES	NO, EXCESSIVE STOW HEIGHT	4,800	–	834 (RESULTS IN 12,500 FT LB BENDING)	SEE ABOVE AREA = 659-2	582	14	(596 X 2 = 1192)
8 ASTROMAST ARTICULATED LATTICE	1	YES	NO, EXCESSIVE STOWAGE HEIGHT	16,000	530	4030	AL, ALLOY TUBULAR	578	150	(728 X 2 = 1456)
	2	YES	NO, EXCESSIVE STOWAGE HEIGHT	4,800	160	1670		233	95	(328 X 2 = 656)
	3	YES	NO, EXCESSIVE STOWAGE HEIGHT	5,200	173	416		75	95	(170 X 2 = 340)
	4	YES	YES	3,840	320	920		158	95	(253 X 2 = 506)
	5	YES	YES	0	0	194		25	95	(120 X 2 = 240)
	6	YES	YES	600 (FRONT) 350 (AFT)	–	103 (FRONT) 64 (AFT)			60 60	
	7	YES	YES	2,650	–	660		138	95	(233 X 2 = 466)
	8	YES	YES	4,800	–	1040		360	95	(455 X 4 = 1820)
	9	YES	NO EXCESSIVE STOWAGE HEIGHT	4 800	–	834 (RESULTS IN 12,500 FT LBS BEND)		920	150	(1070 X 2 = 2140)
10 EXTENDER LMSC	1	YES	NO, EXCESSIVE STOWAGE HEIGHT	16,000	530	4030	LENTICULAR SECT STAINLESS STEEL T = 019 SPACED 18" APART R = 1 90 DIAGONAL MEMBERS ALUM. W = 7 60 LENTICULAR SECT AS BEAM #12	732	6	(738 X 2 = 1476)
	2	YES	NO, EXCESSIVE STOWAGE HEIGHT	4,800	160	1670	SEE ABOVE T = 012 R = 1 2 W = 4.8	293	6	(299 X 2 = 598)
	3	YES	NO, EXCESSIVE STOWAGE HEIGHT	5,200	173	416	SEE ABOVE T = 007 R = 0 7 W = 2 8	96	6	(102 X 2 = 204)
	4	YES	YES	3 840	320	920	SEE ABOVE T = 010 R = 1 00 W = 4 00	204	6	(204 X 2 = 408)
	5	YES	YES	0	0	194	SEE ABOVE T = 004 R = 0 4 W = 1 60	34	34	(40 X 2 = 80)
	6	NO REQUIRES PARTIAL DEPLOYMENT		600 (FRONT) 350 (AFT)	–	103 (FRONT) 64 (AFT)	SEE ABOVE SEE ABOVE		6 6	
	7	NO, REQUIRES PARTIAL DEPLOYMENT		2,650	–	660			6	
	8	YES	YES	4 800	–	1040	SEE ABOVE T = 009 R = 0.9 W = 3 6	167	6	(173 X 4 = 692)
	9	YES	NO	4 800	–	834 (RESULTS IN 12,500 FT LB BENDING)	SEE ABOVE T = 0081 R = 0 81 W = 3 24	133	6	(139 X 2 = 278)

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

MS APPLICABILITY TO SPACE STATION

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1 YIELD SAFETY MARGIN

MECHANISM WEIGHT (LB)	TOTAL BEAM AND MECHANISM WEIGHT (LB)	NO OF BEAMS REQ'D	ANCILLARY STRUCTURE WEIGHT	ANCILLARY MECHANISM WEIGHT	WEIGHT SUMMARY	ANCILLARY MECHANISM COMMENTS EXPERIENCE, COMPLEXITY (EACH WING)	APPLICABILITY SUMMARY
14	(462 X 2 = 924)	2	1350	104	2388		CANNOT BE STOWED
14	(193 X 2 = 386)	2	1118	70	1574		CANNOT BE STOWED
14	(73 X 2 = 146)	2	1128	70	1334		CANNOT BE STOWED
14	(136 X 2 = 272)	2	1128	70	1470	BEAM EXTENDED BY SPRING FORCE PLUS A MOTORIZED JACKSCREW ASSIST AND LOCK TWO SIMPLE, WIDELY USED, MOTORIZED WINCH AND CABLE SYSTEMS REQUIRED FOR PANEL PULL-OUT	SIMPLE SYSTEM LIGHT WEIGHT, A LIKELY CANDIDATE IF RETRACTION IS NOT REQUIRED
14	(34 X 2 = 68)	2	2200	76	2344	BEAM EXTENDS BY SPRING FORCE PLUS A MOTORIZED JACKSCREW ASSIST AND LOCK A MOTORIZED REEL AND CABLE SYSTEM PULL-OUT FORWARD PANELS TWO TO SIX DEPLOYABLE STRUCTURES AND MECH REQUIRED FOR AFT ASSEMBLY	VERY COMPLEX SYSTEM HEAVY, NOT APPLICABLE
12 12	(33 X 4 = 132) 234 (23 X 4 = 92)	4 4	1080	–	1314		IMPRACTICAL DUE TO PARTIAL EXTENSION
14	(156 X 2 = 312)	2	1118	70	1500		IMPRACTICAL DUE TO PARTIAL EXTENSION
14	(256 X 4 = 1024)	4	1080	–	2104	SIMPLE SCREW JACK EXTENDS 3PAM (2 REQUIRED) MOTORIZED REEL AND CABLE SYSTEM PULLS-OUT (2 REQUIRED) A PYROTECHNIC LOCK IS REQUIRED	SIMPLE SYSTEM PIVOT REQUIRES DEVELOPMENT, NOT AS LIKELY A CANDIDATE AS NO 4
14	(596 X 2 = 1192)	2	1010	74	2276		CANNOT BE STOWED
150	(728 X 2 = 1456)	2	1350	104	2910	–	CANNOT BE STOWED
95	(328 X 2 = 656)	2	1118	70	1844		CANNOT BE STOWED
95	(170 X 2 = 340)	2	1118	70	1520		CANNOT BE STOWED
95	(253 X 2 = 506)	2	1128	70	1704	BEAM AND FORWARD PANELS DEPLOYED BY A ROTARY DRUM AND CAM LATCHING MECHANISM. A SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEM REQUIRED FOR AFT PANEL PULL-OUT	A GOOD CANDIDATE, VERY SIMPLE, SHOULD BE EVALUATED WITH NOS 6 AND 7
95	(120 X 2 = 240)	2	2200	76	2516	BEAM AND FORWARD PANELS ASSEMBLY DEPLOYED BY A ROTARY DRUM AND CAM LATCHING MECHANISM TWO TO SIX DEPLOYABLE STRUCTURES AND MECHANISMS REQUIRED FOR AFT ASSEMBLY	EXCESSIVE WEIGHT AND COMPLEXITY
60 60		4 4	1080	–	–	FOUR BEAMS AND PANELS DEPLOYED BY ROTARY DRUM AND CAM LATCHING MECHANISM	A PRIME CANDIDATE TO BE CONSIDERED WITH ONLY 2 BEAMS PER WING (4 PER VEHICLE)
95	(233 X 2 = 466)	2	1118	70	1654	BEAM AND PANELS DEPLOYED BY A ROTARY DRUM AND LATCHING MECHANISM	PRIME CANDIDATE, VERY SIMPLE FULLY RETRACTABLE, LIGHT WEIGHT SYSTEM.
95	(455 X 4 = 1820)	4	1080	–	2900	BEAM AND PANELS DEPLOYED BY A ROTARY DRUM MECHANISM A PYROTECHNIC LOCK IS REQUIRED	EXCESSIVE WEIGHT
150	(1070 X 2 = 2140)	2	1010	74	3244		CANNOT BE STOWED
6	(738 X 2 = 1476)	2	1350	104	2930		CANNOT BE STOWED
6	(299 X 2 = 598)	2	1118	70	1786		CANNOT BE STOWED
6	(102 X 2 = 204)	2	1118	70	1392		CANNOT BE STOWED
6	(204 X 2 = 408)	2	1128	70	1606	BEAM DEPLOYS BY SPRING ENERGY STORED IN LONGERONS, DAMPER REQUIRED TO CONTROL TWO SIMPLE WIDELY USED MOTORIZED REEL AND CABLE SYSTEMS PULL-OUT PANELS	SIMPLICITY OF DESIGN IS FAVORABLE SHOULD BE CONSIDERED A CANDIDATE IF RETRACTION IS NOT REQUIRED
34	(40 X 2 = 80)	2	2200	76	2356	BEAM DEPLOYS BY SPRING ENERGY STORED IN LONGERONS, DAMPER REQUIRED TO CONTROL SIMPLE MOTORIZED REEL AND CABLE SYSTEM DEPLOY FORWARD PANELS TWO TO SIX DEPLOYABLE STRUCTURES REQUIRED FOR AFT SECTION	HEAVY, COMPLEX
6 6		4 4	1080	–	–		WILL NOT BE STABLE AT PARTIAL EXTENSION
6		2	1118	70	–		WILL NOT BE STABLE AT PARTIAL EXTENSION
6	(173 X 4 = 692)	4	1080	–	1772	BEAM DEPLOYS BY SPRING ENERGY STORED IN LONGERONS DAMPER REQUIRED TO CONTROL SIMPLE MOTORIZED REELS AND CABLE SYSTEMS REQUIRED FOR PANEL PULL-OUT A PYROTECHNIC LOCK IS REQUIRED	CANNOT BE STOWED
6	(139 X 2 = 278)	2	1010	74	1362		CANNOT BE STOWED

FOLDOUT FRAME 3

FOLDOUT FRAME 4

NO & NAME OF EXTENDIBLE STRUCTURE	SPACE STATION CONFIGURATION NO	EXTENDIBLE STRUCTURE USABLE IN THIS CONFIGURATION	STOWAGE TO FIT WITHIN EXISTING SHROUD	DYNAMICS LOADS (EACH BEAM) BENDING (WITHOUT GUYS) FT LBS	COMPRESSION (WITH GUYS) LBS	COMPRESSION REACTING PANEL TENSION	STRESS 1 1 YIELD SAFETY MARGIN BEAM ELEMENTS SIZED	BEAM WEIGHT (LB)	MECHANISM WEIGHT	TOTAL BEAM & MECHANISM WEIGHT LB	NUMBER OF BEAMS REQUIRED	ANCILLARY STRUCTURE WEIGHT	ANCILLARY MECHANISM WEIGHT	WEIGHT SUMMARY	(ANCILLARY MECHANISM CO- DEPENDENCE, COMPLEXITY (E/
12 LENTICULAR WELDED BEAM	1	YES	NO	16,000	530	4,030	STAINLESS STEEL T = 0 069 R = 6 9 W = 27 6	2,440			2	1 250	104		
	2	YES	NO	4 800	160	1 670	STAINLESS STEEL T = 0 055 R = 5 5 W = 22 0	1,540			2	1,118	70		
	3	YES	NO	5 200	173	416	STAINLESS STEEL T = 0 041 R = 4 1 W = 16 4	840			2	1,118	70		
	4	YES	YES	3 840	320	920	STAINLESS STEEL T = 0 050 R = 5 0 W = 20 0	1 280	400	(1680 x 2 = 3360)	2	1,129	70	4,548	MOTOR DRIVEN REEL EXTENDS BEAM AND PU SIMPLE, WIDELY USED, MOTORIZED REEL AN FOR A/T PANEL PULL-OUT
	5	YES	YES	0	0	194	STAINLESS STEEL T = 0 031 R = 3 1 W = 12 4	490	250	(740 x 2 = 1480)	2	2,200	76	3,756	MOTOR DRIVEN REEL EXTENDS BEAM AND PU TWO TO SIZE DEPLOYABLE STRUCTURES AND FOR A/T ASSY.
	6	YES	YES	600 (FRONT) 350 (AFT)	-	103 (FRONT) 64 (AFT)	STAINLESS STEEL T = 0 022 R = 2 2 W = 8 8 STAINLESS STEEL T = 0 016, R = 1 6 W = 6 4	247 130	150 75	(397 x 4 = 1588) (205 x 4 = 820) (2408)	4 4	1 080	-	3 588	FOUR MOTOR DRIVEN REELS EXTEND BEAMS
	7	YES	YES	2 650	-	660	STAINLESS STEEL T = 0 032 R = 3 2 W = 12 8	530	300	(820 x 2 = 1640)	2	1,118	70	2,829	MOTOR DRIVEN REEL EXTENDS BEAM AND PU
	8	YES	YES	4 800	-	1 040	STAINLESS STEEL T = 0 050 R = 5 00 W = 20	1 280	400	(1680 x 4 = 6720)	4	1 080	-	7,800	MOTOR DRIVEN REEL EXTENDS BEAM AND PU REQUIRED PER WING A PYROTECHNIC LOCK
	9	YES	NO	4 800	-	834 (RESULTS IN 12 300 FT LB BENDING)	STAINLESS STEEL T = 0 056 R = 5 60 W = 22 40	1 600			2	1,010	74		
13 TRI BEAM (LMSC)	1	YES	NO	16 000	530	4 030	STAINLESS STEEL 0 147 x 14 0W	1 840			2	1,250	104		
	2	YES	NO	4,800	160	1,670	STAINLESS STEEL 0 115 T x 11.5 W	1 253			2	1,118	70		
	3	YES	NO	5 200	173	416	STAINLESS STEEL 0 085 T_1 x 8.5 W	698			2	1,118	70		
	4	YES	YES	3 840	320	920	STAINLESS STEEL 0 105 T_1 x 10 5 W	1 030	450	(1500 x 2 = 3000)	2	1,129	70	4,198	MOTOR DRIVEN REEL EXTENDS BEAM AND PU SIMPLE, WIDELY USED, MOTORIZED REEL AN FOR A/T PANEL PULL-OUT
	5	YES	YES	0	0	194	STAINLESS STEEL 0 065 T x 6 5 W	417	300	(717 x 2 = 1434)	2	2 200	76	3,634	MOTOR DRIVEN REEL EXTENDS BEAM AND PU TWO TO SIX DEPLOYABLE STRUCTURES AND A FOR A/T ASSY.
	6	YES	YES	600 (FRONT) 350 (AFT)	-	103 (FRONT) 64 (AFT)	(FRONT) 0 045 T x 4 5 W (AFT) 0 035 T x 3 5 W	216 139	180 100	(396 x 4 = 1584) (239 x 4 = 956) (2540)	4 4	1,080	-	3,620	FOUR MOTOR DRIVEN REELS EXTEND BEAMS .
	7	YES	YES	2 650	-	660	STAINLESS STEEL 0 075 T x 7 5 W	855	300	(1305 x 2 = 3410)	2	1,118	70	3 608	MOTOR DRIVEN REEL EXTENDS BEAM AND PU
	8	YES	NO	4 800	-	1,040	STAINLESS STEEL 0 110 T x 11 0 W	1 150	450	(1600 x 4 = 6400)	4	1,080	-	7,480	MOTOR DRIVEN REEL EXTENDS BEAM AND PU REQUIRED PER WING A PYROTECHNIC LOCK
	9	YES	NO	4,800	-	834 (RESULTS IN 12 300 FT LB BENDING)	STAINLESS STEEL 0 125 T x 13 5 W	1 710			2	1,010	74		

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

STRUCTURES AND MECHANISMS APPLICABILITY TO SPACE STATION

(ANCILLARY MECHANISM COMMENTS EXPERIENCE, COMPLEXITY (EACH WING)	APPLICABILITY SUMMARY
	CANNOT BE STOWED
	CANNOT BE STOWED
	CANNOT BE STOWED
MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT FWD PANELS SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEM REQUIRED FOR AFT PANEL PULL-OUT	EXCESSIVE WEIGHT
MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT FWD PANELS TWO TO SIZE DEPLOYABLE STRUCTURES AND MECHANISMS REQUIRED FOR AFT ASSY,	HEAVY AND COMPLEX, WOULD BE CONSIDERED ONLY AS A FINAL RECOURSE
FOUR MOTOR DRIVEN REELS EXTEND BEAMS AND PULL-OUT PANELS	A WORTHY CANDIDATE, SHOULD BE REVIEWED FOR OPTIMIZATION AND COMPARED TO OTHER CANDIDATES
MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT PANELS	A GOOD CANDIDATE, SHOULD BE REVIEWED FOR OPTIMIZATION AND THE PROBLEMS OF STOWAGE
MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT PANELS TWO REQUIRED PER WING A PYROTECHNIC LOCK IS REQUIRED	EXCESSIVE WEIGHT
	CANNOT BE STOWED
	CANNOT BE STOWED
	CANNOT BE STOWED,
	CANNOT BE STOWED
MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT FWD PANELS SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEM REQUIRED FOR AFT PANEL PULL-OUT	EXCESSIVE WEIGHT
MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT FWD PANELS TWO TO SIX DEPLOYABLE STRUCTURES AND MECHANISMS REQUIRED FOR AFT ASSY	EXCESSIVE WEIGHT AND COMPLEXITY
FOUR MOTOR DRIVEN REELS EXTEND BEAMS AND PULLS-OUT PANELS	EXCESSIVE WEIGHT
MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT PANELS	CANNOT BE STOWED
MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS OUT PANELS, TWO REQUIRED PER WING A PYROTECHNIC LOCK IS REQUIRED	EXCESSIVE WEIGHT
	CANNOT BE STOWED

14 INSTARECT (SANDERS)	1	YES	NO	16 000	530	4 030		STAINLESS STEEL, AREA OF R_1 IS 21 THICK 0 0386 T_1 = 13 46 W R = 1007 R_1 = 2007	1,510	
	2	YES	NO	4,800	160	1,670	STAINLESS STEEL	0 0308 T_1 = 12 32 W	938	
	3	YES	NO	5,200	173	416	STAINLESS STEEL	0 0232 T_1 = 9 28 W	545	
	4	YES	YES	3 840	320	920	STAINLESS STEEL	0 0279 T_1 = 11 16 W	788	450
	5	YES	YES	0	0	194	STAINLESS STEEL	0 017 T = 6 8 W	310	200
	6	YES	YES	400 (FRONT) 320 (AFT)	-	103 (FRONT) 64 (AFT)	(FRONT) (AFT)	0 020 T = 8 0 W 0 017 T = 6 8 W	402 394	180 100
	7	YES	YES	2,650	-	660	STAINLESS STEEL	0 034 T = 13 6 W	1,170	250
	8	YES	NO	4,800	-	1,040	STAINLESS STEEL	0 040 T = 16 0 W	1,630	450
	9	YES	NO	4,800	-	834 (RESULTS IN 12 500 FT LB BENDING)	STAINLESS STEEL	0 057 T = 22 8 W	3,250	
15 INTERLOCKING EXTENDIBLE REEL STORED	1	YES	NO	16 000	530	4 030	STAINLESS STEEL	0 070 THICK 8 75 RAD	1,430	
	2	YES	NO	4,800	160	1,670	STAINLESS STEEL	0 060 THICK 7 50 RAD	1,050	
	3	YES	NO	5,200	173	416	STAINLESS STEEL	0 040 THICK 5 00 RAD	467	
	4	YES	NO	3,840	320	920	STAINLESS STEEL	0 050 THICK 6.25 RAD	730	400
	5	YES	YES	0	0	194	STAINLESS STEEL	0 032 THICK 4 00 RAD	298	250
	6	YES	YES	400 (FRONT) 320 (AFT)	-	103 (FRONT) 64 (AFT)	(FRONT) (AFT)	0 025 THK 2 125 RAD 0,016 THK, 2 00 RAD,	182 73	150 73
	7	YES	YES	2,650	-	660	STAINLESS STEEL	0 035 THICK 4 375 RAD	357	300
	8	YES	YES	4,800	-	1,040	STAINLESS STEEL	0 050 THICK 6 25 RAD	730	400
	9	YES	NO	4,800	-	834 (RESULTS IN 12,500 FT LBS BEND)	STAINLESS STEEL	0 060 THICK 7 50 RAD	1,050	
16 EXTENDIBLE REEL STORED	1	YES	NO	16,000	530	4,030	STAINLESS STEEL	0 063 THICK 7 875 RAD	1 640	
	2	YES	NO	4 800	160	1 670	STAINLESS STEEL	0 05 THICK 6 25 RAD	910	
	3	YES	NO	5,200	173	416	STAINLESS STEEL	0 04 THICK 5,00 RAD	580	
	4	YES	YES	3,840	320	920	STAINLESS STEEL	0 045 THICK 5 625 RAD	735	365
	5	YES	YES	0	0	194	STAINLESS STEEL	0 032 THICK 4 00 RAD	370	250
	6	YES	YES	400 (FRONT) 320 (AFT)	-	103 (FRONT) 64 (AFT)	(FRONT) (AFT)	0 020 THK, 2 50 RAD 0 016 THK, 2 00 RAD	145 93	120 67
	7	YES	YES	2,650	-	660	STAINLESS STEEL	0 03 THICK 3 75 RAD	325	280
	8	YES	YES	4 800	-	1,040	STAINLESS STEEL	0 045 THICK 5 625 RAD	735	365
	9	YES	NO	4,800	-	834 (RESULTS IN 12,500 FT LB BENDING)	STAINLESS STEEL	0 050 THICK 6.25 RAD	910	

FOLDOUT FRAME 3

FOLDOUT FRAME 4

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	STAINLESS STEEL, AREA OF R_1 15 27 THICK 0 0386 T_1 = 15 44 W R = 100T R_1 = 300T	1,510			2 2	1 350 1,118	104 70			CANNOT BE STOWED CANNOT BE STOWED
STEEL	0 0308 T_1 = 12 32 W	958			2	1,118	70			CANNOT BE STOWED
STEEL	0 0232 T_1 = 9 28 W	545								
STEEL	0 0279 T_1 = 11 16 W	788	450		2	1 129	70		MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT FWD PANELS SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEM REQUIRED FOR AFT PANEL PULL-OUT	EXCESSIVE WEIGHT
STEEL	0 017 T = 6 8 W	310	300	(610 x 2 = 1220)	2	2200	76	3,496	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT FWD PANELS TWO TO SIX DEPLOYABLE STRUCTURES AND MECHANISM REQUIRED FOR AFT ASSY	EXCESSIVE WEIGHT AND COMPLEXITY
(FRONT) (AFT)	0 020 T = 8 0 W 0 017 T = 6 8 W	402 294	180 100	(582 x 4 = 2328) (3904) (394 x 4 = 1576)	4 4	1,080	-	4,984	FOUR MOTOR DRIVEN REELS EXTEND BEAMS AND PULLS-OUT PANELS	EXCESSIVE WEIGHT
STEEL	0 034 T = 13 6 W	1,170	350	(1520 x 2 = 3040)	2	1,118	70	4,228	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT PANELS	CANNOT BE STOWED
STEEL	0 040 T = 16 0 W	1,620	450	(2070 x 4 = 8280)	4	1 080	-	9,360	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS OUT PANELS TWO REQUIRED PER WING A PYROTECHNIC LOCK IS REQUIRED.	EXCESSIVE WEIGHT
STEEL	0 057 T = 22 8 W	3,280			2	1,010	74			CANNOT BE STOWED
STEEL	0 070 THICK 8 73 BAD	1 430			2	1 350	104			CANNOT BE STOWED
STEEL	0 060 THICK 7 50 BAD	1,050			2	1 118	70			CANNOT BE STOWED
STEEL	0 040 THICK 5 00 BAD	467			2	1 118	70			CANNOT BE STOWED
STEEL	0 050 THICK 6.25 BAD	730	400	(1130 x 2 = 2260)	2	1,129	70	3,458	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT FWD PANELS SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEM REQUIRED FOR AFT PANEL PULL-OUT	EXCESSIVE WEIGHT
STEEL	0 032 THICK 4 00 BAD	298	250	(548 x 2 = 1096)	2	2 200	76	3 372	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT FWD PANELS TWO TO SIX DEPLOYABLE STRUCTURES AND MECHANISM REQUIRED FOR AFT ASSY	HEAVY AND COMPLEX
(FRONT) (AFT)	0 025 THK, 3 125 BAD 0.016 THK, 2 00 BAD,	182 75	130 75	(332 x 4 = 1328) (1928) (150 x 4 = 600)	4 4	1 080	-	3,008	FOUR MOTOR DRIVEN REELS EXTEND BEAMS AND PULLS-OUT PANELS	A WORTHY CANDIDATE, SHOULD BE REVIEWED FOR OPTIMIZATION AND COMPARED TO OTHER CANDIDATES.
STEEL	0 035 THICK 4,375 BAD	357	300	(657 x 2 = 1314)	2	1 118	70	2,502	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT PANELS	A GOOD CANDIDATE, SHOULD BE REVIEWED FOR OPTIMIZATION AND COMPARED TO OTHER CANDIDATES
STEEL	0 050 THICK 6 25 BAD	730	400	(1130 x 4 = 4520)	4	1 080	-	5,600	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT PANELS, TWO REQUIRED PER WING A PYROTECHNIC LOCK IS REQUIRED.	EXCESSIVE WEIGHT
STEEL	0 060 THICK 7 50 BAD	1,050			2	1,010	74			CANNOT BE STOWED
STEEL	0 063 THICK 7 875 BAD	1 440			2	1,250	104			CANNOT BE STOWED
STEEL	0 05 THICK 6 25 BAD	910			2	1 118	70			CANNOT BE STOWED
STEEL	0 04 THICK 5,00 BAD	580			2	1,118	70			CANNOT BE STOWED
STEEL	0 045 THICK 5 625 BAD	735	365	(1100 x 2 = 2200)	2	1 129	70	3,398	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT FWD PANELS SIMPLE, WIDELY USED, MOTORIZED REEL AND CABLE SYSTEM REQUIRED FOR AFT PANEL PULL-OUT	EXCESSIVE WEIGHT
STEEL	0 032 THICK 4 00 BAD	370	250	(620 x 2 = 1240)	2	2,200	76	3,516	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT FWD PANELS TWO TO SIX DEPLOYABLE STRUCTURES AND MECHANISM REQUIRED FOR AFT ASSY	EXCESSIVE WEIGHT AND COMPLEXITY
(FRONT) (AFT)	0 030 THK, 2 50 BAD 0 016 THK, 2 00 BAD	145 93	120 87	(265 x 4 = 1060) (1780) (180 x 4 = 720)	4 4	1 080		2 800	FOUR MOTOR DRIVEN REELS EXTEND BEAMS AND PULLS-OUT PANELS	A WORTHY CANDIDATE, SHOULD BE REVIEWED FOR OPTIMIZATION AND COMPARED TO OTHER CANDIDATES
STEEL	0 03 THICK 3 75 BAD	325	280	(605 x 2 = 1210)	2	1 118	70	2,398	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS-OUT PANELS	A GOOD CANDIDATE SHOULD BE REVIEWED FOR OPTIMIZATION AND THE PROBLEM OF STOWAGE
STEEL	0 045 THICK 5 625 BAD	735	365	(1100 x 4 = 4400)	4	1 080	-	5,480	MOTOR DRIVEN REEL EXTENDS BEAM AND PULLS OUT PANELS TWO REQUIRED PER WING A PYROTECHNIC LOCK IS REQUIRED	EXCESSIVE WEIGHT
STEEL	0 050 THICK 6.25 BAD	910			2	1 010	74		-	CANNOT BE STOWED

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4.1 3 Solar Array Flexible Substrate Assembly

With the advent of large space station concepts, photovoltaic power system projected sizes have grown ten times compared to that of the largest previously flown Conventional rigid solar panels needed to meet the new size requirements have outgrown the weight and volume allowances. Since 1964 lightweight solar array design activities have been underway. Fairchild-Hiller and Ryan initiated investigation, followed by Hughes, Boeing, G E., and Lockheed. Several foreign firms and government agencies have also designed flexible type solar arrays, i.e., Royal Aircraft Establishment, British Aircraft and Messerschmitt.

Each evaluated individual components, investigated fabrication processes, built prototype solar arrays ranging in size from 8 1 to 250 ft^2, and conducted component and assembly testing

This section covers the technology review of existing data gleaned from the available investigators reports and manufacturers data sheets, technical conferences, and personal contacts.

The major subjects to be discussed are (1) Flexible materials most commonly used and other possible substrate candidates, (2) Interconnect configurations, materials and joining techniques, (3) Solar cells as selected for flexible solar arrays to date and solar cells presently available for consideration, (4) Feeder harness summary, (5) Flexible material joining techniques, (6) Temperature cycling summary of existing designs, (7) Thermal control design approaches and, (8) On-array electronic power conditioning.

4.1.3.1 Flexible Substrate Materials

The feasibility of flexible light-weight solar arrays became practical with the development of high-strength thin film plastic materials. A candidate material for such a mission as required by the Space Station must meet the demands of both the mechanical requirements and the rigors of a 10-year space environment. Such thin film requirements can thus be listed as follows

- It must be highly flexible, experience minimum elongation under load, and have a high tensile strength.
- It must be an electrical insulator.
- It must be stable in space environment (hard vacuum, radiation, and temperature extremes).
- Ideally, it should be highly transmissive to infrared wavelengths to transfer heat directly from the cell back surface to space or be compatible with thermal coatings that may have to be applied.
- It must be transparent enough to inspect backside solder joints.
- It is also desirable to have a thin film material useable with printed circuit technology and resistant to damage from soldering and other manufacturing operations.

Based upon this, candidate substrate materials that have been evaluated include Kapton, FEP Teflon, Aclar, Nomex, Mylar, and Teflon (FEP and TFE) impregnated fiberglass (see Chart M). These basic materials were most commonly selected by flexible substrate designers for evaluation either because of their mechanical properties, environmental stability, or their applicability to a laminate system. Each has good dielectric strength and is readily available in thin film form and in a variety of thicknesses and widths.

Kapton and Mylar have been widely used because of their structural qualities. Mylar comes in a variety of types. Type T was considered because of its very high tensile strength. When data for Type T were not available, properties of the commonly used Type A were inserted in Chart M. Nomex, a high temperature resistant nylon paper, has not as yet been considered for flight hardware use, however, because of its high tear resistance and low cost, it may be very suitable for use as a mockup substrate for the Space Station array. Teflon and Aclar were chosen as candidate adhesive systems

because of their ability to be heat sealed. (Type C FEP-Teflon is listed in the Chart because its treated surface allows a lower heat sealing temperature and greater adhesion than the untreated Type A). FEP-TFE impregnated fiberglass is not only heat sealable because of its inherent FEP-Teflon, but also has excellent tear resistance. Kapton and Mylar have relatively good edge tear resistance but have very low propagating tear strength (8 gm/mil and 20 gm/mil, respectively).

In a space environment the radiation effects indicate that Kapton is superior to Mylar, which discolors and becomes brittle. In addition, Aclar (the optically clear type 22A) becomes brittle while FEP and FEP-TFE impregnated fiberglass are almost unaffected. In addition, Mylar has a service temperature range of only -70°C to 150°C as compared to a range for Kapton of -270°C to +400°C. FEP-Teflon and FEP-TFE impregnated fiberglass have useful temperature limits of -240°C to +200°C.

From these general observations and the experience of nine domestic and three foreign flexible substrate developers, Kapton, FEP Teflon, and FEP-TFE impregnated fiberglass stand as the most widely used choices for flexible substrates. However, additional critical material property information is required before a final selection can be made for application to the Space Station requirements. Tensile strength, creep values, and tear strength properties as a function of the expected temperature and load ranges are vital in designing for an artificial-g condition where abnormally high loading occurs. The logical approach to obtain the needed information is to procure representative sample substrates from the various developers and include other practical combinations of materials in a test evaluation program.

NO.	MATERIAL	RELATIVE COST	PROPERTY TEMP UNLESS OTHERWISE NOTED	ULTIMATE TENSILE STRENGTH (PSI)	YIELD POINT AT 3% (PSI)	STRESS TO PRODUCE 5% ELONGATION (PSI)	ULTIMATE ELONGATION (%)	TENSILE MODULUS (PSI)	FOLDING ENDURANCE (CYCLES)	TEAR STRENGTH INITIAL (GRAVES) gm/MIL	TEAR STRENGTH PROPAGATI (EMELDORF) gm/MIL	SPECIFIC GRAVITY	DIMENSIONAL STABILITY STRESS (PSI)	DIMENSIONAL STABILITY TIME (HR)	DIMENSIONAL STABILITY TEMP (°C)	DIMENSIONAL STABILITY CREEP %	MELTING POINT (°C)	Z STRE TI (
1	KAPTON H-FILM (POLYIMIDE) (1 MIL)	1.0	-195°C 25°C 200°C	35,000 25,000 17,000	10,000 6,000	13,000	2 70 90	510,000 430,000 260,000	10,000	510	8	1.42	8800 8800 8800 8800	1 12 24 96	100 100 100 100	5.2 5.8 5.9 6.0	NONE	8
2	TEFLON FEP (FLUORO-PLASTIC) (1 MIL)	0.62	25°C	3,000	1,700	NOT REPORTED	300	70,000	4,000	270	125	2.15	NOT REPORTED				260-280	2
3	ACLAR 22A (CTFE) (1.5 MIL)	0.29	ROOM	(MD)8,000 TO 11,000 (TD) 4,000 TO 6,000	NOT REPORTED		(MD)150 TO 250 (TD)200 TO 400	MD- 143,000 TD- 133,000	NOT REPORTED	(MD)480 (TD) 420	(MD)200 (TD) 50	2.08	NOT REPORTED				183-186	
4	NOMEX (TYPE 410) (2-MIL)	0.28	ROOM 200°C	(MD)11,000 (TD) 6,500 (MD) 8,150 (TD) 4,550	NOT REPORTED		(MD) 10 (TD) 8	NOT REPORTED	250,000	NOT REPORTED	(MD)47.5 (TD) 70	0.75 TO 1.1	NOT REPORTED				NONE	
5	MYLAR (TYPE T) (POLYESTER) (1-MIL)	0.08	25°C	45,000	NOT RE-PORTED	23,000	40	800,000	100,000	450	20	1.377	3000 3000 3000 500	24 260 1000 4000	25 25 25 100	0.03 0.1 0.2 0.9	250	NOT REPO
6	FEP, TFE COATED FIBERGLAS (50% FEP, TFE BY WEIGHT)	1 40	NOT REPORTED															

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CANDIDATE SUBSTRATE MATERIAL PROPERTIES

SPECIFIC GRAVITY	DIMENSIONAL STABILITY				MELTING POINT (°C)	ZERO STRENGTH TEMP (°C)	COEFF OF THERMAL EXPANSION (IN./IN./°C)	COEFF OF THERMAL CONDUCTIVITY (CAL) (CM) (CM²) (SEC) (°C)	SPECIFIC HEAT CAL/gm/°C	HEAT SEALABLE	SHRINKAGE	USABLE TEMP LIMITS (°C)	EMISSIVITY	ABSORPTIVITY	TRANSMISSIVITY	REFLECTIVITY
	STRESS (PSI)	TIME (HR)	TEMP (°C)	CREEP %												
1.42	8800 8800 8800 8800	1 12 24 96	100 100 100 100	5.2 5.8 5.9 6.0	NONE	815	2.0×10^{-5} (14° C TO 38°C)	3.72×10^{-4} 4.26×10^{-4}	0.261 @40°C	NO	0.3% @ 250°C 0.5% @ 300°C 3% @ 400°C (FOR 30 MIN)	-269 TO 400	INFRARED $\epsilon \approx 0.34$	NOT REPORTED	0.66	~0.13
2.15	NOT REPORTED				260-280	255	2.55×10^{-5} @ -77°C 5.0×10^{-5} @ 100°C	4.65×10^{-4}	0.28	YES (280°C TO 370°C)	0 7% STRETCH (IN M.D.) 2.2% SHRINK (IN T.D.) 150°C, 30 MIN	-240 TO +200	NOT REPORTED	0 03 FROM 0.5 TO 3.8 μm	96% FROM 0.5 TO 3.8 m	NOT REPORTED
2.08	NOT REPORTED				183-186	NOT REPORTED		5.3×10^{-4}	NOT REPORTED	YES (230°C TO 260°C)	12% STRETCH (IN M.D.) 12% SHRINK (IN T.D.) 150°C, 30 MIN	NOT REPORTED		~0 03 AT 0.8 μm <0.08 TO 6.8 μm	~93% AT 0.8 μm ~80% TO 6.8 μm	NOT REPORTED
0.75 TO 1 1	NOT REPORTED				NONE	NOT REPORTED		0.262	NOT REPORTED		1 6% (IN M D.) 1.9% (IN T.D.) AT 300°C	UP TO 220	NOT REPORTED			
1.377	3000 3000 3000 500	24 260 1000 4000	25 25 25 100	0.03 0.1 0 2 0.9	250	NOT REPORTED	1.7×10^{-5} (30°C TO 50°C)	3.7×10^{-4} (25°C TO 75°C)	0.28	NO (UNLESS COATED OR TREATED)		-70 TO 150	NOT REPORTED			
										YES (SAME AS FEP-TEFLON)	NOT REPORTED					

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Y	ABSORPTIVITY	TRANSMISSIVITY	REFLECTIVITY	DIELECTRIC STRENGTH (1-MIL, 60 CYCLES (VOLTS)	MOISTURE ABSORPTANCE	OUTGASSING WEIGHT LOSS	RADIATION RESISTANCE	AVAILABILITY
D	NOT REPORTED	0.66	~0.13	10,800 7,000 5,600	2.9% IN H_2O FOR 24 HR AT 23.5°C	0 25% IN HELIUM FOR 2 HR AT 400°C	NO LOSS IN TRANSMISSION AFTER 10^{14}, 800 KEV PROTONS/CM^2, 2.6 X 10^{17}, 1 MEV ELECTRONS/CM^2 OR UV UP TO 9600 ESH	0.25 TO 5 MILS 6036 IN. MAX WIDTH
D	0.03 FROM 0.5 TO 3.8 μm	96% FROM 0.5 TO 3.8 m	NOT REPORTED	6,500	<0.01% IN H_2O FOR 24 HR AT 23 5°C	–	NO LOSS IN TRANSMISSION AFTER 10^{14}, 800 KEV PROTONS/CM^2 OR 2 6 X 10^{17}, 1 MEV ELECTRONS/CM^2. 4.5% LOSS IN TRANSMISSION AFTER 2 EQUIVALENT SOLAR YEARS OF UV.	0.5 TO 20 MILS 48 IN. MAX WIDTH
	~0 03 AT 0.8 μm <0.08 TO 6.8 μm	~93% AT 0.8 μm ~80% TO 6.8 μm	NOT REPORTED	3,700	NIL		NO LOSS IN TRANSMISSION AFTER 10^{14}, 800 KEV PROTONS/CM^2. SPECIMENS DEGRADED QUICKLY UNDER 1 MEV ELECTRONS AND UV RADIATION (BECAME BRITTLE)	1.5 AND 5 MILS. 47 IN. MAX. WIDTH
	NOT REPORTED			450	NOT REPORTED			2 TO 30 MILS
	NOT REPORTED			7,500	<0.8% IN H_2O FOR 24 HR AT 23.5°C	NOT REPORTED	NO LOSS IN TRANSMISSION AFTER 10^{14}, 800 KEV PROTONS/CM^2, 5% LOSS AFTER 2.6 X 10^{17}, 1 MEV ELECTRONS, 20% LOSS AFTER 3510 ESH	0.5 TO 1 5 MILS
	NOT REPORTED					0.5% AFTER 5 DAYS AT 350°C	NOT REPORTED	1 TO 30 MILS UP TO 144 INCH MAX WIDTH

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4.1.3.2 Solar Cell Interconnectors

The section which follows presents the results of the literature search on cell interconnectors. Materials, configurations and joining processes are discussed with reference not only to the existing flexible array studies but also to rigid arrays and other applicable areas of technology. In addition, the interconnector data compiled and the results of its evaluation are presented as applicable to the space station array design and fabrication.

4.1.3.2.1 Interconnector Materials. Seven basic materials repeatedly appear in solar conversion literature as either recommended for, or actually used on, solar arrays for cell-to-cell and bus strip interconnections. These materials are aluminum, beryllium-copper, copper, Kovar (an alloy composed of 53-percent Fe, 29-percent Ni, 17 Co), molybdenum, nickel, and silver. Silver and solder are most frequently mentioned coatings, with tin and gold also often used.

To aid in the comparison of the solar cell interconnector materials, their basic physical properties are presented in Table 4-1. Silicon and titanium are included because many of the reports reviewed recommended materials with coefficients of thermal expansion compatible with the silicon cells (e.g., copper in Refs T.3-9, and M.4-2; and Kovar in Refs. N.4-16 and E.2-1), while titanium is used for cell ohmic contacts.

Particular mission requirements dictate material/coating selections. Therefore, selecting an interconnect material/coating has required designers to first examine expected environments to which a solar array will be exposed, then determine how these environments will affect the stresses between cells and interconnects. Final selections then became a function of how various designers balance electrical and thermal characteristics, while keeping in mind the joining processes to be used.

The results of studies published prior to 1968 more or less concerned the "proving out" of particular designs for specific contracted missions or investigations. Since 1968, however, it appears that more emphasis has been given toward conducting specific material comparison tests in an effort to optimize interconnector materials by expanding our knowledge of their basic behavior in the environmental extremes of space.

TABLE 4-1

PROPERTIES OF INTERCONNECTOR MATERIALS

	Specific Gravity (20°) C	Specific Heat Cal/GM-CM	Resistivity	Thermal Cond BTU/HR/ft²/°F/ft	Coefficient of Linear Expansion /°C	Tensile Strength lb/sq in	Joining Properties[1]		
							Soldering	Welding	Brazing
Silicon	2 33	0 181	$1\text{-}10 \times 10^6$	87 5	$2\ 8\text{-}7\ 3 \times 10^6$	-	N/A	N/A	N/A
Aluminum	2 71	0 214	2.655 (20°)	72	$23\ 9 \times 10^{-6}$	24,000	Poor	Good	Poor
Beryllium-Copper	8 21	0.100	5 320 (20°)	105	$9\ 3 \times 10^{-6}$	70-200,000	Exc	Exc	Good
Copper	8 89	0.0921	1.673 (20°)	211	$16\ 5 \times 10^{-6}$	36-40,000	Exc	Fair	Good
Gold	19 32	0.031	2.420 (20°)	172	$14\ 2 \times 10^{-6}$	49-32,000	Poor	Exc	Good
Kovar	8 31	0.105	49 (25°)	9 9	$5\ 7 \times 10^{-6}$	135,000	Exc[2]	Exc	Good[2]
Molybdenum	10 2	0.061	5.70 (20°)	76	$4\ 9 \times 10^{-6}$	100,000	Good[2]	Fair[2]	Fair
Nickel	8 9	0.105	6.84 (20°)	23	$13\ 3 \times 10^{-6}$	155,000	Good	Exc	Good
Silver	10 5	0 056	1.59 (20°)	242	$19\ 7 \times 10^{-6}$	42,000	Exc	Fair	Good
Titanium	4 54	0 126	42 (20°)	7 0	$8\ 5 \times 10^{-6}$	130,000	Good[2]	Good[2]	Good[2]

1 for Solar Cell Applications
2 If material is plated

Unfortunately, a selection of interconnect material/coatings cannot be reduced to a simple formula. For example, molybdenum and Kovar are each good choices for thermal compatibility with silicon. Yet, a principal problem associated with molybdenum is a difficulty in obtaining quality platings (ref. Table 4-2). By the same token, a mission requirement for nonmagnetic materials would eliminate Kovar or Invar because of their high iron content.

Comprehensive new data were published this year by Heliotek in their study reports on Development of an Integrated Lightweight Flexible Silicon Solar Cell Array (Ref. H.3-1 through -4). In these reports they modify somewhat the importance of matching coefficients of thermal expansion to silicon. Instead, they point out that by reducing the thickness of interconnect material, some of the effects of thermal mismatch are greatly reduced. "There is no clear cut indication of the superiority of any one metal interconnect." (taken from the study of Structural Failures in Lightweight Solar Cell Arrays Under Thermal Cycling, Table 4-3 and Bibliography Ref. M.4-2). The metal chosen should be no thicker than 1 mil. This holds true even when temperatures are to be experienced that are on the order of -175°C (Ref. H.3-2). With selected materials kept to 1 mil thicknesses, the emphasis shifts to joining methods and interconnect design (i.e., to keeping interconnect/solar cell joints and interface areas as small as practicable so as to reduce the likelihood of silicon "divoting" at these low temperatures.)

Brief abstracts of each of the seven materials as used by the various manufacturers appear in Tables 4-2 through 4-9

LSSSA Materials Application. In light of the foregoing, it is not yet advisable to reject any of the cited interconnection materials for LSSSA, especially if rejection were to be based only on data presented to date. This stems from the fact that there is a pronounced lack of standardized thermal cycling comparison data, particularly with materials in the 1 mil to 1.5 mil thickness range, configured for optimum stress relief.

A standardized comparison testing program is therefore recommended, since the scattered material selection tests were predominately oriented to verifying adequacy for specific mission objectives. LSSSA's 10 year service life requirement is way beyond the limits envisaged for these missions.

TABLE 4-2

SOLAR CELL INTERCONNECTOR MATERIAL

MOLYBDENUM

Source	Comments	Bib No
AEG-Telefunken	Silver coated molybdenum interconnects gave good performance, as did 50 micro-meter silver mesh, when RC welded to solar cell contacts This is comparable to regular modules interconnected with solder	A 1-1
European Space Research Organization (ESRO)	Molybdenum and Kovar as interconnect materials show great promise	E 2-1
Heliotek	When solar arrays are subjected to a high number of thermal cycles with large temperature excursions - interconnect metal should be thermally matched with silicon (with the emphasis on molybdenum)	H 3-12
Lockheed Missiles & Space Co (LMSC)	Conventional interconnects formed from 3-mil molybdenum with gold flash and silver plate	Classified Report
MIT	Primary cracks were influenced by thermal mismatch between silicon of the solar cells and the interconnect metal Molybdenum gave the best results, copper the worst	M. 4-2
NASA-Goddard	Gold plated molybdenum bus bar is used for series and parallel interconnections of 48 cells in series and 5 cells in parallel - on Explorer XXXIII, Anchored Interplanetary Monitoring Platform	N. 2-10
Ryan Aeronautical	A principle problem associated with molybdenum is the difficulty of obtaining vendors capable of plating molybdenum	R 4-6

MOLYBDENUM (Continued)

Source	Comments	Bib. No
RAE	When mounting and interconnecting solar cells on flexible substrates, current indications favor wrap-around cell, punched holes and simple foil interconnections of silver-plated molybdenum or annealed copper.	R 3-4
TRW	Tests show that when 0.003 inch thick interconnectors of molybdenum, Kovar and copper, were thermal cycled 100°C to -175°C @ 10°C-25°C per minute, failure levels correspond with their relative coefficients of thermal expansion The tests also confirm that failure levels increase with interconnector thickness It was concluded that molybdenum or Kovar joints fail less rapidly than those of copper	T. 3-9

TABLE 4-3

SOLAR CELL INTERCONNECTOR MATERIAL

COPPER

Source	Comments	Bib No
AMAX Copper, Inc.	Cooper joining techniques (welding, brazing, and soldering) are applicable to interconnecting solar cells	Copper Joining Techniques Review
European Space Research Organization (ESRO)	Copper has disadvantages as interconnect material due to coefficient of thermal expansion problems it presents	E 2-1
Heliotek	Copper interconnect offers no fatigue advantage over aluminum.	H 3-1
	For interconnects with coefficients of thermal expansion much higher than silicon (e.g - copper), and for interconnects with coefficients quite near to that of silicon, such as molybdenum, calculated solder stresses show only slight variation. Further, these stresses are quite close to the tensile strength of solder which varies from 6400 psi at room temperature to approximately 10,000 psi at temperatures below -100°C Copper exhibited a steadily increasing number of surface cracks up to a maximum of 92% cracked solder joints at 350 thermal cycles. A large margin in design of interconnect thickness and material is allowed if temperature cycle is in the range of 0°C to -100°C However, if temperatures on the order of -175°C are to be experienced then 0.0035 inch is the thickest interconnect which will provide a safe system (preliminary finding - ref note in TRW below).	H 3-2
	Copper is marginal for design when temperature changes of 150°C or more are encountered.	H. 3-12

COPPER (Continued)

Source	Comments	Bib No
Hughes	Expanded copper mesh, tin-plated, for bus leads on a Flexible Integrated Solar Cell Array (FISCA), was selected.	H. 6-2
	Expanded copper mesh for cell interconnects and etched copper foil for power buses were used on the Large Retractable Solar Cell Array (LRSCA) Etching of 0 0007 inch thick copper foil bus strips on 0 0005 and 0 001 inch thick Kapton base	H. 6-8
LMSC	Dead soft copper was photoetched and sandwiched between two layers of Kapton F-film to form a flexible substrate with integral interconnects It was found that after 1300 thermal cycles between -200°F and +140°F, there was no physical degradation of the interconnect.	L 4-3
	Other tests by MIT - Lincoln Labs indicated that after 1200 thermal cycles between -256°F and +140°F in dry Nitrogen there was cell cratering caused possibly by the amount of solder used	M 4-2
MIT	Primary cracks were influenced by thermal mismatch between silicon and the interconnect metal - molybdenum gave best results, copper the worst	M 4-2
NASA-JPL	When comparing dead soft tin plated copper, nickel A, and Kovar - any one of these can be used However copper has the best electrical conductivity, nickel is the most easily welded, and Kovar provides the best match with silicon in coefficient of thermal expansion.	N 4-1

COPPER (Continued)

Source	Comments	Bib. No
Royal Aircraft Establishment (RAE)	Annealed copper is favored along with silver-plated molybdenum for solar cell interconnections	R 3-4
	Copper foil interconnects (annealed Cu) are favored for mounting and interconnecting solar cells on flexible substrates, along with silver-plated molybdenum	R 3-4
Ryan Aeronautical	Copper foil, aluminum foil, copper-clad aluminum foil, and silver plated aluminum foil were considered initially during the Feasibility Study for the Roll-up Solar Array (Copper-clad aluminum foil was not available, however)	R 4-6
	Copper with silver plate appears to be the best bus bar* material * cell-to-cell	R 4-6 R 4-8
TRW	Tests show that when 0 003 inch thick interconnectors of Copper, Kovar, and molybdenum, were thermal cycled 100°C to -175°C @ 10°C-25°C/minute, failure levels correspond with their relative coefficients of thermal expansion, i e - copper proved to be the worst of the three, particularly poor showings* occurred at lower temperature extremes as the number of cycles at these extremes increased The tests confirm that failure levels increase with interconnector thickness It was concluded that copper joints fail more rapidly than either Kovar or molybdenum *Note Comparison of the 3 materials was not made in any thinner gauges than 0 003 inch Only Kovar was tested in the 0 001 inch thickness. Findings, therefore, conflict somewhat with a more recent study finding by Heliotek which appears above	T 3-9

TABLE 4-4

SOLAR CELL INTERCONNECTOR MATERIALS

ALUMINUM

Source	Comments	Bib No
Alpha Metals Inc	Nickel and tin-nickel are effective barrier coatings that permit joining of normally unsolderable materials such as aluminum and silicon.	A 4-1
Electro-Optical Systems (EOS)	Electroformed aluminum contact solar cells are discussed	E 1-1
Heliotek	Aluminum is recommended as a low Z interconnect material in order to minimize the absorbed energy step function that generates localized thermo-mechanical stresses Type 1100 Aluminum alloy, in an H25 temper condition, and in expanded metal form is used for interconnecting lithium doped hardened solar cells (aluminum is EXMET Corp Part No 2A16-3/0)	H 3-5
Ion Physics	Aluminum ribbon (3 mils thick x 320 mils wide) is bonded to solar cells contacts with a Unitek Z-axis welding unit and a Sonobond Power Supply, using ten grams of tip pressure.	I. 3-12
NASA-JPL	In efforts to improve solar cells, many material systems may be considered Some of these material systems have previously been investigated for use in silicon transistors The more subtle disadvantages are just beginning to be apparent As an example, aluminum is still the material most commonly used as interconnection metal in transistors It is now known to have limitations of (1) reacting with gold, (2) migrating at elevated temperatures and high current densities, (3) attacking silicon dioxide, and (4) forming gross grain structure which increases the resistance	N. 4-2

ALUMINUM (Continued)

Source	Comments	Bib No
NASA-LeRC	Aluminum foil (1 mil thick) is used to interconnect six-cell series strings without physically bonding the foil to the cell Cells and interconnects are sandwiched between 2 layers of FEP Teflon (which is bonded to the cells) Foil is held in pressure contact on the cell contacts by the FEP packaging	N 6-4
RCA	Aluminum foil has been shown to be a practical substrate for fabricating flexible, lightweight (GaAs thin film solar) cells	R 1-8
Ryan Aeronautical	The power bus (as differentiated from the silver-plated copper cell-to-cell interconnects) conductor, aluminum 1100 EC-grade, was selected for its weight advantage Aluminum was silver plated locally where solderability was needed This enabled repeated soldering operations during fabrication Aluminum bus bars with nickel and silver plate and with copper and silver plate streched and wrinkled slightly when exposed to slightly over 100 thermal cycles (-148°F to +168°F @ 54°F/minute)	R 4-8
TRW	Aluminum interconnects joined with ultrasonic bonding techniques is being done at TRW Repair problems were encountered with the process	LMSC Trip Report 10-29-70

TABLE 4-5

SOLAR CELL INTERCONNECTOR MATERIALS

BERYLLIUM - COPPER

Source	Comments	Bib No
General Electric	Photoetched beryllium-copper can be used for interconnect tabs	G. 2-1
	Use of beryllium-copper or silver interconnections for the Roll-Up Solar Array is doubted, because their coefficients of thermal expansion are too great when compared to silicon over the -250°F to +200°F range.	G 2-4

TABLE 4-6

SOLAR CELL INTERCONNECTOR MATERIAL

KOVAR

Source	Comments	Bib No
European Space Research Organization (ESRO)	Kovar and molybdenum as interconnect materials have many advantages	E 2-1
Lockheed Missiles & Space Co (LMSC)	SERT II interconnects were formed from 10-mil, perforated, gold plated Kovar with conventional tabs The rigid arrays for SESP had conventional interconnects formed from 3-mil Kovar with Nickel/Silver plate.	
NASA-JPL	Kovar provides the best match with silicon in coefficient of thermal expansion (when compared with dead soft tin-plated copper, and Nickel A)	N 4-2
	Mariner IV used Kovar for interconnects because of its thermal match to that of silicon.	N 4-16
TRW	Tests show that when 0 003 inch thick interconnectors of Kovar, copper, and molybdenum, were thermal cycled 100°C to -175°C @ 10°C-25°C/minute, failure levels correspond with their relative coefficients of thermal expansion The tests confirm that failure levels increase with interconnector thickness It is concluded that Kovar or molybdenum joints fail less rapidly than those of copper	T 3-9
	For lunar application, use of Kovar interconnects are favored Traditionally photoetched, or stamped interconnects were used as opposed to expanded mesh	LMSC Trip Report 10-20-70

TABLE 4-7

SOLAR CELL INTERCONNECTOR MATERIAL

NICKEL

Source	Comments	Bib No.
NASA-JPL	Of three typical materials available for interconnector selection, dead soft tin plated copper, Nickel A, and Kovar, Nickel A is the most easily welded	N 4-2
Alpha Metals, Inc	Nickel and tin-nickel are effective barrier coatings that permit joining of normally unsolderable materials such as aluminum and silicon	A. 4-1

TABLE 4-8

SOLAR CELL INTERCONNECTOR MATERIAL

SILVER

Source	Comments	Bib No
The Boeing Company	Expanded silver mesh was used on the Large Area Solar Array concept	B 3-8
	Expanded silver mesh (0 002 inch), pulse soldered, was used to interconnect solar cells for the Boeing Mars Mission Solar Array	Semi-annual Report Feb 1970
British Aircraft	In their study, expanded silver mesh is detailed as follows "4. 5 mm x 4 0 mm, with strand width of 0. 25 mm, a thickness of 0. 063 mm and a weight of 130 grams/sq. meter Four welds are made per cell along the top N solar cell contact and up to 9 welds on the bottom P contact.	B 2-2
COMSAT	Solar cells were interconnected* using expanded metal mesh.	U S Patent #3,459,391 Aug. '69
	*Note Section 3, line 39 - Coated over the thin layer of bonding material 17, 18 is a thin layer of tin-lead solder 19, 21 respectively, the solder being necessary for the expanded metal interconnectors (See also - Section 6, line 6)	
European Space Research Organization (ESRO)	Expanded silver mesh, when RC welded to solar cell contacts, is comparable to regular modules interconnected with solder	A. 1-1
Fairchild Hiller	Detailed description of the silver expanded mesh and the soldered interconnections used on Fabrication Feasibility Study of a 30 watt per pound Roll-up Solar Array	F 1-2
	Expanded silver mesh is used and can be soldered on the Fabrication Feasibility Roll-up Solar Array.	F 1-4

SILVER (Continued)

Source	Comments	Bib No.
Fairchild Hiller (continued)	Three mil thick expanded silver mesh soldered with 7 - 9 contact points to each cell with 62-36 solder with 2% silver (Sn 62, per Specification QQ-S-571) was used in the Positive Deployable Solar Array Development Program. The mesh is recommended for future module designs.	F. 1-7
General Electric	Expanded silver mesh used for interconnects on the Roll-up Subsolar Array. Infrared heating of solder used for electroplating on the mesh.	G. 2-5
	60/40 tin-lead is selective plated on expanded silver mesh, with a co-deposit of 2% silver to make it "equivalent" to Sn 62 solder.	G 2-6
Hughes	Coarse silver mesh - favored by bend test data - for the Flexible Integrated Solar Cell Array (FISCA).	H 6-6
Messerschmitt	Welded silver mesh interconnects are attached to substrates without use of a bonding agent. Bond strengths of more than 2 KP/Cell were obtained. For connecting solar cells in parallel, silver mesh from cell-to-cell is welded to an integrated wiring arrangement after it is "inter-meshed" with the substrate	M. 3-1

TABLE 4-9
SOLAR CELL INTERCONNECTOR MATERIAL

OTHER

Source	Comments	Bib. No
General Electric	Schjel Clad 5550 or L7510 - are considered as materials for the bus bar function in the Feasibility Study of the Roll-up Solar Array	G 2-1
Royal Aircraft Establishment (RAE)	"Invar" may be used as an interconnection material for the Ion Engine and Large Solar Array for the X-5 Spacecraft Its coefficient of thermal expansion is close to that of silicon However, it has the advantage of being ferromagnetic.	R 3-5

Should above tests reveal that molybdenum be selected as the best interconnect material, then there would be a pressing need to establish reliable, high-quality low-cost plating techniques for this material. As Ryan Aeronautical stated regarding molybdenum (see Table 4-2), there is now a problem in obtaining vendors capable of plating this material.

IBM claims that a new alloy of aluminum with 4-percent copper added substantially retards electromigration (Materials Engineering Magazine, September, 1970, page 23). This new material is but one example of a material not now being considered, but which might be worthy of inclusion in the selection tests.

Aluminum is recommended as a low-Z interconnect material (see Table 4-4). There is a void in the information regarding the importance of this factor for LSSSA. A decision regarding the importance of low-Z materials is recommended early in the material elimination test phases.

4.1.3.2.2 Interconnector Configurations. This section pertains to electrical interconnections between groups of solar cells in parallel and in series. Electrical power for spacecraft systems is generally provided by large numbers of cells connected in this fashion to obtain the necessary currents and voltages

Almost every company ever concerned with designing solar cell arrays has specific configurations which it considers to be uniquely advantageous and therefore proprietary As a result, a wide variety of interconnect designs exist today, with also a great deal of similarity

By looking at Chart N on Solar Array Interconnections, one can see that six companies have chosen almost identical designs Fairchild-Hiller, General Electric, Hughes, Boeing, British Aircraft Corporation, and Messerschmitt, all use a version of plated and unplated mesh screen wire The major differences are in the materials selected, the method of manufacturing, and the size of the mesh

Other interconnect designs are distinctive in the way that they vary the degree of redundancy (parallel current paths, increased numbers of interconnects, etc.), which is incorporated to increase mission reliability. For example, Ryan Aeronautical (again, referencing Chart N) used a straight-line type cell-to-cell bus bar for their Feasibility Study for a 30 Watts/Pound Roll-Up Solar Array (Refs. R.4-5 through -3). This design provides three points of contact on each cell 'P' surface, four 'N' tab contacts for series connecting the next adjacent cell. All designs incorporate some degree of redundancy. Similar bus bars for 2 by 6 cm cells, were designed by Martin Marietta for the Apollo Telescope Mount (ATM) Solar Cell Module (Ref. M.1-7).

Lockheed Missiles and Space Company (LMSC) and Royal Aircraft Establishment (RAE) rely on the interconnect points to hold the solar cells on an annealed copper or silver-plated molybdenum bus strip. Buses are sandwiched between two layers of Kapton polyimide film. Four points of contact on each cell supply mechanical strength to retain the cells in position and provide required interconnect redundancy.

For their Advanced Lightweight Solar Array (Ref. R.3-4), RAE uses a circular interconnect bus pattern, each circle is selectively exposed to simultaneously pick up two 'N' contacts and two 'P' contacts of four wrap-around solar cells.

There is considerable concern about the stresses involved when joining metal to a glass. These stresses are caused by differences in thermal expansion and conduction of the materials involved, the joining processes involved, and the interconnect forming techniques. If these stresses are allowed to accumulate at one point and exceed the material/joint capabilities, failure will occur" (quoted from Ref. N.4-2). Heliotek, for Development of An Integrated Lightweight Flexible Silicon Solar Cell Array (Refs. H.3-1 through -4), made its interconnects vary in size and shape to achieve particular thermal stress compensation with the solar cells. Heliotek thus avoided connecting adjacent solder joints by a straight section of interconnect. The theory was that the stresses imposed at one solder joint should not be allowed to travel a straight line to an adjacent solder joint. Several other companies, including Lockheed Electronics Company, Electro-Optical Systems (EOS), and TRW (Ref. N.4-2) use similar curved interconnects to avoid stress accumulations.

The LMSC configuration (Ref. L.4-10), while originally designed for connecting stress compensated series tabs to top 'N' contacts of conventional cells, has easily been adapted to wrap-around cell contacts as well.

Nowhere in cell-to-cell interconnection design is there more concern with stresses than in joining series tabs to top 'N' strip solar cell connections. Thermal environment changes in space produce cell expansion and contraction movements. Therefore, stress loops must be added to series tab configurations so that as cell movements take place there is minimum stress imposed at the joints.

These movements can engender stress loop fatigue which, for Z-type interconnects, causes failures to occur predominately at the tops of the stress loops (Ref. H.3-3). Z-type interconnects refer to etched foil designs, not mesh. Hughes uses an expanded mesh Z-strip for their Flexible Roll-Up Solar Array (Ref. H.6-7), illustrated on Chart N. The mesh is intended to absorb cell movement stresses as they occur.

One way to improve stress loop fatigue resistance is to place loops higher above the cell surfaces (Ref. H.3-1). Heliotek developed a method for calculating this stress loop height (Ref. H.3-12). They calculated that a no-fatigure stress loop would have to be 84 mils high (Ref. H.3-1). For Hughes, this would have been too high. Their Flexible Integrated Solar Cell Array (FISCA) (Ref. H.6-2) had the heights of their series tabs limited to less than 25 mils. Higher tabs would have interfered with deployment of the array by increasing changes of snagging.

Optimum flexure resistance of interconnector material appeared to be when its thickness was 1 mil or less. Materials 1 mil or less in thickness were more fatigue resistant than those greater than 1 mil (Ref. H.3-2).

Along with obtaining the right loop design for the series tabs, there is a related problem of reducing stresses on the joints themselves. British Aircraft Corporation, for their Large Solar Cell Arrays (Ref. R.3-6), emphasizes the importance of keeping effects of thermal mismatch small – "by suitable design, for instance, by keeping areas of soldered joints small and avoiding the encapsulation of metal interconnects in silicon cements."

As part of their Development of an Integrated Lightweight Flexible Silicon Solar Cell Array, Heliotek designed a top series tab interconnect system which offers an "immediate and practical solution" (Ref. H 3-1) to the problem of bending fatigue failures. They devised a wrap-around interconnect system that modifies the Z-type interconnect, so that stresses transmitted to the solder joints, from cell-to-cell dimension changes, are greatly reduced. Small stress loops, approximately 5 mils high, are still evident, but they are mostly to allow space for motion of the cell, so that it does not touch the interconnect at an electrical shorting point. Both total span wrap-around and stress relieved wrap-arounds were found by Heliotek to be much superior to all other concepts in fatigue resistance tests. However, when failures did occur, the mechanism consisted of interconnect metal fatigue, with evidence of surface pitting and tearing at the edges, along with a generally crystalline appearance prior to failure (Ref H.3-3)

NASA-LeRC also recently displayed a design concept (Ref N.6-4) that shows promise of providing relief in the area of potential thermal cycling damage (particularly within the silicon at the interconnect joint, for "solder failure at low temperatures is not the major problem, but instead, silicon divoting is a common failure" (from Ref. H.3-2). NASA-LeRC laid foil on the cell contact areas, then sandwiched cells and interconnects between two layers of FEP Teflon (The top FEP layer performs as a filter cover for the cells, the same function now done by conventional covers.) Pressures created by this bonded Teflon holds the foil in intimate contact with the solar cell conductor areas. Interconnects and cells are free to expand and contract under the Teflon and thus can slide across the solar cell contact surfaces, maintaining electrical connection while doing so.

The advent of the wrap-around contact solar cell brings promise of not only being able to increase the effective area of solar arrays, but also, as Heliotek states, "the wrap-around contact offers the ultimate solution to top series tab interconnection problems from a conceptual viewpoint" (quoted from Ref. H.3-1). Their interconnector studies showed a number of configurations that can substantially improve the reliability of the Flexible Lightweight Silicon Solar Cell Array. "Extending these studies to . . . establishing practical handling for the wrap-around contact cells will provide a further weight-saving without reliability loss" (from Ref. H.3-4).

Interconnector Configurations Potentially Adaptable to LSSSA. As a result of this technology evaluation, several interconnector configurations stand out as potentially adaptable to LSSSA However, they are not necessarily directly applicable in their original configuration. Instead, they might better be considered as ingredients. By combining these ingredients, that is, by using certain favorable characteristics from several designs, an interconnect system for LSSSA could emerge which incorporates the best features of each. For example, Heliotek's wrap-around 'N'-strip interconnector concept might be incorporated into LMSC's flexible substrate design (See Chart N) along with their (Heliotek's) recommendation for 1 mil to 1.5 mil interconnector material thickness and use of calculated interconnect stress loop heights.

Another approach would be to incorporate one of the six expanded mesh designs into a configured design, rigidized by encapsulation in layers of Kapton. Selectively exposed interconnect areas would be allowed for 'P' solar cell contacts and to allow configured areas to be attached to the 'N'-strip surfaces. (Refer to RAE and LMSC design concepts discussed earlier in this section)

At this juncture, a most favorable approach" recommendation for a LSSSA interconnection system cannot be sufficiently justified Instead, a rigidly standardized test program is suggested that would compare thermal cycling behavior of some of these designs singly and/or in combinations similar to those suggested above.

Based on technology reviewed to date, another factor which complicates design selection is that no data exist that compares thermal cycling behavior of basic controlled minimum soldered vs. welded/brazed or ultrasonically bonded interconnection joints when materials, material gauges, and configurations have all been objectively standardized for optimum test results This is mandatory if realistic selection of a joining technique is to be made empirically.

Different cell sizes and configurations require examination in light of interconnect design, for their impact could be severe, particularly since cell changes can profoundly affect basic interconnector designs, e.g., 2 cm by 4 cm cells offer a potential of increased packing density, while wrap-around solar cell contacts promise this and also a greatly simplified 'N' interconnector design. Wrap-around cell contacts would eliminate any need for stress loop configurations for 'N' contacts.

Finally, there is the potential of NASA-LeRC's interconnect system described previously Should the FEP premise prove valid as a quartz substitute, then this configuration too should be tested and compared along with above tests before final selection of LSSSA interconnects is made.

4.1.3.2.3 Interconnector Joining Processes and Materials. Jet Propulsion Laboratory, in their Survey and Study for an Improved Solar Cell Module (Ref. N.4-2) provided extensive and detailed information regarding the various interconnect processes and soldering materials in current use. They described each process in sufficient detail that this single publication can be used as a comprehensive overview of industry practice by itself They covered reflow soldering (single point, parallel-gap, infrared and induction heating, and tunnel ovens), resistance welding, and ultra-sonic bonding.

JPL also included information on solder, its composition, recommended fluxes, and other information pertinent to solar cell joining processes, i.e., "The solubility of silver in a tin-lead solder is about 3 percent at 460°F approximately soldering temperature" (from Ref. N.4-2)

It is unfortunate that, like interconnection configurations, most of the other sources concerned with designing solar cell arrays use processes and techniques that they consider to be uniquely advantageous and therefore proprietary. Consequently, processing information was often found to be rudimentary and lacking in sufficient detail to be usefully applied.

For clarity and convenience, processing abstracts of the materials found are listed in Tables 4-10 through 4-12 in a similar topical order to that used by JPL (Reflow Soldering, Resistance Welding and Ultrasonic Bonding). Additional information in soldering and welding may be found in Tables 4-13 and 4-14.

Joining Processes and Materials Applicable to LSSSA Concepts. The majority of solar cell interconnection systems use soldering for the joining technique (See Chart N). However, with reported adverse thermal cycling affects of solder upon solar cell surfaces at -200°F, extensive work is needed in solderless interconnector development to provide reliable alternatives, if necessary, to soldering. This is not to say that soldering

should be abandoned while solderless interconnect investigations are made. Data voids exist in areas of using minimum amounts of solder in conjunction with the best thermal cycling response materials and interconnector configurations. These voids must be filled before the LSSSA interconnector system is selected.

Data on solderless interconnection methods is scattered and sparse. Only two sources reported extensive use of resistance welding – both are European, British (BAC) and German (for ESRO) see Table 4-11 Neither source provided test data with any degree of uniformity or standardization between them Thus, effective evaluation, based on their data, would not be sufficiently reliable or adequate to make a LSSSA design decision. The same can be said for ultrasonic and thermo-compression bonding data (Heliotek and Ion Physics Corp., Table 4-12) which are also sparse Both of these bonding methods and Electro-Optical Systems' electroformed aluminum contact system appear to warrant increased comparative investigation. In addition, no data exists on proposed techniques such as using silver bearing conductive epoxy/polyurethane-type adhesives for interconnect joints, or sandwiching cells and interconnects between layers of FEP Teflon/Kapton for pressure contact joints (NASA-LeRC)

The following three basic studies are recommended to help fill the gaps of knowledge in three areas

(1) Methods and techniques should be developed for repeatedly making high-quality solderless interconnections to solar cells through welding/brazing, ultrasonic and thermocompression bonding, electroforming, using conductive epoxy/polyurethane-type adhesives, or sandwiching interconnections to solar cells.

(2) Thermal cycling behavior of each developed interconnect system should be compared with the best designed soldered joint system for uniformity and minimum size. This is to be accomplished by objectively standardizing materials, material gauges, configurations, and testing methods to establish high levels of confidence in results obtained.

(3) Trade-off studies should be performed to simultaneously compare the relative manufacturing technical and economic merits of each interconnection system as the above baseline methods and techniques are developed. Final interconnection system selection could therefore be based, not only on technical excellence of a particular system for LSSSA application, but also on its merits with respect to high quality and economical manufacture (particularly its adaptability to reliable low cost, high volume production).

Perhaps the most important consideration for this study lies in the fact that all references cited herein avoid mention of repair techniques (particularly those advocating use of welded/brazed or ultrasonically bonded joints). It is difficult, if not impossible, to conceive how any contractor, no matter how skilled, can build a 10,000-square-foot LSSSA without breaking a few solar cells during the processing. Soldering, so far is the only interconnection process that enables one to potentially remove a damaged cell and replace it with a good cell without degrading the circuitry system. An extensive study of repair techniques for all types of joints is needed to either confirm the present position of soldering techniques, or deny it quantitatively, by offering a viable and repairable alternative.

TABLE 4-10

JOINING TECHNIQUES FOR SOLAR CELL INTERCONNECTIONS

REFLOW SOLDERING

Source	Comments	Bib No
Aeropropulsion Labs	The area of cell contact should be as small and free of solder as possible A good connector should be thin (2 mils, or less) and looped to prevent stress transmission from one cell to another	A. 2-3
Alpha Metals	Solder preforms should be shaped as required, with or without flux They can produce superior joints, but are no "panacea" for problems due to improper techniques.	A 4-1
Boeing	For the Large Area Solar Array (LASA), coverglasses are bonded to the cells prior to installing interconnections Next, a paste solder is applied to 7-cells at-a-time with a stencil Finally, a silver mesh interconnector is positioned and held while a pulse soldering machine solders each spot.	B 3-8
European Space Research Organization (ESRO)	Interconnections can be made using resistance soldering, brazing or welding	E 2-1
General Electric	Infra-red soldering can be accomplished with heat from a lamp. Selective plating of tin-lead (Sn 62) solder with a co-deposit of 2% silver (to make it 'equivalent' to Sn 62 solder) can be deposited on silver mesh	G. 2-5 G 2-6
Hughes	Two matrices of solar cells were formed - one had hand soldered wire loop interconnects and the other had machine-soldered, expanded copper mesh interconnects	H 6-1
Lockheed Missiles & Space Co. (LMSC)	Up to six 2 x 2 cm solar cells can be simultaneously soldered in parallel on a 'P' interconnect bus strip using induction soldering.	L 4-2

REFLOW SOLDERING (Continued)

Source	Comments	Bib No
MIT	The amount of solder used for interconnects should be reduced to a minimum in order to minimize structural failures in lightweight solar cell arrays under thermal cycling	M 4-2
NASA-Goddard	After a series of tests comparing various solders, it is concluded that 100% Indium solder and 15% Pb, 80% Sn, 5% Ag solder are both superior to SnPb solder for the purpose of bonding interconnectors to solar cells However, more tests must be performed in order to be sure that there is not some hidden factor which will in some way make these solders unacceptable for use with solar cells	Pic Paper # 1919
NASA-JPL	Rigid busbars of gold-plated Kovar, soldered with 60/40 solder preforms in a soldering 'boat' fixture are used on Mariner Mars 1964 Spacecraft, Mariner Venus, 1967, and Surveyor A-21 (SC-5, -6, & -7) spacecraft	N 4-10
NASA-LeRC	CdS solar cells can be interconnected in series with Indium solder	N 6-5
Hewlett-Packard	An extensive treatise on Design Requirements for Good Soldering and Material Selection for Soldering is presented in Chapters 11 and 12 of this book Note Table 4-13 was compiled from this source.	H 4-1
Royal Aircraft Establishment	In the Advanced Lightweight Solar Array solar cells are mounted and interconnected on flexible substrates using preforms and hot gas soldering as their preferred method of attachment See also R 3-6, -10, -11	R 3-4

REFLOW SOLDERING (Continued)

Source	Comments	Bib No
Sandia Corp	Methods and techniques for obtaining high quality parallel-gap soldering joints can be adapted to top solar cell series tab soldering	S 1-1
Weltek	Reflow soldering iron tip materials, shapes, and techniques can be applied to solar cell series tab reflow soldering	W 1-1

TABLE 4-11

JOINING TECHNIQUES FOR SOLAR CELL INTERCONNECTIONS

RESISTANCE WELDING

Source	Comments	Bib No
AEG Telefunken	Thermo-compression bonding RC Welding and Ultrasonic bonding techniques are applicable to interconnecting solar cells	A 1-1
	Resistance welding technique can be used for joining silver mesh and silver-coated molybdenum strips to solar cell contacts	A 1-2
British Aircraft Corporation (BAC)	A Hughes MCW-558 parallel-gap welding system was used to interconnect expanded silver mesh to solar cells during their Study of an Advanced Solar Array Design	B 2-2
European Space Research Organization (ESRO)	Work with the Hughes MCW-550 parallel-gap welder had provided weld parameters for the optimum welding of silver, gold plated molybdenum and Kovar to silver-plated solar cells See Table 4-14	E 3-2
Western Electric	Laser welders presently available must be refined considerably before satisfactory welds to thin films can be made	El Des Magazine Oct 1 65

TABLE 4-12

JOINING TECHNIQUES FOR SOLAR CELL INTERCONNECTIONS

ULTRASONIC BONDING

Source	Comments	Bib No.
General Electric Syracuse	General information on ultrasonic bonding	G. 1-1
Heliotek	Ultrasonic Bonding of aluminum mesh is superior to thermo-compression bonding. One ultrasonic bond, roughly 0.015 inch to 0.025 inch diameter, is sufficient to make an adequate, reliable, ohmic contact between the aluminum mesh tab and a solar cell contact, although 3 bonds were used for redundancy	H 3-5
IC Engineering Corporation	Treatise on the mechanics of ultrasonic bonding	I 2-1
Ion Physics Corporation	Ultrasonic welding was successfully utilized to achieve aluminum bonds Some problems in repeatability were encountered and were attributed to differences in silicon surface characteristics Soft aluminum ribbons, 3 mils thick, 320 mils wide were ultrasonically bonded to aluminum contacts 2 microns thick by means of three ultrasonic bonds. These have withstood pull tests perpendicular to the cell fact of up to 1,750 grams (the limit of the particular pull tester utilized) The area of the welds was approximately 62 mils in diameter.	Pic Paper #1882
TRW	The radius of an ultrasonic probe is equally as important as time or pressure in obtaining a good bond Radiation Hardened Flexible Array work for AF-APL utilizes aluminum interconnected cell assemblies	LMSC Trip Report 10-20-70
Special Report	Some of the promises and perils of ultrasonic bonding of IC chips are partially applicable to solar cell bonding.	S 1-2

TABLE 4-13

SOLAR CELL SOLDERING PROCESS DATA *

Surface	Flux recommended (mildest possible)		Protective Coating used to Prevent Aging	Restoring Solder-ability	Contamination in Solder		General
	Freshly Prepared	Aged			Dangerous Levels (%)	Effect on joints	
Copper (bare)	Water-white rosin	Activated rosin	Recom-mended	Chemical Treatment	0 3 - 0 8	Grainy, with higher temperature required	Economy and best results
Gold (over Cu, Ni etc)	Water-white rosin	Activated rosin'	No	Remove plating	0 03-0.2 3 0-5 0 (by volume)	Dull and grainy Embrittlement & weakening	Avoid use if possible
Kovar	N/A	Organic Acid	No	Chemical Treatment	None	N/A	Silicon Matching & weldable leads
Silver	Water-white rosin	Activated rosin	Not normally	Chemical Treatment	0 2-1 0	Grainy, with higher temperature required	Avoid Sulfur tarnishing
Tin (Immersion electroless)	Water-white rosin	Loses solder-ability	Yes	Remove coating	N/A	N/A	Not recommended for prolonged storage
Tin-lead (plating)	Water-white rosin	Activated rosin	Not normally	Reflow plating	N/A	N/A	Excellent shelf life (if reflowed)
Tin-lead (reflowed or hot dip)	Water-white rosin	Activated rosin	Not normally	Reflow coating	N/A	N/A	Best shelf life
Tin nickel	Activated rosin	Organic Acid	Yes	Chemical Treatment	None	N/A	Hard-good for contact surfaces

* Ref Bib H 4-1

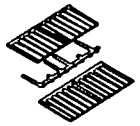
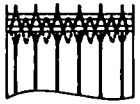
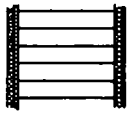
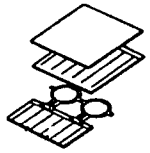
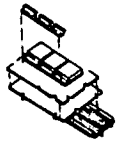
TABLE 4-14 DEVELOPED WELD SCHEDULES FOR SOLAR CELL INTERCONNECTS *

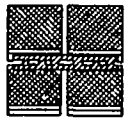
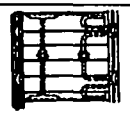
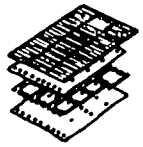
Welding Machine Power - Hughes, Model MCW 550 or MCW-558
Parallel-gap Weld Head - Hughes, Model VTA-66 MV
Electrodes - Symmetrical Molybdenum Carbide

Materials	Base Material Thickness (mm)	Plating Thickness (mm)	Width (mm)	Electrode Pressure (Kg)	Electrode Gap (mm)	Pulse Voltage (V)	Pulse Duration (msec)
Silver-plated Molybdenum	03 (1 18 mils)	5 (2 mil)	2 (78 mils)	2.5	70	65 (top) 70 (bot)	100
Silver Strip	40 (15 7 mils)	-	4 8 (189 mils)	1 14	15	62	100
Expanded Silver Mesh	063 (2 45 mils)	-	Strand 25 (9.8 mils)	1 14	15	62	100

* Ref Bib E 3-2

SOLAR CELL INTERCONNECTOR DESIGNS

NO	COMPANY	GENERAL INFORMATION			ASSEMBLY TECHNIQUES	APPLICATION	TESTING	COMMENTS	BIBLIO NO
		TYPE	MATERIAL	DESIGN FEATURES					
1	RYAN	BAR CONTACT (SOLAFLEX)	SILVER PLATED COPPER		SOLDERED – NO DETAILS REPORTED	USED ON RYAN'S 30 W/LB FLEX ARRAY FOR JPL FEASIBILITY STUDY (NO 951971)	100 THERMAL CYCLES FROM -148°F to +166°F AT 54°F PER MIN NO DAMAGE	SILVER PLATED MOLY WILL WITHSTAND THERMOCYCLING, BUT THERE ARE PROBLEMS WITH PROCUREMENT OF SMALL LOTS LARGE SCALE PRODUCTION MIGHT HAVE INFLUENCED CHOICE	R 4-5 THRU R 4-8
2	FAIRCHILD HILLER	EXPANDED MESH	SILVER		SOLDERED – NO DETAILS REPORTED	USED ON FAIRCHILD HILLER'S 30 W/LB FLEX ARRAY FOR JPL FEASIBILITY STUDY (No 951969)	NO TESTS REPORTED	NO INDICATION OF WHY EXPANDED SILVER MESH WAS CHOSEN	F 1-1 THRU F 1-4
3	GENERAL ELECTRIC	EXPANDED MESH	SILVER		SOLDERED – NO DETAILS REPORTED	USED ON GENERAL ELECTRIC'S 30 W/LB FLEX ARRAY FOR JPL FEASIBILITY STUDY (NO 951970)	117 THERMAL CYCLES FROM -200°F TO +200°F WITH NO DAMAGE. PROBLEMS WHEN RANGE EXTENDED TO -250°F TO +200°F	MESH ALSO USED ON FOLLOW-ON CONTRACT STUDY (NO 952314) POSSIBLE DAMAGE FROM THERMAL CYCLING (34 TIMES FROM -200°F TO +285°F) CAUSED BY MESH FORMING TOOL	G 2-1 THRU G 2-4
4	GENERAL ELECTRIC	PHOTOETCHED	BERYLLIUM COPPER (BERYLCO 10)		SOLDERED – NO DETAILS REPORTED	CANDIDATE FOR USE ON GENERAL ELECTRIC'S 30 W/LB FLEX ARRAY FOR JPL FEASIBILITY STUDY (NO 951970)	THREE MODULES TESTED BETWEEN +200°F TO -200°F FOR 114, 105 AND 100 CYCLES RESPECTIVELY FAILURE IN ALL THREE MODULES DUE TO FORMATION OF CRYSTAL FLAKES ON INTERCONNECTION FEET	TOO STIFF TO BE USED WITH A FLEXIBLE SUBSTRATE AND/OR THIN 0 008 IN THICK SOLAR CELLS	G 2-1 THRU G 2-4
5	HUGHES	PHOTOETCHED MESH	COPPER WITH SOLDER PLATE		VERY AUTOMATED INDUCTION SOLDERED	TO BE USED ON HUGHES' FLEXIBLE ROLLED-UP SOLAR ARRAY (CONTRACT NO F33615-68-C-1676)	100 CYCLES (FROM +300°F TO -300°F TO +200°F IN 8 MINUTES) EXTENSIVE BENDING TESTS SUCCESSFULLY COMPLETED (300,000 CYCLES)	EXCELLENT HANDLING AND SOLDERABILITY	H 6-7 THRU H 6-13
6	BOEING	EXPANDED MESH	SILVER		PULSE SOLDERING PROCESS UTILIZING RAYTHEON WELD-POWER HEAT PROGRAMMER AND A WEIGHTED ELECTRODE FOUR SOLDER DOT PAIRS-N CONTACT FIVE SOLDER DOT PAIRS-P CONTACT	USED ON BOEING'S SEMI-RIGID FOLD-UP SOLAR ARRAY STUDY FOR JPL (NO 951653) - POTENTIAL MARS LANDER	100 THERMAL CYCLES BETWEEN -148°F AND +162°F FOLLOWED BY FLEXURAL FATIGUE AND BY PEEL TESTING NO APPARENT DEGRADATION	NO SOLAR CELL DEGRADATION CAUSED BY SOLDERING PROCESS	B 3-1 THRU B 3-4
7	BRITISH AIRCRAFT COMPANY	EXPANDED MESH	SILVER	MESH HAS DIAMOND 177 BY 16 A STRAND WIDTH OF 01, AND A THICKNESS OF 002	ELECTRONICALLY WELDED WITH HUGHES' PARALLEL GAP WELDING MACHINE (MCW 558)	TO BE USED ON BRITISH AIRCRAFT COMPANY'S 8 1 FT² ARRAY STUDY FUNDED UNDER ESTEC CONTRACT NO 623/61	TO BE COMPLETED	ONLY INTERCONNECT TO BE WELDED STUDY DESIGN AND TEST CONTINUING	B 2-1 THRU B 2-3

NO	COMPANY	GENERAL INFORMATION			
		TYPE	MATERIAL	DESIGN FEATURES	
8	ROYAL AIRCRAFT ESTABLISHMENT	CIRCULAR DO-NUT SHAPE PRINTED CIRCUIT	ANNEALED COPPER OR SILVER PLATED MOLYBDENUM		THE THE NEC SOL ARC
9	EOS (ELECTRO-OPTICAL SYSTEMS)	ELECTROFORMED TAB	SILVER		ELEC WHE ACR BETW LUMI PLAT
10	EOS (ELECTRO-OPTICAL SYSTEMS)	FLEXIBLE INTERCONNECT	MOLY WITH GOLD AND SILVER FLASH OR KOVAR WITH SILVER FLASH		RESIS
11	HELIOTEK	PHOTOETCHED STRESS-RELIEVED WRAPAROUND	2 MIL COPPER		FRO ULE REA AN INS REA INT INJ POI
12	LMSC	PRINTED CIRCUIT	OFHC DEAD SOFT COPPER		FRON *SPEC SOLD INDU
13	NASA LEWIS (A F FORESTIERI)	FOIL	ALUMINUM	1 MIL FOIL NOT PHYSICALLY BONDED TO CELLS BUT HELD IN INTIMATE CONTACT BY THE FEP-TEFLON PACKAGING	CELLS HELD AND TEFLO PRESSI ONTO
14	MESSERSCHMITT -BOLKOW-BLOHM	PRINTED CIRCUIT AND EXPANDED MESH	COPPER CIRCUIT AND SILVER MESH	SILVER MESH LEADING FROM CELL TO CELL IS WELDED TO PRINTED CIRCUIT ON BACK OF SUBSTRATE AND THEN INTERMESHED WITH SUBSTRATE AND ATTACHED TO N-CONTACT OF CELL	MESH WE MESH SO

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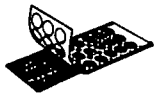
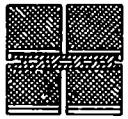
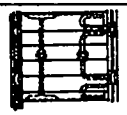
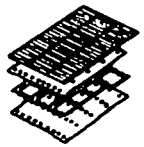
CELL INTERCONNECTOR DESIGNS

N

ENTS	BIBLIO NO
MOLY WILL HERMOCYCLING, E PROBLEMS EMENT OF SMALL E SCALE PRO- GHT HAVE IN- OICE	R 4-5 THRU R 4-8
ON OF WHY LVER MESH WAS	F 1-1 THRU F 1-4
ED ON FOLLOW- T STUDY (NO SIBLE DAMAGE L CYCLING (84 200°F TO +285°F) ESH FORMING	G 2-1 THRU G 2-4
BE USED WITH STRATE AND/ IN THICK	G 2-1 THRU G 2-4
NDLING AND	H 6-7 THRU H.6-13
LL DEGRADA- BY SOLDERING	B.3-1 THRU B 3-4
ONNECT TO TUDY, DESIGN NTINUING	B 2-1 THRU B 2-3

NO	COMPANY	GENERAL INFORMATION: TYPE	GENERAL INFORMATION: MATERIAL	GENERAL INFORMATION: DESIGN FEATURES	ASSEMBLY TECHNIQUES	APPLICATION	TESTING	COMMENTS	BIBLIO NO
8	ROYAL AIRCRAFT ESTABLISHMENT	CIRCULAR DO-NUT SHAPE PRINTED CIRCUIT	ANNEALED COPPER OR SILVER PLATED MOLYBDENUM		THROUGH PERFORATIONS IN THE SUBSTRATE, INTERCONNECTIONS ARE HOT-GAS SOLDERED TO WRAP-AROUND CELLS	TO BE USED ON ROYAL AIRCRAF ESTABLISHMENT S 560 WATT PROTOTYPE ARRAY – IN-HOUSE DEVELOPMENT	TO BE COMPLETED	SIMPLE METHOD OF INTER-CONNECTING WRAP-AROUND CELLS HOWEVER, NO PROVISION FOR STRESS RELIEF WHEN THERE IS CELL MOVEMENT CAUSED BY THERMAL CYCLING	R.3-4
9	EOS (ELECTRO-OPTICAL SYSTEMS)	ELECTROFORMED TAB	SILVER		ELECTROFORMING PROCESS WHEREBY SILVER "GROWS" ACROSS THE GAP (5 MIL) BETWEEN THE CELLS (SILVER-LUME® BRIGHT SILVER PLATING PROCESS)	APPLICABLE TO EITHER RIGID OR FLEXIBLE ARRAYS	ELECTRICAL TESTS SHOWED NO CHANGE IN PERFORMANCE TAB PULL TESTS PERFORMED ON SINGLE-CELL TABS – 1200 g WITHOUT FAILURE SINGLE AND DOUBLE CELL MODULES SUBJECTED TO THERMAL SHOCK, NO CONTACT SEPARATION	PROCESS ETCHES THE SILVER MONOXIDE SURFACE LAYER OF THE CELL-PROBLEM BELIEVED TO BE SOLVABLE COMPLEX MANDREL NEEDED TO HOLD CELLS – MAY BE A PROBLEM WITH MANY-CELLED MODULE UNSUCCESSFUL RESULTS WITH COPPER NO THERMAL CYCLING TESTS	E 1-2
10	EOS (ELECTRO-OPTICAL SYSTEMS)	FLEXIBLE INTERCONNECT	MOLY WITH GOLD AND SILVER FLASH OR KOVAR WITH SILVER FLASH		RESISTANCE SOLDERING	AIR FORCE CONTRACTS	1000 THERMAL CYCLES FROM -100°F TO +180°F ON MOLY AND KOVAR WITH NO DAMAGE 10 THERMAL CYCLES FROM -125°F TO +225°F ON MOLY ONLY– NO DAMAGE	CONVENTIONALLY USED ON RIGID HONEYCOMB BUT COULD BE ADAPTED TO FLEX ARRAYS	
11	HELIOTEK	PHOTOETCHED STRESS-RELIEVED WRAPAROUND	2 MIL COPPER		FRONT CONTACT – SCHEDULED IMPULSE SOLDER, REAR CONTACT – RESISTANCE SOLDER INSULATION NEEDED FOR REAR CONTACT INTERCONNECTOR LAMINATED BETWEEN POLYIMIDE SHEETS	FLEX ARRAYS WITH THIN SUBSTRATE (JPL NO 952560)	INTERCONNECTOR THICKNESSES FROM 2-8 MIL CYCLED 100 TIMES FROM ROOM TEMP TO -195°C AND 100 TIMES FROM ROOM TEMP TO -100°C RESULT – THIN INTERCONNECTS INCUR LESS STRESS. VIBRATION TESTS INDICATE A 10% FAILURE RATE FOR AN EXTRAPOLATED 65 000 CYCLES	MUCH ANALYSIS AND TESTING TO OBTAIN OPTIMUM DESIGN (THICKNESS CONFIGURATION ETC) WRAP-AROUND INSULATION OF 1-INCH, RTV3145 IMPREGNATED GLASS CLOTH NEEDED	H.3-1 THRU H 3-4
12	LMSC	PRINTED CIRCUIT	OFHC DEAD SOFT COPPER		FRONT CONTACT – LMSC "SPECIALIZED" RESISTANCE SOLDERING; REAR CONTACT-INDUCTION SOLDERING	USED ON 50 FT² FLAT PACK AND AN 80 FT² FLAT PACK ARRAY PROTOTYPE BUILT FOR AIR FORCE PROGRAM	LMSC PERFORMED 1800 THERMAL CYCLES BETWEEN +140°F AND -200°F WITH NO FAILURES SOCIETE ANONYME DE TELECOMMUNICATIONS SIMULATED TEMPERATURE CYCLING OF A 10-YEAR SYNCHRONOUS ORBIT WITH NO ELECTRICAL DEGRADATION (SOME MECHANICAL DISCONTINUITIES) MIT-LINCOLN LABS CONDUCTED EXTENSIVE TEMPERATURE SHOCK AND THERMAL CYCLING TESTS (-160°C TO 60°C, 1200 CYCLES ONE CELL CRATERING FAILURE)	AN INTEGRAL DESIGN THAT USES NO ADHESIVE. FUNDED STUDY TO DEVELOP INTEGRATED CIRCUIT FOR WRAP-AROUND CELLS	L 4-19 S.3-2 M.4-2
13	NASA LEWIS (A F FORESTIERI)	FOIL	ALUMINUM	1 MIL FOIL NOT PHYSICALLY BONDED TO CELLS BUT HELD IN INTIMATE CONTACT BY THE FEP-TEFLON PACKAGING	CELLS AND INTERCONNECTS HELD TOGETHER BY A FRONT AND BACK LAYER OF FEP-TEFLON HEAT SEALED WITH PRESSURE AND TEMPERATURE ONTO SOLAR CELLS	INTERNAL NASA LEWIS STUDY BY A.F FORESTIERI; AND J D BRODER	NO DEGRADATION AFTER 1016 VACUUM THERMAL CYCLES FROM 40°C (HELD 1 HOUR) TO -125°C (HELD 1/2 HOUR) ONE MONTH AT 90% R.H ALSO CAUSED NO CHANGE	APPLICABLE TO ANY TYPE OF ARRAY ESPECIALLY ONE WHERE THE INTERCONNECTS HAVE TO BE SHIELDED (HIGH VOLTAGE SOLAR ARRAYS)	N 6-4
14	MESSERSCHMITT -BOLKOW-BLOHM	PRINTED CIRCUIT AND EXPANDED MESH	COPPER CIRCUIT AND SILVER MESH	SILVER MESH LEADING FROM CELL TO CELL IS WELDED TO PRINTED CIRCUIT ON BACK OF SUBSTRATE AND THEN INTERMESHED WITH SUBSTRATE AND ATTACHED TO IN-CONTACT OF CELL	MESH TO PRINTED CIRCUIT-WELDED MESH TO SOLAR CELL-SOLDERED	USED ON MESSERSCHMITT'S 20 METER² SELF RIGIDIZING DEPLOYABLE SOLAR ARRAY	NO SPECIFIC TESTS ON INTERCONNECT ASSEMBLY REPORTED	REPORTED TO BE AN EASILY AUTOMATED PROCESS	M 3-1

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4.1.3.3 Solar Cells

The standard 2 by 2 cm n/p solar cell was selected as part of the baseline design of the Space Station solar array because of the wide range of programs this cell has been successfully used on. Solar cells are similar to interconnects in that almost as many cell configurations exist as there are solar panels. Prior to making a final selection for the Space Station array, that would require two million by 2 cm cells, trade-offs must be made in the areas of cell size, cell configuration and thickness, type of contacts, optical coatings required, and special efficiency improving processes to obtain maximum end of life power for the least cost.

This section of the report includes a review of solar cells used to date on flexible array programs and a discussion of the overall solar cell technology as it applies to the Space Station solar array development task.

4.1.3.3.1 Solar Cells Used on Flexible Substrate Systems. Since 1965, the conventional silicon solar cell has been adapted quite successfully to flexible substrate solar array systems. During this time 14 investigators have evaluated most of the size, thickness, and solar cell material configurations available to the industry. Chart 0 at the end of this section is a summary of this information, and includes data not only of the cells to be considered for final design, but also some early development concepts

Additional information presented on this same chart includes cell cover materials, interconnect materials and joining methods, substrate material, and cell bonding techniques. These data are relevant, since the adaptability of an assembly to mechanical and environmental requirements is related to the entire system and not just to a single component of a composite design.

A review of Chart 0 indicates that, excluding cadmium sulfide cells, the only areas of similarity in the silicon solar cells selected is the fact that all cells used were predominately of the n/p type. Sizes varied from 1 by 2 cm, 2 by 2 cm, and 2 by 6 cm for the conventional cells to 1 by 30 cm for the dendritic cells to 2 by 2 cm for the wrap-around contact cells. The thicknesses varied from 4 to 14 mils. Both 2 ohm-cm and 10 ohm-cm cells were used. The cover type ranged from fused silica to microsheet to

Corning type 8871 ribbon glass to cerium doped microscope glass. Zone-soldered, conventional soldered, and solderless cells have been used. Because of availability there was almost total agreement on using silicon monoxide coated cells with silver titanium contacts. Finally, numerous interconnect and attachment procedures were used in conjunction with the cells.

Cadmium sulfide cells are mainly experimental cells still in the development phase. Production quantities have efficiencies of only 4 percent or less as compared to 11 to 12 percent for silicon. The Clevite Corporation supplies the CdS cells in a standard size of 3 by 3 in., but they have supplied larger ones to TRW for a Multimission Electric Spacecraft Study. The contact material of the CdS cells is gold-plated copper. The covers most frequently used are Mylar and Kapton.

From the above it can be seen that there is, in fact, much variation on the type of cells used with flex arrays. There are trends, however, that are noted as follows. Most of the cells used were required by contract to be 8 mil, 2 by 2 cm cells with covers of 6 mil or thinner 0211 microsheet. This resulted from the fact that a higher power-to-weight ratio was required, but possibly with some compromise in radiation resistance. If there was no specific contractual requirement, the tendency was to use even thinner cells and covers. With few exceptions, this is because the flexible arrays designed to date resulted from study contracts with non-earth orbiting missions. Therefore, the tendency was to use the lightest state-of-the-art components available. To produce a more efficient or more easily manufactured array, large cells, wrap-around electrode cells, and solderless cells have been used. These variations are all within the state-of-the-art, and cells with these features will probably have more widespread use in the future.

4.1.3.3.2 Evaluation of Solar Cell Technology for Space Station Use. Solar cell technology is adequate for meeting the requirements established for a Space Station solar array. Presently available and potentially applicable candidates are summarized in the following tabulation.

CANDIDATE SILICON SOLAR CELLS

	Type	Thickness	Base Resistivity	Air Coating	Contact	Size CM
Conventional	N/P	4-16 Mil	1-3 7-14	SiO TiOx CeOx	Ag Ti Ag-Pd-Ti Al	1 by 2 2 by 2 -10 3 by 3
(Gettering) (Advanced)	N/P P/N		Low to High	ZuS/MgF2	Ag Ni-Cu-Au Ni Au-Ni	
Lithium Doped	P/N					
Wrap-Around Contacts	P/N & N/P	4-16 Mil	1-3 7-14	SiO CeOx TiOx	Ag Ti Ni-Cu-Au	2 by 2

Although the technology is adequate, this is the single area where minor improvements can have major system impact. Reducing system size by cell efficiency improvements not only saves cell area and cost, but greatly reduces structure and orientation system requirements. It is, therefore, very important to consider every area of recent cell development for application to the Space Station.

4.1.3.3.3 Solar Cell Technology Status. The types of solar cells currently in use or being developed are summarized in Table 4-15. Conventional production solar cells are silicon and are presently predominantly manufactured in the non-p configuration. The base silicon material is positive doped with boron to 10-ohm-cm or 2-ohm-cm resistivity and used to produce single crystals of approximately 1.5 in. diameter and 8 in. long.

Table 4-15

SOLAR CELL CATEGORIES

Major Category	Subcategory	Variations
Silicon	Conventional, diffused n on p junction, 2 by 2 cm.	Crystal orientation. 4 to 16 mil thick. 2 and 10 ohm-cm base resistivities.
	Lithium-Doped, diffused p on n junction.	Lithium source is painted on, evaporated, or implanted as an ion. Lithium concentration distribution profile and oxygen content varies. Diffusion barrier to hold lithium.
	Wrap-around contact, derived from conventional cell.	Geometry of negative contact brought to back of cell.
	Ion-implantation n on p junction formed by implanting n dopant ions.	Conventional n on p, lithium-doped p on n
	Large area (derived from conventional cell).	Width 2 cm to 1.5 in. Length 2 cm to 6 in.
	Aluminum contact	Interconnections made by electric welding and ultrasonic bonding.
Thin Film	Cadmium sulfide, CdS	1 by 1 in. to 3 by 3 in. in area 3 to 5 mils thick, including flexible substrate.
	Cadmium telluride, Cd Te	Fabrication process steps under investigation to develop temperature stable cell.

The crystal is sliced and lapped to a thickness of from 4 to 16 mils and cut to a cell area of from 2 to 12 cm^2. The non-p junction is then formed by n-type diffusion with phosphorous diffusing into the cell surface. Relatively high production yields of cells with 11-percent efficiency at room temperatures, outer space sunlight conditions (AMO), and at thicknesses above 7 mils are achieved.

Spectral response of silicon cells was improved slightly in the short wavelength area a few years ago and has remained fairly constant in this area since. Depending on the properties of the antireflection coating, junction depth, and base resistivity, peak cell responses range from 0.8 to 0.9 micron and the blue response extends down to 20 to 40 percent of the peak value at about 0.45 micron. For every ^{o}C increase in temperature there is a corresponding 0.6 percent loss in original power at temperatures above $-20^{o}C$.

Radiation degradation of conventional silicon solar cells continues to be a problem for space applications. The solution for most missions involves one or a combination of the following conditions.

- Array is oversized to allow for degradation.
- Cell cover material and thickness selected for cell protection.
- Cell designs are selected for radiation resistance.

While the solutions are also reflected in increased system weight and cost, the system design for a specific mission radiation environment and lifetime can be optimized to minimize the above increases. Development efforts are being directed to further reduce the impact of space radiation on system cost and weight. A silicon solar cell without a cell cover in a 600-nm polar orbit will degrade approximately 20 percent in one year and at 1500-nm (an altitude of strong radiation) will degrade 40 percent in one year. Depending on the thickness of the protective cover, these figures can be reduced.

The present major domestic suppliers of conventional silicon solar cells are Centralab, Division of Globe-Union, El Monte, California, and Heliotek, a Division of Textron, Inc., Sylmar, California. Texas Instruments Inc., Dallas, Texas, a former supplier, is not presently producing solar cells but does produce high-purity silicon for the

fabrication of solar cells, as does Dow Corning. Ion Physics Corporation, Burlington, Mass., produces an ion-implanted junction cell in relatively small quantities. Non-domestic suppliers include Societe Anonyme de Telecommunication (S.A.T.) of France, Telefunken of West Germany, Siemens of West Germany, Selemia of Italy, and several Japanese Firms. Ferranti of England has stopped production but is maintaining a capability to resume when they desire to do so. A number of U.S. and foreign institutions including universities, privately-owned laboratories, and government laboratories do research and development work in solar photovoltaic devices. Many firms, including LMSC, have the capability to fabricate silicon solar cells. Past and present market conditions of very cyclical demand, however, result in relatively few firms having the experience and equipment to handle production orders with good yields and competitive prices.

Conventional Silicon Solar Cells

Cell Production and Cost Trends

Both Centralab and Heliotek can produce the equivalent of 30,000 to 50,000 2 by 2 cm cells per week with present facilities. The shipable numbers will be a 40-to-70-percent yield on the above rates, based on the tightness of the procurement specification. Floor space is available now to install additional machinery and to increase each of the above rates by 100 percent. To provide a large number of cells, such as for a large space station array (2 million cells), in a reasonable length of time is a difficult logistics problem; a possible solution is early selection of the cell design and stockpiling of a part of the Heliotek and Centralab outputs. Both silicon cell vendors would consider this because of the leveling effect it would have on present production rate fluctuations.

The price of the bulk silicon and other materials is going up. The cost lines can be held or reduced by several conditions, some of which are not likely to be affected in the near future. In this latter group is the reduction of fluctuation in production orders. When no cells are being produced an engineering staff is carried. Production people are laid off, with the resulting cost of retraining new hires when production is resumed. It is estimated that this factor represents a 10 to 15 percent increase in cell costs.

Costs of cells can be reduced if many of the present manual handling tasks were automated. For example, for each of approximately 15 process steps there is a manual loading and unloading step, accompanied by a cleaning process with another manual loading and unloading operation. The high cost of additional automation is not justified by expected production rates at these facilities. Standardization of cells into one, two, three or four design specifications would result in significant cost savings, since cells are now produced to a different specification with every new procurement.

Some cost improvements that the vendors can control to a higher degree than those above and that are receiving attention include the following

- Improve fabrication process steps, handling, and testing techniques so that fabrication costs are reduced.
- Improve cell efficiency and design so that dollars/watt is improved.
- Develop production capability for larger area cells, also a dollars/watt improvement at the cell production level.
- Place the cell cover assembly activity in the solar cell fabrication line, where the cover technique used is compatible with the fabrication line.

Review of Heliotek and Centralab cell production reveals that while the overall process steps by function are the same for the two vendors, the method and equipment used for many of the steps vary. No edge by one vendor in total fabrication expertise is apparent.

Conventional Silicon Cell Improvements

The cell improvements sought are in cost and weight reduction, radiation resistance, and higher efficiencies, with at least no decrease in reliability while being compatible with large production requirements. Several areas of cell improvement are under investigation, while some investigations performed over the past few years have been completed or discontinued.

Development of the dendritic grown large area silicon cells pioneered by Westinghouse, and the silicon solar cells with non-uniform impurity concentration profiles versus cell base material depth (drift field), have been discontinued because the improvements gained were not significant or were not cost competitive. New developments in cover techniques or less costly impurity gradient control might revive interest in these developments.

New Dopants

Boron and phosphorous are the conventional p-type and n-type dopants, respectively. Attention has been given to boron replacements and to additives to improve silicon solar cell radiation resistance. Lithium doping (additive) has had success in improving radiation resistance and is discussed later. The replacement of boron by aluminum in the p-type silicon is under study by Northrop Corporate Laboratories for JPL. They have demonstrated that Al-doped silicon following a heat treatment is significantly less sensitive to gamma radiation than boron doped material. This limited investigation is a part of the JPL directed Lithium Solar Cell Development Program to develop cells for use in radiation environments. Much more research will be required before a new dopant (such as aluminum) will replace boron. The development of additives to the boron and phosphorous doped cells has been limited to lithium.

Gettered Cells

It has been established that the cell fabrication processes degrade the lifetime of excess minority carriers. This degradation in I_{sc} is approximately 4 percent going from a 14-mil cell to a 10-mil cell and approximately 8 percent in going from a 10-mil cell to a 6-mil cell. The degradation is much stronger for thinner cells than for thicker cells and the output of thinner cells has been observed to be lower than was theoretically predicted. Telefunken has developed a method of regenerating the lifetime of the carriers by a getter step that can be applied to the nearly-assembled solar cell. Complete collection of photogenerated excess carriers can be achieved in the gettered solar cells and the output of the cells approaches the practical limit.

The degradation in the lifetime of minority carriers is caused by mechanical preparation of silicon wafers that produce lattice defects in the crystal and by elevated temperature treatments employed during diffusion or cell contact sintering that introduce additional impurities, mainly heavy metals, that act as recombination centers for photogenerated carriers. The regeneration of carrier lifetime is achieved by establishing a quasi-liquid layer on the surface of the cell. The solubility of the undesired impurity atoms is higher in this layer than in silicon. The process is carried out at a temperature when these impurities are quite mobile in silicon. The main portion of the impurities can be segregated in the getter layer and eliminated as effective

recombination centers. Telefunken has developed a practical low temperature getter technique based on the above principles that is compatible with solar cell production methods. The getter effect seems to be more effective for cells less than 10 mils thick. The gettered cell I_{sc} is 4-percent higher than a standard cell at 14 mils thickness and 8-percent higher at 6 mils thickness.

Antireflective Coating

The recent efforts by AEG-Telefunken, Crabb and Atzei of ESTEC, Roger and Coladelle of SAT, Iles of Centralab, and Schwartz of Globe-Union, Inc., have all demonstrated consistent I_{sc} improvements of greater than 4 percent when conventional antireflective coating of SiO are replaced by achromatic coating. The most common of these being TiO_2 and CeO_2. The theory behind this thinking was to try to optically match indexes of refraction between silicon coating and coverglass adhesives. As it turns out, the most efficient optical matching lies between 0.55 and 0.6 microns at n = 2.40. Silicon monoxide (SiO) optimized is approximately 1.85, with a minimum of absorption loss. When rates of evaporation are optimized, TiO_2 can realize refractive indexes of 2.35 with negligible absorption in the short wavelength range. Although it is recognized that TiO_2 and CeO_2 are more difficult materials to control during evaporation (rate increases have a major effect on absorption increase and result in high cell operating temperatures), a definite overall improvement exists that can be directly applicable to any silicon cell selected.

Multi-Junction Solar Cells

The multilayer concept involves several layers of alternate n and p materials that give increased junction and/or multiple junctions. The objective of the design is to prevent the loss through recombination of minority carriers generated deep within a solar cell by red light and thus improve cell efficiency and radiation resistance over present cell design. Investigations in this area were performed in this country by Westinghouse in 1968 with AFAPL support. The design involved epitaxial deposition procedures, the use of a vapor phase transport technique, to obtain an impurity gradient profile while generating buried junction areas. The analysis and fabrication of a multi-junction cell is complex and further development effort has not been spent on this concept.

Increased Output Cells

Laboratory developments of advanced high output silicon solar cells have been achieved but the advances have been difficult to achieve in production. Similarly, higher output designs are sometimes less temperature stable or radiation resistant. P.A. Iles, of Centralab, recently reported on improved cell outputs achieved by several steps in both n/p and p/n junction 2 by 2 cm cells. The steps included

a. The use of moderately high resistivity silicon (5 to 100 ohm-cm).

b. The use of improved diffusion methods, giving good quality shallow layers, with low sheet resistance and high I_{sc}, with a low fraction of inactive dopant and minimum damage introduced into the bulk silicon by the diffusion. The surface left after diffusion was capable of treatment to give low reflectivity over the spectral range of interest when coated with thin antireflecting films.

c. The use of a back surface finish, and metal contacts with good reflectivity for unabsorbed radiation, giving the chance of extra absorption on the reflected path.

d. The reduction of contact resistance by providing a highly doped like-impurity layer at the back surface

e. Adjustment of the drift field resulting from the gradient of the like-impurities to prevent minority carrier recombination at the back surface.

f. V_{oc} was increased without decreasing I_{sc}. For p/n cells this resulted from diffusion of a thin, layer of lithium into the n-silicon. For n/p cells, suitable heat treatments apparently gettered recombination centers and decreased I_o.

Maximum values of the photovoltaic parameters were obtained as follows

I_{sc} by steps (a), (b), (c) and (e)

V_{oc} by steps (b) and (f)

CFF by steps (b) and (d).

The power output of the cells was increased 15 percent over conventional cells.

Radiation tests are in progress to compare these advanced cells with conventional cells and the results will help determine their usefulness for space application An additional factor is the determination of the cost premium for these cells, which is anticipated to be small. The improvements are also expected to stimulate work towards improved theoretical understanding of silicon solar cells.

Crystal Orientation

The orientation of the silicon crystal planes can be controlled in the crystal growing process by the orientation of the planes of the small starting crystal with respect to the melted silicon and the pulling direction. The orientation of crystal planes in a silicon solar cells has been established in the past, although control within several degrees is easily accomplished. Recent thermal cycling tests conducted on cells bonded to interconnects by solder indicate, according to some observers, that cells with their large planar area parallel to the (111) silicon crystal plane are more resistant to cleavage and also silicon cratering at backside solder joints. Other tests have indicated that no difference in cell strength can be ascribed to selected crystal plane orientations. A further opinion is that if a difference does exist, no advantage can be taken by preferred orientation of the solar cell. This is because the cell in the operating environment is essentially stressed equally in all directions and only the orientation of the cell failure could be controlled. In any event, the existence of a difference and its significance have not been established at this time.

Wrap Around Contact Cells

The wrap around contact cell is designed to place the contact bar or contact corner darts, located on the front surface of conventional silicon solar cell, on the back surface of the solar cell. This is accomplished by forming the junction so that it wraps around one edge of the cell but is isolated by a dielectric from shorting to the base material. The front surface contact grid is deposited so that it extends across the front surface of the cell and around the edge of the cell, following the junction The grid terminates in several rear surface contact designs including a bar, two corner pads, and a single pad centered at the edge of the cell. This contact design can be supplied to cells of 10 mils thickness or greater. A hoped for advantage of wrap around cells was increased cell output due to the reduction of contact surface on cell front. This increase has apparently been offset by the reduction in back contact area due to area required by the wrap around contact. An optimized contact configuration has not been arrived at as yet. The second advantage is believed to be a cost reduction in cell interconnecting activities where the same bonding technique is used for all cell contacts and all connections are made on one side of the cell.

Both Heliotek and Centralab have successfully made small quantities of wrap-around contact cells in the laboratory to meet small orders for evaluation purposes but have not received any using program orders.

Heliotek would like to see more development effort in diffusion and masking techniques for wrap arounds to optimize the cell design and the fabrication process. They fell that the number of process steps can be the same as present conventional cells. The fabrication process in the laboratory does not appear to be completely defined and repeatable for good yields, but no development problems are anticipated.

Solar cell users have not optimized array fabrication techniques for wrap-around cells, so the advantages have not been fully demonstrated. This process is proceeding at a slow pace at this time. Small quantities of wrap around contact 2 by 2 cm cells can be obtained at about $10.00 each for evaluation purposes (less than cost to vendor).

Wrap around contact solar cells have been investigated recently for flexible array use by LMSC and RAE. Cells of this type are considered to have high potential for use in mass production of flexible arrays and are therefore very significant for Space Station consideration. A thorough discussion of wrap around contact cells is included here for that reason.

In patent number 3,255,047 titled, "Flexible Fabric Support Structure for Photovoltaic Cells", filed 7 September 1961 and issued 7 June 1966, Escoffery proposed wrap around contact or backside contact cells. In the mid 60's, all of the domestic cell vendors fabricated pilot runs of wrap around contact cells and attempted to solicit industry acceptance. A major objection thereto was that no joint inspection could occur after panel assembly. In retrospect, this argument was only half valid because with cells characteristically mounted to rigid substrates there never was an opportunity after assembly to inspect the backside parallel contacts.

With the advent of flexible substrates, predominantly of Kapton or laminates thereof, joint visibility after assembly is possible, either with substrates that incorporate the circuit, or with independently interconnected solar cells if transparent adhesives are used.

More recently, Ferranti has fabricated 1000 4-mil thick backside contact cells for RAE. Backside contact cells were used in the RAE flexible array work reported by Treble and Crabb. In the Lockheed 90-ft^2 flex array, one electrical module, 100 cells, is made up of Centralab wrap-around electrode cells.

Quoting directly from the Final Report, Development of an Integrated Lightweight Silicon Solar Cell Array, JPL Contract No. 952560 to Heliotek, page 4-1, the following recommendations are stated.

> "The use of wrap around contact solar cells will simplify the interconnector design and also reduce weight and costs of interconnecting the cells". And further, "Using wrap around contact cells and perfecting methods of bonding, mechanically and electrically, these cells to a laminated metallic polyimide substrate will provide not only a large weight reduction, but also a decrease in the array assembly cost through the deletion of the tedious interconnector and bonding techniques now required with top contacted cells."

The intent of the preceding commentary is to point out that the advocation of backside contact solar cells is not unique to only one cell vendor or user; their suggested use is not new, and a government-funded program, independent from the Space Station array technology program, has recommended their development.

Table 4-16 lists some of the advantages that could occur with the development of wrap around electrode cells.

Lithium Doped Cells

Investigations of lithium doping in boron and phosphorous doped silicon solar cells have been in process for over four years. These efforts have been directed to develop an improved radiation-hardened solar cell. Both NASA, through the Jet Propulsion Laboratory and the Air Force, through AFAPL, Wright-Patterson AFB, have supported various industry, government, and university groups in this development effort. The NASA concern is with natural space radiation and the Air Force has the same concern along with nuclear weapons effects. The latter effects include both nuclear interactions and heating by energy deposition.

Table 4-16

BACKSIDE CONTACT SOLAR CELL DEVELOPMENT POTENTIAL

Background Problems	Desired Output Change	Potential Payoff
Topside electrodes make generous stress relief series tabs mandatory complicating panel assembly.	Develop backside contact cells thereby eliminating GSR series tabs.	Would make panel design feasible for fully automated assembly to flexible substrate. Parallel and series contacts could be made simultaneously, resulting in $82/ft^2 savings.
Series spacing to accommodate series tabs increases cell spacings.	Same as above	Reduction of series spacing to 10 mils results in area reduction of 166 ft^2, based on a 100-kW Space Station array.
Virtually all temperature cycling testing has identified the series tab as a potential failure mechanism.	Same as above	Backside electrodes would allow the use of an in-plane stress relief interconnect design with the majority of the interconnect properly encapsulated and supported. Cycle life could increase by a factor of 3X.
Proper stress relieved series tabs protrude above the cell/cover surface, complicating and compromising stowed padding methods.	Same as above	A reduction in padding thickness and weight could occur, along with elimination of tab deformation and padding hang ups.
Both flight and ground tests have confirmed accelerated cell degradation due to n-bus gap problems.	Develop backside contact cells.	Both busses on cell backside allows a total surface cover and reduction in cover and reduction in cover dimensional criteria. Also makes cell more compatible with FEP teflon covers.

The lithium doped cells, which are p on n junctions, appear to be overcoming an early drawback, namely initial output was less than a comparable undoped cell. Thus, a less expensive undoped cell might take a year or so of space radiation before its absolute power degraded to the value of a more stable lithium doped cell similarly exposed. Laboratory 2 by 2 cm lithium doped cells are being made with 60 Mw, AMO, outputs.

The AFAPL program includes the procurement of lithium doped cells without contacts. These cells are then given aluminum contacts, placed in modules with aluminum interconnections, given integral cell covers, and tested in weapons radiation environments.

Normal dopant concentrations in the cell base (p/n or n/p) are in the range 5 by 10^{14} to 5 by 10^{16} atoms/cc. The top surface layer is shallow (0.3 to 0.5 microns) and is highly doped to provide the best output when illuminated. The additional doping with lithium provides mobile lithium ions that can interact with lattice defects produced by radiation to reduce recombination of minority carriers. The lithium is also an active electrical dopant (donor impurity) that can alter the properties of the cell. Type n silicon is the usual base material. After the shallow p-type layer is formed on the front of the cell, the front surface contacts and the antireflection coating are added. The lithium is usually introduced from the back surface before the back contact is applied. There are several methods of introducing lithium to the cell, including paint-on suspensions of lithium metal, thermal evaporation of metal, and deposition from lithium vapor. These methods are combined with a diffusion cycle with temperatures between 350°C to 500°C, and corresponding times from hours to minutes to provide degrees of diffusion severity. A relatively severe initial diffusion cycle provides initial distributions. This can be followed by cooling the cell, removing excess lithium from the back surface, and subjecting the cell to an additional diffusion cycle. Redistribution cycles can provide more uniform profiles, and they cause loss of lithium (30 to 60 percent) due to diffusion and escape of the lithium. The final lithium concentration will also lower the base resistivity of 20 ohm-cm n material to 1 ohm-cm or less. Competing effects appear to be that high lithium content increases cell recovery but decreases cell output, and that higher oxygen impurity content in the starting silicon increases initial lithium-doped cell output but decreases cell recovery.

The JPL Program Development has been in two major areas. One area involves the cell vendors and the development of processes and fabrication techniques to control the various parameters of lithium doped cells to provide high yields and high efficiencies. The other involves theoretical studies, environmental testing, and correlation of test results. The number of variables in the above two development areas is very high. These include composition of starting materials, concentration profiles of lithium in the cell, types and energies of radiation, irradiation rates in testing and in space, and temperature history of cells during irradiation and post-irradiation periods.

Several conclusions have been reported to date. Lithium has the capability of associating with almost all radiation-induced defects and of reducing the effectiveness of the defect in acting as a recombination center for electron hole pairs that would otherwise contribute to cell power. The rate of this repair depends on the diffusion rate of Li in Si. This rate increases with temperature, with reduction of oxygen impurity in the silicon or with increase in ratio of lithium to oxygen impurity concentration. Good efficiency lithium doped cells have been fabricated with repeatability and have exhibited recovered powers that are more than 20-percent higher than state-of-the-art n on p cells after exposure to 3 by 10^{15} 1 MeV electrons/cm^2. All indication are that the improvement is even greater when the irradiation is by the heavier particles, protons, and neutrons.

Considerable work is still required to further understand the interaction between Si radiation-induced defects and Li. The characteristics of lithium-doped cells under space conditions of temperature cycling, thermal shock, under temperature storage, and under low-rate irradiation must be determined. The fabrication process must be translated to production scale and yields, and costs must be established. The ability of lithium to diffuse to a cell effect also allows it to change its concentration distribution in the cell and to escape the cell during fabrication, storage, and operation. Diffusion barrier concepts are being investigated for solar cells to limit undesirable lithium diffusion.

Large Area Cells

Studies by solar cell vendors have indicated that the use of solar cells, made larger in area than the present standard 2 by 2 cm cell, will result in solar arrays with

improved watts/dollar performance. Within the constraints of installed silicon crystal growing equipment and efficient utilization of each crystal volume, a number of larger cell designs are possible, with a resultant reduction in cell manufacturing costs/watt in production. The more common designs that have been made are 2 by 3, 2 by 4, 2 by 5, 2 by 6, 2 by 8 and 2 by 10 cm with the negative contact bar located along one of the long edges. Investigations have been performed to evaluate the impact of large area cells on the total solar array fabrication and operation in space. The interaction caused by the difference in thermal coefficient between the coverslide, adhesive, and silicon system can be handled by available adhesives that are sufficiently resilient over the cell/cover glass operating temperature range. Where the cell is bonded to a substrate with an adhesive the differences in thermal expansion are more significant, particularly if operating temperatures drop below $-100^{\circ}C$ where the resilience of adhesives is reduced. Above this temperature, the adhesive system will perform satisfactorily. For low temperature extremes, partially bonded areas of cells reduce the thermal stresses. These can be combined with smaller tacked pads that provide support during launch vibration, but can fail in orbit when thermal stress limits are reached. The partially bonded area can still provide the required mechanical support. On flexible substrates, where the electrical contacts are also the mechanical cell support, as in the LMSC design, concepts have not been developed and tested (an experimental 2 by 4 cm cell flexible substrate module of 9 cells is being tested at this time). Cell spacing, particularly in the long cell dimension direction, must consider substrate contraction to prevent cell-to-cell interference when the substrate contracts at the low temperature limit. The problems associated with interconnect designs and materials used for large area cells is similar to that for 2 by 2 cm cells. An evaluation of likely cell fracture locations and their effect on large area cell current flow shows that the large cell reliability is equal to, if not better than, the reliability of 2 by 2 cm cells.

Economic considerations indicate that although fewer parts are being handled and fewer cell/interconnect junctions are being made, the labor costs are not significantly lower in all areas of fabrication. Labor required to apply separate cell covers tends to increase more with area than by parts. Where adhesives are used to attach cells to substrates, cost is also a function of area. In the material area for cells that have been produced, the cell prices increase at a rate less than the increase in area. This

is for production quantities, and small orders of large area cells usually cost more per area of silicon than 2 by 2 cm cells. Cell vendors emphasize the fact that the present grown silicon crystal size allows silicon cells of any size fitting in an area 2.54 cm by 6 cm to be made economically in large quantities. Investigations by Heliotek in the range of 2 cm by 3, 4, 5 and 6 cm leads them to believe that the 2 by 4 cm cell will replace the 2 by 2 cm as the standard within two years.

Limited handling experience by the vendors indicates their percentage losses in cell fabrication will be the same as for a comparable 2 by 2 cell. The lack of large area cell handling experience makes it difficult to pick the length value that may be limiting for flexible solar array application. It is apparent that cell damaging bending moments are more likely to appear in handling flexible arrays as the length-to-width ratio of the cells goes beyond a yet undetermined value. Wrap around techniques for 2 by 2 cm cells will be readily applicable to large area cells, as will be integral covers and lithium doping.

The economic effect on separate coverslides is unpredictable, reduced handling should reduce costs, but larger area thin cell cover (6 mils) handling will increase breakage.

Ion Implantation

Ion Physics Corporation (IPC), a wholly-owned subsidiary of High Voltage Engineering, produces a silicon solar cell junction by using a high voltage ionized particle accelerator. Phosphorous ions of 80 to 100 Kev are directed at p-type silicon wafers to provide the shallow n-type layer on the face of the cell. The process enables tight control of doping and junction depth. The base material is procured as-cut from a supplier, such as Texas Instruments, or procured with a lapped finish. Ion Physics is installing a new Van de Graaf accelerator that is the first system designed specifically for ion implantation operations. Present equipments are adaptations of accelerators. The ion implantation cells are not competitive on a cost basis at present but could be if a production facility was in existence. Small quantities (~2000/week) of ion implantation 2 by 2 cm cells can be produced by Ion Physics with existing equipment. No electrical performance advantages of ion implantation solar cells are claimed.

In addition to standard n on p junction production, ion implanation is being used to dope cells with lithium and to implant diffusion barriers to control lithium migration.

Aluminum Contact Cells

Aluminum contacts can be placed on any of the silicon solar cells discussed Following are some of the advantages over the conventional titanium-silver contacts

- The contacts can be sintered after deposition on the cell at 300°C rather than 600°C used on Ti-Ag contacts This reduces stressing of the cell
- The degree of internal reflection of solar illumination at the cell back contact provides improved conversion efficiency.
- Humidity resistance is better.
- The cells are used in non-soldered cell contact/interconnect systems that may improve thermal cycling life capability.
- Aluminum is a low Z (atomic number) material, that for a given thickness will result in lower attenuation of incident short wavelength electromagnetic radiations. Thus, the energy deposition and resulting contact temperature rise caused by x-rays and gamma rays from nuclear weapons will be less than for the higher Z contact materials.

The contacts are vapor deposited on the cell in vacuum similar to the Ti-Ag contacts The cost of cells with aluminum contacts are similar to cells with other contact materials The development of bonding techniques using nonsoldered aluminum contact-aluminum interconnect circuits is being encouraged and lower costs than for solder joining systems are predicted for solar array fabrication. The designs of interconnect circuits and substrates and array fabrication processes have not been developed or optimized at this time.

The contact resistance of evaporated aluminum contacts per unit area has been reported to be 8 by 10^{-2} ohm-cm^2 compared to 5 by 10^{-2} ohm-cm^2 for Ti-Ag contacts. Very shallow junction cells, less than 0.2 microns, are adversely affected by aluminum penetration to the junction. Ti-Ag contacts work well down to junction depths of 0 1 microns. Since most cells are built with junction depths of 0.3 to 0.5 microns, the aluminum contacts present no problem in this area. The process of applying the aluminum contacts is also controlled to limit the p-type doping with aluminum of the n-type diffusion layer on the surface of the cell and thus limit counter voltage effects.

Recent investigations of electroforming aluminum contacts on solar cells have been performed by JPL under NASA contract The method takes advantage of the fact that a highly doped semiconductor such as a solar cell possesses sufficient conductance to carry the current required to electroplate aluminum from an anhydrous diethylether The method eliminates the formation of oxides between the contact material and the silicon and thus reduces contact resistance (1.3 by 10^{-2} ohm-cm^2) compared to the vapor deposited aluminum contacts. Some penetration of the aluminum through the junction occurs but shunting amounts to only 0.03 percent of the cell current. The ultimate objective of the electroforming technique is to develop a one-step process of laying contacts and interconnections on to cells, making use of a mandrel for the interconnect formation.

Predominant Foreign Silicon Solar Cell Sources

AEG-Telefunken

Solar cells are manufactured in a modern cell production facility at the Heilbronn, Germany plant. This plant also includes an R&D facility with a small pilot production line. The Hamburg plant has a modern solar panel assembly facility.

AEG-Telefunken purchases boron doped p-type silicon in single crystal cylindrical form and proceeds from there to slice, lap, and size the cells prior to diffusing phosphorous into the cell to form the n on p junction. As of a year ago they had manufactured 24,000 2 by 2 cm solar cells for the German Azur satellite and they have since produced over 100,000 2 by 2 cm solar cells for the INTELSAT IV Program at the rate of 2000-3000 cells per week. An SiO antireflection coating is placed on the cells.

AEG has done little work in thin silicon cells and only exploratory work on lithium doping They have done wrap around contact cell development and titanium palladium silver contact development (passivated contacts) The palladium is not a layer between the titanium and the silver but is alloyed with the titanium. The alloy is more stable than the titanium alone. These cells can also be solder dipped. Without solder, the contacts can operate at 400 to 500°C, allowing interconnect bonding to the contacts by resistance welding.

Domestic evaluation of passivated contacts has been done by Bishop of Boeing, Ralph of Heliotek, Ling and Isles of Centralab, and Becker of the University of Pennsylvania.

Societe Anonyme de Telecommunications (SAT)

SAT solar cells are manufactured at a new facility at Lannion on the Brittany coast 300 miles from Paris. Solar arrays are fabricated at the Paris facility.

SAT purchases boron doped, P type, float zone silicon wafers from either Dow Corning or Wacker Chemie. The wafers are close to the final 2 by 2 cm size when bought and are sized by etching prior to diffusion of the phosphorous to form the n on p junction. Silver titanium contacts and an SiO antireflective coating are placed on the cells.

SAT has produced over 40,000 1 by 2 cm cells for several European satellites and 20,000 2 by 2 cm cells for INTELSAT III. They have also produced 6000 2 by 2 cm cells for D-2 and 50,000 2 by 2 cm solar cells for INTELSAT IV.

SAT has a licensing agreement with Heliotek and the SAT cell is similar to the Heliotek cell.

SOLAR CELL USAGE ON FLEXIBLE SUBSTRATE

NO	SOLAR CELL CANDIDATE	TYPE	SIZE(cm)	THICKNESS	BASE RESISTIVITY	AR COATING	CONTACT MAT'L	SOLDER/ SOLDERLESS	COVER TYPE	MANUFACTURER		APPLICATION	FUNDING AGENC
										CELL	SUBMODULE		
1	Si (CONVENTIONAL)	N-P	2 X 2	0 008	2 Ω CM	SIO	Ag-Ti	SOLDERLESS	0 003 0211 MICRO-SHEET	HELIOTEK	BOEING	BOEING-LASA LARGE AREA SOLAR ARRAY	NASA FUNDED
2	SI (CONVENTIONAL)	N-P	2 X 2	0 008	10Ω CM	—	Ag-Ti	SOLDERLESS	—	FERRANTI	BAC	ESRO, ADVANCED SOLAR ARRAY DESIGN	BRITISH AIRCRAFT CORPORATION LTD STUDY FOR ESRO
3	SI (CONVENTIONAL)	N-P	1 X 2	0 013	10Ω CM	SIO		SOLDERED	0 006 0211 MICRO-SHEET	HELIOTEK		FAIRCHILD-HILLER FIRST GENERATION	NASA FUNDED
	SI (CONVENTIONAL)	N-P	2 X 2	0 008	10Ω CM	SIO	Ag-Ti	SOLDERED	0 003 0211 MICRO-SHEET	HELIOTEK	FAIRCHILD-HILLER	FAIRCHILD-HILLER 30 WATT/LB ROLL-UP SOLAR ARRAY	NASA FUNDED
4	SI (CONVENTIONAL)	N-P	2 X 2	0 008	2Ω CM	SIO	Ag-Ti	SOLDERED	0 003 0211 MICRO-SHEET	HELIOTEK	HELIOTEK	GE 30 WATT/LB ROLLUP SOLAR ARRAY FEASIBILITY STUDY	NASA FUNDED
	SI (CONVENTIONAL)	N-P	2 X 2	0 008	2ΩCM	SIO	Ag-Ti	SOLDERED	↕	HELIOTEK	BOEING	GE 30 WATT/LB ROLLUP SOLAR ARRAY FOLLOW ON STUDY	NASA FUNDED ↕
	SI (CONVENTIONAL)	N-P	2 X 2	0 008	2ΩCM	SIO	Ag-Ti	SOLDERED		HELIOTEK	EOS		
	SI (CONVENTIONAL)	N-P	2 X 2	0 008	2ΩCM	SIO	Ag-Ti	SOLDERED		HILIOTEK	SPECTROLAB		
	SI (CONVENTIONAL)	N-P	2 X 2	0 008	2ΩCM	SIO	Ag-Ti	SOLDERED	0 003 0211 MICRO-SHEET	HELIOTEK	CENTRALAB	GE 30 WATT/LB ROLLUP SOLAR ARRAY FOLLOW ON STUDY	NASA FUNDED
5	SI(DENDRITIC)	N-P	1 X 30	0 016	—	SIO	Ag-Ti	SOLDERLESS	0 006 1 X 30 CM	WESTINGHOUSE	HUGHES	HUGHES FISCA, FLEXIBLE INTEGRATED SOLAR CELL ARRAY	AF 33(615)-2750
	SI(DENTRITIC)	N-P	1 X 30	0 008	—	SIO	Ag-Ti	SOLDERLESS	0 003 1 X 30 CM	WESTINGHOUSE	HUGHES	HUGHES FISCA, FLEXIBLE INTEGRATED SOLAR CELL ARRAY	AF22(615)-2750
	SI (CONVENTIONAL)	N-P	1 X 2	—	—	SIO	Ag-Ti	—	0.006	HELIOTEK	HUGHES	HUGHES FISCA, FLEXIBLE INTEGRATED SOLAR CELL ARRAY	AF 33(615)-2750
	S_i (CONVENTIONAL)	N-P	2 X 2	0 008	—	SIO	Ag-Ti	—	0 006	HELIOTEK	HUGHES	HUGHES FRUSA, FLEXIBLE ROLLUP SOLAR ARRAY (NAME CHANGED TO LRSCA)	AF33615-68-C-167 FLIGHT PENDING

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

SOLAR CELL USAGE ON FLEXIBLE SUBSTRATE

CONTACT MAT'L	SOLDER/ SOLDERLESS	COVER TYPE	MANUFACTURER		APPLICATION	FUNDING AGENCY	REMARK	BIBLIO NO
			CELL	SUBMODULE				
Ag-Ti	SOLDERLESS	0 003 0211 MICRO-SHEET	HELIOTEK	BOEING	BOEING-LASA LARGE AREA SOLAR ARRAY	NASA FUNDED	CELLS SOLDERED SERIES AND PARALLEL BY EXPANDED 2-MIL SILVER MESH THE CELL ASSEMBLY WAS THEN BONDED TO A 0 003 X 0 014 IN FIBERGLASS STRIP LATTICE SUBSTRATE WITHIN BERYLLIUM FRAMES NOTE CdS_2 SOLAR CELLS WERE ALSO CONSIDERED, 18 0 X 8 FT STRIPS STRETCHED WITHIN THE SAME FRAMEWORK AS THE CONVENTIONAL CELL BUT WITHOUT THE FIBERGLASS LATTICE (KAPTON ENVELOPED CdS_2 CELL)	B 3-1 THRU B 3-4
Ag-Ti	SOLDERLESS	—	FERRANTI	BAC	ESRO, ADVANCED SOLAR ARRAY DESIGN	BRITISH AIRCRAFT CORPORATION LTD STUDY FOR ESRO	CELL ATTACHED TO SUBSTRATE BY TWO METHODS: (1) CELL WELDED TO 2-MIL KAPTON, CELLS ON TOP, INTERCONNECTS ON BACKSIDE, (2) SOLAR CELL WELDED TO INTERCONNECT THEN BONDED TO 2 MIL KAPTON	B 2-1 THRU B 2-3
	SOLDERED	0 006 0211 MICRO-SHEET	HELIOTEK		FAIRCHILD-HILLER FIFST GENERATION	NASA FUNDED	CELL MODULES BONDED TO KAPTON SUBSTRATE	F 1-5 THRU F 1-7
Ag-Ti	SOLDERED	0 003 0211 MICRO-SHEET	HELIOTEK	FAIRCHILD-HILLER	FAIRCHILD-HILLER 30 WATT/LB ROLL-UP SOLAR ARRAY	NASA FUNDED	CELLS SOLDERED TO 2-MIL EXPANDED SILVER MESH INTERCONNECTS (CONVENTIONAL DESIGN) SUB-MODULE IS ATTACHED TO 2-MIL KAPTON H FILM	F 1-1 THRU F 1-4
Ag-Ti	SOLDERED	0 003 0211 MICRO-SHEET	HELIOTEK	HELIOTEK	GE 30 WATT/LB ROLLUP SOLAR ARRAY FEASIBILITY STUDY	NASA FUNDED= --	CELLS SOLDERED TO FLEXIBLE 0 003 PHOTOETCHED BERYLLIUM-COPPER INTERCONNECTS CELL SUBMODULE MOUNTED ON 2-MIL KAPTON BY ADHESIVE HELIOTEK USED A WRAP-AROUND SERIES TAB CONCEPT	G 2-1 THRU G 2-4
Ag-Ti	SOLDERED		HELIOTEK	BOEING	GE 30 WATT/LB ROLLUP SOLAR ARRAY FOLLOW ON STUDY	NASA FUNDED	CELLS SOLDERED TO SILVER EXPANDED MESH AND ATTACHED TO 3-MIL KAPTON (CONVENTIONAL DESIGN)	G 2-5 - -9
Ag-Ti	SOLDERED		HELIOTEK	EOS			CELLS SOLDERED TO MOLY (Au/Ag FLASH) FLEXIBLE CHEM-MILLED INTERCONNECT (CONVENTIONAL DESIGN)	
Ag-Ti	SOLDERED		HILIOTEK	SPECTROLAB			CELLS SOLDERED TO COPPER (Ag FLASH) FLEXIBLE CHEM-MILLED INTERCONNECTS (CONVENTIONAL DESIGN)	
Ag-Ti	SOLDERED	0 003 0211 MICRO-SHEET	HELIOTEK	CENTRALAB	GE 30 WATT/LB ROLLUP SOLAR ARRAY FOLLOW ON STUDY	NASA FUNDED	CELLS SOLDERED TO EXPANDED MESH (CONVENTIONAL DESIGN)	G 2-5 - -9
Ag-Ti	SOLDERLESS	0 006 1 X 30 CM	WESTINGHOUSE	HUGHES	HUGHES FISCA, FLEXIBLE INTEGRATED SOLAR CELL ARRAY	AF 33(615)-2750	CELLS SOLDERED TO 3-MIL Cu EXPANDED MESH SUB-MODULES ATTACHED TO SUBSTRATE BY HUGHES EPOXY TO 0 0015 TFE IMPREGNATED FIBERGLASS MESH (ZIG-ZAG) CONFIGURATION USED	H 6-1 THRU H 6-6
Ag-Ti	SOLDERLESS	0 003 1 X 30 CM	WESTINGHOUSE	HUGHES	HUGHES FISCA, FLEXIBLE INTEGRATED SOLAR CELL ARRAY	AF22(615)-2750	CELLS SOLDERED TO 3-MIL Cu EXPANDED MESH SUBMODULES ATTACHED TO SUBSTRATE BY HUGHES EPOXY TO 0 0015 TFE IMPREGNATED FIBERGLASS MESH (ZIG-ZAG) CONFIGURATION USED.	H 6-1 THRU H 6-6
Ag-Ti	—	0 006	HELIOTEK	HUGHES	HUGHES FISCA, FLEXIBLE INTEGRATED SOLAR CELL ARRAY	AF 33(615)-2750	CELLS SOLDERED TO SILVER MESH	H 6-1 THRU H 6-6
Ag-Ti	—	0 006	HELIOTEK	HUGHES	HUGHES FRUSA, FLEXIBLE ROLLUP SOLAR ARRAY (NAME CHANGED TO LRSCA)	AF33615-68-C-1676 FLIGHT PENDING	CELLS SOLDERED 0 002 PHOTOETCHED Cu MESH (Z-STRIPS) ASSEMBLY WAS BONDED IN COMBINATION WITH 0 001 FIBERGLASS TO 0 001 KAPTON H-FILM	H 6-7 THRU H 6-12

FOLDOUT FRAME 2

FOLDOUT FRAME 3

SOLAR CELL USAGE ON FLEXIBLE SUBSTRATES

NO	SOLAR CELL CANDIDATE	TYPE	SIZE(cm)	THICKNESS	BASE RESISTIVITY	AR COATING	CONTACT MAT'L	SOLDER/ SOLDERLESS	COVER TYPE	MANUFACTURER		APPLICATION	FUNDING AGENC
										CELL	SUBMODULE		
6	SI (CONVENTIONAL)	N-P	2 X 2	0 008	—	—	Ag-Ti	—	0 0013-0 0018 CORNING RIBBON GLASS TYPE 8871	HELIOTEK	HELIOTEK	JPL SUBCONTRACT, DEVELOPMENT OF AN INTEGRATED LIGHTWEIGHT FLEXIBLE SILICON SOLAR CELL ARRAY	NASA FUNDED
7	SI (CONVENTIONAL) SI (CONVENTIONAL) SI (CONVENTIONAL) SI (CONVENTIONAL) SI (WRAP-AROUND)	N-P N-P N-P N-P N-P	2 X 2 2 X 2 2 X 2 2 X 2 2 X 2	0 014 0 014 0 010 0 004 0 013	2Ω CM 2Ω CM 10Ω CM 10Ω CM 2Ω CM	SIO SIO SIO SIO SIO	Ag-Ti Ag-Ti Ag-Ti Ag-Ti Ag-Ti	SOLDERED SOLDERLESS ZONE SOLDERED SOLDERLESS WRAPAROUND	0 012 FUSED SILCA 0 003 FUSED SILCA	CENTRALAB CENTRALAB CENTRALAB TEXAS INSTRUMENT CENTRALAB	LMSC LMSC LMSC LMSC LMSC	LMSC INDEPENDENT DEVELOPMENT FUNDED; CONSIDERED FOR REPLACEMENT OF RIGID SOLAR ARRAY SYSTEM ON AF CONTRACT	ID FUNDED BY LMSC, STUDY TO DEVELOP FOR FLIGHT APPLICATION
8	SI (CONVENTIONAL)	—	2 X 2	—	—	—	—	—	—	—	BBG	SPACE STATION/ COMMUNICATION MULTIKILOWATT POWER SYSTEMS	MESSERSCHMITT (BBG) IN-HOUSE STUDY
9	SI (CONVENTIONAL)	N-P	2 X 6	0 008	2Ω CM	SIO	Ag-Ti	SOLDERED	0 006 0211 MICRO-SHEET	—	FAIRCHILD-HILLER	SPACE STATION, MCDONNELL DOUGLAS ASTRONAUTICS CO	NASA FUNDED SPACE STATION DEFINITION
10	SI (WRAP-AROUND)	N-P	2 X 2	0 004 to 0 006	10Ω CM	CERIC OXIDE	Ni-Cu-Au	SOLDERED	0 004 CHANCE CMD MICROSCOPE GLASS DOPED WITH 5% CERIC OXIDE, MgF_2 COATED, NO BLUE FILTER	FERRANTI	RAE	RAE, ADVANCED LIGHTWEIGHT SOLAR ARRAY	RAE STUDY
11	SI (CONVENTIONAL)	N-P	2 X 2 2 X 6	0 008	10Ω CM	SIO	Ag-Ti	SOLDERED	0 003 GLASS (CONSIDERED 0 0031 CORNING RIBBON GLASS TYPE 8871)	HELIOTEK	HELIOTEK	RYAN 30 WATT/LB ROLLUP SOLAR ARRAY	NASA FUNDED
12	SI (CONVENTIONAL) SI (CONVENTIONAL)	N-P N-P	2 X 2 2 X 2	0 006 0 008	2Ω CM 2ΩCM	SIO SIO	Ag-Ti Ag-Ti	ZONE SOLDERED SOLDERED (BACK ONLY)	0 003 GLASS 0 006 GLASS	CENTRALAB	TRW TRW	TRW, 40 WATT/LB SPACECRAFT SOLAR ARRAY TRW, LUNAR SURFACE SOLAR ARRAY	TRW INDEPENDEI DEVELOPMENT STUDY NASA/TRW STUD MINOR HARDWA AND TESTING OCCURRED
13	CdS	N/A	3 0 X 3 0 IN	THIN FILM	—	—	Au PLATED Cu	THIN FILM	0 001 MYLAR 0 001 KAPTON 0 001 Cu 0 001 KAPTON WITH CONDUCTIVE COATING	CLEVITE CORP	LEWIS RESEARCH CENTER	EXPLORE CONSTRUCTION PROBLEMS ASSOCIATED WITH THIN FILM; TWO ARRAY SIZES; REVIEWED 23 4 FT^2/158 FT^2	NASA LEWIS STUDY, SERT II PROPOSED
14	CdS	N/A	2 93 X 3 68 IN	THIN FILM	—	—	Au PLATED Cu	THIN FILM	0 001 MYLAR	CLEVITE CORP	TRW	INTERPLANETARY ELECTRICALLY PROPELLED SPACECRAFT	TRW MULTI-MISSION ELECTR PROPULSION SPACECRAFT STUDY

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

SOLAR CELL USAGE ON FLEXIBLE SUBSTRATES

CONTACT MAT'L	SOLDER/ SOLDERLESS	COVER TYPE	MANUFACTURER		APPLICATION	FUNDING AGENCY	REMARK	BIBLIO NO
			CELL	SUBMODULE				
Ag-Ti	—	0 0013-0 0018 CORNING RIBBON GLASS TYPE 8871	HELIOTEK	HELIOTEK	JPL SUBCONTRACT, DEVELOPMENT OF AN INTEGRATED LIGHTWEIGHT FLEXIBLE SILICON SOLAR CELL ARRAY	NASA FUNDED	INTERCONNECTORS (2 MIL COPPER) BETWEEN TWO POLYIMIDE SHEETS THAT HAD HOLES THROUGH WHICH METAL TABS PROTRUDED AND MADE CONTACT TO THE CELLS A 1-MIL FIBERGLASS STRIP IS REQUIRED FOR INSTALLATION OF REAR CONTACT	H 3-2 THRU H 3-4
Ag-Ti Ag-Ti Ag-Ti Ag-Ti Ag-Ti	SOLDERED SOLDERLESS ZONE SOLDERED SOLDERLESS WRAPAROUND	0 012 FUSED SILCA 0 003 FUSED SILCA	CENTRALAB CENTRALAB CENTRALAB TEXAS INSTRUMENT CENTRALAB	LMSC LMSC LMSC LMSC LMSC	LMSC INDEPENDENT DEVELOPMENT FUNDED, CONSIDERED FOR REPLACEMENT OF RIGID SOLAR ARRAY SYSTEM ON AF CONTRACT	ID FUNDED BY LMSC, STUDY TO DEVELOP FOR FLIGHT APPLICATION	EACH CELL IS INDUCTION SOLDERED TO THE SUBSTRATE (PRINTED LAMINATE CIRCUIT) 1 MIL KAPTON 0 5 MIL FEP 2 MIL Cu (OFHC) 0 5 MIL FEP 1 MIL KAPTON } LAMINATE SUBSTRATE TABS ARE FORMED BY UPSETTING EXPOSED PRINTED CIRCUITRY	L 4-3
—	—	—	—	BBG	SPACE STATION/ COMMUNICATION MULTIKILOWATT POWER SYSTEMS	MESSERSCHMITT (BBG) IN-HOUSE STUDY	THE SUBSTRATE IS KAPTON WITH Cu PRINTED CIRCUIT FOR CELL BACKSIDE WIRING Ag MESH IS WELDED TO THE Cu TO FORM THE SERIES INTERCONNECT FOR THE CELL NO ADHESIVE IS USED TO BOND THE CELL TO THE KAPTON OTHER THAN SOLIDER	M 3-1
Ag-Ti	SOLDERED	0 006 0211 MICRO-SHEET	—	FAIRCHILD-HILLER	SPACE STATION, MCDONNELL DOUGLAS ASTRONAUTICS CO	NASA FUNDED SPACE STATION DEFINITION	MAC DAC SELECTED FAIRCHILD-HILLER ROLL-OUT DRUM	M 2-2
Ni-Cu-Au	SOLDERED	0 004 CHANCE CMD MICROSCOPE GLASS DOPED WITH 5% CERIC OXIDE, MgF_2 COATED, NO BLUE FILTER	FERRANTI	RAE	RAE, ADVANCED LIGHTWEIGHT SOLAR ARRAY	RAE STUDY	CELLS SOLDERED THROUGH 2-MIL KAPTON IL KAPTON FILM INTERCONNECTS ON KAPTON WERE 1-MIL Ag PLATED Mo	R 3-4
Ag-Ti	SOLDERED	0 003 GLASS (CONSIDERED 0 0031 CORNING RIBBON GLASS TYPE 8871)	HELIOTEK	HELIOTEK	RYAN 30 WATT/LB ROLLUP SOLAR ARRAY	NASA FUNDED	CELLS SOLDERED TO SILVER PLATED COPPER INTERCONNECTS (CONVENTIONAL DESIGN), SUBMODULE IS ATTACHED TO 1 MIL KAPTON H-FILM	R 4-5 THRU R 4-8
Ag-Ti Ag-Ti	ZONE SOLDERED SOLDERED (BACK ONLY)	0 003 GLASS 0 006 GLASS	CENTRALAB	TRW TRW	TRW, 40 WATT/LB SPACECRAFT SOLAR ARRAY TRW, LUNAR SURFACE SOLAR ARRAY	TRW INDEPENDENT DEVELOPMENT STUDY NASA/TRW STUDY, MINOR HARDWARE AND TESTING OCCURRED	CELL/INTERCONNECT ASSEMBLY BONDED TO 2-MIL KAPTON CELLS SOLDERED TO FLEXIBLE CHEM-MILLED INTERCONNECTS THE 3-CELL SUBMODULE WAS THEN BONDED TO KAPTON H-FILM	T 3-19 T 3-7
Au PLATED Cu	THIN FILM	0 001 MYLAR 0 001 KAPTON 0 001 Cu 0 001 KAPTON WITH CONDUCTIVE COATING	CLEVITE CORP	LEWIS RESEARCH CENTER	EXPLORE CONSTRUCTION PROBLEMS ASSOCIATED WITH THIN FILM, TWO ARRAY SIZES, REVIEWED 23 4 FT^2/158 FT^2	NASA LEWIS STUDY, SERT II PROPOSED	CELLS ARE SOLDERED IN SHINGLE FASHION USING INDIUM SOLDER, 5 SERIES BY 5 PARALLEL MODULES, THREE TYPES OF SUBSTRATES WERE CONSIDERED	N 6-5, -6
Au PLATED Cu	THIN FILM	0 001 MYLAR	CLEVITE CORP	TRW	INTERPLANETARY ELECTRICALLY PROPELLED SPACECRAFT	TRW MULTI-MISSION ELECTRIC PROPULSION SPACECRAFT STUDY	CELLS ARE SOLDERED IN SHINGLE METHOD, 5 IN PARALLEL, 5 IN SERIES SUBMODULE IS MOUNTED ON A 1 MIL KAPTON LATTICE BY MEANS OF THERMOSETTING ADHESIVE THIS MODULE BECOMES THE BASIC BUILDING BLOCK	T 3-6

FOLDOUT FRAME

FOLDOUT FRAME 2

3

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4.1.3.4 Coverglass Technology Evaluation

4.1.3.4.1 Available Technology. There are two reasons that coverglasses are installed on solar cells. The first and primary reason is to reduce the cell operating temperature in space. Typically, a bare silicon solar cell with a silicon monoxide coating has an emittance of approximately 0.6 and a solar absorptance of approximately 0.88. At 1 a.u. normal incidence to the sun with solar constant of 140 mw/cm^2 and back surface emittance of 0.9, the equivalent temperature of the solar cell would be 65°C (Ref. Bibliography C.3-4). The emittance of the first surface may be increased by glass of certain organic materials that are transparent in the wavelength region where the cell is able to convert solar energy into electrical energy and absorptive in the region where it emits radiation. Historically, Corning 0211 microsheet or Corning 7940 fused silica have been used for this purpose. Corning 0211 microsheet is a fire-polished drawn glass available in thickness from 0.005-in. The 7940 fused silica is made by vapor deposition from Si and is extremely pure. It must be cut to size and polished.

If either of these glasses (with an antireflection coating to decrease reflectance in the wavelength range where the cell is responsive) is cemented to a cell, the coverglass-solar cell unit will have an emittance of $\approx$ 0.84 and a solar absorptance of $\approx$ 0.83. This produces an in-space operating temperature of 46°C (Ref. C.3-4) There is a slight transmission loss from the glass and the adhesive but there is a net power gain of 11 percent over the base cell. This fact points out one advantage of using coverglasses.

The second reason for using coverglasses is to reduce the damage to the cell resulting from space environmental radiation. The two commonly used coverglass materials vary greatly in radiation resistance. Corning 7940 fused silica is very resistant to radiation. There was no loss in transmission after 10^{15}, 1 MeV electrons/cm^2, 10^{12}, 5 MeV proton/cm^2; or 300 equivalent solar days of UV (See Chart P at the end of this section) Under the same fluences of radiation, however, 0211 microsheet suffered a 15-percent transmission loss from the electrons and a 10-percent transmission loss from the protons. The UV offered a slight annealing effect. Thus, fused silica is commonly used where charged-particle radiation is a problem and microsheet is used where it is not

As stated, the two aforementioned coverglass materials have received more usage than any other material However, over the past few years there has been an increasing number of studies to develop new coverglass systems at a lower cost than fused silica, but with the same excellent radiation resistance.

It has been determined by Heliotek (Ref H 3-1 through -4) that, in general, there are six areas that affect the cost associated with a coverglass

Purchased Coverglass Cost

1 Cover substrate material
2. Type of optical coating and filter applied
3 Tolerance or dimensions

Installation Costs

4. Amount of breakage associated with thickness of covers
5. Cover to cell location tolerance
6. Type of cover bonding adhesive used

On the basis of covering 500,000 cells/year with 6-mil covers of fused silica, tight dimensional tolerance, and an AR but no blue filter, the cost would be $3.49 per cell. Microsheet of the same specifications would cost $2.44 per cell.

One of the first attempts to reduce this cost was to deposit an integral cover on the cell, thereby eliminating the entire adhesive operation. Hoffman Electronics (Ref. C.3-1 and -2), under a NASA-Goddard contract, developed a procedure of powdering a borosilicate glass that was then dispersed in a slurry and deposited on the solar cell surface in a centrifuge. The particles were then fused to the cell surface at temperatures ranging up to 900°C Nominal thickness of 1 mil were produced. There were initial problems with diffusion on the N-contact caused by the high temperature but, even when they were overcome, the fabricated cell exhibited radiation darkening of the glass comparable to 0211 microsheet.

NASA-Goddard then contracted Ion Physics (Ref. I.3-2 through -9) and Texas Instruments (Ref. T 2-1) to investigate other methods of integral cover-slipping. Ion Physics developed the method of using a high vacuum ion beam (HVIB) to sputter Corning 7940 fused silica onto solar cells Nominal deposition rates of 200 Å/min were obtained

(approximately 33 hours to deposit one mil of SiO_2) The films produced exhibited severe compressive stresses at thicknesses above about 6 mils. However, films below 3 mils are well bonded to the cell and show the same optical properties as 7940 coverslides cemented to the cells. Texas Instruments investigated the method of radio frequency (rf) sputtering of 7940 fused silica onto cells. Films obtained from this method were deposited at rates of approximately 1600 Å/min. These films also exhibited severe compressive stresses at thicknesses above 6 mils.

NASA-Goddard conducted an evaluation of the three above-mentioned integral coverslips (Ref. N.2-1) Significant results of this study were 1) the borosilicate glass degrades severely under proton irradiation, 2) both HVIB and rf-sputtered covers showed a normalized maximum power loss of 6 percent after 10^{14}, 500 KeV protons/cm^2 and no power loss after 10^{14}, 2.0 MeV proton/cm^2, 3) 5 of 10 rf-sputtered test cells failed catastrophically after two weeks at 95 percent RH and 70°C. In view of this, study is continuing on the HVIB approach of installing thin integral coverslips.

Heliotek (Refs H.3-1 through -4) has also studied the HVIB approach to solar cell covers and they estimate that in comparison to the $3.49 for fused silica covers cemented to the cells by conventional techniques, comparable integral coverslides should cost about $0.86 per cell.

LMSC is also studying integral covers under independent development funding. The present Lockheed approach, not to be confused with the earlier "Marks" coating, entails a sprayed-on fluorocarbon film. The process involves dissolving the fluorocarbon, spraying it onto the cell, and then heat curing it. It is a new program and is still under development, but it shows promise of cost reductions over conventional fused silica covers with the radiation resistance of other fluorocarbons (Ref. N.6-2).

There have been several other attempts at using a fluorocarbon as a coverglass. The first and major effort has been the heat sealing of FEP-teflon directly on a solar cell. Initial work was begun at LMSC, followed by a study at NASA/Lewis (Ref. N.6-21). The process involves laying a piece of FEP-Teflon on one or several solar cells and, with the heat and pressure of a platen press (≈450°F, ≈1000 psi), fusing it directly to the cell The temperatures experienced require the use of a solderless cell. However, covers from one-half to 20 mils can be heat sealed onto multiple

cells at once In another NASA/Lewis study (Ref N.6-2), the radiation resistance of FEP-Teflon was shown to be nearly the same as fused silica. There was no loss in transmission after 10^{14}, 800 KeV protons/cm^2 or 10^{17} 1 MeV electrons/cm^2. The study did show, however, a four and one-half percent loss in transmission after two equivalent solar years in UV.

LMSC is studying the applicability of a tape technique utilizing FEP-Teflon's high transmissivity (>93 percent up to 3 μm) and radiation resistance in conjunction with one of two silicon adhesives – one pressure sensitive and one heat curable. One obvious advantage in this technique is a very rugged and inexpensive process capable of covering any number of solar cells at once. Preliminary results show that the adhesives that will adhere to FEP-Teflon are also very resistant to ultraviolet radiation, thereby eliminating the need for a blue filter. This study is continuing.

Another fluorocarbon under study (by the British) is ACLAR, the Allied Chemical Company trade name for CTFE, a fluorohalocarbon film. The film has high transmissivity (>93 percent to 0.8 μm) and is heat sealable. Indications are, however, that it becomes very brittle when exposed to UV (Ref. N.6-22).

The final coverglass system under development, for the specific purpose of reducing cost, is the ribbon glass approach. Both Heliotek (Ref. H.3-1 through -4) and Ryan (Ref. R.4-6) have studied the approach. Heliotek, however, has done much more investigation and has determined that, compared to the previously mentioned cost of $3.49 for a fused silica cover, a comparable ribbon glass cover would cost about $0.65 per cell. The glass studied by both companies was Corning 8871 glass, 0.003 inch thick. It is flexible and in the form of a rolled-up piece of tape. The potentially automated process involves the bonding of the glass to the cells in a continuous process and trimming away the excess. Development is continuing at Heliotek. Indications are that other types of glass (including 0211 microsheet) whose radiation resistances have been determined are available from Corning if the quantity merits.

In addition to reduced cost, another advantage of all of the above cell covers is the variety of thicknesses available. Fused silica must be cut and polished to a desired thickness. At thicknesses below 0.006 inch, the cost may become excessive because

of to handling breakage. Bulk thermal properties desirable in a coverglass can be obtained in thicknesses as small as 0.001 inch. So, from a systems standpoint, the other types of coverglasses other than fused silica make appreciable cost reduction possible.

The aforementioned coverglasses were studied with hopes of reducing cost but still maintaining a coverglass with high transmission and radiation resistance. In effect, they involved unconventional and untested methods of installation.

Another cost-savings technique being investigated is that of doping less expensive glass materials as a means of radiation resistance improvement. This glass would be assembled like conventional covers being installed by an adhesive system. It is hoped that the cost of these glasses will fall between that of microsheet and fused silica.

The first attempt was the doping of microscope glass with cerium by Mullard Ltd. (Ref. M.5-1). The glass used is readily obtainable in Europe. It is reported that with a 5-percent ceria dope, there were no transmission losses after 10^{15}, 1 MeV electrons/cm^2, 10^{12}, 5 MeV protons/cm^2, or 300 days of UV. This compares to a 5.5 percent loss after protons and 1 percent loss after electrons of the same fluence in undoped microscope glass (see Chart P).

Another attempt at cerium doping was at NASA/Langley (Ref. N.5-1) by Gilbert Haynes. In that study, microsheet was used. Mr. Haynes reports that with a 3-percent cerium dope, there was a 6-percent loss in wideband transmission after 5 by 10^{14}, 1 MeV electrons (26 percent loss in undoped microsheet) and 1 percent loss in wideband transmission after 10^{13}, 22 MeV protons (23 percent loss in undoped microsheet). He also suggests that a one and one-half percent cerium dope is about the optimum for microsheet. This is a result of tradeoffs between a basic loss in initial transmission with a high cerium dopent level and a lower radiation resistance with a low cerium dopent level.

The last type of doped or treated coverglass was the hydrogen-impregnated cover (Ref. T.-10). Ten types of glasses were impregnated (including 0211 microsheet) and it was found that all exhibited improved radiation resistance at low dose levels (10^6 rads). Some glasses resisted color center darkening even at higher dose levels.

It must be stated that fused silica was not tested because of its inherent radiation resistance.

The last type of coverglass reported was one developed by NASA/Lewis (Ref. N.6-1) for use with cells with a high blue response (the so-called super-blue cells). The coverglass system essentially eliminates a radiation degradable adhesive. They are prepared by evaporation of cerium silver contacts on the glasses through the same mask used to put contacts on silicon solar cells. Cell and glass are then solder dipped, placed together, and heated. There is no need now for a blue filter but the span between the cell and cover give rise to possible thermal "greenhouse" effects. Also, the basic handling and alignment problems continue to exist with their related cost impact.

4.1.3.4.2 Applicability to Space Station Requirements. Considering the vast amount of test and flight data that exists today as the result of 10 years of photovoltaic power experience, cover glass materials and adhesives, such as fused quartz 7940 and Sylgard 182, more than adequately meet the needs for the Space Station. However, new, less costly, lighter weight, and easier applied materials are in the immediate offing which make for an attractive overall cost savings. It is obvious that certain application and production problems need appropriate attention as well as further environmental testing before serious consideration can be given. Basic areas of concern were discussed in the existing data section.

4.1.3.4.3 Recommendations. There appears to be at least four areas that need further study, as discussed below

(1) Cerium doping shows promise of improving the radiation resistance of microsheet to where it is comparable to fused silica but at a reduced cost. There should be further study to determine the optimum level of cerium doping and its associated problems.

(2) There are studies that indicate that the multilayer interference blue filter is no longer necessary with today's adhesives (Ref. E.4-2). Tests should be conducted to determine the effect of UV radiation on these adhesives and compare it to the degradation experienced now by the blue filter itself. In addition, thermal studies should be conducted to determine if the blue filter has a cooling effect on the cell. With the data obtained, trade studies can be made comparing loss in transmission resulting from the blue filter and loss in transmission due to a degraded blue filter, to the losses in power due to a possible degraded adhesive (no blue filter) and perhaps a higher cell operating temperature.

(3) FEP-Teflon exhibits high transmission and good radiation resistance. Its potential as a simple, rugged, and inexpensive cover merits detail consideration.

(4) There should be more detailed studies to determine the optical properties of the various cover glasses as a function of temperature and radiation environment.

GENERAL SOLAR CELL COVER SUMMARY

NO	COVER TYPE	SPECIFIC GRAVITY	THICKNESS OPTIONS	RADIATION EFFECT	EMMISSIVITY	REFLECT-IVITY	TRANS-MISSIVITY	COATINGS AR	COATINGS UV	APPLICATION TECHNIQUES	COMMENTS	BIBLIO NO
1	FUSED SILICA (CORNING 7940)	2 20	0 003 AND UP	NO TRANSMISSION LOSS AFTER 10^{15} 1 MEV ELECTRONS/CM^2, 10^{12}, 5 MEV PROTONS/CM^2, or 300 DAYS UV	0.84 (GLASS CELL COMBINATION)	4.2%	>95% 0 45 to 0 9 μM	YES	YES	CONVENTIONAL ADHESIVE	• EXCELLENT RADIATION RESISTANCE (NO NEED TO H_2 IMPREGNATE) • EXPENSIVE	O 1-1 E 4-2 M.5-1
2	SOLDERED COVER GLASS (FOR 'SUPER BLUE' CELL) (ANY TYPE OF GLASS)	← THIS DATA APPLICABLE TO TYPE OF GLASS USED →						YES	NO	COVER GLASS IS METALLIZED WITH A PATTERN IDENTICAL TO TOP SOLAR CELL CONTACT CELL AND COVER GLASS ARE SOLDERED TOGETHER	• GREATER RESPONSE THAN CEMENTED CELLS IN THE 0 4 TO 0 5 MICRON RANGE • NO UV FILTER NEEDED • 5% HIGHER TOTAL RESPONSE • POSSIBLE HEATING OF SOLAR CELL DUE TO "GREEN HOUSE" EFFECTS	N 6-1
3	HYDROGEN DOPED	NOT REPORTED	NOT REPORTED	IMPROVED RADIATION COLORATION RESISTANCE IN LOW DOSE RANGES SOME GLASSES RESIST COLORATION AT VERY HIGH DOSE LEVELS	← NOT REPORTED →			YES	YES	CONVENTIONAL ADHESIVE	• NOT APPLICABLE TO LARGE PRODUCTION QUANTITIES • H_2 CONCENTRATION RANGES FROM ~.2 CC TO 1 5 CC PER CC OF GLASS • FUSED SILICA (CORNING 7940) NOT TESTED DUE TO ITS INHERENT RADIATION RESISTANCE	T 1-1
4	MICROSHEET (CORNING 0211 WITH MULTILAYER UV FILTER)	2 53	0.003 AND UP	TRANSMISSION LOSS • 15% AFTER 10^{15}, 1 MEV ELECTRONS/CM^2 AT 0 48 μM (ANNEALED TO A 6% LOSS AFTER 300 DAYS UV) • 10% AFTER 10^{12}, 5 MEV PROTONS/CM^2 AT 0.48 μM (ANNEALED TO A 6% LOSS AFTER 300 DAYS UV)	0.84 (GLASS CELL COMBINATION)	4 2%	~90% 0.45 TO 0.9 μM	YES	YES	CONVENTIONAL ADHESIVE	• MUCH DEGRADATION BUT INEXPENSIVE	O 1-1 M 5-1
5	CERIUM DOPED MICROSHEET (CORNING 0211)	2 50	0 003 AND UP	FOR 3% CERIUM DOPED • 6% LOSS IN WIDE-BAND TRANSMISSION AFTER 5 x 10^{14}, 1 MEV ELECTRONS (26% LOSS IN UNDOPED μSHEET) • 1% LOSS IN WIDE-BAND TRANSMISSION AFTER 10^{13}, 22 MEV PROTONS (23% LOSS IN UNDOPED μSHEET)	NOT REPORTED	NOT REPORTED	NOT REPORTED	YES	YES	CONVENTIONAL ADHESIVE	• 'OPTIMUM' DOPANT LEVEL IS BETWEEN 1% AND 2% • 2% CERIUM DOPE CAUSES 5% LOSS IN WIDE-BAND TRANSMISSION OVER UNDOPED 0211 GLASS • HIGH DOPANTS (> 5%) HAVE ABSORPTION BAND AT ~ 0 57 μM • TEST SPECIMENS WERE 4 TO 40 TIMES THICKER THAN NORMAL COVER GLASSES	N 5-1
6	MICROSCOPE GLASS	2 55	NOT REPORTED	TRANSMISSION LOSS • 5 5% AFTER 10^{15}, 1 MEV ELECTRONS AT 0 5 μM (ANNEALED TO A 2% LOSS AFTER 300 DAYS UV) • 1% AFTER 10^{12}, 5 MEV PROTONS/CM^2 AT 0.5 μM (SLIGHT ANNEAL AFTER 300 DAYS UV) • MAX LOSS AT LOW WAVE LENGTHS	NOT REPORTED	NOT REPORTED	~93% 0.4 TO 0.9 μM	YES	YES	CONVENTIONAL ADHESIVE	• SUBJECT TO COLOR CENTER DARKENING	M 5-1
7	5% CERIUM DOPED MICROSCOPE GLASS	2 62	NOT REPORTED	NO TRANSMISSION LOSS AFTER 10^{15}, 1 MEV ELECTRONS/CM^2, 10^{12}, 5 MEV PROTONS/CM^2, or 300 DAYS UV	NOT REPORTED	NOT REPORTED	>85% 0 4 TO 0 9 μM	YES	NO	CONVENTIONAL ADHESIVE	• SUGGEST AGAINST USE OF UV FILTER – POSSIBLE DAMAGE TO ADHESIVE • NO DARKENING DUE TO RADIATION • APPEARS AS GOOD AS FUSED SILICA • DOPING CAUSES TRANSMISSION LOSSES	M.5-1
8	RIBBON GLASS CORNING 8871 (HELIOTEK JPL 952560)	3.60	0.0013 TO 0.0018	← NOT REPORTED →				YES	YES	BONDING OF GLASS TO CELL AS CONTINUOUS PROCESS AND TRIMMING AWAY EXCESS GLASS (DIAMOND SCRIBE WAS OPTIMUM CUTTER) (CONVENTIONAL ADHESIVE)	• ELECTROSTATIC BONDING WAS TRIED FAR FROM OPTIMIZATION BUT PROCESS HAS POTENTIAL • OTHER TYPES OF GLASS AVAILABLE (INCLUDING 0211 MICROSHEET) FROM VENDOR IF LARGE QUANTITY • POTENTIAL 2/3 REDUCTION IN COST OVER CONVENTIONAL FUSED SILICA OR μSHEET	H 3-1 THRU H 3-4

NO		COVER TYPE	SPE GR
9	INTEGRAL COVERS	RIBBON GLASS (CORNING 8871) (RYAN JPL 951971)	
10	INTEGRAL COVERS	ACLAR	
11	INTEGRAL COVERS	RADIO FREQUENCY SPUTTERED FUSED SILICA (CORNING 7940 SiO_2) (TEXAS INSTRUMENTS NAS5-10319)	
12	INTEGRAL COVERS	FUSED BOROSILICATE GLASS (HOFFMAN ELECTRONICS NAS5-3857)	
13	INTEGRAL COVERS	HIGH-VACUUM – ION SPUTTERED FUSED SILICA (CORNING 7940 SiO_2) (ION PHYSICS NAS5-10236)	
14	INTEGRAL COVERS	SPRAYED FLUOROCARBON FILM (LMSC ID)	
15	FEP-TEFLON COVERS	FEP-TEFLON (TYPE C) HEAT SEALED ONTO SOLAR CELL (NASA-LEWIS AND LMSC ID)	
16	FEP-TEFLON COVERS	FEP-TEFLON WITH SILICONE ADHESIVE (LMSC ID)	

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VER SUMMARY

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	COVER TYPE	SPECIFIC GRAVITY	THICKNESS OPTIONS	RADIATION EFFECT	EMMISSIVITY	REFLECT-IVITY	TRANS-MISSIVITY	COATINGS AR	COATINGS UV	APPLICATION TECHNIQUES	COMMENTS	BIBLIO NO
INTEGRAL COVERS	RIBBON GLASS (CORNING 8871) (RYAN JPL 951971)	3 60	0 0013	• 8871 GLASS WITH RTV 602 ADHESIVE HAD 1/2 OF 1% LOSS AFTER EXPOSURE TO 17 5 HR OF UV AT 5 SUN LEVEL	← NOT REPORTED →			YES	YES	BONDING OF GLASS TO CELL AS CONTINUOUS PROCESS AND TRIMMING AWAY EXCESS GLASS (DIAMOND SCRIBE WAS OPTIMUM CUTTER) (CONVENTIONAL ADHESIVE	• OTHER TYPES OF GLASS COULD BE DEVELOPED	R 4-6
	ACLAR	2 08	0.001 AND UP	• NO TRANSMISSION LOSS AFTER 10^{14}, 800 KEV PROTONS/CM^2 • TEST SPECIMEN BECAME TOO BRITTLE TO TEST AFTER 2 6 x 10^{17}, 1 MEV ELECTRONS • TEST SPECIMEN BECAME BRITTLE VERY QUICKLY UNDER UV	NOT REPORTED	NOT REPORTED	>93% AT 0.8 μM >80% TO 6.8 μM	NOT RE-PORTED	YES	HEAT SEAL WITH HEAT AND PRESSURE OR USE AN ADHESIVE	• VERY STRONGLY AFFECTED BY UV AND 1 MEV ELECTRONS, TEST SPECIMENS BECAME BRITTLE	N 6-20
	RADIO FREQUENCY SPUTTERED FUSED SILICA (CORNING 7940 SiO_2) (TEXAS INSTRUMENTS NAS5-10319)	2 20	UP TO 2 MILS	WITH 1 x 2 CM, N/P, 10 Ω.CM, (CeO_2 AR CELL COATING) 13 MIL SOLAR CELLS (2 MIL SHIELD) • FOR 500 KeV PROTONS AFTER $10^{14}/CM^2$ • NO I_{SC} DROP • ~6% V_{oc} LOSS • ~6% NORMALIZED P_{MAX} LOSS • FOR 2.0 MeV PROTONS AFTER 10^{14} PROTONS/CM^2 ALMOST NO DEGRADATION IN EITHER I_{SC}, V_{oc}, P_{MAX} • COMPARATIVE CELLS WITH 6 MIL CORNING 7940 COVER-SLIDES SHOWED NO DAMAGE • AFTER 500 EQUIVALENT SOLAR HOURS, NO PHYSICAL DEGRADATION RESULTED	NOT REPORTED	4% TO 10%, 0 4 TO 1 0 M (1 MIL SLIDE ON CELL	>90%, 0 4 TO 1.2 μM (< 2 MILS SLIDE)	YES	NO	1600 Å/MINUTE	• SEVERE COMPRESSIVE STRESS EXHIBITED IN THICK FILMS (>6 MILS) • 5 OF 10 TEST CELLS FAILED CATASTROPHICALLY AFTER 2-WEEKS AT 95% R H AND 70°C • H_2 IMPREGNATION OF COVER SLIDE INCREASED I_{SC} BETWEEN 5% AND 9% (NO ANNEAL) • CeO_2 AR CELL COATING BECAUSE OF BETTER OPTICAL MATCHING THAN SIO WITH INTEGRAL COVERSLIDES • 300 THERMAL CYCLES FROM +100°C TO -100°C (10 MINUTES EXTREME TEMPS) – NO DAMAGE	N 2-1 T 2-1
	FUSED BOROSILICATE GLASS (HOFFMAN ELECTRONICS NAS5-3857)	2 23	2 TO 20 MILS	SAME AS RF SPUTTERED EXCEPT 16 MIL CELLS, SIO AR CELL COATING, 1 MIL SHIELD – SEVERE DEGRADATION AFTER PROTON IRRADIATION, NO UV TESTS PERFORMED	0 93 TO 0 96 0° TO 100°C POLISHED, 30 MICRON SAMPLE	NOT REPORTED	NOT REPORTED	YES	NO	POWERED BORO-SILICATE GLASS DE-POSITED ON SOLAR CELL IN CENTRIFUGE AND FUSED AT ~750°C	• RADIATION DARKENING COMPARABLE TO CORNING 0211 MICROSHEET • INITIAL PROBLEMS WITH N-CONTACT DIFFUSION	N 2-1 C 3-1 C.3-2
	HIGH-VACUUM – ION SPUTTERED FUSED SILICA (CORNING 7940 SiO_2) (ION PHYSICS NAS5-10236)	2 20	UP TO 2 MILS	SAME AS RF SPUTTERED EXCEPT 15 MIL CELLS WERE USED	← NOT REPORTED →			YES	NO	• 200 Å/MINUTE – WITH A ROTATING DRUM, IT TAKES ~80 HR TO DEPOSIT 1 MIL FILM ON 800 CELLS • FILMS ARE EXTREMELY WELL BONDED TO CELLS	• SEVERE COMPRESSIVE STRESS EXHIBITED IN THICK FILMS (>6 MILS) • NO DEGRADATION AFTER 2 WEEKS AT 95% RH AND 70°C • H_2 IMPREGNATION CAUSED AVERAGE OF 6 MILLIAMPS INCREASE IN I_{SC} AFTER 20 MINUTE, 300°C ANNEAL • CeO_2 AR CELL COATING	N 2-1 I 3-2 THRU I 3-9
	SPRAYED FLUOROCARBON FILM (LMSC ID)	2 15	1/4-20 MILS	UNDER INVESTIGATION	0 85	UNDER INVESTI-GATION	UNDER INVESTI-GATION	NO	NO	FLUOROCARBON IS DISSOLVED, SPRAYED ONTO SOLAR CELL, AND CURED WITH HEAT	STILL UNDER DEVELOPMENT	L 4-21
FEP-TEFLON COVERS	FEP-TEFLON (TYPE C) HEAT SEALED ONTO SOLAR CELL (NASA-LEWIS AND LMSC ID)	2 15	1/2-20 MILS,	NO DEGRADATION AFTER 10^{14}, 800 KeV PROTONS/CM^2 OR 10^{17}, 1 MeV ELECTRONS/CM^2 4-1/2% LOSS IN TRANSMISSIVITY AFTER 2 EQUIVALENT SOLAR YEARS	0.85 (GLASS CELL COMBINATION)	UNDER INVESTI-GATION	>96% TO 3 5 μM	NO	NO	HEAT SEALED WITH HEAT (~450°F) AND PRESSURE (~1000 PSI)	PROCESS PERMITS COVER INSTALLATION ON UP TO 30 CELLS AT A TIME	N 6-21 L 4-20 N 6-2
	FEP-TEFLON WITH SILICONE ADHESIVE (LMSC ID)	2 15	1/2-20 MILS	SEE ABOVE FOR RADIATION EFFECT ON FEP EFFECT OF RADIATION ON ADHESIVES IS BEING DETERMINED	0.85 (GLASS CELL COMBINATION)	UNDER INVESTI-GATION	UNDER INVESTI-GATION	NO	NO	HEAT CURABLE OR PRESSURE SENSITIVE ADHESIVE AVAILABLE	STILL UNDER DEVELOPMENT BUT SHOWS PROMISE OF BEING INEXPENSIVE, EASY TO INSTALL, AND CAPABLE OF COVERING A LARGE NUMBER OF CELLS IN A SHORT TIME	

V

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4.1.3.5 Technology Evaluation for Array Feeder Harness

A primary candidate for the power feeder harnesses on the Space Station Solar Array is flat conductor cable. Flat Conductor Cable (FCC) is a generic name, describing the principal feature of flat conductors, as opposed to round conductors. Both FCC and RWC (round wire cable) are produced as flat cables, having the conductors in one plane. During the last few years, the names have been established for both types. A flat cable with flat conductors is called FCC, and a cable in flat form having round conductors is called a ribbon cable. The FCC can be made in several different ways by extrusion, laminating, chemical etching, or weaving. The most common methods are laminating and checmical etching.

Where extensive bending and flexing occur, multistrand ribbon cable may be preferred over FCC. Such a case occurred on an early Air Force/Agena reset tracking array where the Cicoil Corporation of North Hollywood, California provided such a transfer or flex harness for the array-vehicle interface. The feeder harness for a space station array will be subjected to very few flexures corresponding to array deployment and retraction. Therefore, the feeder harness technology evaluation, as opposed to rotational power transfer flex harness, was concentrated on more conventional flat cable technology. The survey, (ref. Chart Q), revealed that both printed circuit (etched) and roll laminated conductor harnesses were developed for use with flexible substrate arrays.

It was of interest to note that flat cable conductors did not originate with the aerospace industry. Aerospace use of flat conductor cable generally followed the developments by NASA Marshall Space Flight Center, that began in 1956. The concept was first conceived, however, as early as 1884, when a patent (No. 303, 735) was granted to Charles Temple Jackson, of New York. This patent featured flat copper conductors cemented with shellac between strips of high voltage paper. Intended use of this original FCC was for concealed electrical house wiring.

All of the survey material used in developing the Feeder Harness Chart Q was taken from array studies in the 20 to 30 watts per pound category. Over half of the material is from the NASA 30 watt per pound studies and was furnished by Ryan, Fairchild-Hiller, and General Electric.

There is universal agreement that flat conductor cabling should be considered for large deployable arrays. Compared to round conductors, the flat conductor is easier to package, is more flexible and is lighter in weight. The weight advantage comes from the fact that there is less insulation required, the insulation material used is of lighter weight, and a higher current density can be used because of the higher surface area (heat radiating area) in relation to cross-section area. Some favor the use of aluminum conductors and some favor copper, however, for larger arrays such as the Space Station solar array the use of aluminum conductors, if larger wire sizes are required, may result in significant weight savings. Wide variances were noted in the current density allowances, some of which could be accounted for by different voltage drop priorities.

In the reports reviewed, there was very little data on harness termination techniques. Proper termination of individual conductors will be important to the producibility, maintainability, and reliability of a selected design. The work currently underway at Martin, Denver on the "Design, Development, Manufacturing, Test and Delivery of Devices for Connection of Solar Panel Circuitry to Flat Conductor Cable Solar Cell Array Harness", NAS8-26114, for NASA-MSFC, will be a valuable information source for FCC termination on flexible solar arrays.

The second sheet of Chart Q illustrates some of the terminations peculiar to the Boeing rigid periphery frame lightweight array. These methods were design-peculiar, however, they incorporated unique ideas on insulation and interconnecting that may be adaptable to feeder harness terminations at the root of the array where the array substrate panels interface with base structure.

Some of the studies pointed out that if the feeder harness was located on the back of the substrate, consideration should be given to through-the-substrate shorts. It should also be noted that if the feeder harness is located on the back of array panels, as opposed to the edges adjacent to the solar cell modules, that localized higher cell temperatures may occur due to the increased backside thermal barrier the harness introduces, and the introduction of heat via feeder harness IR losses. These and other considerations can be treated in tradeoff analyses during the next contract period.

Because of the large area of the Space Station array, the lightest possible busing system is needed. The present technology, as condensed in the matrix, forms a basis that is directly applicable and fairly comprehensive except for the copper/aluminum choice conflicts, and greater detail on conductor termination techniques. General flat cable technology has been significantly advanced by the pioneering work at NASA-MSFC. Their recent publication, "Flat Conductor Cable Design, Manufacture, and Installation", dated 9 January 1970 (NASA TMS-53975) provides extensive information for hardware selection, design, manufacture, and quality control for flat conductor cable interconnecting harness applications.

FLEXIBLE ARRAY FEEDER HARNESS SUMMARY

NO	ARRAY	OPERATING VOLTAGE	OUTPUT/BUSED SECTION (AMP)	BUS CONDUCTOR AND SIZE	AREA (SQ MILS)	CURRENT DENSITY (SQ MILS/AMP)	PLACEMENT OF BUS	DETAILS	MAX TEMP (°F)	COMMENTS	BIBLIO NO
1	TRW 2 5 KW CdS, 31 W/LB AT 25°C, 672 SQ FT	77	4 TO 16	COPPER SHEET 4 x 1600 MILS TO 4 x 6200 MILS	6400 TO 24,800	1600	BACK EDGES OF SUBSTRATE NOT STACKED	TABS EXTEND BEYOND HINGE LINE AND JOINED AFTER MECHANICAL SEAM	130	STEPPED WIDTH OF BUS SELECTED TO MINIMIZE BUS WEIGHT AND THE DIMENSIONS LIMIT THE OHMIC LOSSES TO 1%	T 3-1
2	BOEING 50 KW, 20 W/LB, 4924 SQ FT (SAME BASIC DESIGN USED IN CONTRACTS 951653 AND 951934)	28 & 100	NOT REPORTED	ALONG SUBPANEL: COPPER, FLAT 4 TO 6 MILS x 1 IN WIDE	4000 TO 6000	NOT REPORTED	BONDED TO PANEL FRAME ON SUN SIDE PLUS AND MINUS PAIRS STACKED	INSULATION BETWEEN PAIRS; SPRAYED ON IN LAYERS WITH NEW PROCESS (SEE FIG 1 BUS DETAILS)	NOT REPORTED	MAGNETIC EFFECTS EMPHASIS IN DESIGN AND EXTENSIVE MAGNETIC EFFECTS ANALYSIS	B 3-1 THRU B 3-8 & B 3-16
				ALSO ALONG SUBPANEL: ALUMINUM, FLAT THICKER THAN COPPER BUS, AND 1-1/4 IN WIDE	UNKNOWN		BONDED TO PANEL FRAME ON SUN SIDE AND SIDE PLUS AND MINUS PAIRS STACKED	INSULATION BETWEEN PAIRS BONDED SHEET FILM (TOO RIGID FOR SPRAY) (SEE FIGS 2 & 3, BUS DETAILS)		REASON FOR ALUMINUM BUS NOT STATED STATEMENT "TOO RIGID FOR SPRAY" IS NOT CLEAR DETAILED DRAWINGS OF BUS TERMINATIONS	
				PANEL TO PANEL ACROSS HINGE LINE: TYPICAL – SIZE EQUAL TO NO 6 AWG			ACROSS HINGE LINE			MADE FROM NO 34 COPPER STRANDS, LAID STRAIGHT AND PARALLEL AND WRAPPED WITH GLASS FIBER INSULATION FOR FLEXIBILITY PAIRS TIGHTLY TWISTED FOR LOW MAGNETIC EFFECTS (SEE FIG ,)	
				ARRAY TO VEHICLE: TWISTED WIRE CONDUCTORS							
3	HUGHES 20 KW 26 W/LB (CONTRACTS 2750 AND 1676	39	3 2	TIN PLATED EXPANDED COPPER MESH EQUIVALENT TO NO 22 AWG, CHANGED TO 0 7 MIL ETCHED COPPER IN 1676 CONTRACT	500 (2750 CONTRACT)	156 (2750 CONTRACT)	BACK OF SUBSTRATE	2750 CONTRACT MESH PREPARED FROM 0 003-IN COPPER FOIL BOND TO BACK NO ADDITIONAL INSULATION OTHER THAN THE SUBSTRATE 1676 CONTRACT 0 7 MIL ETCHED COPPER, INSULATED WITH KAPTON FRONT TO BACK CONNECTIONS MADE BY FOLDING BUS STRIP AROUND EDGE OF PANEL RATHER THAN THROUGH HOLES	175	REASONS FOR USING MESH NOT STATED VERY FEW DETAILS OR DOCUMENTED TRADE-OFFS	H 6-1 THRU H 6-13
4	RYAN 250 SQ FT, 30 W/LB, 10 W/SQ FT (CONTRACT 951107 AND 951971)	76	3 1	BUSES ACROSS EACH OF THE 13 MODULES: ALUMINUM 0 002 x 0 5 IN	1000	320	BACK OF SUBSTRATE	ALUMINUM IS BONDED BETWEEN KAPTON DOUBLERS WITH FM-1044B ADHESIVE MULTILAYER FOIL CONDUCTORS, PLUS REVERSING JUXTAPOSED CIRCUITS MINIMIZES MAGNETIC FIELDS LOCALLY SILVER PLATED FOR SOLDER CONNECTIONS ACCESS BY SLOTS IN THE KAPTON SUBSTRATE	NOT REPORTED	COPPER CLAD ALUMINUM FOIL RECOMMENDED HOWEVER, NOT CHOSEN IN THIS DESIGN BECAUSE IT WAS NOT AVAILABLE AT THAT TIME. THE STATEMENT "LAMINATIONS TO MINIMIZE MAGNETIC FIELDS" IS ASSUMED TO MEAN STACKING OF PLUS AND MINUS BUSES	R.4-1 THRU R.4-8
				BUS DOWN THE ARRAY TO VEHICLE: ALUMINUM FOIL – 1100 EC-GRADE 0 001 IN THICK, WIDTH OF BUS INCREASES FROM 0 706 IN (OUTBOARD MODULE) TO 5 235 IN (NO 13 INBOARD MODULE) TO MAINTAIN LOSS OF 0 10 WATTS/SQ FT BUS TERMINATES ON A TERMINAL BOARD AT INBOARD END OF ARRAY	706	230 NOT INCLUDING REDUNDANT BUS	BACK OF SUBSTRATE	REDUNDANCY BY BUSES ALONG BOTH EDGES OF ARRAY FLEXIBLE FOIL OR EXPANDED MESH JUMPERS CONDUCT ACROSS SUBPANEL JOINTS WIRE RIBBON AND OTHER METALS WERE CONSIDERED IN TRADE-OFF STUDIES SELECTED ALUMINUM BECAUSE OF LEAST WEIGHT			
5	FAIRCHILD-HILLER 250 SQ FT, 30 W/LB, 10 W/SQ FT CONTRACT 951969	74	0 77	COPPER, FLAT – EACH CONDUCTOR 0 026 x 0 006 IN	156 x 2 CONDUCTORS = 312	206 EACH CONDUCTOR, 2 CONDUCTORS USED FOR REDUNDANCY	LACED TO EDGES OF THE ROWS OF MODULES	EACH MODULE HAS 2 FLAT CONNECTORS FOR REDUNDANCY SPARE PINS OF THE CONNECTORS SERVE AS TEST POINTS FOUR HARNESSES RUN THE LENGTH OF THE ARRAY TO CONNECT THE MODULES EACH HARNESS HAS 48 0 26 x 0 006 COPPER CONDUCTORS IN 2 LAYERS (24 EA LAYER) WITH 0 03-IN SPACE BETWEEN CONDUCTORS HARNESS IS MADE OF THE 2 CONDUCTOR LAYERS SANDWICHED BETWEEN LAYERS OF KAPTON AND BONDED WITH RTV 108 ADHESIVE CONNECTORS ARE CANNON TYPE MTB CROSS-SECTION OF CONDUCTORS TO NEAR MODULES SAME AS THOSE TO FAR MODULES FOR UNIFORMITY	NOT REPORTED	SECOND QUARTERLY HAS EXTENSIVE CALCULATIONS SHOWING COPPER TO BE SUPERIOR TO ALUMINUM CONSIDERING WEIGHT AND POWER LOSS, IF THE WEIGHT OF THE INSULATION IS CONSIDERED	F 1-1 THRU F 1-4
6	GE 250 SQ FT 30 W/LB, 10 W/SQ FT (CONTRACT 951970 AND 952314)	102	NOT REPORTED	PRINTED CIRCUIT	NOT REPORTED		BACK OF SUBSTRATE	BASIC SUBSTRATE MATERIAL IS SCHUEL-CLAD L-7510 (1/2 OZ FT²) COPPER ON 2-MIL KAPTON-H FILM, ETCHED TO FORM THE BACK SIDE BUS STRIP PATTERN COPPER BUS IS THEN COVERED WITH KAPTON PRESSURE-SENSITIVE TAPE (TECHNICAL FLOROCARBON ENGINEERING P/N 603 1) CONNECTIONS FROM SIDE TO SIDE ARE MADE AROUND THE EDGES RATHER THAN THROUGH HOLES CROSSOVERS ARE MADE BY TAPE INSULATION AND BRIDGE JUMPER STRIPS JUMPER STRIPS ARE USED WHEN PIECES OF THE SUBSTRATE NEED TO BE JOINED BUS STRIP CIRCUIT RESISTANCE WAS MEASURED TO BE BETWEEN 0 75 AND 1 06 OHMS	NOT REPORTED	KAPTON S LOW RESISTANCE TO TEAR WAS CIRCUMVENTED BY THE BUS BARS AND KAPTON INSULATION BONDED TO THE EDGES (PLUS THE CELL TO SUBSTRATE BONDS) HOWEVER, BECAUSE OF WRINKLE AND FLATNESS PROBLEMS, THIS APPROACH WAS CHANGED TO THE PRINTED CIRCUIT WITH PRESSURE SENSITIVE TAPE INSULATION IN THE FOLLOW-ON CONTRACT (952314) SOME SUBSTRATE RIPPLE NOTED AFTER ETCHING WHICH RESULTED IN ADHESIVE VOIDS IN THE MODULES WHEN ASSEMBLED TO THE SUBSTRATE LONGITUDINAL PRELOADS ARE BEING IMPLEMENTED TO ELIMINATE THAT PROBLEM RECOMMEND A STRESS-FREE SUBSTRATE FOR BETTER APPROACH SYSTEM VOLTAGE OF 102 WAS CHOSEN IN A TRADE-OFF STUDY FOR LOWEST BUS WEIGHT AND POWER LOSS POWER LOSS IN BUS IS 2%	G 2-1 THRU G 2-8
7	LMSC F-95 SATELLITE PROPOSAL	28	0 65	COPPER – FLAT FROM 0 11 x 0 002 IN TO 0 25 x 0 002 IN	220 TO 500	340 TO 770	EDGE OF SUBSTRATE	44 CONDUCTORS OF VARIOUS SIZES STACKED IN 5 LAYERS CABLE MADE OF LAYERS OF KAPTON CONDUCTORS AND ADHESIVE CABLE DIMENSIONS ARE 2 x 0 027 IN INDIVIDUAL CONDUCTOR TO EACH MODULE VOLT DROP OF 0 6 FOR LONGEST RUN (SEE FIG 4a b c, BUS DETAILS 1	NOT REPORTED		L 4-9

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FLEXIBLE ARRAY FEEDER HARNESS SUMMARY
(Feeder Bus Details)

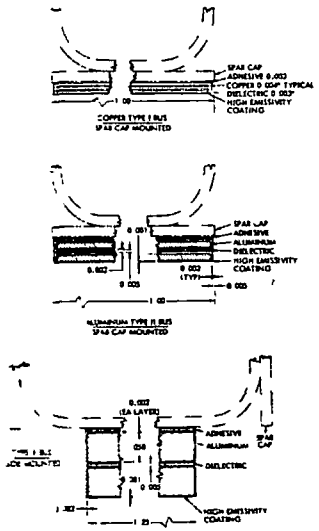

Fig 1. ELECTRICAL BUSES

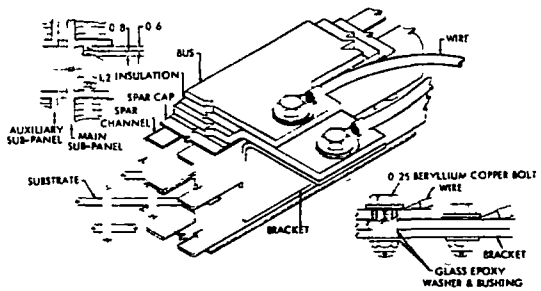

Fig 2 CROSSOVER-MAIN SUBPANEL, TO MAIN SUBPANEL

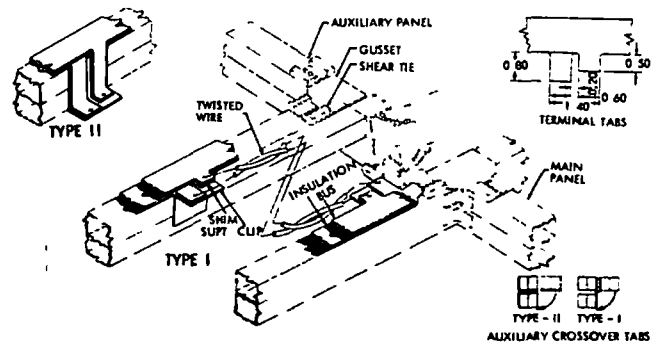

Fig 3 CROSSOVER-AUXILIARY TO MAIN SUBPANEL

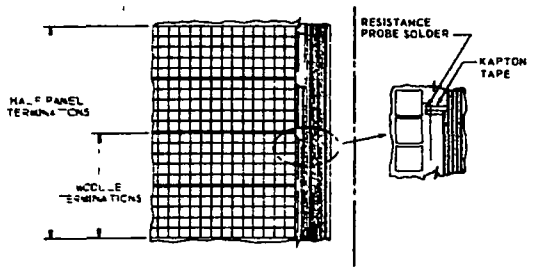

Fig 4a. FEEDER HARNESS TERMINATION

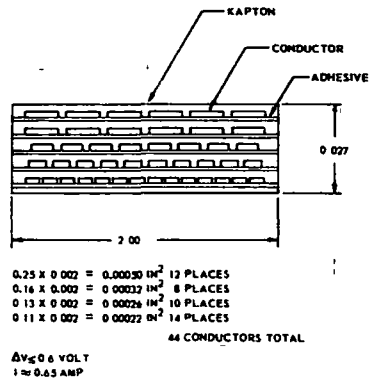

Fig 4b FEEDER HARNESS CROSS SECTION

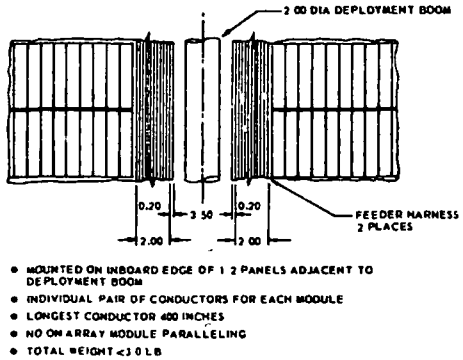

Fig 4c FEEDER HARNESS

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4 1 3 6 Substrate Assembly Joining Techniques

Joining techniques for thin film substrate materials have been considered by all investigators who have dealt with flexible array substrates. The width of present-day materials are limited by suppliers manufacturing capabilities requring some joining method to reach the necessary final array size. This is not particularly a disadvantage, since smaller segments compliment the preferred modular concept by facilitating the assembly of solar cell to substrate assembly, test, repairs and replacement.

Charts R and S list the features of the various methods investigated. The methods used generally fall into the three categories of adhesive, tape, or mechanical. Mechanical methods such as the use of lacing, velcro, or pin splicing (piano hinging) require more labor and tooling than the other categories; however they appear best for removal and disassembly. The early joint investigations in the Lockheed Independent Development programs favored the use of Fluoroplastics Adhesive 80. Later work pointed up advantages of Kapton-silicon adhesive tape.

One of the longest term evaluations of adhesive for Kapton joining (breakstrength and creep tests) has been conducted at NASA-Goddard. The testing was initiated to determine if Kapton substrates could be feasibly joined by adhesives for solar array applications. Break strength testing was performed on a Hunter Spring (Division of Amtek) tester. The samples are 2-1/16 in. wide, 7-9/16 in. long, and 2 mils thick and all bonded with approximately 5 mil thick adhesive with a 1/2-in. overlap except for some unbonded Kapton controls. On the tester, the distance between sample clamps was 5-9/16 in. The tester separates the clamps at a constant rate regardless of tension and indicates the breakpoint force and the accumulated separation movement at the breakpoint. The tests were performed at room temperature. All the Kapton material breaks occur in the total tension force range of 80 to 100 lb, and variation is ascribed to variations in the sample parameters such as in thickness and in local defects. The bonding is preceeded by a chemical etch or abrasion with No. 40 emory paper of the surfaces to be bonded. Prior to break testing, the samples were cycled 25 times in liquid nitrogen and boiling water. With the exception of Sylgard 182, all bonded joints with the adhesives used held to the point at which the Kapton broke, in an area other than at the joint. The adhesives used were Sylgard 182 and Sylgard 186, RTV 41 and RTV 8243.

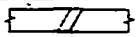
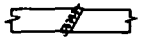
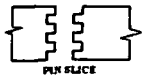
The creep tests, which NASA-Goddard also performed at room temperature, have been in progress for over a year The test samples include a Kapton control (no bonded joint) and Kapton-to-Kapton bonded specimens similar to the break strength test items. The adhesives tested are RTV 8243 (3 samples), RTV 41 (3 samples), Sylgard 186 (3 samples) and Sylgard 184 and 186 in equal parts (3 samples) The samples are attached to a support frame approximately three feet high. A characteristic noted is that with the initial addition of a 5-lb weight the creep rate starts at some relatively high value and decreases soon to a very low value. At this point, another 5-lb weight has been added to the test specimens with the same results observed but with lower creep rates. The samples are presently loaded with a total weight of 40 lb. One of the Sylgard 186 samples has failed, apparently by some slippage in the bonded joint that resulted in unsymmetrical loading at the joint and then caused a tear and a break at the joint.

Detailed analysis of the information collected at NASA-Goddard over the test periods has not been made and has an internal low priority. The objective of tests, namely the demonstration of the feasibility of bonding Kapton to Kapton, has been accomplished. Etching or mechanically preparing the surfaces to be bonded prior to bonding appeared to be required.

With the 3-ft maximum manufactured width in Kapton it is apparent that substrate joining for both permanent and removable joints will need be considered in design analysis. Adhesive and also heat sealable bonding, possibly with FEP or thermoset epoxy, may be considered for permanent bond applications. The technology is available for permanent substrate bonds. The techniques are available for removable joints, and, dependent upon selected solar cell module and panel designs, a variety of maintainable joint concepts have been evolved. Additional tensile and creep tests under this program will demonstrate which concepts are most feasible for the space station application.

FLEXIBLE SUBSTRATE JOINING TECHNIQUES

R

NO	APPLICATIONS	METHOD	DESCRIPTION	TEST	EASE OF REMOVAL	BIBLIO. NO
1	LMSC 50 FT² ID FLAT PACK	LAP BOND	ADHESIVE 60 FLUORO PLASTICS INC PHILADELPHIA PA	LAP SHEAR TESTS	FAIR	L 4-3
2	LMSC 60 FT² ID ARRAY	SHEAR BOND (DOUBLE SIDED TAPE) LAP BOND (TAPED)	KAPTON TAPE PERMACEL EE-6761	LAP SHEAR TESTS	FAIR	L 4-19
3	LMSC ID MODULE JOINING EVALUATION 1963	SEE FOLLOWING CHART	SEE FOLLOWING CHART	PRODUCIBILITY EVALUATION		L 4-19
4	GENERAL ELECTRIC 30 W/LB ROLLUP SOLAR ARRAY	 LAP BOND	KAPTON-TO-KAPTON WITH G.E SHRD 745 COMPOUND	LAP SHEAR TEST KAPTON TO GOLD PLATED COPPER ->90 LB/IN	FAIR	G.2-1 THRU G.2-4
5	HUGHES FLEXIBLE ROLLUP SOLAR ARRAY	LAP BOND	0.25 IN. LAP BOND KAPTON TO KAPTON (0.003) BONDED WITH HUGHES FORMULATED ADHESIVE	SOLAR PANEL (CELLS BONDED TO FIBER-GLASS SUBSTRATE) WAS TEMP. CYCLED +60 TO -300°F SUCCESSFULLY TENSILE LAP SHEAR ~73 LB/IN.	FAIR	H 6-7 THRU H 6-13
6	FAIRCHILD-HILLER 30 W/LB ROLLUP SOLAR ARRAY	 LAPPED AND LACED LAP BOND	0.003 KAPTON WITH HOLE PATTERN ALONG EDGE OF 2 x 3 FT SUBSTRATE SECTIONS. TWO SUCH SECTIONS ARE LACED TOGETHER BY LAPPING THE HOLES. FIX WAS TO BOND END OF LACE WITH ADHESIVE. B-FILM TO HPO FILM THERMAL SET; DOW A-1000 SILICONE ADHESIVE; AND PERMACEL 18	LAP SHEAR TEST -0 LB/IN. FAILED BY UNLACING. ADEQUATE SINCE DESIGN LOAD EXPECTED WAS 0.1 LB/IN	GOOD FAIR	F 1-1 THRU F 1-4
-	RYAN 30 W/LB ROLLUP SOLAR ARRAY	LAP BOND	KAPTON-TO-KAPTON WITH FM 1044B ADHESIVE	PEEL STRENGTH ~0.3 PSI; SHEAR STRENGTH >109 PSI	FAIR	R.4-5 THRU R.4-6
-	TACONIC PLASTICS INC TFE GLASS CATALOG	 PIN SLICE SEWN SEAM	ALLIGATOR LACING THROUGH WHICH A PIN IS PLACED TO COMPLETE THE SPLICE. SUBSTRATE IS OVERLAPPED AND SEWN (MORE APPLICABLE TO IMPREGNATED FIBERGLASS CLOTH)		GOOD POOR	

LOCKHEED KAPTON JOINING TECHNIQUES INVESIGATION

NO.	TYPE DESCRIPTION	METHOD	BOND TYPE WITHSTANDING LOADS	FABRICATION DIFFICULTY	HIGH TEMP CURING	NUMBER OF OPERATIONS	METHOD OF APPLICATION	TAPE TYPE	PASS OR REMOVAL	IN-PLANE STRESS	HIGHLIGHTS
1	ADHESIVE TO PLAIN KAPTON, INC		4	GOOD	YES	2	BRUSH OR SPRAY	NOT REQUIRED	FAIR	GOOD	L 4-19
2	DRIPOINT ADHESIVE 4070	LAP JOINT	3	GOOD	NO	3	BRUSH OR SPRAY	RC-403	FAIR	GOOD	
3	DR POINT ADHESIVE 4980		3	GOOD	NO	3	BRUSH OR SPRAY	RC-403	FAIR	GOOD	
4	DR POINT ADHESIVE 4050		3	GOOD	NO	3	BRUSH OR SPRAY	RC-403	FAIR	GOOD	
5	ALUMINUM REINFORCED 5 MIL AL BONDED WITH ADHESIVE TO TO MYLAR, LAP BONDED AND STAPLED	KAPTON, ALUMINUM, MYLAR, KAPTON, STAPLE	4	GOOD	-	4	BRUSH OR SPRAY AND STAPLER	N/A	GOOD	GOOD	
6	VELCRO PAD BONDED TO KAPTON WITH ADHESIVE 40	VELCRO, KAPTON	4	FAIR	-	3	PRESSURE	N/A	GOOD	GOOD	
7	20 MESH AL SCREEN SANDWICHED BETWEEN 2 LAYERS OF 1 MIL MYLAR BONDED TO KAPTON WITH ADHESIVE 40 WITH THIN BONDS		4	FAIR	-	4	-	N/A	GOOD	GOOD	
8	20 MESH AL SCREEN SANDWICHED AND BONDED BETWEEN AL FOIL AND KAPTON WITH THIN BONDS	SIMILAR TO ABOVE	4	FAIR	-	4	-	N/A	GOOD	FAIR	
9	1 MIL AL BACK TAPE 1 IN. WIDE MYSTIC TAPE BONDED ON (?)	LAP JOINT	1	GOOD	-	3	PRESSURE	N/A	GOOD	GOOD	
10	1 MIL MYLAR BONDED TO KAPTON AND FORMED INTO "PLANE BONDS"	MYLAR, WIRE, KAPTON	4	FAIR	-	4	LACE	N/A	GOOD	POOR	
11	KAPTON LAPPED INTO PRINCIPLE AND LACED WITH KAPTON STRIP		1	POOR	-	3	LACE	N/A	GOOD	POOR	L 4-19

4.1.3.7 Flexible Substrate Thermal and Optical Properties

4.1.3.7.1 Background and Requirements. The space station solar array thermal design is of major significance because of the high performance and long mission life requirements in a potentially damaging solar space environment. Array operating temperatures strongly influence solar cell efficiency and array material life. Large temperature changes are anticipated as the array is alternately subjected to intense solar radiation and darkness during the space station's orbit around the earth. These temperature changes, ranging from -180°F to +160°F, could be repeated up to 58,000 times, depending upon altitude and inclination as the array moves in and out of the earth's shadow.

Maximum array steady-state temperature predictions are used primary for initial design purpose and the establishment of basic test requirements. These temperatures are determined largely by the optical properties of the exposed array surfaces and the amount of incident radiant energy upon those surfaces. These properties include solar absorptivity and infrared emissivity. Solar cell electrical power output is strongly temperature dependent and drops significantly with increased operating temperature. Minimum array steady-state temperatures are determined largely by the infrared emittance of exposed surfaces and the amount of reflected or radiated energy that is absorbed by these surfaces while in the earth's shadow. The source of this energy may be reflection or radiation from the earth or other spacecraft surfaces.

Minimum transient temperatures are strongly influenced by the heat capacity of the array and infrared emittance-infrared absorptance of exposed surfaces while in the earth's shadow. The combination of large array area and light weight provide a low thermal mass (heat capacity) that greatly increases array cool-down and heat-up rates as the spacecraft orbits from sun to shadow.

The reliability of thermal-optical property values for array materials are important to the thermal designer for thermal analysis and accurate temperature predictions. Initial property values are required as well as degraded values after 5 to 10 years of exposure to the damaging solar space environment. Many of these properties are temperature dependent and must be known for the anticipated temperature range.

Temperature Requirements and Predictions. Satellite orbital altitudes vary from 100 nautical miles to 22,000 nautical miles (synchronous altitude). This variation has a very significant effect upon expected flexible array temperatures where a transient minimum may run as much as 200°F lower in synchronous orbit than in a 100 nautical mile orbit. Flexible array life may therefore be much longer in the Space Station orbit of 270 miles. This difference is due to the presence of solar reflection (albedo) from the earth and the earth's atmosphere. Additional infrared radiation is emitted from the earth (earth shine). The presence of these two radiation sources is most noticeable at low altitudes and approaches insignificance at synchronous altitude. The effect of this extra energy at low altitude is to greatly increase the minimum temperature while in earth's shadow and to only slightly increase the maximum temperature while in the sun.

There are two important thermal differences between flexible solar array assemblies such as the one planned for the Space Station and conventional rigid panel honeycomb assemblies such as will be used in Skylab. These differences are

- The increased heating and cooling rate of flexible systems that is the result of the comparatively lower mass of these systems (1/5 to 1/3 the weight per sq ft of the honeycomb assemblies).
- Variations in upper and lower equilibrium temperature extremes due to the above transient effects plus differences in the absorbing, emitting, and reflecting and conduction properties of the materials of construction used in the two types of assembly. This effect can be in either direction for either temperature extreme, depending upon specific configurations chosen and thermal control materials employed.

An example of these differences is shown in Fig. 4-3, which plots the results of a simulated sun-shade cycle conducted in the same chamber at the same time using the Lockheed flexible cell assembly and a sample of a flight qualified honeycomb solar cell panel. Note the higher heating and cooling rates for the flexible panel, which allowed it to reach a level "shade-side" temperature while the honeycomb panel was still dropping at the end of the 47-minute shade period. In this case, for this particular pair of designs, the flexible assembly achieved a substantially lower equilibrium sun-shade temperature. To ensure validity of results, these tests were re-run with the instrumentation exchanged between samples and temperatures were further checked

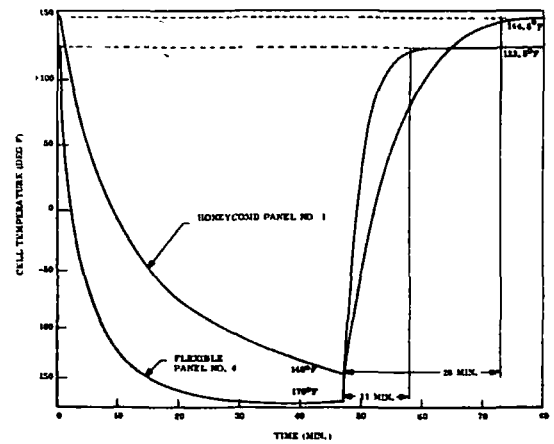


Fig. 4-3 Cooling and Heating Rates for Solar Panels (Flexible and Honeycomb)

against variations in cell output. These steps revealed no anomalies in measurement. The 144.5-degree maximum temperature shown for the rigid panel matches within two degrees with equilibrium temperatures recorded in flight at normal incidence on similar panels in a 300-mile orbit (which is very close to the proposed Space Station orbit). These upper limits are thus believed to the reasonably valid, with the exception that albedo was not simulated during this test and this energy source could cause temperature raising (greenhouse) effects on some flexible panel designs. This area needs further evaluation. Since this test was run in a liquid nitrogen cooled wall chamber with no external heat source during the shade portion of the test, the lower limit temperatures are known to be unrealistically low. As an example, the test shows a minimum temperature of -140°F for the honeycomb panel, whereas the lowest shade side temperature ever recorded on a Lockheed satellite in this altitude range in dozens of flights is -100°F. This higher temperature is due to the combined effects of earth radiation and heat inputs from the spacecraft. An optimistic appraisal of this test would lead, then, to a maximum temperature cycle prediction of -100°F to +125°F.

However, until thermal analyses are conducted that are specific to the Space Station solar array configuration, the assumption for design and preliminary test purposes will be a conservative temperature cycle range +160°F to -180°F. This conservative approach is used to avoid repeating testing that might be underway before thorough thermal analysis and supporting flight data are available.

4.1.3 7.2 Review of Significant Data. A review of available thermal design technology reveals some data that can be applied to the design or construction of the Space Station solar array. Optical property values, orbital parameters, and preliminary temperature predictions have been gathered from the available literature on flexible solar array design. These data, together with a brief description of the designs and data source, are tabulated in Chart T, Substrate Thermal/Optical Properties, and discussed as follows.

Initial optical property values tabulated for solar cell front surfaces show a significant variation with solar absorptance (α_s) ranging from 0.70 to 0.81 and infrared emittance (E_{IR}) ranging from 0.80 to 0.85. A portion of this variation is due to multiple combinations of antireflectance coatings, filters, adhesives, and covers. A variation in front surface solar absorptance of $\Delta\alpha_s$ = 0.09 (0.81-0.70) may amount to a change in maximum steady-state array temperature of 18°F. Thermal/optical properties are especially scarce at low temperatures. Lockheed currently has an in-house program to evaluate such properties over wide temperature ranges.

Initial optical properties of both front cell surfaces and back-substrate surfaces are expected to degrade in the solar space environment. Degraded optical property values are not available in the literature for either front or rear surfaces for 5 to 10 year missions. These degraded values are required to predict array operating temperatures throughout mission life.

The initial optical property values tabulated for substrate back surfaces show a greater range than front surface properties. This is due to the larger variety of substrate materials and the lack of reliable optical property values for these relatively new materials. These values have a significant effect upon the minimum array temperatures which in turn affects material thermal fatigue life.

Thermal-Optical Property Temperature Dependency. The thermal-optical properties of array materials will change significantly with temperature. Infrared emissivity and heat capacity are both expected to change during the large temperature excursions predicted during a low altitude orbit. Infrared emittance values and specific heat values are generally available for the common metals and dielectrics in the anticipated array temperature range. These temperature-dependent properties are generally unknown for the less common flexible array materials and were not found in available technology.

Flexible Array Substrate Thermal Design. A large variation in flexible array substrate design was noted during this technology review. Many different design configurations were revealed that have a very significant influence upon array operating temperatures and in turn affect electrical efficiency and array life. Most of the substrate designs were described, but in general were not supported by sufficient thermal analysis to determine their effect upon array temperature.

Researching the various design approaches revealed the following substrate design factors of thermal engineering significance.

1. The size and placement of possible openings in the substrate that permit direct exposure of the cell back surface. (Ref. Bibliography R. 3-4 through -6, L. 4-3, and H. 3-1 through -4).
2. The optical properties of the cell back surface when directly exposed (as in item 1 above) or when the substrate material is partially transparent to infrared or solar radiation. (Ref. Bibliography R. 3-4 through -6).
3. The attachment method used to fasten the solar cells to the array substrate. Some designs are based upon adhesive bonded cell-substrates (Ref. Bibliography G. 2-1 through -4, and H. 6-1 through -13), where thermal energy can be easily conducted from the cell through the adhesive into the substrate. Other designs rely upon soldered or welded electrical connectors for attachment purposes (Ref. Bibliography L. 4-3, R. 3-4, and M. 3-1). Thermal energy in this case may be less efficiently transferred by a combination of radiation-transfer between the cell back surface and substrate plus thermal conductance through the electrical connectors.

4. The size and location of possible cell cushioning materials fastened to the back of the substrate for protection during ascent and stowage conditions. (Ref. Bibliography G.2-1 through -9, F.1-1 through -4, and R.4-1 through -4). These materials are generally good thermal insulators and will strongly influence array operating temperatures.

5. The possible use of a thermal control coating on the back surface of the substrate. (Reference RAE Report R.3-4 and -11).

4.1.3.7.3 Summary of Missing Array Thermal Technology. Based upon the review of available thermal technology, it is apparent that additional knowledge will be required for Space Station flexible array thermal design purposes. The most significant missing technology areas are itemized as follows

- Long-Term Thermal Cycling Performance. The acquisition of performance data will require development of suitable test conditions to provide a meaningful simulation of the expected environment. A study of the candidate material properties will provide knowledge that may reduce test time and cost. Long term thermal cycling tests should then be conducted on flexible array material-design combinations in a simulated space station environment. (This is discussed further in Section 4.1.3.8).

- Initial Thermal-Optical Properties. Thermal-optical property values are known for many commercially available candidate materials at room temperature. The optical properties of array substrate combinations are generally unknown. Additional laboratory measurements are required to establish suitable engineering emissivity values for the front and rear surface combinations. Since this property is known to vary with temperature these measurements should be made over the anticipated temperature range. Specific heat values should also be determined for various substrate combinations over the anticipated temperature range. Several substrate design factors appear particularly applicable to the Space Station solar array and may justify further investigation. Included are the use of openings on the substrate to permit direct exposure of the cell back surface for better thermal conductance.

- Long-Term Optical Property Degradation. The optical properties of thermal control surface-materials are well documentated for short-term spacecraft use. Considerable knowledge and data have been developed on the damaging effects of the ultraviolet, proton, and electron environments as simulated in the laboratory. Only a limited amount of short-term flight data are available on the degradation of thermal control surfaces. Additional long-term laboratory testing is required, as well as reliable flight data on candidate thermal control surfaces.

SUBSTRATE THERMAL / OPTICAL

COMPANY SOURCE	ARRAY DESIGN DESCRIPTION	CELL FRONT SURFACES OPTICAL PROPERTIES		SUBSTRATE BACK SURFACE OPTICAL PROPERTIES		
		α_S	ϵ_{IR}	α_S	ϵ_{IR}	
HUGHES FLEXIBLE ARRAY STUDY	FLEXIBLE ARRAY USING 3 AND 6-MIL CORNING 0211 MICROSHEET, AR AND UV COATED COVERS BONDED TO 4, 8, AND 15-MIL N-P CELLS SUBSTRATE CONSISTS OF 1 5-MIL TEFLON-GLASS CLOTH BONDED TO THE CELL BACK WITH A MODIFIED EPOXY ADHESIVE	-	-	0.56	0 84	1: 3-
BRITISH AIRCRAFT CORP., U.K.	FLEXIBLE ARRAY DESIGN USING 6-MIL GLASS COVERS BONDED TO 8-MIL N-P CELLS WITH A SILICONE ELASTOMERIC ADHESIVE. THE SUBSTRATE CONSISTS OF A 2-MIL THICK KAPTON FILM WITH 1-CM DIAMETER CIRCULAR OPENINGS WHICH PERMIT DIRECT INFRARED RADIATION FROM THE CELL BACK.	0.76	0.83	-	0 35 (KAPTON FILM ONLY) 0 9 (POLYZOTE CUSHIONING)	H 1:
RYAN	FLEXIBLE ARRAY DESIGN USING CORNING 0211 MICROSHEET COVERS BONDED TO 8-MIL N-P CELLS WITH GE RTV-602 ADHESIVE SUBSTRATE CONSISTS OF A 1-MIL KAPTON FILM BONDED TO THE CELL BACK WITH DOW CORNING 3145 ADHESIVE.	-	-	-	0.35 (FILM ONLY) 0.34 (THROUGH FILM FROM ADHESIVE) 0 69 (TOTAL BACKSIDE)	1 PC PC
GENERAL ELECTRIC	FLEXIBLE ARRAY DESIGN USING 3-MIL MICROSHEET BONDED TO 8-MIL N-P CELLS WITH SYLGARD 182 ADHESIVE. SUBSTRATE IS 2-MIL KAPTON BONDED TO BACK OF CELL WITH GE SMRD-745 ADHESIVE	0 71	0 80	-	0.67	HI AI
MC DONNEL DOUGLAS SPACE STATION	FLEXIBLE ARRAY DESIGN USING 6-MIL CORNING 0211 MICROSHEET BONDED TO 8-MIL N-P CELLS. CELL COVER HAS ANTI-REFLECTANCE COATING SUBSTRATE IS 3-MIL THICK KAPTON-GLASS CLOTH BONDED TO BACK OF CELL.	0.68	0 85	0 40	0 75	24 AI
ROYAL AIRCRAFT CO., U.K.	FLEXIBLE ARRAY DESIGN USING 4-MIL THICK CHANCE CMO MICROSCOPE GLASS COVERS BONDED TO 5-MIL N-P CELLS WITH GE RTV-602 ADHESIVE. COVER HAS MgF_2 ANTI-REFLECTANCE COATING. SUBSTRATE IS 2-KAPTON FILM BONDED TO BACK OF CELL WITH AN ADHESIVE. CIRCULAR OPENINGS IN THE SUBSTRATE EXPOSE 60% OF CELL BACK WHICH IS BLACK CHROME PLATED.	-	-	HIGH (BLACK CHROME PLATE)	0.85 (BLACK CHROME PLATE)	S\
NORTH AMERICAN	FLEXIBLE ARRAY DESIGN USING 6-MIL CORNING 0211 MICROSHEET BONDED TO 10-MIL N-P CELLS WITH ADHESIVE; ANTI-REFLECTANCE COATING AND UV FILTER USED. SUBSTRATE IS 3-MIL KAPTON FILM BONDED TO CELL BACK	0.78	0 82	0.35	0 75	27 IN
FAIRCHILD-HILLER	FLEXIBLE ARRAY DESIGN USING 3-MIL GLASS BONDED TO 8-MIL N-P CELLS SUBSTRATE IS 2-MIL KAPTON BONDED TO CELL BACK WITH GE RTV-108 ADHESIVE.	0 70 (DESIGN VALUE)	0 85 (DESIGN VALUE)	1:0 0.7 0 4 } DESIGN VALUES	0 89 (KAPTON PLUS ADHESIVE ON ALUMINUM) 0.78 (31-MIL POLYEURETHANE FOAM OVER KAPTON OVER KAPTON OVER ADHESIVE OVER ALUMINUM) 0.96 (RTV-108 ADHESIVE OVER ALUMINUM	1C FL.
HUGHES	FLEXIBLE ARRAY DESIGN USING 6-MIL GLASS COVERS. 1-MIL GLASS, 1-MIL KAPTON BONDED TO CELL BACK WITH KAPTON THE OUTER LAYER. COPPER MESH Z-STRIP INTERCONNECTIONS ARE USED	0 81	0 83	0 40	0.81	4C O S\

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

MAL / OPTICAL PROPERTIES

OPTICAL PROPERTIES ϵ_{IR}	ORBITAL PARAMETERS	ORBITAL TEMPERATURE RANGE (STEADY STATE IF NOTED S.S.) MAX °C	MIN °C	COMMENTS	BIBLIO. NO.
0.84	150 TO 22,000 NM, 90° INCLINATION, 3-YR LIFETIMES, 10% EFFICIENCY	79°C (175°F) 79°C (175°F)	-73°C (-100°F) at 150 NM -184°C (-300°F) AT 22,000 NM	UNLIKELY THAT THE MAX TRANSIENT TEMP WOULD BE THE SAME AT 150 NM AS AT 22 000 NM	H 6-6
(KAPTON FILM ONLY) POLYZOTE CUSHIONING)	HIGH ORBITAL ALTITUDE 132-MIN SHADE TIME	50°C (122°F)	-180°C (-292°F)	TRANSMITTANCE VALUE FOR KAPTON FILM IS 0 425	B.2-1
(FILM ONLY) (THROUGH FILM FROM ESIVE) (TOTAL BACKSIDE)	1 A U (VENUS CONDITION EXTRA-POLATED TO 1 A U W/SQ FT POWER/OUTPUT	56°C KAPTON (134°F KAPTON) 134°F+8% FIBERGLASS TEMP BASED UPON 40% BACKSIDE CUSHIONING	-	DESCRIPTION OF THERMAL ANALYSIS IS UNCLEAR.	R 4-8
0.67	HIGH ORBITAL ALTITUDE AT 1 A.U AND 0 733 A.U 10-W/SQ FT POWER	49 4–51 7°C (DEPEND ON PROXIMITY TO VEHICLE) AT 1 A U. (S.S.)	-		G 2-4
0.75	246 NM, 50° INCLINATION, EQUINOX AND SOLSTICE ORBITS	69°C (157°F) (S.S.)	-90°C (-130°F) (S.S.)		M 2-2
(BLACK CHROME PLATE)	SYNCHRONOUS ORBIT	51° or 58°C (CEMENTED OR SOLDER-THROUGH BACK)	-186°C		R 3-4
0 75	270 NM, SUN-ORIENTED, SUN LINE IN ORBIT PLANE	79°C (175°F)	-82°C (-115°F)		N.9-1
(KAPTON PLUS ADHESIVE ALUMINUM) (31-MIL POLYEURETHANE M OVER KAPTON OVER TON OVER ADHESIVE OVER MINUM) (RTV-108 ADHESIVE OVER MINUM	100 NM EARTH ORBIT AND VENUS FLY BY	83°C (181°F) AT 100 NM (AWAY FROM STRUCTURE) (S.S.)	-	PREDICTED TEMP BASED ON AVERAGE FRONT AND REAR SURFACE ϵ_{IR} = 0 85 SUBSTRATE SURFACE RADIATIVE PROPERTIES DETERMINED BY EXPERIMENTAL MEASUREMENT	F.1-6
0.81	400 NM NOON CIRCULAR POLAR ORBIT SYNCHRONOUS EQUITORIAL ORBIT	82°C (180°F) AT 400 NM 60°C (140°F) AT SYNCHRONOUS	-84°C (-120°F) AT 400 NM -184°C (-300°F) AT SYNCHRONOUS	THERMAL ANALYSIS NOT REPORTED	H.6-7 THRU H.6-9

4 1 3 8 Thermal Cycling

Long-term solar array thermal cycling data suitable for Space Station array design purposes are not available from current technology Estimates of environmental requirements indicate that if no resupply occurs the array may have to survive over 58,000 thermal cycles over an approximate temperature range of -180°F to +160°F A limited number of thermal cycling tests have been conducted on flexible array components in both the U.S and in Europe (See thermal cycling of flexible substrates, Chart U) These tests were conducted on a great variety of substrate assemblies for varying and relatively few number of cycles In addition, there were wide variations in the temperature cycle range and rate One indication of the poor background available in this area is that there has been no testing of more than one flexible approach under a given set of conditions, so that there is little basis for even elementary comparison of candidate approaches.

Some of the tests were radiative, being conducted in a vacuum, such as the Boeing tests. The majority of tests conducted were convective, or if conducted in vacuum in some cases the specimens' performance were not measured in situ, but the specimens were removed to room ambient for performance of electrical measurement To date no temperature cycling tests on flex modules have been conducted which, with identical test and control specimens, have attempted to accurately assess the validity of the accelerated convective testing as compared to near realtime vacuum in situ tests In very few cases did the reported data include all test parameters, such as dwell at extremes, maximum rate of change, and cycle period – peak to peak

There are, therefore, very few design facts that could be extrapolated from the data It is indeed clear that a parametric test of existing and experimental substrate assemblies is needed using the anticipated Space Station environment

Of the test facilities reviewed, those at NASA-Goddard and LeRC are best suited to testing that most closely simulates on orbit conditions Both facilities utilize vacuum radiative testing and are equipped so that electrical measurements can be made on the specimens without removing them from the chamber LeRC has been

performing temperature cycle tests for AFAPL on Hughes flexible array module specimens As of mid-September 1970, one specimen had successfully completed 400 cycles for -125°C (-193°F) to +85°C (185°F) The NASA-Goddard facility is unique in that it contains two chambers, the smaller one holding 6 each 6 by 6-inch specimens and the larger one capable of 36 each 6 by 6-inch specimens The specimens are mounted on a carrousel so that they can be rotated, raised or lowered to place the test specimen in position in front of an illumination port for in situ electrical measurements Full details of this facility are contained in the paper by J W Fairbanks and M E Eck, "A Programmable Dynamic Thermal Vacuum System for Solar Array Component Testing", presented at the Fifth Space Simulation Conference, Gaithersburg, Maryland, September 1970

THERMAL CYCLING OF FLEXIBLE SUBSTRATES

NO	COMPANY, DEV UNIT/VT CONTRACT NO	TEST SAMPLE	TEST CONDITION	RESULTS	COMMENTS	BIBLIO NO.
1	LMSC SOLAR POWER STUDY, 1967 HYBRID UNIT (PVK/CD/PVT (PVK/GAAS)	TWENTY-FIVE 2 X 2 CM (FILM (PVK IN SERIES FIVE IN PARALLEL), ETCHED (FIL) HYBRID UNIT CELLS IN KAPTON-FEP FALS LAMINATE	1000 THERMAL CYCLES AT TWO CYCLES/HR BETWEEN -200°F AND +140°F	NO PHYSICAL DEGRADATION OF CONTACTS OR INTERCONNECTS; HIGHER ELECTRICAL DEGRADATION		L.H-3
2	NASA/TT ANONYMOUS TFLA (COMMUNICATION LOCKHEED SUPPLIED TEST MODULE THERMAL CYCLING TEST JULY 31 1970	TWENTY 2 X 2 CM CELLS (PVK IN PARALLEL, FIVE IN SERIES) LMSC KAPTON-FEP FLEX MODULE	1200 THERMAL CYCLES BETWEEN -310°F AND 135°F AT ~1 CYCLE/HR	MINOR CRACKING CURRENT BETWEEN 100 AND 350 CYCLES FIVE LOOSE INTERCONNECT TABS BUT NO ELECTRICAL DEGRADATION AFTER 1200 CYCLES NO FAILURES BETWEEN 1000 AND 1200 CYCLES	SIMULATION OF A TEN-YEAR SYNCHRONOUS ORBIT	R.3-2
3	DR. ALAN STANLEY MIT LINCOLN LAB 9TH PHOTOVOLTAIC SPECIALISTS CONF AUGUST 1970 LOCKHEED SUPPLIED TEST MODULE	FIFTEEN 2 X 2 CM CELLS (FIVE IN PARALLEL, THREE IN SERIES) LMSC KAPTON-FEP FLEX MODULE	1250 THERMAL CYCLES BETWEEN -320°F AND 140°F IN DRY NITROGEN 217 THERMAL CYCLES BETWEEN LIQUID NITROGEN TEMP AND 140°F (MAX 150°C/HR.)	NO FAILURE OF SUBSTRATE ONE CELL CRACKED AND LIFTED	STATED THAT SILICON CRYSTAL ORIENTATION (1:1:1 DIRECTION MAY BE OPTIMUM) AND AMOUNT OF SOLDER WERE POSSIBLE CAUSES OF FAILURE	M.4-3
4	ROYAL AIRCRAFT ESTABLISHMENT ADVANCED LIGHT-WEIGHT SOLAR ARRAY JULY 1970	GOLDEN THROUGH INTER CONNECTS 1 X 2 CM WRAP-AROUND CELLS (4-MIL) KAPTON SUBSTRATE	500 THERMAL CYCLES AT UNREPORTED RATE FROM -200°F AND 170°F	NO FAILURE REPORTED	MORE TESTS ARE PLANNED	R.3-4
5	HELIOTEK LIGHTWEIGHT SILICON SOLAR CELL ARRAY JPL 55250	INTERCONNECTOR SAMPLES OF 0.060 IN. WIDE COPPER STRIPS SOLDERED TO 14-MIL THICK SILICON SOLAR CELLS COPPER THICKNESSES WERE 1, 4, 6 AND 8 MILS	• 100 THERMAL CYCLES BETWEEN ROOM TEMP AND -320°F • 100 THERMAL CYCLES BETWEEN ROOM TEMP AND -140°F	• FAILURES EVENLY DISTRIBUTED AMONG INTERCONNECT THICKNESSES • 4 AND 8 MIL SAMPLES: 50% FAILURE • 2 AND 6 MIL SAMPLES LESS THAN 10% FAILURE		R.3-1 THRU R.3-4
6	SOCIETE ANONYME DE TELECOMMUNICATION, HELIOTEK SUPPLIED TEST MODULE PAPER GIVEN AT ECOSEC INTERNATIONAL COLLOQUIUM IN JULY, 1970	HELIOTEK MODULE WITH 18 2 X 3 CM CELLS (3 IN PARALLEL, 6 IN SERIES); STRESS RELIEVED WRAPAROUND INTERCONNECT ALUMINUM SUBSTRATE	APPROXIMATELY 4000 THERMAL CYCLES FROM +125°F TO -270°F AT ONE CYCLE/HR	• JOINTS THAT HAD NOT FAILED AFTER SEVERAL HUNDRED CYCLES PASSED 4000 CYCLES AND THESE REPRESENTED ABOUT TWO-THIRDS OF THE TOTAL QUANTITY	• ALUMINUM SUBSTRATE • MOST THERMAL CYCLES REPORTED	H 3-12

THERMAL CYCLING OF FLEXIBLE SUBSTRATES (CONT)

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NO.	COMPANY DOCUMENT CONTRACT NO.	TEST SAMPLE	TEST CONDITION	RESULTS	COMMENTS	BIBLIO. NO.
7	GENERAL ELECTRIC ROLLUP SUBSOLAR ARRAY JPL 062314	THREE MODULES (TWO 4 X 4 AND ONE 5 X 5) OF 2 X 2 CM CELLS INTERCONNECTED WITH EXPANDED SILVER MESH MODULES BONDED TO KAPTON WITH CUSHION BUTTONS AND AN ETCHED COPPER STRIP ON THE OPPOSITE SIDE	34 THERMAL CYCLES (EACH CYCLE FROM +250°F TO -200°F TO +250°F IN 50 MIN	FRACTURE OF METAL STRANDS IN LOCALIZED AREAS	FAILURES OCCURRED ONLY IN AREAS WHERE INTERCONNECT LOOP HAD BEEN SCORED BY MESH FORMING TOOL	G. 2-5 THRU G. 2-9
8	HUGHES FLEXIBLE INTEGRATED SOLAR CELL ARRAY AF33(615)-2750	• TEN 2 X 2 CM CELLS (FIVE IN SERIES, 2 IN PARALLEL), EXPANDED COPPER MESH INTERCONNECT	TESTS IN SEQUENCE: • -250°F FOR 2 HR AT 2×10^{-6} mm Hg PRESSURE • +250°F TO 250°F CYCLE AT 90°F/MIN MAXIMUM 5 CYCLES	• CELL 5R SEVERELY CRACKED • CELL 1R CRACKED DURING THIRD CYCLE NEW CRACK IN CELL 5R		H 6-1 THRU H 6-5
		• TEN, 2 X 2 CM CELLS (SERIES CONNECTED), EXPANDED COPPER MESH INTERCONNECT	• 70°F TO 250°F SHOCK AT 90°F/MIN MAX • 70°F TO -250°F SHOCK AT 90°F/MIN MAX • 70°F TO 250°F SHOCK AT 90°F/MIN MAX • -250°F SOAK FOR 2 HR • 70°F TO -300°F SHOCK AT 90°F/MIN MAX • -300°F SOAK FOR 2 HR • -300°F TO +250°F CYCLE AT 90°F/MIN MAX ; 0.5-HR SOAK AT -300°F; 4 CYCLES	• NO DAMAGE • NO DAMAGE • NO DAMAGE • NO DAMAGE • NO DAMAGE • N-STRIP BEGINNING TO LIFT ON ONE CELL • N-STRIP COMPLETELY LIFTED ON SAME CELL NOTED PREVIOUSLY		
9	HUGHES FLEXIBLE ROLLED UP SOLAR ARRAY F33615-68-C 1576	REPRESENTATIVE PANEL SEGMENT	100 THERMAL CYCLES (EACH CYCLE FROM +200°F TO -300°F TO +200°F IN 5 MIN	MINOR QUALITY CONTROL PROBLEMS		H 6-7 THRU H 6-13
10	BOEING LARGE AREA SOLAR ARRAY DESIGN JPL 951853	SEVERAL CELLS INTERCONNECTED WITH EXPANDED SILVER MESH	100 THERMAL CYCLES BETWEEN -148°F AND +108°F IN VACUUM FOLLOWED BY FLEXURAL FATIGUE	• NO PHYSICAL DAMAGE • SMALL REDUCTION IN OPEN CIRCUIT VOLTAGE	THERMAL CYCLING REDUCED EFFECTIVENESS OF SOLDER JOINT	B. 3-1 THRU B. 3-4

THERMAL CYCLING OF FLEXIBLE SUBSTRATES (CONT)

U

NO.	COMPANY, DOCUMENT CONTRACT NO	TEST SAMPLE	TEST CONDITION	RESULTS	COMMENTS	BIBLIO NO.
11	BOEING, LARGE AREA SOLAR ARRAY – PHASE II JPL 951834	ENTIRE OPERATIONAL SUBPANEL OF THE LARGE AREA SOLAR ARRAY	RANGE OF TEMPERATURES AND SOLAR SIMULATOR INTENSITIES WHILE IN A VACUUM OF 10^{-5} TORR (SEE B 3-8 FOR ACTUAL TEST SEQUENCE AND CONDITIONS)	NO PHYSICAL OR ELECTRICAL DEGRADATION OCCURRED AS A RESULT OF THE THERMAL-VACUUM-SHOCK TESTS		B. 3-5 THRU B. 3-8
12	HYAN FEASIBILITY STUDY 30W/LB ROLLUP SOLAR ARRAY JPL 951971	• 8-CELL MODULE 2 X 8 CM CELLS, ALUMINUM WITH NICKEL FLASH AND SILVER PLATE INTERCONNECT • 6 CELL MODULE, 2 X 6 CM CELLS ALUMINUM WITH COPPER FLASH AND SILVER PLATE INTERCONNECT • 4-CELL MODULE 2 X 6 CM CELLS COPPER WITH SILVER PLATE INTERCONNECT • 6-CELL MODULE, 2 X 6 CM CELLS, MOLYBDENUM WITH SILVER CLAD INTERCONNECT • BAR CONTACT INTERCONNECT ON ALL MODULES	• ALL MODULES WERE CYCLED BETWEEN -148°F AND +108°F AT 50°F PER MINUTE FOR 100 CYCLES WITH THE EXCEPTION OF THE MOLYBDENUM MODULE WHICH WAS CYCLED 50 TIMES • ONE MINUTE TIME SOAK AFTER TEMPERATURE STABILIZATION	• TWO ALUMINUM SAMPLES STRETCHED AND WRINKLED SLIGHTLY • SILVER PLATING ON MOLY OXIDIZED TO CAUSE SEVERE DISCOLORATION • COPPER WITH SILVER PLATE SHOWED NO SIGN OF DEGRADATION	• BAR CONTACT COPPER INTERCONNECT SUCCESSFULLY PASSED 100 THERMAL CYCLES BETWEEN -148°F AND +108°F	B 4-5 THRU B. 4-8
13	GENERAL ELECTRIC FEASIBILITY STUDY 30W/LB ROLLUP SOLAR ARRAY JPL 951970	• THREE 5 X 5 CELL MODULES (2 X 2 CM CELLS) WITH PHOTOETCHED, 3-MIL THICK BeCu INTERCONNECTS • ONE 5 X 5 CELL MODULE (2 X 2 CM CELLS) WITH EXPANDED SILVER MESH INTERCONNECTS	• THREE BeCu MODULES CYCLED BETWEEN -200°F AND +200°F FOR 114, 105 AND 100 CYCLES RESPECTIVELY • SILVER MESH MODULE CYCLED 117 TIMES BETWEEN -200°F AND 200°F AND AN ADDITIONAL 88 TIMES BETWEEN 250°F AND +200°F	• BeCu MODULES SHOWED VARIOUS SIGNS OF DEGRADATION • NO DAMAGE TO SILVER MESH AFTER 200°F TO +200°F CYCLES • EXTENSIVE DAMAGE TO SILVER MESH WHEN RANGE EXTENDED TO -250°F TO +200°F	• SILVER MESH SUCCESSFULLY PASSED 117 THERMAL CYCLES BETWEEN -200°F AND +200°F	G 2-1 THRU G 2-4

4 1 3 9 On-Array Electronics

On-array electronics are defined as electronic devices mounted on or near the flexible solar array substrate for the purpose of conditioning solar cell power at the source Also included in the definition of on-array electronics are the more commonly used blocking/isolation diodes and by-pass diodes. This concept is new as compared to the more conventional method of locating all power conditioning/battery control electronics on the vehicle In concept, on-array electronics appears to have several advantages over the conventional method. One advantage is that voltage and current control can become more versatile by switching in or out specified electrical sections, depending on battery and system demands. Another advantage is that excessive heat is ideally dissipated from the solar array source by direct radiation rather than adding to the heat load. The third and most important potential advantage is the potential reliability increase associated with modular power conditioning as apposed to large, central power conditioning units Work to date with on-array electronics has been conceptual, more development of such a technique is needed before specific space station feasibility is decided. Further, although much guidance can be obtained from the work presented in the following sections, selection of a Space Station approach will be a unique function of the basic flexible module design and the power conditioning and battery charging requirements of the Space Station.

History and development is very limited to date on the use of on-array electronics to voltage limit and/or power regulate the output of a solar array In the conditioning function, only voltage limiting has had flight history and only on two applications, one by JPL and the other by LMSC, both using zener diodes to limit over-voltage. Both applications used the zener function in the early portion of their missions to limit what would be higher than desired battery/system voltage. Design problems of zeners used in this application are heat dissipation and the zener voltage variations with changing temperature. Advantages include high reliability because of being a passive system, light weight, and installation in an ideal location from which to dissipate heat

On-array electronics to completely regulate array output has been found feasible with present technology in three separate studies by G E , Boeing, and Hughes These concept studies were for a 1 kV to 16 kV array, however, although they were applied

in a relatively high voltage range the general concepts are still of value when considering a low voltage application All three studies envision short-circuiting series connected solar cell groups for voltage regulation, and using array switching techniques for current regulation An on-board computer would control the various switching functions Problem areas include charged particle radiation and thermal transient effects, high local power dissipation in semiconductor switches and electronic packaging, and feeder harness complexity Advantages include minimal total system power dissipation, high power transfer efficiency, light weight, high reliability, and the potentiality for a finer current control for battery charging than that normally feasible by on-board electronics

Blocking/isolation diodes mounted on the array have had extensive successful flight history. These are used to prevent battery discharge through the array during shadow periods and to protect the electrical system from array shorts. By-pass diodes to protect the array from the "hot-spot" failure mode have been proposed several times but do not have any flight history. This failure mode is being discussed in Section 4.1 3 9 3

4.1 3 9.1 Conditioning Electronics (reference Chart V). Array temperatures for flexible arrays are reported to vary over a maximum range from -180°F to +160°F in the earth orbit mode of operation. It is noted in the General Electric high voltage study (Ref Bibliography (G-2-11) that there is an absence of performance data for electronic devices below -55°C Therefore, testing of the electronic components below -55°C will be necessary.

An observation on voltage control comes from the General Electric study, where limits on regulation are emphasized in connection with digital switching of solar cell modules In this case the voltage of the individual solar cell becomes the incremental limit for regulation precision. However, as the study points out, if so desired, regulation precision may be obtained by means of the linear regulator switching device. In concept, the ideal use of this device can allow very small incremental steps for the operation of a digital voltage control of solar arrays.

The Boeing high voltage solar array study (reference B. 3-10) uses simultaneous sensing of both voltage and current to track the peak power point (PPP) on the I-V

characteristic of the solar array. The quantities are compared to references in a spacecraft computer, from which switching command signals are retransmitted to the array

Regulation of voltage only has been chosen by General Electric and Hughes in their high voltage studies. Hughes, however, conceives a fine current control injected into the control loop. The effect is to superimpose a small shift of the characteristic along the voltage axis for a corresponding change in current This would adjust the operating point more nearly at the peak power point operation, which is approximated by system design On the other hand, General Electric asserts that "the capability of power tracking configurations present no advantage to the HVSA (High Voltage Solar Array) system, and implementation of the inductor and capacitor components required in micro-circuit form would present a significant if not impossible, packaging challenge."

Failure protection has been used in the "power block" systems of the three high voltage studies, where each block is separately regulated with switch ties to a number of different loads. Redundance in circuit design is used extensively in the same three high voltage studies This includes redundant blocking diodes, switching diodes, solar modules, and redundant cells in each sub-module.

The radiation environment anticipated for the high voltage solar arrays includes altitude dependent proton and electron flux and probability of proton flux due to solar flares. Discussions on radiation and temperature may be found in the General Electric HVSA report (Ref. Bibliography G.2-11), section 9.1, page 131, and in the Hughes HVSA report (Ref. Bibliography H 6-20), page 77. All recommend the use of shielding around the electronic parts for protection against radiation. General Electric suggests the use of tantalum as a shielding material, Hughes suggests the use of tungsten, and Boeing believes that there should be more evaluation before proceeding in that direction. However, it may be inferred from the HVSA discussions that lower radiation dosage will be experienced by on-array electronics at low earth orbits, in comparison to the higher altitudes, extending to the synchronous orbit. Polar orbits are recognized as exceptions However, it may be possible that for selected orbits the need for protective shielding could be considerably reduced.

Flexibility in scaling the size of an array is relatively independent of on-array electronic power conditioning of the output. There are two reasons for this

- The ratio of electronic devices to the total number of solar cells is not required to change, with changes in size.
- Although the electronic device ratio must change for some design revisions of load current, the change could be minor, being mainly a change to increase the current rating of certain transistor shorting switches

Assuming an effective basic module design, thermal limitations with regard to scaling flexibility appear to pose no problem, because the electronic control devices are uniformly distributed over the area of the array. No concentration of heat should be expected due to the scaling procedure.

The problem of heat dissipation was solved in all three HVSA studies by

- Selection of microelectronic devices for minimum heat dissipation.
- Provision of large heat sink radiation areas.
- Use of shielding against the sun's radiant heat.

The Boeing report asserts that "to avoid thermal run-away, the transistor heat sink should be designed to dissipate significantly more power than required when the transistor is ON " General Electric asserts that "large heat sink areas (64 cm^2 and greater) are required to limit semiconductor chip temperatures." It could be significant that the scale factor given by the Hughes report is for earth orbit at 270 nautical miles, at an operating temperature of 70°C The concern expressed for proper heat sink in all HVSA studies suggests that the factor of heat sink radiation area should be carefully evaluated before proceeding with a design. Further, an additional problem could develop with increasing area of the heat sink, in that it must be flexible to be compatible with stowage and deployment.

The use of shielding over the microelectronic chips for protection against the sun is recommended by the Hughes HVSA report. This could explain the seemingly small heat sink radiation area calculation. Therefore, the use of the recommended quartz mirrored chips over the microelectronic devices becomes an important consideration

The limits on size for an equivalent low voltage solar array are indicated in the HVSA studies to be associated with the thickness of the microelectronic packages The thickness of these packages is caused by the use of alumina base for the electronic chips and tantalum or tungsten shielding against proton and electron radiation. The General Electric report assigns an electronic package thickness of 0 095 in., the Hughes report speaks of 0 25 in., and the Boeing study is limited to conceptual designs of electrical configurations.

The voltage reference should be located on board the vehicle, according to General Electric and Hughes The Boeing HVSA study chose to locate the voltage reference on the array. An array location makes the temperature problem more severe.

It is important to realize that on-array electronics to regulate an array exists only in conceptual studies. Component development would probably be necessary, even for a low voltage application, but the extent is not known, since the existing studies are for a high-voltage application only

4.1 3.9.2 Blocking/Isolation Diodes. Diodes used to prevent battery discharge through the array during shadow periods and to protect the electrical system from array shorts have been used successfully in many flights. Some recent studies of roll-up arrays propose not using these diodes, since the substrate is usually an insulator This greatly reduces shorting possibilities on the array. In certain missions there is either no shadowing (or eclipse) or the battery leaking back through the array during shadow periods is less than the power lost in the forward resistance of the diode However, if the feeder harness is located on the back of the substrate, as is depicted in some roll-up array studies, consideration must be given to the possibility of through-substrate shorts Each mission and design would necessitate trade-off studies to determine if the diodes are needed

4.1.3 9.3 By-Pass Diodes. The "hot spot" failure mode may be considered a malfunction, with either a functional or environmental cause. This type of failure occurs within a sub-module, composed of a group of cells connected in parallel The malfunction of one or more of these sub-module cells will cause the balance of the cells in the sub-module to experience a reverse voltage across the sub-module in question. The product

of the reverse voltage and the circuit current can result in a localized overheating and the generation of a "hot spot" sufficient to melt solder The effect can be cumulative to the point of catastrophic failure. The cause may be breakage from operational causes, shadowing resulting from the physical position of the space vehicle relative to sun line of sight, or damage from meteorites This type of failure has been reported by Baron and Virobik of Thompson Ramo Woolridge (TRW), Blake and Hanson of General Electric Company, and Rauschenback of TRW Systems, among others Shunting or by-pass diodes provide the recommended solution to the problem. Since this problem is much more severe with high voltage arrays, it was considered in detail in the high voltage solar array studies at General Electric, Hughes, and Boeing The "hot spot" severity and necessity of by-pass diodes for a low voltage system must be evaluated relative to the selected electrical design configuration. A recent development by Heliotek includes the by-pass diode as an integral part of the silicon solar cell (Ref. Bibliography S.5-11). They report having tested the unit over a temperature range from -20°C to +100°C. That report shows no consideration of radiation or very low temperatures on the diode performance

ON ARRAY ELECTRONICS

		GE HIGH VOLTAGE SOLAR ARRAY STUDY BIBLIO NO. G.2-11	HUGHES HIGH VOLTAGE SOLAR ARRAY STUDY BIBLIO NO. H 6-15	BOEING HIGH VOLTAGE SOLAR ARRAY STUDY BIBLIO NO. B 3-10	MARINER VENUS 67 SOLAR PANEL BIBLIO NO. A.3-7	LMSC AF CONTRACT SOLAR ARRAY BY PROJECT INTERVIEW
INSTALLATION	MISSION	100 MILE ORBIT, RAISE TO SYNCHRONOUS ORBIT IN 90 DAYS, SYNCHRONOUS ORBIT – 5 YEARS, HIGH VOLTAGE LOADS. ION PROP	HIGH VOLTAGE SOLAR ARRAY TO RAISE SATELLITE FROM LOW EARTH ORBIT TO SYNCHRONOUS ORBIT, 5 YEAR MISSION ION PROPULSION	EARTH ORBIT WITH CAPACITY TO CLIMB TO SYNCHRONOUS ORBIT, 5 YEAR MISSION. ION PROPULSION	VENUS PROBE	EARTH ORBIT
INSTALLATION	CONSTRUCTION	FLEXIBLE, ROLLUP 2-MIL KAPTON SUBSTRATE	FLEXIBLE, ROLLUP 5-MIL KAPTON SUBSTRATE	FLEXIBLE, ROLLUP 3-MIL KAPTON SUBSTRATE	RIGID 4-MIL AL SUBSTRATE W/MINOR TRUSS	RIGID AL. HONEYCOMB SUBTRATE
INSTALLATION	CELL CONFIGURATION	BUILDING BLOCK CONFIGURATION REGULATION SECTION TYPICAL STRING 10p x 2909s	POWER BLOCK CONFIGURATION REGULATION SECTION TYPICAL STRING 14p x 286V BOL	BUILDING BLOCK CONFIGURATION REGULATION SECTION TYPICAL STRING 6p x 1442s	6 STRINGS 7p x 105s	20 STRINGS 6p x 80s
INSTALLATION	PERFORMANCE DATA	SYSTEM 1 / SYSTEM 1 24.6 W/LB BOL / 24.4 W/LB BOL 2800 SQ FT / 2650 SQ FT ESTIMATE 4 WINGS 15 KW EOL	24 6 W/LB BOL ESTIMATE 2400 SQ FT ESTIMATE 2 WINGS 15 KW EOL	29 8 W/LB BOL 2750 SQ FT ESTIMATE 4 WINGS 15 KW EOL	6.4 W/LB 43 6 SQ FT 4 WINGS 400 WATTS BOL	4 4 W/LB 51 SQ FT ONE WING 400 WATTS BOL
DESIGN	ARRAY TEMPERATURES	SYNCHRONOUS ORBIT -173°C TO +83°C 100 MILE ORBIT -80°C TO +83°C	SYNCHRONOUS ORBIT -180°C TO +110°C LOW EARTH ORBIT -110°C TO +76°C	SYNCHRONOUS ORBIT -180°C TO +95°C EARTH ORBIT +95°C	+52°C TO +171°C	60°C MAX
DESIGN	RATED VOLTAGE	LOADS – RANGING 2Kv TO 16Kv 16 TO 25 B.B. USED IN 4 CONFIGURATIONS. EACH B.B. – 750 VOLTS TO 1340 VOLTS	LOADS – RANGING 2Kv TO 16Kv 16 POWER BLOCKS – 1Kv EACH	LOADS – RANGING 2Kv TO 16Kv BUILDING BLOCK VOLTAGES 2Kv, 3Kv, 6Kv, 8Kv, 11Kv.	50 VOLTS	25 VOLTS
DESIGN	POWER CONDITIONING ON VEHICLE	COMPUTER ON THE VEHICLE EXERCISED ALL CONTROL FUNCTIONS FOR POWER CONDITIONING ON THE ARRAY. POWER TRACKING OFFERS NO ADVANTAGE. ● VOLTAGE SENSING ON VEHICLE	USE OF COMPUTER ON VEHICLE FOR CONFIGURATION SWITCHING AND MONITOR VOLTAGE REGULATION. COMPUTER USED TO MAKE COARSE ADJUSTMENTS FOR LOAD CURRENT. ● SIGNAL SENSING ON VEHICLE	COMPUTER ON VEHICLE TO PROCESS ALL LOGICAL OPERATIONS FOR CONTROL OF BOTH CURRENT AND VOLTAGE FOR PPP* OPERATION. VOLTAGE AND CURRENT TRIMMER SECTIONS OF BUILDING BLOCK USED IN REGULATION OF POWER UNDER COMPUTER CONTROL.	NO POWER CONDITIONING ON VEHICLE	NO POWER CONDITIONING ON VEHICLE
DESIGN	POWER CONDITIONING ON ARRAY	VOLTAGE REGULATION USES TRANSISTOR SHORTING OF WEIGHTED SERIES CELL GROUPS IN EACH BUILDING BLOCK ALL ELECTRONICS ON "IC" CHIPS ELECTROMAGNETIC VACUUM SWITCHES FOR LOAD AND CONFIGURATION SWITCHING	VOLTAGE REGULATION AND FINE CURRENT CONTROL BY TRANSISTOR SHORTING SWITCHES APPLIED TO WEIGHTED SERIES CELL MODULES INTERMEDIATE CONTROL LOGIC LOCATED WITH ON-ARRAY REGULATION SWITCHES VACUUM OR MECH. RELAYS FOR LOAD CONFIG.	VOLTAGE REGULATION BY CONTROL TRANSISTORS APPLIED AS SHUNTS TO BINARY WEIGHTED MODULES CURRENT REGULATION INCLUDED TO OBTAIN PPP* OPERATION ● VOLTAGE & CURRENT SENSORS ON ARRAY. MECH SWITCHES FOR LOAD CONFIGURATION	SHUNT REGULATION 6 ZENER DIODES PER SECTION 3 SECTIONS PER WING	SHUNT REGULATION 4 ZENER DIODES PER SECTION 2-TYPE 1H SILVER ZINC BATTERIES
DESIGN	FAILURE PROTECTION ON ARRAY	BLOCKING DIODES BYPASS DIODES REDUNDANT DESIGN APPLIED TO- CELLS . . MODULES DIODES . . . SWITCHES BUILDING BLOCKS FUNCTION AS SEPARATELY REGULATED SUBSYSTEMS TANTALUM RADIATION SHIELDS AROUND IC CHIPS	BLOCKING DIODES BYPASS DIODES REDUNDANT DESIGN APPLIED TO- CELLS . POWER BLOCKS SWITCHES POWER BLOCKS FUNCTION AS SEPARATELY REGULATED SUBSYSTEMS TUNGSTEN RADIATION SHIELDS FOR ELECTRONIC PACKAGES	BLOCKING DIODES SHUNTING DIODES REDUNDANT DESIGN APPLIED TO- CELLS . . MODULES DIODES . SWITCHES EACH BUILDING BLOCK A SEPARATELY REGULATED SUBSYSTEM RADIATION SHIELDS REFERENCED BUT NOT SELECTED	DATA NOT AVAILABLE	BLOCKING DIODES USE OF "HI-REL" COMPONENTS

		GE H SOLA BIBLIC
EVALUATION	POTENTIAL FOR SCALING UP OR DOWN	SINGLE BUILDI EXPANDED OR USE OF MULTIP LINEAR DIGITA FOR DESIGN V THAN THE 1Kv
EVALUATION	RELIABILITY	DESIGN GOAL MAIN ITEMS- BLOCKING & QUAD REDUN REDUNDANT AND MODUL REDUNDANT
EVALUATION	HEAT DISSIPATION	EACH ELECTRO REQUIRE A FLE LARGE HEAT SI VACUUM RELA DISSIPATION S
EVALUATION	LIMITS ON SIZE	SIZE OF ELECTR RADIATION SHI 0 095 INCH IN TOTAL HVSA H ESTIMATED AT
EVALUATION	FACTORS AFFECTING MANUFACTURE ASSEMBLY OR REPAIR	CHOICE OF MA SHIELDING SEMICONDU SUN SHIELD SELECTION OF CONFIGURATI POSSIBLE USE C INTEGRAL DIO
EVALUATION	FACTORS OF COST	DEVELOPMENT PACKAGING SELECTION OF COMPUTER SOF
EVALUATION	ANALYSES AND TESTS	TRADE OFF STU SHUNT, AND P CONDITIONIN DESIGN PROBL TRANSIENTS VOLTAGE REFE BE MOUNTED C PERFORMANCE LOW VOLTAGE

*PPP – PEAK POWER POINT

FOLD

FOLDOUT FRAME 1

FOLDOUT FRAME 2

S V

GE HIGH VOLTAGE SOLAR ARRAY STUDY BIBLIO NO G 2-11	HUGHES HIGH VOLTAGE SOLAR ARRAY STUDY BIBLIO NO H 6-15	BOEING HIGH VOLTAGE SOLAR ARRAY STUDY BIBLIO NO B.3-10	MARINER VENUS 67 SOLAR PANEL BIBLIO NO A 3-7	LMSC AF CONTRACT SOLAR ARRAY BY PROJECT INTERVIEW
SINGLE BUILDING BLOCK MAY BE EXPANDED OR CONTRACTED USE OF MULTIPLE BUILDING BLOCKS LINEAR DIGITAL SHUNT REGULATOR FOR DESIGN VOLTAGES MUCH LOWER THAN THE 1Kv OF THIS DESIGN	EXPANSION OR CONTRACTION OF POWER BLOCK USE OF MULTIPLE POWER BLOCKS	EXPANSION OR CONTRACTION OF BUILDING BLOCK USE OF MULTIPLE POWER BLOCKS	NO LIMITATION REPORTED WITH REGARD TO ON-ARRAY ELECTRONICS	HEATING COULD BE A FACTOR
DESIGN GOAL . 0 99 MAIN ITEMS BLOCKING & BY-PASS DIODES QUAD REDUNDANT DIODES & SWS. REDUNDANT DESIGN FOR CELLS AND MODULES REDUNDANT SUBSYSTEMS	DESIGN GOAL 0 99 SOME SUGGESTED COMPONENTS WITH UNCERTAIN RELIABILITY MAIN ITEMS BLOCKING & BY-PASS DIODES REDUNDANT DESIGN FOR CELLS AND SWITCHES REDUNDANT SUBSYSTEMS	DESIGN GOAL . . 0.99 MAIN ITEMS BLOCKING & BY-PASS DIODES REDUNDANT DESIGN FOR CELLS, MODULES, DIODES, AND SWITCHES. REDUNDANT SUBSYSTEMS	DEPENDENT UPON SELECTION AND APPLICATION OF COMPONENTS	RELIABILITY MAINTAINED BY USE OF HI-REL ZENER DIODES
EACH ELECTRONIC PACKAGE WILL REQUIRE A FLEXIBLE, RELATIVELY LARGE HEAT SINK. VACUUM RELAY IN PLACE OF HIGH DISSIPATION SOLID STATE SWITCHES	HEAT SINK AREA ESTIMATED AT 13 SQ CM PER WATT OF INTERNALLY DISSIPATED HEAT. QUARTZ MIRRORS OVER ELECTRONICS ON SUN SIDE OF ARRAY	DESIGN HEAT SINKS WITH AMPLE MARGIN BEYOND "TRANSISTOR ON" STATE	NO REPORT OF OVERHEATING PROBLEMS	SOME POSSIBILITY OF OVER HEAT
SIZE OF ELECTRONIC PACKAGES WITH RADIATION SHIELDS APPROXIMATE 0.095 INCH IN THICKNESS TOTAL HVSA HEAT SINK AREA ESTIMATED AT 27 SQ FEET	ELECTRONIC PACKAGES USING TUNGSTEN SHIELDS APPROXIMATE 0 060 INCH IN THICKNESS OVER CONSERVATIVE DESIGN, RESULTING IN EXCESSIVE SIZE	ON-ARRAY SPATIAL REQUIREMENTS FOR BOTH CURRENT SENSING	NO APPARENT LIMITATION	NO APPARENT LIMITATION
CHOICE OF MATERIALS FOR. SHIELDING . HEAT SINK SEMICONDUCTOR SUBSTRATE SUN SHIELD SELECTION OF LOAD AND CONFIGURATION SWITCHES POSSIBLE USE OF SOLAR CELLS WITH INTEGRAL DIODES	SAME FACTORS AS FOR GE HVSA	SAME FACTORS AS FOR GE HVSA	CHARACTER OF MOUNTING FINS FOR ELECTRONICS	CHARACTER OF MOUNTING FINS FOR ELECTRONICS
DEVELOPMENT OF ELECTRONIC PACKAGING SELECTION OF LOAD SWITCHES COMPUTER SOFTWARE	SAME FACTORS AS FOR GE HVSA	SAME FACTORS AS FOR GE HVSA	SELECTION OF COMPONENTS METHOD OF PACKAGING THERMAL CONSIDERATIONS	SELECTION OF COMPONENTS METHOD OF PACKAGING THERMAL CONSIDERATIONS
TRADE OFF STUDIES ELIMINATE SERIES, SHUNT, AND PPP POWER CONDITIONING DESIGN PROBLEM OF VOLTAGE TRANSIENTS VOLTAGE REFERENCE SHOULD NOT BE MOUNTED ON ARRAY PERFORMANCE LOSS RELATIVE TO A LOW VOLTAGE ARRAY, 4-1/2%	COVERSLIDE THICKNESS SHOULD EQUAL CELL THICKNESS BORON DOPED CELLS CHOSEN OVER LITHIUM GENERALLY, ON-ARRAY POWER CONDITIONING MAY BE USED FOR MOST APPLICATIONS PERFORMANCE RELATIVE TO A LOW VOLTAGE ARRAY, 11% GREATER	PROTECTIVE CIRCUIT AND DEVICE REQUIREMENTS CAN BE SATISFIED WITH PRESENT TECHNOLOGY PERFORMANCE LOSS RELATIVE TO A LOW VOLTAGE ARRAY, 4-1/2%	NO REPORT OF ANALYSES OR TESTS	OVERHEATING POSSIBILITY UNDER TEST

POWER POINT

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4 2 Orientation Drive and Power Transfer System

Evaluation of the technology related to array drives and power transfer assemblies is contained in this section. As a prelude to presentation of detailed subject material, a discussion of selected satellite programs with successful histories of orientation drive and power transfer systems is included. Subsequent to that review, there are three main sections which contain matrix charts and comments concerning that data Those sections are Drive Systems, Power Transfer Devices, and Lubrication.

4 2 1 Satellite Program Review

Several space programs have used orientation drive and power transfer systems. OGO, Nimbus and OSO are three that have provided valuable experience from the standpoint of flight history. For this reason a short history of these programs is included.

4.2 1.1 Orbiting Geophysical Observatory (OGO)

All OGO spacecraft have two limited rotation shafts, one is used by the solar array and the other positions an experiment package so that it is looking forward into the orbit plane. Both drives are similar, use much of the same hardware and are controlled in a bang-bang (or on-off) manner. Driving torque is supplied by a two-phase gearhead servomotor driving a TRW wabble gear. The servomotor and gearhead is within a hermetically sealed bellows. The wabble gear and bearings are plated with precious metal. Power and signal transfer is accomplished with a flex cable having a total angular travel of 460 degrees. Program history is as follows:

- <u>OGO I</u>

  Launched 4 September 1964 (ETR). Horizon scanner locked on undeployed appendage causing gas jets to spin up the spacecraft. After this the spacecraft was operated in the spin

- OGO I (cont'd)

  stabilized mode Seventeen of the 20 experiments were still returning data until January 1969 The observatory is now deactivated.

- OGO II

  Launched 14 October 1965 (WTR). Deactivated February 1968.

- OGO III

  Launched 6 June 1966 (ETR). Twenty experiments still returning data as of January 1969. Now deactivated.

- OGO IV

  Launched 28 July 1967 (WTR). Tape recorder failed 19 January 1969, spacecraft exceeded expected lifetime.

- OGO V

  Launched 4 March 1968 (ETR). Twenty-three of twenty-four experiments returning data.

- OGO VI

  Launched 5 June 1969 (WTR). Twenty-three of twenty-five experiments returning data.

4.2.1.2 Nimbus

The Nimbus spacecraft serves as a testbed for research and development of new meteorological sensors, subsystems and system configuration. Nimbus has a single axis solar array drive (two 8 by 3 feet panels). Slip rings are used to carry signals and power across the gimbals Operational status is as of 31 December 1970

- Nimbus I

  Launched 28 August 1964 (WTR) Returned cloud cover photos until 23 September 1964. The solar array drive failed after three months due to lubrication failure in the motor gearhead caused by excessive heat from the rotor

- Nimbus II

  Launched 15 May 1966 (WTR). Silenced 18 January 1969. Met all requirements for 30 months, then a failure in the forward scanner of the Attitude Control System occurred. Also, experienced a tape recorder failure.

- Nimbus III

  Launched 14 April 1969 (WTR). Returning IR, UV, geodetic and TV data. Still meeting all requirements after 18 months in orbit.

- Nimbus IV

  Launched 8 April 1970 (WTR). Still meeting all technical requirements after six months in orbit.

4.2.1.3 Orbiting Solar Observatory (OSO)

All OSO spacecraft have two brush type torque motors, a slip ring assembly about the azimuth axis, and flex cables across the elevation axis. All bearings, slip rings and motor brushes were lubricated with Vac Kote. The following is the flight history of the OSO programs as of 31 December 1970

- OSO I

  Launched 7 March 1962. Operated 75 days (1,823 hours of data transmission) and was incapacitated by radiation damage from the Starfish Nuclear Test. After one year in orbit and

- OSO I (cont'd)

  again at 18 months (Phase III and V) OSO interrogation indicated satisfactory slip ring performance continued

- OSO II

  Launched 3 February 1965 Operated 9 months (4,590 hours of data transmission) and became inoperational because of the pitch pneumatic gas depletion resulting from incorrect magnetic compensation prior to launch. Satellite was turned off after ninth month (Phase II) Eight months later OSO II was commanded on by Fort Meyers for approximately 150 hours (Phase III) Slip ring performance was again satisfactory

  OSO II was then turned off (Phase IV) for seven months. In December 1966, OSO II was commanded to acquire the sun for approximately two hours - torque motor, bearings and slip ring performance appeared to be satisfactory.

- OSO III

  Launched 8 March 1967 Forty-five months later it is still capable of being operated. It is presently being turned on for about 30 orbits or 2 days a week and the entire drive system still functions properly.

- OSO IV

  Launched 18 October 1967 Thirty-eight months later it is still capable of being operated It is presently being turned on for about 30 orbits or two days a week and the entire drive system still functions properly.

- OSO V

  Launched 22 January 1969 Twenty-three months later it is still fully operational

- OSO VI

  Launched 9 August 1969 Seventeen months later it is still fully operational

4 2 2 Drive Systems

For the purpose of this technical review, a drive system is defined as a unit having a motor to supply rotational power, a slip ring or power transfer device for taking electrical power across the rotating joint and its own bearings so that it maintains alignment

On the "Drive System" chart, AA, there are entries covering most of the major known systems of this type used on space vehicles or other applicable hardware. The matrix charts show the type of system, the size, the type of components and where available, both test history and flight history on the unit.

A review of the Drive Systems charts shows that all of the systems except ATM, are between 2 inch to 8 inch diameter range These systems are all "inside" drive systems, i e., designed and adapted to the spacecraft in such a way that the specific spacecraft structure is wrapped around the drive system. The ATM/Skylab drive system is an outside drive system since the drive ring is wrapped around the structure.

It should also be noted that approximately 50 percent of the systems listed provide full rotation, while the remaining 50 percent provide limited rotation from $\pm 6^{\circ}$ up to $\pm 360^{\circ}$. All this information substantiates the premise that drive systems have not been standardized, but are designed specifically for each application and associated requirements. The individual components of drive systems can be used from system to system, but the packaging of these components is unique for each requirement

The ATM/Skylab system is the only system designed to date that is comparable in size to the ODAPT. The ATM roll ring is 110 inches in diameter and supported by four roller bearing clusters. The roll travel of 150 degrees is provided by a 7 foot-lb Inland Torque motor that is geared to a large gear mounted on the 110 inch diameter roll ring Power transfer

is provided by flex cables The pitch and yaw travel of the ATM is $\pm 6^{\circ}$, and is provided through flex pivots driven by torque motors.

All the other drive systems are much smaller and cannot be scaled up for use on the ODAPT However, the technology used to develop the smaller scale drive systems can be applied to the design of this system. Specifically, the technology used for the bearings, motors and gearing will be applicable. Problems to be considered when designing components for this size system pertain to installation, handling, and maintenance before and during mission flight. Safety requirements must also be considered when designing an electrical power transfer device for manned flight which has the current capacity anticipated. Trade-off studies will be made to determine the most desirable design configuration.

Technology already developed for bearings and motors is definitely applicable to Space Station design. The problem to date is, without the aid of 10 year flight experience or long term ground testing to Space Station environmental or operational conditions, the element of maintenance and man's role in such needs must be further evaluated Analysis within this contract will include investigation of storing or resupplying lubricants to sliding or rotating surfaces and the study of techniques for routine maintenance and replacement of failed units. The results of such analysis are becoming more important as space vehicle design life and missions have increased in magnitude.

DRIVE SYSTEMS

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NO.	MANUFACTURER AND PROJECT OR OTHER IDENT	NUMBER OF AXES	DEGREE OF TRAVEL	WEIGHT OF DRIVE ASS Y	BEARINGS			MOTORS					ELECTRICAL POWER TRANSFER DEVICE			TEST HISTORY	FLIGHT HISTORY	GENERAL REQUIREMENTS AND REMARKS	BIBLIO NO.
					TYPE	SIZE O.D	TYPE OF LUBE	TYPE	TORQUE IN -LB	BRUSH LUBE	GEAR RATIO	GEAR LUBE	TYPE	SIZE	TYPE OF LUBE				
	BALL BROTHERS RESEARCH CORPORATION																		
1	OSO-I (S-16) Azimuth Drive	1	Full Rotation	Integral Est #11	Ang Cont New Dept 52100 st	1 5 x 3 5 1 4 x 3 1	Dry Vac Kote	Inland Torque T-4047-A	1 81	Dry Vac Kote	Direct	N/A	Breeze Disc Sil Graphite on Coin Silver	2" ; x 2-1/2"	Dry Vac Kote	Vibration steady state accel Thermal Vacuum to Qual Spec	75 days (1823 hrs) of data transmission	Launched 3/7/62 Data transmission ended as a result of radiation damage Ref OSO-I Final Report, See Para III A	
2	OSO-I (S-16) Elevation Drive	1	± 6°	Integral Est #6	Radial New Dept 52100 st	0 98 x 2 4 0 98 x 2 4	Dry Vac Kote	Inland Torque T-2977-A	0 85	Dry Vac Kote	Direct	N/A	Two flat flex cables w/ Mylar insulation	32 circuits each	N/A				
3	OSO-II (B-2) Azimuth Drive	1	Full Rotation	Integral Est #11	Ang Cont New Dept 52100 st	1 5 x 3 5 1 4 x 3 1	Liquid Vac Kote	Inland Torque T-4047 A	1 8	Liquid Vac Kote	Direct	N/A	Breeze Disc Sil Graphite on Coin Silver	2" ; x 2-1/2"	Liquid Vac Kote	Same as OSO-I	9 months (4590 hours)	Launched 2/3/65 Satellite was deactivated after 9 months operation with no spacecraft failures It was reactivated for an additional 152 hours operation after an 8 month shut down	
4	OSO-II (B-2) Elevation Drive	1	± 6°	Integral Est #6	Radial New Dept 52100 st	0 98 x 2 4 0 98 x 2 4	Liquid Vac Kote	Inland Torque T-2977-A	0 85	Liquid Vac Kote	Direct	N/A	Two flat flex cables w/ Mylar insulation	37 circuits each	N A				
5	OSO-III thru VI (E-1, D, F, G) Azimuth Drive	1	Full Rotation	Integral Est #11	Ang Contact New Dept CEVM 440C	1 5 x 3 5 1 4 x 3 1	Liquid Vac Kote	Inland Torque T-4047-A	1 8	Liquid Vac Kote	Direct	N/A	Breeze Disc Sil Graphite on Coin Silver	2" - x 2-1 2"	Liquid Vac Kote	Same as OSO-I	See remarks	OSO-III Launched 3/8/67 42 months of operation with no spacecraft failures OSO-IV, Launched 10/18/67 35 months of operation with no spacecraft failures OSO-V, Launched 1/22/69 20 months of operation with no spacecraft failures OSO-VI, Launched 8/9/69 14 months of operation with no spacecraft failures	
6	OSO-III thru VI (E-1, D, F, G) Elevation Drive	1	± 6°	Integral Est #6	Radial New Dept CEVM 440C	0 98 x 2 4 0 98 x 2 4	Liquid Vac Kote	Inland Torque T-2977-A	0 85	Liquid Vac Kote	Direct	N/A	Two to five flex cables w/ Mylar insulation (OSO-6 had silicone insulation)	37 circuits each (Max)	N A				
	BELL TELEPHONE LABORATORIES																		
7	Bi-Ax Antenna	2	± 100° prim axis ± 85° sec axis	120 est	Duplex pair radial ea axis	5 25" 4"	Vac Kote	Inland T4412A Brush	18 peak	Vac Kote	Direct Drive	N A	Rot wave guide flex cable coax			Vib therm vac accep tes	Classified (unknown)	Prototype was built and successfully qualified Two flight models were built and qualified	

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DRIVE SYSTEMS

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NO.	MANUFACTURER AND PROJECT OR OTHER IDENT	NUMBER OF AXES	DEGREE OF TRAVEL	WEIGHT OF DRIVE ASS'Y.	BEARINGS TYPE	BEARINGS SIZE O.D	BEARINGS TYPE OF LUBE	MOTORS TYPE	MOTORS TORQUE IN -LB	MOTORS BRUSH LUBE	MOTORS GEAR RATIO	MOTORS GEAR LUBE	ELECTRICAL POWER TRANSFER DEVICE TYPE	ELECTRICAL POWER TRANSFER DEVICE SIZE	ELECTRICAL POWER TRANSFER DEVICE TYPE OF LUBE	TEST HISTORY	FLIGHT HISTORY	GENERAL REQUIREMENTS AND REMARKS	BIBLIO NO.
	GENERAL ELECTRIC COMPANY																		
8	NIMBUS I	1	Full Rotation	Approx 5 lbs	Support Bearings Deep Gr Torque Tube, ABEC Class 1 or better	2 5"	G300 Grease						Slip rings Drum type (1) set for sad (made by Poly-Scientific)	4 Power 20 signal 10 Amps per ring	Rhenium plated silver rings 88 7 ag 12% MoS_2 brushes	2 mon of approx 24 hr rm amb tests plus (3) 13 day cyclic T/V tests at 10^{-6} torr and tempe of >5° C to >40° C output speed 1 rev per 108 min	SAD failed after 3 mon due to lube breakdown in motor-gear hd caused by excessive heat from rotor	Nimbus I, II, & III have a single motor gearhead drive for the solar array device, information obtained thru personal communications See Paragraph III A	GC 1-4 GC 1-5
					Gear Hd Bearings Shielded, Deep Gr ABEC 7 Class	3750 5000 6250	G300 Grease	Size 8 Servo Motor 400 Hz, 2ϕ sine excitation		N/A	84000 1 Spur Grease (Gear Hd g.r = 12121:1)	G300 Grease							
9	NIMBUS II	1	Full Rotation	Approx 5 lbs not incl elect	Same as NIMBUS I			Size 11 Servo Motor 400 Hz, 2ϕ sine excitation	3 in-oz stall	N/A	Same as NIMBUS I		Same as NIMBUS I			Same as NIMBUS I	Met all perf rqmts for 36 mons then a failure in the forward scanner of the acs occurred Tape recorder failures	Launched 5/15/66, information obtained thru personal communications, report NASA TM-D-4881 Feb 1969	
10	NIMBUS III	1	Full Rotation	Approx 5 lbs not incl elect	Same as NIMBUS I			Same as NIMBUS I		N/A	Same as NIMBUS I		Same as NIMBUS I			Same as NIMBUS I	All rqmts still being met after 18 months	Launched 4/14/69, information obtained thru personal communications	
11	NIMBUS IV (Drive System Sub-contracted by TRW)	2	Full Rotation	25 lbs ea incl slip rings & elec	Support Bearings Radial Dp Gr. ABEC 1	3 937	Bray oil MPT-4 & Grease Plate										All tech obj still being met after 6 months	Launched 4/8/70, wabble slip clutch output capable of withstanding 600 in-lbs min slip torque = 100 in-lbs; max slip torque = 350 in-lbs Hsg Brg & slip friction ≤ 50 in-oz Wabble drive friction ≤ 5 in-oz Infor obtained thru personal communications & TRW reports EO2-214 & 06380-6003-RO-00	TT.1-2 TT.1-3
					Gear Hd Bearings Rad Dp Gr ABEC 7	3750 5000 6250	MoS_2 Burnish w/ Bray MPT-4 Oil	Size 11 Servo Motor	3 in-oz stall	N/A	183 1 (GH only) over-all GR 1000000 1	Bray Oil MPT-4 with KN949B Grease Plate	Slip rings disc type on two sides (made by Litton Poly Scien)	1 Pwr 16 signal 10 Amps per ring	Rings Bray oil MPT-4 w/ Mylacint Resv brushes 85 5% AG 12 5% MoS_2 2 5% Cu				
12	ADVENT	1	± 180° rotation		Full complement deep groove ball brgs	3 875	Electroplated Gold	2 DC torque mtrs 1 is driver, other is tach harmonic drive output		Self lubr 50% AG & 50% graphite		Electroplated Gold	Flex cable 180° rotation			T/V life test for 1 yr at 100 rpm with no failures or perf degrad		Power system deployed & oriented 600 watt solar array for nickel-cadmium batteries SAD housing was hermetically sealed to ensure adequate wear perf. of graphite lube Information obtained thru personal communications Information was limited since program was cancelled and spacecraft never launched	

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NO.	MANUFACTURER AND PROJECT OR OTHER IDENT	NUMBER OF AXES	DEGREE OF TRAVEL	WEIGHT OF DRIVE ASS'Y	BEARINGS			MOTORS					ELECTRICAL POWER TRANSFER DEVICE			TEST HISTORY	FLIGHT HISTORY	GENERAL REQUIREMENTS AND REMARKS	BIBLIO NO.
					TYPE	SIZE O.D	TYPE OF LUBE	TYPE	TORQUE IN -LB	BRUSH LUBE	GEAR RATIO	GEAR LUBE	TYPE	SIZE	TYPE OF LUBE				
	HUGHES AIRCRAFT COMPANY																		
13	Tacsat - Despin Platform BAPTA	1	360	150	Ball	8"	Vac Kote	Pancake Torquer w/brushes	60 in oz	Vac Kote	None (Direct Drive)	N/A	Power & Signal Slip Rings		Vac Kote		Launched 2/10/69	Information obtained through personal communication Life requirement - 3 years, Design life - 5 years, 8 2 x 10^7 rev In orbit performance satisfactory to date (11/01/70)	HB 1-5
14	Intelsat IV Despin Platform	1	360	150	Ball	8"	Met Lube Vac Kote	Brushless Pancake Torquer		N/A	None (Direct Drive)	N/A	Power-slip rings Signal-rot transformer				Qual Complete To be launched in 1970	Information obtained through personal communication Life requirements - 7 years, Design life - 5 years, 2 3 x 10^8 rev	
15	Advanced Satellite Despin Platform	1	360	180	Ball		Met Lube	Brushless Pancake Torquer		N/A	None (Direct Drive)	N/A	Power and Signal Slip Ring				Qual Complete	Information obtained through personal communication Life requirements - 3 years, Design life - 5 years, 10^8 rev	
16	Intelsat IV Antenna Positioner	2			Ball		Dry MoS_2	Stepper Motor			Spur gears and jack screw 4000:1		Flex Cable				Qual Complete To be launched in 1970	Information obtained through personal communication Life requirements - 7 years, Design life - 10 years, Adjustment Only - 50 degrees	
17	Advanced Satellite Load Positioner	2			Ball		Dry MoS_2	Stepper Motor			Harmonic Drive 100:1		Flex Cable				Qual Complete	Information obtained through personal communication Life requirements - 3 years, Design life - 5 years, 4 7 x 10^5 degrees	
18	Surveyor Solar Array Positioner	1			Ball & Journal		Dry MoS_2	Stepper Motor			3 Stg Planetary 286:1		Flex Cable				Performed on Moon as required 1966-67 all vehicles now dormant	Life requirement - 2 weeks, Design life - 2 months, 1 5 x 10^4 degrees Information obtained through personal communication	
19	FRUSA Solar Array Positioner	1			Ball		Dry MoS_2	Pancake Torquer w/brushes			None Direct Drive	N/A	Power & Signal Slip Rings				In development Tests, Launch Sept 1971	Life requirements - 6 month mission 5 year design - 6000 cycles/year Ref HAC Report #AD 863684 and #AD 867358	HB 1-3 HB 1-4
20	Advanced Satellite Load Positioner	1			Ball		Dry MoS_2	Stepper Motor			2 Stg Spur Gear		Flex Cable				Qual Complete In Life Test	Information obtained through personal communication Life requirements - 3 years, Design life - 5 years, 5 x 10^5 degrees	

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DRIVE SYSTEMS

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NO.	MANUFACTURER AND PROJECT OR OTHER IDENT	NUMBER OF AXES	DEGREE OF TRAVEL	WEIGHT OF DRIVE ASS'Y	BEARINGS			MOTORS					ELECTRICAL POWER TRANSFER DEVICE			TEST HISTORY	FLIGHT HISTORY	GENERAL REQUIREMENTS AND REMARKS	BIBLIO NO.
					TYPE	SIZE O.D	TYPE OF LUBE	TYPE	TORQUE IN -LB	BRUSH LUBE	GEAR RATIO	GEAR LUBE	TYPE	SIZE	TYPE OF LUBE				
	HUGHES AIRCRAFT COMPANY																		
21	Development Antenna Positioner				Ball		Dry MoS_2	Stepper Motor			Harmonic Drive 160:1		Flex Cable				Completed life testing & Closed Loop Demonstration	Information obtained through personal communication Life requirements - 3 years simulation	
22	Despin Antenna Motor Bearing Assembly				Ball		Wet Lube Vac Kote	Brushless		N/A		None Direct Drive	Rotary RF Coupling			Vibration Functional testing completed	None	Information obtained through personal communication Life requirements - 3 years	
23	BAC Development Experimental Despin Assembly				Ball		Wet Lube Vac Kote	Conventional AC Synchronous				None Direct Drive	Power, & Signal Slip Rings			Tested 5000 hrs in vacuum	None	Information obtained through personal communication	
24	Telsat Despin Assembly				Ball		Wet Lube Vac Kote	Brushless		N/A		None Direct Drive	Rotary RF Coupling			None yet. In procurement phase	None	Information obtained through personal communication Life requirements - 7 years	
	JET PROPULSION LABORATORIES																		
25	Ranger 1 through 9	1	180°	3 lbs	Angular contact	Aprox 1 0"	Silicone grease	Servo-mtr w/ gear hd			Double worm reduction	Silicone grease	Rotary RF joint					Information was obtained through personal communication	

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NO.	MANUFACTURER AND PROJECT OR OTHER IDENT	NUMBER OF AXES	DEGREE OF TRAVEL	WEIGHT OF DRIVE ASS'Y	BEARINGS			MOTORS					ELECTRICAL POWER TRANSFER DEVICE			TEST HISTORY	FLIGHT HISTORY	GENERAL REQUIREMENTS AND REMARKS	BIBLIO NO.
					TYPE	SIZE O.D	TYPE OF LUBE	TYPE	TORQUE IN -LB	BRUSH LUBE	GEAR RATIO	GEAR LUBE	TYPE	SIZE	TYPE OF LUBE				
	LOCKHEED AIRCRAFT COMPANY																		
26	Air Force Program Type I	1	330° unidirectional	290			Electrofilm MoS_2 coating	Superior Elect Co slosyn dc stepper motors	200 in oz	N/A	2:1	Electrofilm MoS_2 coating	Flex harness	N/A	N/A	Qual		Classified Program Three Flights	
27	Air Force Program Type II	1	330° unidirectional	260			Electrofilm MoS_2 coating	Superior Elect Co slosyn dc stepper motors	200 in oz		1 1	Electrofilm MoS_2 coating	Flex harness	N/A	N/A	Qual	45 Days Max	Classified Program Two Flights	
28	Air Force Program Type III	1	355° stop to stop unidirectional	160			F-50 Silicone Oil	AC Globe Induction Mtrs	700 in oz		6000:1	F-50 Silicone Oil	Flex harness	N/A	N/A	Qual	30 Days to one year	Classified Program Ten Flights - 3 motors per vehicle 4% Duty Cycle	
29	Air Force Program--Zombie	2	360° bidirectional	110			BBRC Vac Kote	Inland DC Brush Type Torque Mtrs	60 in oz	BBRC Vac Kote	Direct	BBRC Vac Kote	23 slip rings & flex (flat) cable AG-rings AG-C-MoS_2 brushes		BBRC Vac Kote	Qual	None		
30	Air Force System No 5	1	360°	120			F-50 Silicone Oil	AC stepper mtrs	182 in oz			G300 Silicone Grease	16 slip rings 6-power 10-transfer AG-rings AG(cu) MoS_2 brushes			Qual		Classified Program No published data Work and gear differential drive	

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DRIVE SYSTEMS

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NO.	MANUFACTURER AND PROJECT OR OTHER IDENT	NUMBER OF AXES	DEGREE OF TRAVEL	WEIGHT OF DRIVE ASS'Y	BEARINGS			MOTORS					ELECTRICAL POWER TRANSFER DEVICE			TEST HISTORY	FLIGHT HISTORY	GENERAL REQUIREMENTS AND REMARKS	BIBLIO NO.
					TYPE	SIZE O.D	TYPE OF LUBE	TYPE	TORQUE IN -LB	BRUSH LUBE	GEAR RATIO	GEAR LUBE	TYPE	SIZE	TYPE OF LUBE				
	MASSACHUSETTS INSTITUTE OF TECHNOLOGY																		
31	Lincoln Experimental Satellite LES I	1	360°	8"	Ball	2"	Liquid Vac Kote	Stepper		N/A	N/A	N/A	Slip ring	20 circuits	Vac Kote		1 year operation	Satisfactory bearing and slip ring performance for 1 year design life	LL 2-32
	NASA MARSHALL SPACE FLIGHT CENTER																		
32	Apollo Telescope Mount - Roll Drive		150°		Roll ring 6061-T6 alum/ spring loaded rollers	110"	MoS_2	Inland DC Torque Motor	84 0	Self-lubricating compact mat'l Boeing 046-45	10 1 \espel pinion gear mated with Stn Stl drive gear	Self lubricating \espel Pinion gear	Flex cables Flat copper strip encapsulated in plastic material. Wrapped on a drum	--	N/A			Dual motor used for redundancy; information obtained through personal communication	
	PHILCO-FORD																		
33	Skynet NATO SIR10S	1	Full rot.	3 5"	23506-1 Ang contact	1 75"	Vac Kote	Rslur Comm brushes DC torquer 23969-1			Direct Drive		Rotary wave guide			Qualified	Flown on Skynet	Final version MDA Philco-Ford - Flown on Skynet Selenia - Rome Italy - Eval Eng'g model	

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DRIVE SYSTEMS

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NO.	MANUFACTURER AND PROJECT OR OTHER IDENT	NUMBER OF AXES	DEGREE OF TRAVEL	WEIGHT OF DRIVE ASS'Y.	BEARINGS			MOTORS					ELECTRICAL POWER TRANSFER DEVICE			TEST HISTORY	FLIGHT HISTORY	GENERAL REQUIREMENTS AND REMARKS	BIBLIO NO.
					TYPE	SIZE, O.D	TYPE OF LUBE	TYPE	TORQUE IN -LB	BRUSH LUBE	GEAR RATIO	GEAR LUBE	TYPE	SIZE	TYPE OF LUBE				
	TRW, INC																		
34	INTELSAT III (Drive system subcontracted by Sylvania)	1	360°	8#	Ball Dup Pair	3 5 in	Liquid Vac Kote	Stepper	40 in oz	N/A	N/A	N/A	----FREE	STANDING	WAVE GU	4300 hours	See Remarks	Continuous rotation at 100 rpm - no evidence of bearing wear at end of test ITS III No 1 and No 5 Booster failed and satellite did not achieve orbit ITS III No 2 - Launched 12/18/68 Performed adequately (with 2 or 3 outages) during 2 year orbit life Deactivated March 1970 ITS III No 3; No 4; No 6 and No 7 have operated 20, 18, 12, and 3 months respectively and are still operating ITS III No 8 - Orbit injection failure Lost in space	
35	Applications Technology Satellite (ATS III) (Drive system subcontracted by Sylvania)	1	360°	5#	Ball	2 5 in	Liquid Vac Kote	Stepper	20 in oz	N/A	N/A	N/A	----FREE	STANDING	WAVE GU	8000 hours	-- 24 mo	Continuous rotation at 100 rpm - no evidence of bearing wear at end of test Satisfactory in-orbit performance for 24 month design life	
36	Orbiting Geophysical Observatory (OGO)	1	240° max	8#	2-Ball Dup pairs	2 625 in	(1) Gold MoS_2 (1) Bray oil NPT-4	Size 11 stepper		N/A	24,000 to 1 spur years	Au pltd steel Sinite impreg w/MoS_2)	Flex cable	50 - 100 circuits	N/A	3 units tested	-- See Remarks	3 units life tested to 12,250 hours, 10,350 hours and 8500 hours 6 units have been flown OGO I launched September 1964 Experienced spin problem but experiments returned data until deactivation January 1969 OGO II launched October 1965 Data returned until deactivation Feb 1969 OGO III launched June 1966 20 experiments returned data until deactivation January 1969 OGO IV launched July 1967 Tape recordered failed but spacecraft exceeded expected life OGO V launched March 1968 23 of 24 experiments returning data OGO VI launched June 1969 23 of 25 experiments returning data	
37	Defense Systems Communications Satellite (DSCS II)	2	± 10°	14 2#	Ball Dup Pr & Rad Dup Pr	3 5 and 4 0	Bray oil NPT-4	Size 15 90° stepper		N/A	2860: 1	Bray oil NPT-4	Flex cable/ flex wave guide	1 circuit	N/A	Passed qual testing			
38	Solar Array Drive Assembly Use Classified	1	Full rot	10# (est)	BBRC SCD #'s 22377 22383	2 8"	Vac Kote	Inland torquer (2) BBRC SCD 22043		Vac Kote	Direct Drive		Slip ring BBRC SCD 22086	2 4 OD x 2 8 long	Vac Kote	Qualified	Yes Application classified	Solar array drive assembly for TRW qualified for 1600 in-lb moment load 300 # Axial load + environmental	

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4.2.2.1 Bearings

The bearing charts, BB, show not only components from drive systems but many tests run solely for the purpose of testing bearings

Examination of the charts for "Drive Systems" AA and "Bearings" BB indicates that only ball bearings, either deep groove radial and/or preloaded angular contact, were used in previously flown spacecraft, i.e., neither hydrostatic gas bearings or roller bearings were employed. In the case of gas bearings smooth uniform almost negligible torque performance can be obtained, however, large weight penalties for heavy pressurized tanks and associated plumbing are required to obtain the radial and axial stiffnesses necessary to endure launch loads and prevent damage to the bearing surfaces. Of course, it is possible to install launch locks to protect bearings from launch loads, but additional weight penalties must be considered. To date, this approach has not been used on any known major space drive system.

Roller bearings which have stiffness values comparable to ball bearings usually require more torque to drive than ball bearings because they are line contact, whereas ball bearings are point contact. Roller bearings are also more susceptible to skewing loads caused by built-in misalignments which increase the torque losses and reduce bearing life. Ball bearings will tolerate misalignments to a greater degree than roller bearings without as much increase in torque or reduction in bearing life.

A notable exception to the bearing type and design utilized in the drive systems previously flown is that employed in the ATM drive system which is being built for NASA/Marshall Space Flight Center and is scheduled for launch in 1972 (AA-32). It includes four roller bearing clusters equally spaced around two large gimbal rings (approximately 7 ft diameter) which support the ATM experiment canister (10 ft long) and 6,000 lbs of solar experiments

Two each pitch and yaw actuators join the gimbal ring to the roll ring and the canister to the pitch-yaw gimbal ring respectively The actuators are identical and consist of flexure bearings which provide limited rotation in the pitch and yaw axes The flexure bearings serve the purpose of providing a support system with mechanical rotation similar to ball bearings but with several unique advantages. A flexure bearing functions much like a torsional spring but is designed to have a low torsional spring rate, with no friction. These bearings have no radial and axial play and have no moving parts in the sense of rotating balls in a ball bearing race. However, they do have limited rotation capability. They are eminently suited for space application where a hard vacuum exists and temperatures are highly variable.

The ball bearings used on Nimbus (BB-13, BB-14), the later model OSO's (BB-7, BB-8, BB-9), and most of the later space flights are constructed of 440C stainless steel rings and balls. Torque critical applications usually require ABEC Class 5 or better bearings. Phenolic retainers are normally used where oil/grease lubrication is employed, because of its lubricant retention capability.

Lubrication systems in which the bearings were charged with an initial supply of lubricant and never replenished have been used in most of previously flown spacecraft. That is, the lubricant was self-contained in the bearings. Once the lubricant was consumed and/or evaporated, the bearings would be dry and consequently its life, thereafter, would be doubtful. A notable exception to this system is that employed by BBRC where in the case of liquid lubricant, reservoirs containing the lubricant are positioned outside the bearings to replenish lubricant via molecular transfer.

Metal shields, not seals, were used in some of the bearings previously flown, but they were located on the outboard faces of the outboard bearings only. Shields are usually mounted in the outer ring and extend radially to form a non-contacting labyrinth with the inner ring to prevent contamination

and/or retard lubricant migration. Seals, on the other hand, are more effective than shields but because of their rubbing contact, they do generate some accountable friction loss.

The largest bearing previously flown had an approximate 9 0 inch outside diameter and was used in the BAPTA TACCOM SAT (BB-15, BB-16) Spacecraft built by Hughes Aircraft Company

The predominant types of lubricants used in the bearings listed were greases and oils Notable among these were F50 oil (FF-24), G300 grease (FF-35), Bray oil NPT-4 (FF-28), KK949B grease plate and liquid Vac Kote (FF-25) which were used to lubricate the bearings in the Nimbus, OGO and OSO spacecrafts respectively. One of the longest known flight successes with bearings containing dry lubricant is the OSO I Spacecraft (75 days, 1,823 hours).

Large bearings in excess of 4.0 feet O. D. have been used in large earth moving equipment, turntables, worktables, indexing tables, and transfer tables, steering mechanisms, etc., where high loads and/or slow intermittent smooth operation may be required as will be the case in the Space Station. A few of the bearing manufacturers who make large bearings in excess of 5-foot diameter bores are Kaydon Engineering Corporation, Rotek, Inc. and Messinger Bearings, Inc. An example can be found in the April 25, 1968 edition of Machine Design, page 29, in which a 2,350 lb, 165-7/16 inch O. D. double row angular contact bearing which contains 744 one-inch balls as built by the Kaydon Engineering Corporation, is shown

The technology already developed for bearings is definitely applicable unless some unusual mounting arrangement (unsupported or partially supported bearings) would invalidate the methods of predicting bearing life, torque and deflection characteristics. In that event, development tests may be conducted in order to derive the new relationships. Bearing lubrication systems must be designed to meet the ten-year life requirement Assuming

that periodic maintenance can be performed, it is not beyond the "state of the art" to develop a lubrication system meeting these life requirements Undoubtedly, weight will be an important and limiting factor for a system this size. Should ball or roller bearings be selected, it may be desirable to consider bearings having hollow rolling elements and bearing rings having recessed bearing seats i.e., a compliant bearing. Some weight advantage may be gained from this type of design. However, the theory associated with compliant bearings has not yet been fully derived Development testing would undoubtedly be required to establish its design limits.

Individual rollers can be manufactured to provide the rotary motion required by this large system and there is precedence for this type of design in the ATM. These smaller units could be made replaceable thus giving them an advantage over a large bearing.

The trade-off between these two ideas can only be made after extended study and testing. The primary idea (either large bearings or individual rollers) is a part of the present program and will be tested. However, since these elements are so important to the space station life expectancy, it is recommended that testing of the alternate method also be accomplished as a backup to the baseline approach. The only way to obtain confidence in either system is through testing and since they each have advantages and disadvantages the final choice should be made from test data.

BEARINGS

NO.	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	SIZE: O D IN	SIZE: I D. IN.	MATERIAL: OUTER RACE	MATERIAL: INNER RACE	MATERIAL: BALLS	MATERIAL: RETAINER	MATERIAL: SEALS	TEST HISTORY: TIME HRS	TEST HISTORY: PRESS	TEST HISTORY: TEMP °F	TEST HISTORY: FAILURE MODE	TEST HISTORY: SPEED RPM	FLIGHT HISTORY: TIME HRS	FLIGHT HISTORY: PRESS	FLIGHT HISTORY: FAILURE MODE	FLIGHT HISTORY: SPEED RPM	LOADING: TYPE	LOADING: AMOUNT	LUBRICATION: TYPE	LUBRICATION: METHOD OF APPLICATION	REMARKS	BIBLIO NO.
	BALL BROTHERS RESEARCH CORPORATION																							
1	OSO I Flight Hardware S 16	New Departure ND-3308XR7, ND R 18 XR7 ABEC 7 Rad Dp Groove	3 5433 2 1/8	1 5748 1 1/8	52100 STL	52100 STL	52100 STL	Synthane Phenolic	No	17 000 (7206 x 10^6 revs)			No Failures	30 rpm	24 mo 40 min on, 20 min off	350 mi circ orbit	Bearing perf normal after 24 mon flight	30 rpm 40 min on 20 min off			Vackote (Dry)	BBRC Process BPS 14 00 (proprietary)	Ref Report OSO Report	BB 1-18
		Rad Dp Groove ABEC 7 ND 3305 XR7	2 4409	9843	52100 STL	52100 STL	52100 STL	Synthane Phenolic	No															
2	Qual Report OSO S 17	New Departure Rad Dp Groove ND 3305XR7 ABEC 7	2 4409	9843	52100 STL	52100 STL	52100 STL	Synthane Phenolic	No	4200 (17.2 x10^6 revs)	10^{-7} torr	25 ± 5° C	None	60 ± 5	N/A	N/A	N/A	N/A			VacKote (Liquid)	BBRC Process Spec 14 01 Vacuum Impregnation process (proprietary)	Ref Report Qual Report OSO S-17	BB 1-34
		ND R18 ABEC 1 Barden 39SS	2 1/8 1 0236	1 1/8 3543	52100 STL	52100 STL	52100 STL	Rib-steel 39SS-ribbon steel	Rib No 39SS Double Shield	4200 (low speed) 45 (hi speed)	10^{-7} torr	25 ± 5° C	None	60 ± 5 & 1000 ± 50	N/A	N/A	N/A	N/A						
3	T/V Test of Star tracker components	Barden A 540 D Ex thin torque tube Duplex pair	1 3125	8750	440C S S	440C S S	440C S S	Teflon	No	50 (run in) 2500 (life)	4x10^{-8} torr	26°C	No Failures	8 hr slew to 50°	N/A	N/A	N/A	N/A			VacKote (Dry)	BBRC Process BPS 14 00 (proprietary)	Ref Report F64-1	BB 1-39
4	Qual Test OSO S 17	New Departure ND 3308XR7 Rad Brg ABEC 7	3 5433	5748	52100 Stl	52100 Stl	52100 Stl	Phenolic		40 hours (8 days) 0 72 x 10^6 revs	10^{-4} torr	30 ± 5° C	Retainer failures	30 ± 3	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)	Two bearings tested Bearings were noisy during test Retainer broke due to insufficient lubrication retention and retainer porosity	BB 1-43
5	OSO brg Qual	New Departure Rad Brg ABEC 7 ND 3305 - 4 ea	2 4409	9843	52100 Stl	52100 Stl	52100 Stl	Phenolic			10^{-6} torr	-15° C	None	± 5° arc. Deg-Osc	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Same	Daily monitoring of brg torque temperature, chamber press All brgs performed satisfactorily Results indicate the lubrication procedure is adequate for OSO spacecraft	BB 1-44
		ND 3308 - 4 ea Rad Brg	3 5433	1 5748	52100 Stl	52100 Stl	52100 Stl	Phenolic		10 4 x 10^6 revs	10^{-6} torr	-10° C	None	60	N/A	N/A	N/A	N/A			Vac Kote (Luquid)	Same		
		ND R-18 - 4 ea	2 125	1 125	52100 Stl	52100 Stl	52100 Stl	Phenolic		10 4 x 10^6 revs	10^{-6} torr	-10° C	None	60	N/A	N/A	N/A	N/A			Vac Kote (Liquid)			
6	OSO II Flight	New Departure R3308XR7 - Rad Brgs QR18XR7 - Rad Brgs ABEC 7	3 5433 2 125	1 5748 1 125	52100 Stl	52100 Stl	52100 Stl	Phenolic		17000 total	350mi 200mi	Apogee Perigee	None	30 40 min on 20 min off	N A	N/A	N/A	N/A	Launch & Orbit Loads		Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)	Bearing performance satisfactory for at least 24 months life	BB 1-45
		New Departure Q3305XR7 Rad Brgs	2 4409	9843	52100 Stl	52100 Stl	52100 Stl.	Phenolic		17000 total	350mi 200mi	Apogee Perigee	None	Oscil motion ± 5°	N/A	N A	N A	N/A	Same		Vac Kote (Liquid)	Same	Bearing performance satisfactory for at least 24 months life	

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BEARINGS

NO.	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	SIZE: O D IN	SIZE: I D IN	MATERIAL: OUTER RACE	MATERIAL: INNER RACE	MATERIAL: BALLS	MATERIAL: RETAINER	MATERIAL: SEALS	TEST HISTORY: TIME HRS	TEST HISTORY: PRESS	TEST HISTORY: TEMP °F	TEST HISTORY: FAILURE MODE	TEST HISTORY: SPEED RPM	FLIGHT HISTORY: TIME HRS	FLIGHT HISTORY: PRESS	FLIGHT HISTORY: FAILURE MODE	FLIGHT HISTORY: SPEED RPM	LOADING: TYPE	LOADING: AMOUNT	LUBRICATION: TYPE	LUBRICATION: METHOD OF APPLICATIO	REMARKS	BIBLIO NO.
	BALL BROTHERS RESEARCH CORPORATION																							
7	OSO III Flight	MRC Radial Brg MRC308 ST15 2 ea	3 5433	1 5476	440C	440C	440C	Phenolic		------ REFER TO QUALIFICATION TESTS ---					165-60 (20 x 10⁶ revs)	350mi circular orbit	None - performance excellent	30	Launch & Orbit Loads		Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)		
		Radial Brg MRC R18 ST3 2 ea	2 125	1 125	440C	440C	440C	Phenolic		------ REFER TO QUALIFICATION TESTS ---					Same	Same	Same	30	Same		Vac Kote (Liquid)	Same		
		Radial Brg MRC 305 ST24 2 ea	2 4405	.9843	440C	440C	440C	Phenolic		------ REFER TO QUALIFICATION TESTS ---					Same	Same	Same	Oscillatory motion ± 5°	Same		Vac Kote (Liquid)	Same		
8	OSO IV Flight	MRC Radial Brg MRC 308 ST15 2 ea	3 5433	1 5476	440C	440C	440C	Phenolic		------ REFER TO QUALIFICATION TESTS ---					11,160	350mi circular orbit	None - bearing torques are normal	30	Launch & Orbit Loads		Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)		
		MRC R18 ST3 Radial Brg 2 ea	2 125	1 125	440C	440C	440C	Phenolic		------ REFER TO QUALIFICATION TESTS ---					Same	Same	Same	30	Same		Vac Kote (Liquid)	Same		
		MRC 305 ST24 Radial Brg 2 ea	2 4409	9843	440C	440C	440C	Phenolic		------ REFER TO QUALIFICATION TESTS ---					11,160	Same	Same	Oscillatory motion ± 5°	Same		Vac Kote (Liquid)	Same		
9	OSO V Flight	MRC Radial Brg MRC 308 ST15 2 ea.	3 5433	1 5476	440C	440C	440CC	Phenolic		------ REFER TO QUALIFICATION TESTS ---					1440 (1.7 x 10⁶ revs)	350mi circular orbit	None - bearing torques are normal	30	Launch & Orbit Loads		Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)		
		Radial Brg MRC R18 ST3 2 ea	2 125	1 125	440C	440C	440C	Phenolic		------ REFER TO QUALIFICATION TESTS ---					Same	Same	Same	30	Same		Vac Kote (Liquid)	Same		
		Radial Brg 2 ea MRC 305 ST24	2 4405	9843	440C	440C	440C	Phenolic		------ REFER TO QUALIFICATION TESTS ---					Same	Same	Same	Oscillatory motion ± 5°	Same		Vac Kote (Liquid)	Same		

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BEARINGS

NO.	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	SIZE: O D IN	SIZE: I D. IN.	MATERIAL: OUTER RACE	MATERIAL: INNER RACE	MATERIAL: BALLS	MATERIAL: RETAINER	MATERIAL: SEALS	TEST HISTORY: TIME HRS	TEST HISTORY: PRESS	TEST HISTORY: TEMP °F	TEST HISTORY: FAILURE MODE	TEST HISTORY: SPEED RPM	FLIGHT HISTORY: TIME HRS	FLIGHT HISTORY: PRESS	FLIGHT HISTORY: FAILURE MODE	FLIGHT HISTORY: SPEED RPM	LOADING: TYPE	LOADING: AMOUNT	LUBRICATION: TYPE	LUBRICATION: METHOD OF APPLICATION	REMARKS	BIBLIO NO.
	BELL TELEPHONE LABORATORIES																							
10	BTL Comp Feas test #1	Kaydon KA 47AH--Dupl Pr KA 35AH--Rad Brg	4 750 3 500	5 250 4 000	52100 52100	52100 52100	52100 52100	Phenolic Phenolic		128	10^{-6} torr	-20°C to +80°C	None	33 cpm ± 100°/cy	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)	No evidence of degradation Bearing lubrication and tests subcontracted to BBRC	BB 1-40
		New Departure Radial Brg ND 3305	2 4409	9843	52100 Stl	52100 Stl	52100 Stl	Phenolic		Same	Same	Same	None	Same	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Same	No evidence of degradation Bearing lubrication and tests subcontracted to BBRC	
11	BTL Comp Feas test #4	Kaydon KA 47AH - Dupl Pr KA 35AH - Rad Brg	4 750 3 500	5 250 4 000	52100 52100	52100 52100	52100 52100	Phenolic Phenolic		475 70	2 x 10^{-6} to 9 6x 10^{-8} torr	-20° C to +80° C	None	28 cpm ± 100°/cy	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)	No evidence of degradation Bearing lubrication and tests subcontracted to BBRC	BB 1-40
		New Departure ND 3305 Rad Brg 2 ea	2.4409	9843	52100 Stl	52100 Stl	52100 Stl	Phenolic		475 70	Same	Same	None	Same	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Same	No evidence of degradation Bearing lubrication and tests subcontracted to BBRC	
12	BTL Comp Feas test #3	New Departure ND 3305 Rad Brg 2 ea	2.4409 09	.9843	52100 Stl	52100 Stl	52100 Stl	Phenolic		832	10^{-7} torr	-20° C to +40° C	None	20 cpm ± 100°/cy	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)	No evidence of degradation Bearing lubrication and tests subcontracted to BBRC	BB 1-40

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BEARINGS

NO.	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	SIZE: O.D IN	SIZE: I.D. IN.	MATERIAL: OUTER RACE	MATERIAL: INNER RACE	MATERIAL: BALLS	MATERIAL: RETAINER	MATERIAL: SEALS	TEST HISTORY: TIME HRS	TEST HISTORY: PRESS	TEST HISTORY: TEMP °F	TEST HISTORY: FAILURE MODE	TEST HISTORY: SPEED RPM	FLIGHT HISTORY: TIME HRS.	FLIGHT HISTORY: PRESS	FLIGHT HISTORY: FAILURE MODE	FLIGHT HISTORY: SPEED RPM	LOADING: TYPE	LOADING: AMOUNT	LUBRICATION: TYPE	LUBRICATION: METHOD OF APPLICATION	REMARKS	BIBLIO NO.
	GENERAL ELECTRIC COMPANY																							
13	NIMBUS I, II, III	SBB; Lebannon, N H Div of MBB Keene, Radial Deep Groove	Support Bearings 2 8750	3125	440C	440C	440C	One pc Phenolic	Shielded only on outboard side of outboard brgs	Aprox 2 mo of 24 hour operation at amb cond & (3) 13 day cyclic T/V tests	Atmos press	25° ± 10° C	None	Support brgs ran at 1 rev per 180 min	Aprox 2000 hours	10^{-6} torr or better	Nimbus I mtr-gearhd brgs failed after 3 mon flight duration due to lubrication breakdown caused by excessive heat from the rotor Nimbus II & III - no brg failures	Support brgs 1 rev per 180 min	Orbit Loads	Almost negligible (inertia loads only)	G300 grease	Supt Brgs Packed 25% fill Distributed hyperdermic needle Vac impregnated retainers w/F-50 oil		
		Bardon, Danbury Conn Radial Deep Groove	Mtr - Gearhead Brgs 3750 5000 6250	1250 1875 2500	440C	440C	440C	Ribbon S S Ret	Shielded only on outboard side of outboard brgs		10^{-4} torr	+5° C to +40° C	None	Mtr grhd brgs ran at 800 to 4500 rpm				Mtr-gh: 800 to 4500 rpm				Mtr-grhd Bearings: Packed 25% fill with hyperdermic needle	Support bearings are preloaded to 15 lbs via spring washers	
14	NIMBUS IV	Support brgs Ray-Tee Monark TB-7311KR1 Radial Deep Groove	Support Bearings 3 9372	5591	440C	440C	440C	Riveted ribbon ret	Shielded only on outboard side of outboard brgs	Aprox 2 mo of 24 hour operation at amb cond & (3) 13 day cyclic T/V tests	Atmos pres	25° ± 10° C	None	Sup brg 1 rev per 180 min	Aprox 4000	10^{-6} torr or better	None	Support brgs 1 rev/ 180 min	Orbit Loads	Almost negligible (inertia loads only)	Supt Brgs Bray Oil NPT-4 & Grease Plate KK 949B	Grease Plate	Shaft and brgs of the unit shall be capable of withstanding 2140 lbs shear load such that a moment of 34,300 in-lbs is applied, also reverse thrust loads of 2175 lbs are applied	TT 1-2 TT 1-3
		MPB, Keene, N H Radial Deep Groove	Mtr - Gearhead Brgs 3750 5000 6250	1250 1375 2500	440C	440C	440C	Riveted ribbon Riveted ribbon Riveted ribbon						Mtr-gh 1020 to 4080 rpm				Mtr-gh 1020 to 4080 rpm	Launch Loads: Steady State Vibration	8 g's ± 4 g's @ 22 Hz	Mtr-gh: MoS_2 Burnish Ext brg is also gold plated	Burnish & Plating		

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BEARINGS

NO.	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	SIZE: O D IN	SIZE: I D. IN.	MATERIAL: OUTER RACE	MATERIAL: INNER RACE	MATERIAL: BALLS	MATERIAL: RETAINER	MATERIAL: SEALS	TEST HISTORY: TIME HRS.	TEST HISTORY: PRESS	TEST HISTORY: TEMP °F	TEST HISTORY: FAILURE MODE	TEST HISTORY: SPEED RPM	FLIGHT HISTORY: TIME HRS	FLIGHT HISTORY: PRESS	FLIGHT HISTORY: FAILURE MODE	FLIGHT HISTORY: SPEED RPM	LOADING: TYPE	LOADING: AMOUNT	LUBRICATION: TYPE	LUBRICATION: METHOD OF APPLICATIO	REMARKS	BIBLIO NO.
	HUGHES AIRCRAFT COMPANY																							
15	BAPTA (Taccom Sat-A) Life Test	New Departure Radial Dp Groove ND 3L30X7 2 ea ABEC 7	8 8583	5 9055	52100 Stl	52100 Stl	52100 Stl	Phenolic		6500 (50 x 10^6 revs)	10^{-8} torr		None - 9 mo life test indicates excellent results	55 to 110	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)	Life test hardware Bearing lubrication and test subcontracted to BBRC	
		Split Ball Brg angular contact Ball 3 TAR 14-21-U	1 3125	8750	440C S S	440C S S	440C S S	Phenolic		Same	Same		Same	175 to 185	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Ball Process Spec 14 02 Vacuum Impregnation process (proprietary)	Life test hardware Bearing lubrication and test subcontracted to BBRC	
		Split Ball Brg angular contact 3 TAR 21-28-U	1 7500	1 3125	440C S S	440C S S	440C S S	Phenolic		Same	Same		Same	110 to 175	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Same	Life test hardware Bearing lubrication and test subcontracted to BBRC	
16	BAPTA (Taccom Sat-A flight) hardware	New Departure Radial dp groove ND 3L30X7, ABEC 7	8.8583	3.9055	440C	440C	440C	Phenolic		N/A	N/A	N/A	N/A	N/A	1440 (5 2 x 10^6 revs)	Syn chro orbit	None - bearing performance normal	60	Launch & Orbit Loads		Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)	Tac Comsat launched February 1969	
		Split Ball Brg Angular contact ball 3 TAR 14-21 U	1 3125	.8750	440C	440C	440C	Phenolic		N/A	N/A	N/A	N/A	N/A	Same	Same	Same	60	Same		Vac Kote (Liquid)	Ball Process Spec 14 02 Vacuum Impregnation process (proprietary)		
		Split Ball Brg Angular contact ball 3 TAR 21-28 U	1 7500	1 3125	440C	440C	440C	Phenolic		N/A	N/A	N/A	N/A	N/A	Same	Same	Same	60	Same		Vac Kote (Liquid)	Same		
17	OLSCA	NRC Ang Cont Dupl Pair 118KRDB ABEC 3	5.5118	3.5433	52100 Stl	52100 Stl	52100 Stl	Machined aluminum with 18 self lubr cylindrical inserts radially fitted & bonded in place in ball pockets		282	Amb to 5 6 x 10^{-6} torr	Amb	None - high torque experienced at various test conditions due to wear and loading of self-lubr inserts	50 to 1725	N/A	N/A	N/A	N/A	Preload	40 lbs	Boeing lube composite 046-15 80% MoS_2 5% Ta 15% Mo	Insert bonded into oversize retainer ball pockets	Bearing development tests for design study	BB 1-6

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BEARINGS

NO.	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	SIZE: O D IN	SIZE: I D. IN.	MATERIAL: OUTER RACE	MATERIAL: INNER RACE	MATERIAL: BALLS	MATERIAL: RETAINER	MATERIAL: SEALS	TEST HISTORY: TIME HRS.	TEST HISTORY: PRESS	TEST HISTORY: TEMP °F	TEST HISTORY: FAILURE MODE	TEST HISTORY: SPEED RPM	FLIGHT HISTORY: TIME HRS.	FLIGHT HISTORY: PRESS	FLIGHT HISTORY: FAILURE MODE	FLIGHT HISTORY: SPEED RPM	LOADING: TYPE	LOADING: AMOUNT	LUBRICATION: TYPE	LUBRICATION: METHOD OF APPLICATION	REMARKS	BIBLIO NO.
	T.R.W. INCORPORATED																							
18	ITS III Life Test Assem	Kaydon angular cont Ball KA 30 3 ea	3 500	3 000	52100 Stl	52100 Stl	52100 Stl	Phenolic		4300 14 1 x 10^6 revs	10^{-8} torr		None - bearing performance OK for life test	100	N/A	N/A	N/A	N/A	N/A	N/A	Vac Kote (Liquid)	Ball Process Spec .4 01 Vacuum Impregnation process (proprietary)	Life test hardware Bearing and Lubrication Tests Subcontracted to BBRC	
		Angular Cont Ball KA-25 3 ea	3 000	2 500	52100 Stl	52100 Stl	52100 Stl	Phenolic		Same	Same		Same	100	N A	N/A	N/A	N/A	N/A	N/A	Vac Kote (Liquid)	Same		
19	ITS III (1)	Kaydon angular cont Ball KA-30 3 ea	3 500	3 000	52100 St.	52100 Stl	52100 Stl	Phenolic							2700 (.6 2 x 10^6 revs)	Synchro orbit	Satellite performance continues to be normal	100	Launch & Orbit Loads		Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)	Bearing and Lubrication Tests Subcontracted to BBRC	
20	ITS III (2)	Kaydon Angular cont Ball KA-25 3 ea	3 000	2 500	52100 Stl	52100 Stl	52100 Stl	Phenolic							1200 (7 2 x 10^6 revs)	Synchro orbit	Satellite performance continues to be normal	100	Launch & Orbit Loads		Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation pro-	Bearing and Lubrication Tests Subcontracted to BBRC	
21	TRW/STL Feasibility Study	New Departure Rad Brg ND 3305 - 2 ea	2 4409	9843	52100 Stl	52100 Stl	52100 Stl	Phenolic		553 total	5 x 10^7 torr	25 ± 5° C	None	034 in /sec	N/A	N/A	N/A	N/A			Vac Kote (Liquid)	Ball Process Spec 14 01 Vacuum Impregnation process (proprietary)	No evidence of wear or debris Bearing and slip rings were evaluated for proposed design of TRW/STL satellite Bearing and Lubrication Tests Subcontracted to BBRC.	BB 1-32

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4 2 2 2 Motors

Chart CC treats any component of drive systems that provide the motive power for the system. Any type of motive power is considered a motor for this discussion Where there was gearing concerned with the motor, it is also shown on this chart There are two different types of lubrication involved. The first is that required for the brushes of the motor, if it is a brush-type motor The second is that required for bearings or other mechanical surfaces.

A review of the motors listed on the "Drive System" and "Motor" charts indicates that almost all of them were brushless motors, either AC servo, DC stepper, or DC torquer. The only brush type motors listed which have flown were used on OSO and Tacsat. The motors for the other spacecraft programs drive through gears which produce overall gear ratios for their respective drive systems ranging from 1 1 to 1,000,000 1. One of the largest known motors to be flown is the 345.6 in-oz DC brush type motor used on the OSO spacecraft (CC-1) built by BBRC. Brush and brushless type DC motors having a peak torque output of 518.4 in-oz were tested by Hughes for the OLSCA program (CC-5). However, they were tested only as part of the design study program and were never flown. The present OSO-H spacecraft (which has not been launched) uses a 1150 in-oz DC motor. One of the motors with the longest known successful flight history is the one used on OSO III which has accumulated 42 months life (12,265 hours) without failure as of 28 September 1970, and the spacecraft is still transmitting data. This motor, a DC brush type, has a rated capacity of 345.6 in-oz. Other motors which have achieved long space flight history are those flown in Nimbus (CC-2, CC-3, CC-4) and OGO (CC-6) spacecraft which were built by G. E. and TRW, respectively.

The predominant type of lubricant used on the gearing associated with all the motors listed was an oil or grease. The types of oils/greases used with F-50 silicone oil (FF-24), Bray NPT-4 with and without grease plate

of KK949B (FF-25), liquid Vac Kote (FF-25), and G-300 silicone grease (FF-35) Electrofilm MoS_2 coatings were used on the gearing for the Air Force type I and II spacecraft built by Lockheed (FF-2).

The brush material used in the DC motors for the spacecraft were grade RS-S2 (GG-2) consisting of 50 ± 5 percent silver and 50 ± 5 percent graphite OLSCA design study program redevelopment tests were performed on DC brush type motors consisting of 15 percent molybdenum, 80 percent molybdenum disulfide and 5 percent tantalum.

Motors of the rating required for this system (10 to 15 ft-lbs) have been built for commercial use However, the ten-year life requirement will impose limitations upon the applicable technology. Periodic maintenance and component replacement will be a major consideration for the design. The selection of the motor which will meet all the design and performance requirements must be made during the trade-off study. Both brush and brushless type motors have been used in previous spacecraft. None of the spacecraft have used an "on-axis" motor with a large bore through its center. One of the largest motors of that type found in the catalogs is an Inland DC permanent magnet torque motor, No. T-36001 which has a 25.625 in bore and 41 inch outside diameter. A direct scale-up to a motor having a five foot diameter bore is questionable. Most probably an "off-axis" motor will be selected which drives through a gear reduction. Many applications can be found both in aerospace and commercial work which use motors in this manner. If this drive arrangement is selected, conventional existing motor design can be used. While motor technology is fairly well known, the combination of the motor and gear box or gear reduction system will have to be designed specifically for the orientation drive assembly. Since this is a key part of the assembly, it is suggested that the testing be extended to include life testing of the unit. The purpose would be to

determine failure modes, reliability and the spares requirements for various components in the assembly. The test would probably run for several years with the expenses small since little or no maintenance is required The results would fill one more of the technical gaps in a large drive system Past experience indicates that the motor-gear reduction system, is an area prone to failure. However, the failures in this type assembly are not predictable. They are unique to a particular design in almost every case and the only method of determining actual failure modes is by running a life test on the unit.

MOTORS

CC

NO.	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	TORQUE: INCH OZ	TORQUE: RPM	NO LOAD SPEED RPM	BRUSH: MATL	BRUSH: LUBRICATION	BRUSH: METHOD OF APPLICATION	BRUSH: CONTACT RESIST	TEST HISTORY: TIME HRS	TEST HISTORY: PRESS	TEST HISTORY: TEMP °F	TEST HISTORY: RPM	TEST HISTORY: TEST RESULTS	FLIGHT HISTORY: TIME HRS	FLIGHT HISTORY: PRESS	FLIGHT HISTORY: TEMP °F	FLIGHT HISTORY: RPM	FLIGHT HISTORY: FLIGHT RESULTS	GEARING: RATIO	GEARING: LUBRICATION	GEARING: GEAR TYPE	REMARKS	BIBLIO NO
	BALL BROTHERS RESEARCH CORPORATION																							
1	OSO I-VI Flights	Inland Torque T-4006C Azimuth Drive	345 6	312		50±5%Ag 50±5% C BrushGr RS-S2 W/ HA12 Treatmt	Dry Vac-Kote	Vac-Kote Process BPS 13 0 13 11 vac impreg pro cess prop	10 9 ohms	5000 max (10 x 106 revs)	1 8 x 10^{-6} to 4 7 x 10^{-9} torr	+10°C to +25°C	6 to 180	Motor perf was satisfac-tory Neglib-iblo brush wear	OSO I-17000 OSO II 17000 OSO III 16560 OSO IV 11,160 OSO V 1440	350 mi circu-lar orbit		30	Performance of motors has been satis-factory since all satellites have been launched	Direct	N/A	N/A		
		Inland Torque T-2907-B Elevation Drive	163 2	382		"	Dry Vac-Kote	"	16 8 ohms	4800 max (17 3 x 10^6 revs)	10^{-8} torr	-15 to +25°C	±5°OSC to 60 rpm	"	"		Oscil-latory Motion ±5°			Direct	N/A	N/A		
	GENERAL ELECTRIC																							
2	Nimbus I	Kearfott, Size 8 Servo Motor	1 (stall)	800	4500	N/A	N/A	N/A	N/A	Approx 120 hrs at amb (3)13 day cy-clic T/V Tests	Atmos 10^{-6} torr	+15°C to +35°C +5°C to +40°C	800 to 4500 800	No failures until in flight 3 mon	Approx 2000	10^{-6} torr or bet-ter	Approx +5°C to +40°C	800	Mtr brgs failed after 3 mons due to lubrica-tion break-down caused by excessive heat from rotor	12121 1 (g h only) Over-all 84,847 1	G-300 grease	SPUR	Information obtained thru personal communication	
3	Nimbus II and III	Kearfott, Size 11 Servo Motor	3 (stall)	800	4500	N/A	N/A	N/A	N/A	Approx 1200 hrs at amb (3)13 day cy-clic T/V Tests	Atmos 10^{-6} torr	+15°C to +35°C +5°C to +40°C	800 to 4500 800	No failures	(II) Approx 24000 (III) Approx 12000	10^{-6}	Approx +5°C to +40°C	800	Nimbus II - No drive fail-ures after 36 mons Nimbus III - No drive fail-ures after 18 mons	12121 1 (g h only) all 84,847 1	G-300 grease	SPUR	Information obtained thru personal communication	
4	Nimbus IV	Kearfott, Size 11 Servo Motor	.3	1020 (norm) 4080 (slew)	6800	N/A	N/A	N/A	N/A	Aprox 1200 hrs at amb (3)13 day cy-clic T/V Tests	Atmos 10^{-6} torr	+15°C to +35°C +5°C to +40°C	1020 to 4080	During Qual Tests a motor stall failure occurred which re-sulted in a change in gear ratio from 40/1 to 183/1	Approx 6000	10^{-6} torr	Aprox +5°C to +40°C	.020 to 4080	No drive fail-ures after 6 mons	183 1 (g h only) Over-all 100000 1	BRAY oil NPT-4 with KK949B grease plate		Wabbel slip clutch output	TT 1-2 TT 1-3

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MOTORS

CC

NO.	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	TORQUE: INCH OZ	TORQUE: RPM	NO LOAD SPEED RPM	BRUSH: MATL	BRUSH: LUBRICATION	BRUSH: METHOD OF APPLICATION	BRUSH: CONTACT RESIST	TEST HISTORY: TIME HRS	TEST HISTORY: PRESS	TEST HISTORY: TEMP °F	TEST HISTORY: RHM	TEST HISTORY: TEST RESULTS	FLIGHT HISTORY: TIME HRS	FLIGHT HISTORY: PRESS	FLIGHT HISTORY: TEMP °F	FLIGHT HISTORY: RHM	FLIGHT HISTORY: FLIGHT RESULTS	GEARING: RATIO	GEARING: LUBRICATION	GEARING: GEAR TYPE	REMARKS	BIBLIO NO
	HUGHES AIRCRAFT COMPANY																							
5	OLSCA	Aeroflex Brushless D C Torque Motor Type 47-3P	518 4		250	N/A	N/A	N/A	N/A	Vacuum tested briefly during development test program to verify performance. Performance was satisfactory					N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tests conducted to determine motor performance for design study	SB 1-6
		Inland Brush Type Motor, Type T5134D	518 4		22	15% Mo 80%MoS_2 5% Ta	---	---	6 7 Ohms per winding	A brush type D C motor of this type was used during most of the development test program and for running in bearings and test rig assembly Performance was excellent					N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		
	T.R.W. SYSTEMS																							
6	OGO	Kearfott, R119 Size 11 Servo Motor	0 6		6200	N/A	N/A	N/A	N/A	8500, 10,350 & 12,750				3 Units Life Tested					21 Built 12 Units - Flown	24000 1	Gold plated stool - sinite impreg with MoS_2 -wabble	wabble-17-4 PH St Stl Spur - internal	Information obtained through personal communication	
	LOCKHEED MISSILE AND SPACE COMPANY																							
7	Type I	Superior Elect Co Slo-Syn DC Stepper SS-150-1014	200 max at 1 step per deg 300 (energized)	200 steps per rev		N/A	N/A	N/A	N/A										Flt #1-Array #2 failed to extend, flt #2-Control box #2 failed flt #3-Battery lost, pwr sys lost 2 - 3 Days	2 1	Electrofilm MoS_2 coating			LL 2-22
8	Type II	Superior Elect Co Slo-Syn DC Stepper SS-150-1014	300 max (energized)	200 steps per rev		N/A	N/A	N/A	N/A										2 flts - 1 logic failure 45 days max	1 1	Electrofilm MoS_2 coating			LL 2-22 LL 2-31
9	Type III	AC Globe Induction Mtrs 400 Hz, 2φ	0 8	6000	8000	N/A	N/A	N/A	N/A										9 flts - 1 switch problem 30 days to 12 months each	6000 1	F50 Silicone oil			LL 2-22
10	Zombie	Inland Mtr Co DC Brush Type Torque Mtrs	60	10°/sec min															bo flts Qualified for for low alt orbit-1 year	Direct	N/A	N/A		LL 2-22 LL 2-10
11	System#5	AC Stepper Mtrs	182		N/A	N/A	N/A	N/A	N/A														Worm and Gear Differential Drive	LL 2-22

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4.2.3 Power Transfer Devices

Before going into any detail on the various schemes, it is expedient to consider what sort of current magnitudes will be required. The power levels specified for the large space station are 25 KW nominal and 100 KW maximum. There is a wide range of voltages and corresponding currents that will yield the specified power levels. The ultimate voltage and current determination is involved in the total space station system study However, based on Space Station studies to date, the lowest probable DC voltage will be 56 volts, yielding maximum array currents of 2000 amperes.

The selection of materials to be used in ODAPT will be influenced by the current/voltage ratio used in the make-up of power consumed by the space station.

Dielectrical properties of the electrical insulation will obviously be more important for the high voltage system, but the high current system will require heavier conductors and, hence, high mechanical strength in the insulation material in order to support the heavier loads during launch.

The high current system will require more or larger contacts (brushes, meshing gears, or clutches), and more power will be consumed in overcoming the greater frictional drag. Electrical heating due to contact resistance and heating in brushes and conductors (I^2R) will also result in lost power and cause brushes to run hotter. The higher operating temperature in brushes, for example, will affect the choice of and evaporative loss rate of an impregnating liquid lubricant. Disposing of heat through radiation in addition to conduction will be an additional consideration for the high current system. The high voltage system appears to offer the possibility of fewer material problems, but until the overall system analysis is made on the current/voltage ratio, the relative importance of electrical insulation considerations compared with considerations associated with the high-current system cannot be adequately assessed. Obviously, a compromise band of ratios will be found to exist

somewhere between the two extremes rather than at either end

For the purpose of the ODAPT study, no data has been found to cause a change from the original estimate of 100 volts and 1,000 amps, since a factor of two or three either way will not change the basic conclusions reached in this study.

For the purpose of the survey, power transfer devices were divided into two categories. The first is slip rings, primarily because slip rings are the most universally used transfer devices across rotary joints. All other types of power transfer devices are grouped under a heading called "Other" and these include rotary transformers, rolling contact devices, etc.

An attempt has been made to study not only the things that are known to work well, but to also look for new ideas that might have been tested or that might be capable of being tested and that may be usable on a large space station. This type of device is shown on the chart headed "Electrical Power Transfer Devices Other Than Slip Rings".

The technology of power transfer across a rotating joint was already highly advanced when the space age began, and it was concentrated in slip ring/brush assemblies. The experience gained during W. W. II with prevention of brush wear in high altitude aircraft provided a sound basis for developing brushes suitable for space vacuum environments. The literature search has clearly revealed this relationship, but it has also shown the considerable further advancement which has occurred in development of brush compositions specifically intended for space vacuum applications, especially dry and liquid brush lubricants.

Very little work has been done on other types of continuously rotating power transfer devices, as revealed by the literature survey. Some preliminary tests have been conducted on power-level current transfer

through meshing gears and across alternately engaged power clutches used with flex-cables. Tests with only signal-level currents have been conducted successfully with purely rolling contact devices (ball bearings)

Of all the spacecraft that detailed information pertaining to the power transfer device was available on, every one used slip rings where continuous rotation is required and flex cables where limited rotation is acceptable. Hughes Aircraft is using a rotary transformer to carry signals across a rotating joint on Intelsat IV (EE-21) which has been qualified but not flown.

4 2 3 1 Slip Rings

The information presented in charts DD-1 through DD-36 show that slip ring operation in vacuum, both in test chambers and outside the earth's atmosphere, has become quite common and a large amount of data is available The largest slip rings, in terms of current, that have been flown are on the Nimbus spacecraft (DD-22) and are capable of 10 amps/circuit continuous current The largest diameter slip rings flown as far as has been determined are less than 5 inches.

Dr F J Clauss of Lockheed Missiles and Space Company supervised a program to provide radiation inside a large aerospace environmental chamber (Ref· Bib LL. 2-4). The radiation was to simulate albedo and earthshine (or secondary radiation) to the spacecraft under test and was provided by banks of tungsten filament lamps. To simulate the radiation received by a tumbling spacecraft, it is necessary to rotate the lamp banks. The entire installation is rated at 1 megawatt, and the slip ring tests were run with 75 amps and current density about 300 amps per square inch. Optimum brush composition determined from these tests is from 82 5 to 85 percent silver, 2 5 percent copper, and 12. 5 to 15 percent molybdenum disulfide (GG-5).

Current densities in the various applications shown on the charts range from 75 to 300 amps per square inch. The amount of power required by the space station is not a problem, as long as the current densities are maintained comparable to that of successful tests and flights, the large amount of current necessitates more brush area Additional brush area means more brushes, larger brushes, or both.

Although there is no flight history of slip rings operating in orbit for ten years, several satellites with slip rings have compiled substantial time in orbit. The longest time is the OSO III spacecraft (AA-5) that has been in orbit since March 1967 Although the experiments are not being

turned on, the despin drive with the slip rings is presently being turned on about two days per week and all spacecraft systems are operating normally. It is worthwhile noting that when OSO III is not turned on, the relative motion between the wheel and the sail is zero and the batteries are pulse charged as the sail rotates The slip ring brushes are carrying the pulse current while still. This operation closely simulates that of the space station power transfer for some attitude modes. Dr. Clauss (DD-33 and DD-34) tested brushes and slip rings stationary for up to 50 hours while carrying full current

A rather impressive array of data pertaining to slip-ring operation in a vacuum is now available To apply it to the space station task, questions of scaleup and the ten year mission will require more testing.

As a part of the technology survey, an inquiry letter was sent to 69 companies listed in the 1970 Thomas Register as manufacturers of slip rings, collector rings and/or slip ring assemblies. The inquiry letters were mailed on August 17, 1970, and responses have now been received from 42 of the companies. The letter outlined the power-type slip ring requirements for ODAPT (without identifying it), giving such items as

- Transfer up to 100 KW power
- Operate in air and hard vacuum
- Ring diameter up to seven feet
- Rotary and oscillatory motion
- Current conduction while stationary and at slow sliding-speeds
- Relatively short sliding distance but long time duration

The letter then requested copies of whatever catalogs, brochures, papers, reports, etc. the company could submit to indicate its capabilities along these lines.

Of the 42 responses, 7 companies have indicated their interest and, at least to some extent, their ability in power-type slip ring technology. Those seven companies are as follows:

a. Poly-Scientific Division of Litton Industries, Blacksburg, Virginia
b. Electro-Tec Corporation, Blacksburg, Virginia
c. Superior Carbon Products, Inc., Cleveland, Ohio
d. Engelhard Industries, Attleboro, Massachusetts
e. Welco Industries, Inc., Cincinnati, Ohio
f. Industrial Electric Reels, Inc., Omaha, Nebraska
g. Electro-Miniatures Corporation, South Hackensack, New Jersey

Figure 4-4 illustrates the various slip ring configurations that are mentioned on the slip ring charts (DD).

The technology developed for small satellites is applicable to the large rings that will be required for the space station power transfer.

Scaling up slip rings should offer very few problems from the electrical aspect because the current density in the brushes is the important parameter and the brush area can be enlarged by using larger brushes or more brushes to accommodate the desired current. The ring itself, of course, must be sized to handle the current.

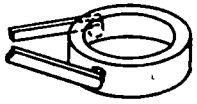
The large shaft diameter means more mechanical runout and this will influence the brush holder design. These very large diameter rings will quite likely require special plating tanks, and the mechanical design problems of providing a structure that can withstand ground handling and the launch environment will require much attention.

Slip rings approaching the size of the space station application have been made and successfully operated. Electro-Tec Corporation made a slip ring assembly that mounted around a four-foot diameter solar telescope tube. This assembly has four power-conducting rings rated at 2,500 amps

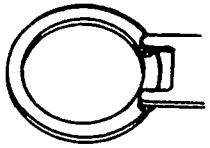
a V-Groove Ring
Wire Brushes

b. U-Groove Ring
Wire Brushes

c. Drum Ring
Wire Brushes



d. Drum Ring
Button Brushes



e. Disc Ring
Button Brushes

Fig 4-4 Slip Ring Configurations

each, plus 94 "signal" circuits ranging from 10 to 20 amps each While this is an atmospheric application, the technology is directly applicable to making power slip rings for a large space station. Radio telescopes, tracking radars, and large centrifuges are applications where very large slip rings have been used

The ten-year life, the stop and go operation and the large currents involved are the reasons for the testing now under way As mentioned in earlier discussions, there are slip rings in orbit that have operated in a stand-still mode for extended periods of time and are still operable after five years but the conditions (current density, brush pressure, heating, etc) are different. The present series of tests will advance the technology enough to allow the design to proceed with confidence

SLIP RINGS

DD

NO.	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	NO. OF CIR	AMPS PER CIR	BRUSHES PER RING	BRUSH CONFIGUR	RING CONFIGUR	MATERIAL: BRUSH	MATERIAL: RING	TEST HISTORY: TIME	TEST HISTORY: PRESS	TEST HISTORY: TEMP	TEST HISTORY: BRUSH SPEED	TEST HISTORY: BRUSH PRESS	TEST HISTORY: BRUSH TRAVEL	TEST HISTORY: TEST CURR	FLIGHT HISTORY: TIME	FLIGHT HISTORY: TEMP	FLIGHT HISTORY: BRUSH SPEED	FLIGHT HISTORY: BRUSH PRESS	FLIGHT HISTORY: BRUSH TRAVEL	FLIGHT HISTORY: OPER CURR	LUBRICATION: TYPE	LUBRICATION: METHOD OF APPLICATION	REMARKS	BIBLIO NO
	BALL BROTHERS RESEARCH CORPORATION																									
1	OSO-I	Breeze Corp	14	1 Avg	2	Button	Disk	75% Ag 20% Graphite 5% MoS_2	Coin Silver	1339 Hours	10^{-8}	75° ± 5° F	26 5 ft/min	17-29 Grams	2 1 x 10^6 revolutions	None; Noise Tested Only	24 Mos	-10° C to +35° C	30 rpm	16-28 Gms	4 4 x 10^6 Ft		Vac Kote BBRC low volatility oil and special additive	Ball Process Spec 13 11 Vacuum impregnation process (proprietary)	"On" during orbit day (60 minutes) "Off" during orbit night (30 minutes) Commanded "ON" 12 and 18 months after launch and slip rings still operating satisfactorily	BB 1-18 BB 1-32 BB 1-33
2	OSO-II	Breeze Corp	18	1 Avg	2	Button	Disk	75% Ag 20% Graphite 5% MoS_2	Coin Silver	Qualification based on above test and satisfactory performance of OSO-I ring assembly in orbit							18 Mos	-10° C to +35° C	30 rpm	16-28 Gms	3 5 x 10^6 Ft		Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I	60 Min On; 30 Min Off Slip ring performance was satisfactory for the 9 mos operational period and was turned off After 8 mos , it was commanded on for approximately 150 hrs Slip ring performance was again satisfactory OSO-II was then turned off for 7 mos In Dec 1966, OSO-II was acquired for approximately 2 hrs--slip ring performance appeared to be satisfactory	
3	OSO-III	Breeze Corp	22	1 Avg	2	Button	Disk	75% Ag 20% Graphite 5% MoS_2	Coin Silver	Qualification based on above test and satisfactory performance of OSO-I ring assembly in orbit							42 Mos	-10° C to +35° C	30 rpm	16-28 Gms	8 x 10^6 Ft		Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I	60 Min On; 30 Min Off Still operable as of September 1970	BB 1-9
4	OSO-IV	Breeze Corp	22	1 Avg	2	Button	Disk	75% Ag 20% Graphite 5% MoS_2	Coin Silver	Qualification based on above test and satisfactory performance of OSO-I ring assembly in orbit							36 Mos	-10° C to +35° C	30 rpm	16-28 Gms	6 9 x 10^6 Ft		Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I	60 Min On; 30 Min Off Still operating	
5	OSO-V	Breeze Corp	22	1 Avg	2	Button	Disk	75% Ag 20% Graphite 5% MoS_2	Coin Silver	Qualification based on above test and satisfactory performance of OSO-I ring assembly in orbit							20 Mos	-10° C to +35° C	30 rpm	16-28 Gms	3 8 x 10^6 Ft		Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I	60 Min On; 30 Min Off Still operating	
6	OSO-VI	Breeze Corp	22	1 Avg	2	Button	Disk	75% Ag 20% Graphite 5% MoS_2	Coin Silver	Qualification based on above test and satisfactory performance of OSO-I ring assembly in orbit							14 Mos	-10° C to +35° C	30 rpm	16-28 Gms	2 7 x 10^6 Ft		Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I	60 Min On; 30 Min Off Still operating	
7	OSO Slip Ring Second Source Qual	Poly-Scientific ET-1709	40	2 Amps 200 ma 50 ma	2	Rectangular X-section rod	V-groove	Neo Oro 28A (gold alloy)	24k gold with Orotherm Flash	4320 Hours	$< 10^{-6}$	25° ± 5° C	30 rpm continuous		15.6×10^6 revolutions	2 amps 200 ma 50 ma	----------	----------	Test Program O-1	----------	----------		Vac Kote See OSO-I	Ball Process Spec 13 12 See OSO-I	Completely successful slip ring and lubrication system performance	BB 1-21

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SLIP RINGS

DD

NO.	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	NO. OF CIR	AMPS PER CIR	BRUSHES PER RING	BRUSH CON-FIGUR	RING CON-FIGUR	MATERIAL: BRUSH	MATERIAL: RING	TEST HISTORY: TIME	TEST HISTORY: PRESS	TEST HISTORY: TEMP	TEST HISTORY: BRUSH SPEED	TEST HISTORY: BRUSH PRESS	TEST HISTORY: BRUSH TRAVEL	TEST HISTORY: TEST CURR	FLIGHT HISTORY: TIME	FLIGHT HISTORY: TEMP	FLIGHT HISTORY: BRUSH SPEED	FLIGHT HISTORY: BRUSH PRESS	FLIGHT HISTORY: BRUSH TRAVEL	FLIGHT HISTORY: OPER CURR	LUBRICATION: TYPE	LUBRICATION: METHOD OF APPLICATION	REMARKS	BIBLIO NO
	BALL BROTHERS RESEARCH CORPORATION																									
8	OSO Slip Ring Second Source Qual	Poly-Scientific ET-1161	40	2 amps 200 ma 50 ma	2	Button	U-groove	75% Ag 20% Graphite 5% MoS_2	Coin Silver		$< 10^{-6}$	25° ± 5° C	30 rpm continuous.		15.6×10^6 revolutions	2 amps 200 ma 50 ma	----------	----------	Test Program Only	----------	----------	----------	Vac Kote See OSO-I	Ball Process Spec 13 12 See OSO-I	Wear on brush and ring higher than normal due to brush and ring geometry. Lubrication system satisfactory	BB 1-21
9	Vac Kote Evaluation Test #1	Breeze Corp	24	1 amp				75% Ag 25% Graphite	Coin Silver	1339 Hours	$< 4 \times 10^{-8}$	25° ± 5° C	120 rpm		9.64×10^6 revolutions	1 amp	----------	----------	Test Program Only	----------	----------	----------	Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I	Minimum slip ring and brush wear	BB 1-33
10	Vac Kote Evaluation Test #2	Breeze Corp AF8001	12	63 ma and 400 ma		Cantilevered button	Disk	75% Ag 25% Graphite	Coin Silver	2210 Hours	6×10^{-8}	25° ± 5° C	30 rpm 20 min on 40 min off		1.16×10^6 revolutions	63 ma and 400 ma	----------	----------	Test Program Only	----------	----------	----------	Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I	Satisfactory test--negligible wear	BB 1-34
11	Slip Rings Mat'ls Test	Electro Tec Development Model	12			Button and Sintered Block	Disk	Rings and Brushes all Different Materials (12 Combinations)		254 Hours	5×10^{-8} Avg	25° ± 5° C	10 rpm	3 Grams Force	0.21×10^6 revolutions	375 ma	----------	----------	Test Program Only	----------	----------	----------	Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I	Coin silver ring and 75% Ag 25% C brush was best combination	BB 1-37 BB 1-12
12	Slip ring Feasibility Study for TRW	Breeze Corp AT-8001	12			Button	Disk	75% Ag 25% Graphite	Coin Silver	500 Hours	10^{-7}	25° ± 5° C	30 rpm continuous		0.8×10^6 revolutions	60 ma to 375ma	----------	----------	Test Program Only	----------	----------	----------	Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I	Completely successful	BB 1-32
13	Lubrication Development Test #1	Breeze AJ8003-12	12	2 & 0.01		Cantilevered button	Disk	75% Ag 20% Graphite 5% MoS_2	6 Ag 6 Au	100 Hours	10^{-5}	25 ± 5° C	30 rpm continuous		180,000 revolutions	2 amps & 10 ma	----------	----------	Test Program Only	----------	----------	----------	None	N/A	Heavy wear, less wear on silver plated rings, test terminated with slip ring failure	BB 1-36
14	Lubrication Development Test #2	Breeze AF8001-12	12	2 & 0.01		Cantilevered button	Disk	75% Ag 20% Graphite 5% MoS_2	Coin Silver	150 Hours	10^{-5}	25° ± 5° C	30 rpm continuous		270,000 revolutions	2 amps & 10 ma	----------	----------	Test Program Only	----------	----------	----------	None	N/A	Heavy wear--test terminated with ring failure	BB 1-36
15	Lube Development Test #7	Breeze AF8003-12	12	2 amps & 10 ma		Cantilevered button	Disk	75% Ag 20% Graphite 5% MoS_2	Coin Silver	500 Hours	10^{-8}	25° ± 5° C	30 rpm continuous		900,000 revolutions	2 amps & 10 ma	----------	----------	Test Program Only	----------	----------	----------	Vac Kote on 6 rings See OSO-I	Ball Process Spec 13 11 See OSO-I	Rings 1 thru 6 had no lubrication and indicated heavy wear Rings 7 thru 12 had Vac Kote P2973 and showed virtually no wear	BB 1-32
16	Lube Development Test #8	Breeze AF8003-12	12	2 amps & 10 ma		Cantilevered button	Disk	75% Ag 20% Graphite 5% MoS_2	Coin Silver	550 Hours	10^{-8}	25° ± 5° C	30 rpm continuous		10^6 revolution	2 amps & 10 ma	----------	----------	Test Program Only	----------	----------	----------	Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I	Satisfactory - minimum wear	BB 1-32

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SLIP RINGS

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NO	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	NO. OF CIR	AMPS PER CIR	BRUSHES PER RING	BRUSH CON-FIGUR	RING CON-FIGUR	MATERIAL: BRUSH	MATERIAL: RING	TEST HISTORY: TIME	TEST HISTORY: PRESS	TEST HISTORY: TEMP	TEST HISTORY: BRUSH SPEED	TEST HISTORY: BRUSH PRESS	TEST HISTORY: BRUSH TRAVEL	TEST HISTORY: TEST CURR	FLIGHT HISTORY: TIME	FLIGHT HISTORY: TEMP	FLIGHT HISTORY: BRUSH SPEED	FLIGHT HISTORY: BRUSH PRESS	FLIGHT HISTORY: BRUSH TRAVEL	FLIGHT HISTORY: OPER CURR	LUBRICATION: TYPE	LUBRICATION: METHOD OF APPLICATION	REMARKS	BIBLIO NO
	BALL BROTHERS RESEARCh CORPORATION																									
17	Test Program	Electro-Tech			10			Paliney #7 (Pro-cious metal alloy)	Cu + Ag over-plate	2000 Hours	10^{-8}	ambi-ent	10 rpm			050/ 375	----------	----------	Test Program	Only	----------	Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I		BB 1-12
18	Test Program	Electro-Tech			10			Ney Oro 28A (gold alloy)	Cu + Ag over-plate	2000 Hours	10^{-8}	ambi-ent	10 rpm			050/ 375	----------	----------	Test Program	Only	----------	Vac Kote See OSO-I	Ball Process Spec 13 11 See OSO-I		BB 1-12

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	GENERAL ELECTRIC																									
19	Nimbus I A	Poly-Scientific	4 Pwr 20 Sig	6 Avg	2		Drum 3 1" Dia	88% Ag 12% MoS_2	Rhenium On Silver On Gold								25 days	-10°C to +55°C	0 01 to 0 1 rpm	80-100 40-60 Gms					The solar array drive on all Nimbus vehicles is energized during orbit day (70 minutes) and the slip rings are carrying current, and the drive is not active during orbit night (36 minutes)	
20	Nimbus II C	Poly-Scientific	4 Pwr 20 Sig	6 Avg	2		Same	Same	Same								32 Mos	-10°C to +55°C	0 01 to 0 1 rpm	80-100 40-60 Gms						
21	Nimbus III (B2)	Poly-Scientific	4 Pwr 20 Sig	6 Avg	2		Same	Same	Same								10 Mos	-10°C to +55°C	0 01 to 0 1 rpm	80-100 40-60 Gms					Still operating	
22	Nimbus IV	Litton Poly-Scientific	4 Pwr 16 Sig	10			Disk	85% Ag 12 5% MoS_2 2 5% Cu									6 Mos						NPT-4 (Synthetic ester oil)		Still operating	
23	Feasibility Study Roll-up Solar Array		2	13.8	2		1" Dia	Silver /Niobium Diselenide	Silver					340 Gms		75 amps/in²										LL 1-4

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NO	SYSTEM MANUFACTURER: PROJECT	SYSTEM MANUFACTURER: MANUFACTURER, TYPE, AND PART NUMBER	NO. OF CIR	AMPS PER CIR	BRUSHES PER RING	BRUSH CONFIGUR	RING CONFIGUR	MATERIAL: BRUSH	MATERIAL: RING	TEST HISTORY: TIME	TEST HISTORY: PRESS TORR	TEST HISTORY: TEMP	TEST HISTORY: BRUSH SPEED	TEST HISTORY: BRUSH PRESS	TEST HISTORY: BRUSH TRAVEL	TEST HISTORY: TEST CURR	FLIGHT HISTORY: TIME	FLIGHT HISTORY: PRESS	FLIGHT HISTORY: BRUSH SPEED	FLIGHT HISTORY: BRUSH PRESS	FLIGHT HISTORY: BRUSH TRAVEL	FLIGHT HISTORY: OPER CURR	LUBRICATION: TYPE	LUBRICATION: METHOD OF APPLICATION	REMARKS	BIBLIO NO
	HUGHES AIRCRAFT COMPANY																									
24	Hughes ECRA	Airflyte Electronics 252440	4 Pwr 20 Sig	36 for pwr 1 for Sig	2			Ag Graphite	Ag	95 days 2000+ hours	10^{-7} torr	ambient	55 rpm		22.5×10^6 in	36 amps (Pwr) 1 amp (Sig)							Vac Kote			BB 1-14
25	Hughes ECRA	Airflyte Electronics 252440	4 Pwr 20 Sig	36 for pwr 1 for Sig	2			Ag Graphite	Ag	60 days	10^{-7} torr	ambient	55 rpm		22.5×10^6	36 amps (Pwr) 1 amp (Sig)							Vac Kote		60 more days run of the slip ring assembly tested above	BB 1-14
26	Test Program							95% Ag 5% MoS_2	Ag	1144 hours	$< 10^{-8}$	-130° C to +90°C	27 2 meters per minute		2 085 x 10^9 meters	Intermittent 20 amps per cm^2 Continuous 9 3A/cm^2									Test terminated because chamber was required for another program Friction independent of current Friction was less in vacuum than in 1 atmosphere, and declined with time of test NAECON '70 RECORD J P Dallas, NTS HAC	
27	TACSAT	Airflyte Corporation	7 primary pwr 7 secondary pwr 20 sig	15 amps 2 amps 100 ma	2 2 2	Rectangular .150 x .30 .150 x .150 .150 x .150	Drum (flat) Drum (flat) Drum (flat)	75% Silver 25% Graphite	Coin Silver	6600 hours	10^{-6}	23° C	100 rpm (300°/min)	30 gms 7 gms 7 gms	48 x 10^6 rev (150 x 10^6 in)	150 amps/sq in	20 Mo Launched Feb 1969	10° C Avg	55 rpm	7 gms 7 gms	1" dia	5 A 2 A 100ma	Vac Kote	BPS 13 01 Ball Process Spec Vacuum impregnation process (Proprietary)	Still operating very well	BB 1-14

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	LOCKHEED MISSILES AND SPACE COMPANY																									
28	Lockheed	R58769	25			Button	Drum	75% Ag 25% Graph-ite	Coin Silver	200 hours	10^{-6}	75° ± 5° F	40 ± 10 rpm			0 5A 0 9A							Vac Kote		Rings carried current only when noise tests were made--otherwise no current flowed	BB 1-24
29	Lockheed	R58770	35			Button	Drum	75% Ag 25% Graph-ite	Coin Silver	200 hours	10^{-6}	75° ± 5° F	40 ± 10 rpm			0 5A 0 9A							Vac Kote		Same as above	BB 1-24
30	Lockheed DOD/Aero-jet		150 total		2		1 8" Dia										Clas-sifi-ed		6 rpm				Vac Kote			
31	Lockheed/ DOD		6 Pwr 10 Sig	3 5 Avg	2			85% Ag 12 5% MoS_2 2.5% Cu	Coin Silver								Clas-sifi-ed						F-50 Oil			
32	Lockheed Test Pro-gram for Large En-vironmen-tal Cham-ber	Pacific Scientific	19	4 05 amps	1-in 1-out	090" wide 150" long contou-red	2 1/4" Dia	80% Ag 20% Graph-ite	Elec-trode-posit-ed Ag	500 hours	10^{-6} torr	room amb-ient	424 in /min	6 or 10 psi	25 x 10^6 in	300 amps/ in^2	----------TEST PROGRAM ONLY----------						No oil	N/A		LL 2-4
33			8	75 amps	2-in 2-out	437" wide 750" long contou-red	6-3/4" Dia	90% Ag 10% Graph-ite	Elec-trode-posit-ed Au	700 hours	10^{-7} torr	room amb-ient	318 in /min	10 psi	13.4 x 10^6 inches	75 amps 229 amps/ sq in	----------TEST PROGRAM ONLY----------						No oil	N/A	Stationary for 40 hours in vacuum	LL.2-4
34			24	4 05 amps	1-in 1-out	090" wide 150" long contou-red	2-1/4" Dia	85% Ag 5% Cu 10% MoS_2	Elec-trode-posit-ed Ag	630 hours	10^{-6} torr	room amb-ient	424 in /min	6 or 10 psi	16 x 10^6 in	300 amps/ in^2	----------TEST PROGRAM ONLY----------						No oil	N/A	Stationary for 10 hours in vacuum	LL 2-4
35			24	4 05 amps	1-in 1-out	Same	2 1/4" Dia	85% Ag 5% Cu 10% MoS_2	Elec-trode-posit-ed Au	630 hours	10^{-6} torr	room amb-ient	424 in /min	6 or 10 psi	16 x 10^6 in	300 amps/ in^2	----------TEST PROGRAM ONLY----------						No oil	N/A	See reference for other composi-tions tested	LL.2-4
36			24	4 05 amps	1-in 1-out	Same	2 1/4" Dia	75% Ag 15% Mo 10% MoS_2	Elec-trode-posit-ed Ag	500 hours	10^{-6} torr	room amb-ient	424 in /min	6 or 10 psi	12.7 x 10^6 in	300 amps/ in^2	----------TEST PROGRAM ONLY----------						No oil	N/A		LL.2-4

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4 2 3 2 Other Power Transfer Devices

As has been stated, all known spacecraft flown to date, that require continuous rotation, have used slip rings. It could be assumed that slip rings have no serious competition and that they should be selected for this drive system However, this survey turned up several ideas that have merit and one or more of them could, with development, replace slip rings The most promising contender, at present, is the power clutch.

When continuous rotation is not required, a direct cable is possible. Of course the cable must be flexible enough to allow the required rotation and this, in the wire sizes necessary for large power transfer, requires more development and testing. Following are several of the "other" candidates for power transfer across a rotary joint.

4. 2. 3. 2. 1 Flexible Cables

As mentioned before, every spacecraft that information was received on used flex cables for power transfer across limited rotation gimbals. Both the OGO and OSO spacecraft use flex cables (EE-11 and EE-1). Paragraphs 4. 2. 1. 1 and 4 2. 1 3 summarize the flight history of these two observatories, and together they have logged more than 25 satellite-years of successful flex cable operation Lockheed (EE-10) has used flex cables on one of the Agena Satellite programs. OGO (EE-11) has the largest travel capability of the flex cable which is ± 220 degrees (or 440 degrees total). OSO (EE-1) has the smallest which is ± 15 degrees (or 30 degrees total).

F. J Clauss (Ref. Bib. LL. 2-4) considers flex cables for transmitting power into a large aerospace environmental chamber. Current level in this application is 2,000 amps.

This is the same application as discussed in Paragraph 4. 2. 3. 1 for supplying simulated secondary radiation to a test satellite in the chamber

Flex cables are required for the operation of the power clutch type devices, which are discussed in Paragraph 4 2 3 2 2

With the very satisfactory performance history of space operation, there should be no hesitation in considering flex cables for the space station power transfer task

The examples of industrial usage of flex cables are quite numerous, elevators and traveling cranes are two common applications The technology of designing the conducting element with respect to fatigue can no doubt be applied directly from industrial experience The technology of flexing insulation in a vacuum developed for the small applications (such as OGO and OSO) can be applied to the large cables required by the ODAPT program

The torque required to flex the cables is an important consideration, and in particular the change in the torque due to age. Further, if the gimbal design allows the flex cable to receive direct solar radiation, the insulation's resistance to UV damage must be determined. The adaptation of flex cables to the space station power transfer job should be very straightforward although additional testing will be required.

4 2 3.2.2 Power Clutch

A very interesting approach to the problem of power transfer has been disclosed by H T Haynie of the Boeing Company (EE-14), which he calls a power clutch

The Special Products and Applied Research (SPAR) division of the deHavilland Aircraft of Canada, Ltd. has what they call a "snap back system" (EE-15) They are applying for a patent on the device and not much is known about it From the information available the device can be classified under a generic term of "power clutch"

BBRC has a conceptual design that is a variation of the power clutch (EE-13) This concept would allow continuous rotation of a drive system at any reasonable speed without interruption of the power circuit The design contains three clutch assemblies, electrically in parallel, that travel, one at a time, around a large conducting ring The maximum wrap-up on the associated flex cable is about 120 degrees The device will run either direction or remain stopped without varying the power across it

Power Clutch Design*

The design described here represents a different approach to power transfer It is made up of three pairs of rotors and stators, each pair is complete circuit. Cable pairs are used to reduce the conductor size Adjacent rotors and stators are insulated by a Teflon washer Fig 4-5 shows a typical wiring circuit that can be quickly reset during an all-sunlight orbit Fig 4-6 is a low-current housekeeping clutch with several circuits Adjacent conductors are insulated by a Teflon washer.

A central tube of nylon, the structural backbone of the system, serves as the rotor pivot, it also houses the recycle actuator and guides the clamping piston. An extension handle protruding from the center enables manual actuation.

The stator assemblies are made up of circular plates with a metal-matrix solid-lubricant composite attached with silver-foil diffusion bonding The stators are held concentric by the nylon backbone tube and are prevented from rotating by the cabling connection. The composite lubricant is Boeing Compact 046-46, which prevents vacuum welding to the rotor

* This part of this paragraph, including figures, has been essentially excerpted from H Theron Haynie's paper "Rotary Relay for Space Power Transfer " (Ref Bib - BB 3-3)

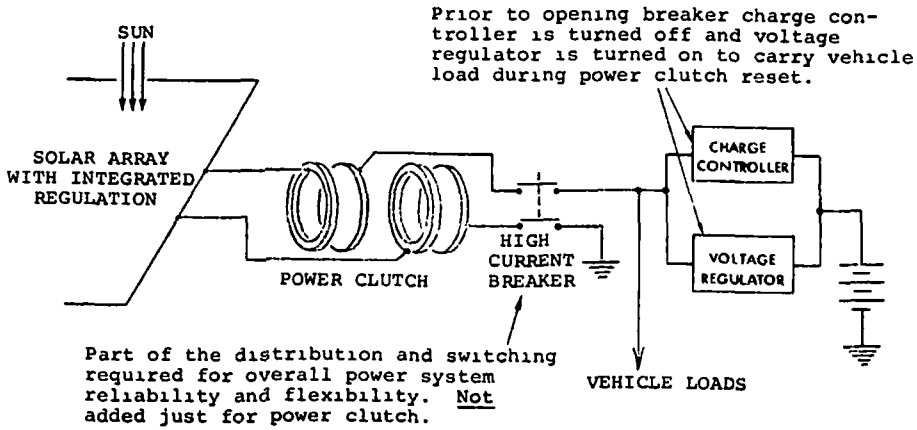

Fig 4-5 Power Clutch Reset During an All-Sunlit Orbit

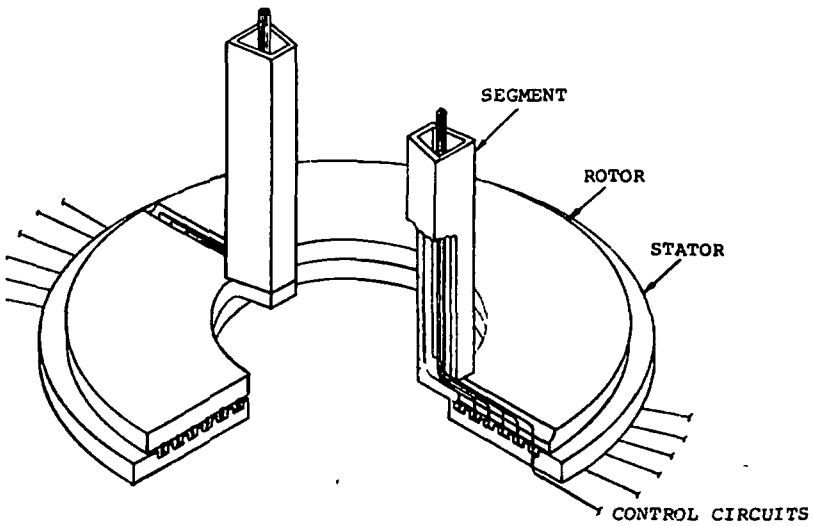

Fig 4-6 Low-Current Housekeeping Clutch

The rotor assemblies are circular plates assembled to the conducting segment. The segments pivot around the nylon tube and are separated from each other by Teflon insulating bars. Flexible, straightlay multi-strand No. 30 wire (0.010 in. diameter) constitutes the cables bolted to the segments. The umbilical is made of two cables for each rotor assembly

The operating piston and springs supply the clamping action to maintain the rotors and stators in contact for good electrical conducting properties Recycle driving torque is supplied by a clock spring. A stepper motor or a gear train can also be used.

Earth satellites and space stations that are required to be earth or stellar-oriented during orbit will ordinarily be designed to have symmetrical solar panels mounted at the end of the boom. In service, the boom rotates one revolution per orbit to keep the panel pointed toward the sun. The cabling is routed inside and along the axis of the boom. The electrical connections to the spacecraft power bus have sealed pass-through connections in the pressure barrier. A manual override release can be mounted in the pressurized compartment.

* * * * * * End of Excerpt of Mr Haynie's paper * * * * *

A small working model using this concept has been fabricated and demonstrated The model uses on-axis concentric circuits that would not be acceptable on the space station inner gimbal because of the five foot passageway running through the power boom The concept can be modified to overcome this objection, and the technology to develop the rest of the device is available Development of this device has been suspended due to lack of funds.

Since the power clutch uses flex cables, the entire flex cable discussion applies In addition, the power clutch clamp and release mechanism must be developed. However, this mechanism should be a straightforward design job and could be approached with a high degree of confidence

The lubrication of the mating surfaces is an application that will require analysis and testing, since the surfaces will be clamped tightly, then released and clamped again in a new position

4 2 3 2 3 Rolling Contacts

Pure rolling contacts have some appeal in a vacuum application because there is little or no sliding action which results in wear A general drawback to this type of device is the relatively small contact area obtained unless one of the members is deformed to mate with the other, but this leads to fatigue problems W P. Fleming of MIT has developed a working model of a rolling contact power transfer device (EE-17).

Actually two working models have been made for laboratory test and demonstration One model has been used on current transfer tests while the other has been used for driving torque tests Neither has been tested in a vacuum as yet.

The concept is quite interesting and could easily have applications in the future although it would appear that it is not nearly far enough along in its development to be seriously considered for ODAPT

There are some areas where more work is needed but the concept is intriguing and some space will be devoted to a description of the idea as written by Fleming in his paper (Ref. Bib MM 2-2).

The way this device achieves continuous non-sliding contact may be illustrated by the action of a ring rolling inside a slightly larger ring (Fig 4-7). If both rings are rigid, then rolling point contact exists. If, however, the rings have some depth and one or both rings possess a small amount of flexibility, then a contact area exists It is apparent that if the rings are nearly the same size, then very large contact areas will be formed with very little deformation of either ring.

INNER RING ROTATES, OUTER RING STATIONARY

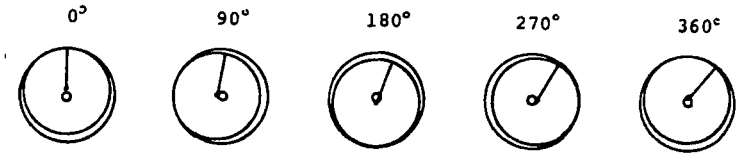

Fig 4-7 Movement Pin Rotation

If the inner ring is constrained so that it cannot rotate about its own center, the outer ring is caused to rotate about its center. The final result, then, is an orbital motion of the inner ring and a rotary motion of the outer ring Because the "orbit" is quite small, it is practical to attach leads to it, and allow them to flex slightly as the device operates They will not twist or wind up, because the inner ring does not revolve, it only orbits It is equally apparent that leads connected to the outer ring will revolve continuously In this way, continuous physical contact is maintained between a ring which rotates and a ring which does not rotate

Referring to the orbiting movement of the inner ring and the rotary movement of the outer ring implies, of course, that a friction driving force exists between them. If the contact surfaces of the two rings (neglecting any ring flexibility) were not smooth but had teeth, then a positive gear drive would result. Figure 4-8 shows the similarity between the contact ring motion and the gear engagement. This internal/external gear pair is the classic wobble gear, a well-known and effective differential type of speed reducer

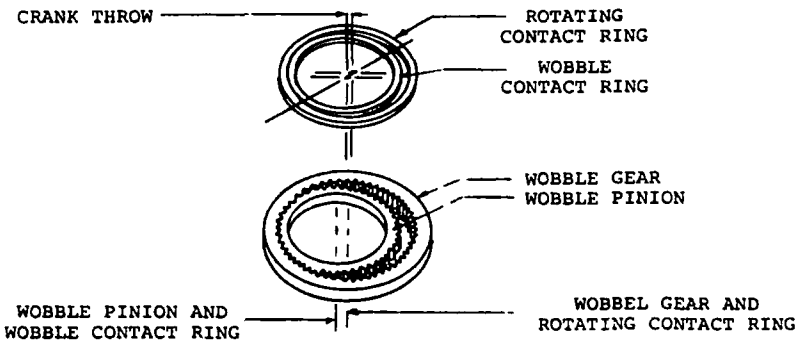

Fig 4-8 Contact Ring/Drive Gear Pair
(Separated for easy viewing)

By attaching the wobble pinion and wobble contact ring of Fig 4-8 to a common cylindrical support up through the center of each, and likewise attaching the wobble gear and rotating contact ring to a common cylindrical member around the outside of each, then both will operate together exactly as previously described In this way, the gear mesh will carry the torque load required for the inner cylinder to drive the outer cylinder, and the contact rings will contact just as before By stacking up several contact ring pairs on these cylinders, with each pair insulated from its adjoining pairs, then a contact assembly of several circuits can be assembled

The application of a gear set fixes the speed ratio between the rings Because of this, careful ring sizing is required to achieve zero contact slippage, while by the same token, deliberate forward or reverse

slippage may be built in by sizing the contact diameters or gears accordingly

Another approach to the pure rolling contact was developed and tested by Edward J Devine of Goddard Space Flight Center (EE-16). The device is basically a special ball bearing with gold-plated balls and MoS_2 lubrication A demonstration model has been extensively tested in a vacuum chamber with satisfactory results.

Electrical energy transfer through rolling contact (either gears or bearings) is a highly attractive idea and probably deserves more development work. However, it does not appear that this technology is far enough along to be available for a 1977 launch.

4 2 3.2 4 Liquid Metal Slip Rings

The liquid metal slip ring is included here mainly in the interest of completeness. This is a very attractive concept and SKF (EE-8), among others, has done work on the device However, the present state of the liquid metal slip ring art is not sufficiently advanced to be seriously entertained for a mid-70 space station launch

4 2 3 2 5 Rotary Transformers

A natural inclination is to turn to rotary transformers when transferring power across rotary joints for very long periods of time. The reason for this is the absence of any mechanical contact For example, Dr Clauss of Lockheed considered rotary transformers for the power transfer to the secondary radiation simulators to the large aerospace environmental chamber (Ref. Bib LL 2-4) and Hughes Aircraft Company considered the rotary transformers for the power transfer job for the OLSCA study (Ref Bib HH 1-6) In both cases, as in all other similar studies, the rotary transformer loses in the final trade-offs because of high weight or low efficiency

Two comprehensive analyses and design studies have been conducted by E E Landsman at MIT (EE-22) (Ref Bib MM 2-3) and F J Clauss at Lockheed (EE-19) (Ref Bib LL 2-4) to define equations and parameters necessary for rotary transformer design

With air gaps that can be maintained on usual sized rotating equipment, rotary transformer efficiencies up to 96-97 percent are possible, given enough core material, which means enough weight However, in cases where the electrical energy on both sides of the rotary joint is DC, the conversion losses must also be charged to the power transfer system The inverter efficiency is probably 85 to 90 percent while the rectification and filtering is around 95 percent If the ODAPT space station uses AC and the conversion would have to be done anyway, the conversion losses would not be charged to the power transfer equipment

Nine rotary transformer manufacturers were contracted with requirements similar to those given the slip ring manufacturers (Para 4 2 3.1)

The only response was from the S Himmelstein and Company, Elk Grove Village, Illinois, one of the leading rotary transformer manufacturers Their response was that there is no fundamental reason why the ODAPT power transfer requirements cannot be met by a rotary transformer

Following is a short discussion on the operating principle of a rotary transformer *

Figure 4-9 illustrates an elementary rotary transformer One winding (the rotor) is mounted on a rotating shaft while the other winding (the stator) is fixed to an outer housing An air gap is provided between the rotor and stator sections to allow rotation without physical contact. The magnetic circuit is designed so that there is no intentional change of flux linkages

* Extracted from literature supplied by S. Himmelstein and Company

when relative motion between the rotor and stator occurs This is exactly opposite rom motors and resolvers where a change of the flux linkages with rotation is desired

With this arrangement, electrical signals and power can be coupled between the rotating and stationary member without any contact - brushes, fluid couplings, etc The energy transfer is independent of shaft speed or direction - from shaft stopped through maximum rated speed

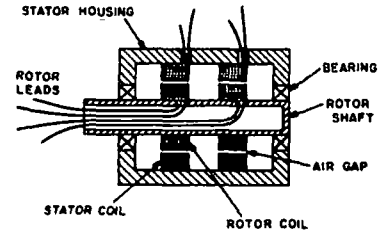

Fig 4-9 Rotary Transformer

A rotary transformer has the following inherent advantages

1 No wear or wear products
2 No arcing
3 No friction or heating effects
4 No viscous drag from liquid contact
5. Energy transfer is unaffected by the presence of oil, water, vacuum and other environment-borne contaminants

The rotary transformer can be designed with extremely high electrical performance even when compared to fixed transformers

Almost all of the technology available for transformer design for atmospheric application is usable for the space station application Material selection is necessary because the winding encapsulent and the insulating material may be exposed to ultraviolet radiation Also, the outgassing properties of these materials must be considered The materials problem has been

solved for windings in general and the flight-proven technology can be applied to the rotary transformer design with confidence Some attention is required to removing the heat generated by transformer losses in the absence of convection cooling This, too, has been solved on other equipment and is not considered a serious problem

Rotary transformer design has been reduced to practice and is quite straightforward However, the problems involved with getting several parallel circuits (some power and some low level signal) across a rotary joint are not all obvious Getting one large power circuit across the joint seems to be no prlblem but the complication of many circuits might prove to be difficult or impossible The basic idea of a rotary transformer is very attractive however and a study to investigate its possibilities has been suggested This study should be run in parallel with the rest of the program so that the information could be compared to other transfer device tests now in progress

ELECTRICAL POWER TRANSFER DEVICES
(other than slip rings)

EE

NO	ORIGIN	TRANSFER MECHANISM	DEVELOPMENT STATUS	WORKING CURRENT	SCALE-UP POTENTIAL	TRANSMISSION CHARACTERISTICS	REMARKS	BIBLIO NO
	FLEX CABLES							
1	Ball Brothers Research Corporation	Flex Cable Power and Signal	Flight history--OSO Satellite	1 amp max	Feasible	Efficiency can be as close to 100% as weight and torque permit	6 Flights--no failures 30° rotation	BB 1-42 BB 1-41
2	Ball Brothers Research Corporation	Flex Cable Power, Signal and Coax	Qualified		Feasible	Efficiency can be as close to 100% as weight and torque permit	Bi-Ax for pointing antenna on Nimbus spacecraft 216° rotation, each axis Personal communications	
3	Ball Brothers Research Corporation	Flex Cable, Power and Signal + Rotary RF Joint	Qual Model Fabricated, Project Cancelled	1/2 amp	Feasible	Efficiency can be as close to 100% as weight and torque permit	200° rotation	BB 1-40
4	General Electric Company	Flex Cable	Advent Program - Cancelled before any flights		Feasible	Efficiency can be as close to 100% as weight and torque permit	+ 180° rotation Personal communications	
5	Hughes Aircraft Co	Flex Cable	Qualified, 1970 launch scheduled		Feasible	Efficiency can be as close to 100% as weight and torque permit	Bi-Ax Antenna Positioner for Intelsat IV Personal communications	
6	Hughes Aircraft Co	Flex Cable	Qualified		Feasible	Efficiency can be as close to 100% as weight and torque permit	Bi-Ax Load Positioner on Advanced Satellite Personal communications	
7	Hughes Aircraft Co	Flex Cable	Flight history - Surveyor spacecraft		Feasible	Efficiency can be as close to 100% as weight and torque permit	Solar Array Positioner - Performed as required on all flights Personal communications	
8	Hughes Aircraft Co	Flex Cable	Life Tested		Feasible	Efficiency can be as close to 100% as weight and torque permit	Antenna Positioner Development Personal communications	
9	Hughes Aircraft Co	Flex Cable	Qualified - Life Test in progress		Feasible	Efficiency can be as close to 100% as weight and torque permit	Single Axis Load Positioner Advanced Satellite Personal communications	

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ELECTRICAL POWER TRANSFER DEVICES
(other than slip rings)

EE

NO	ORIGIN	TRANSFER MECHANISM	DEVELOPMENT STATUS	WORKING CURRENT	SCALE-UP POTENTIAL	TRANSMISSION CHARACTERISTICS	REMARKS	BIBLIO NO
	FLEX CABLES CON'D							
10	Lockheed Missile and Space Co	Flex Cable	10 Flights - 30 days to one year Total Cycles - 1,000 to 12,000	7 0 amps on single conductor PR (4 PR signal conductors in same cable)	Feasible	Efficiency can be as close to 100% as weight and torque permit	Classified Program 3 Drive System per Vehicle ±175° rotation wind-up cable - no power system failures	
11	TRW, Inc	Flex Cable	Flight History OGO Satellite		Feasible	Efficiency can be as close to 100% as weight and torque permit	440° rotation 6 Flights, no flex cable failures Solar array and Experiment shafts Personal communications	
12	TRW, Inc	Flex Cable	Qualified		Feasible	Efficiency can be as close to 100% as weight and torque permit	Military communication satellite Personal communications	

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ELECTRICAL POWER TRANSFER DEVICES
(other than slip rings)

EE

NO	ORIGIN	TRANSFER MECHANISM	DEVELOPMENT STATUS	WORKING CURRENT	SCALE-UP POTENTIAL	TRANSMISSION CHARACTERISTICS	REMARKS	BIBLIO NO
	POWER CLUTCH							
13	Ball Brothers Research Corporation	Power Clutch	Conceptual Design	N/A	Feasible	Can be close to 100% Requires flex cables	An adaption of H T Haynie's idea but modified for off-axis operation	
14	The Boeing Co	Power Clutch	Working Model	500 amps	Feasible	Can be close to 100% Requires flex cables	Uses heat rotor and spring reset No work in progress	BB 3-3
15	SPAR Aerospace Products Limited	Snap back system	Demonstration Model			Can be close to 100% Requires flex cables	Automatically reset mechanically with no additional power	
	ROLLING CONTACT							
16	Goddard Space Flight Center	Current-carrying ball bearing	Working model developed by E J Devine	1 amp briefly 10 ma continuous	Doubtful	Should be around 93% on the working model	Extensive vacuum tests made with various materials	GG 4-2
17	Massachusetts Institute of Technology	Non-sliding rotary electrical connector	Working model developed by W F Fleming	2 amp	Doubtful	Should be around 98% on the working model	Has not been tested in actual jet	MM 2-2
	LIQUID METAL SLIP RING							
18	SKF	Liquid Metal Slip Ring						

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ELECTRICAL POWER TRANSFER DEVICES
(other than slip rings)

EE

NO	ORIGIN	TRANSFER MECHANISM	DEVELOPMENT STATUS	WORKING CURRENT	SCALE-UP POTENTIAL	TRANSMISSION CHARACTERISTICS	REMARKS	BIBLIO NO
	ROTARY TRANSFORMERS							
19	Lockheed Missile and Space Company	Rotary Transformer	Design Study	N/A	Feasible	Can be designed for 95 to 97% efficiency if weight is not critical	Design Parameters	LL 2-4
20	Lockheed Electronics	Rotary Transformer	Development Model		Feasible	Can be designed for 95 to 97% efficiency if weight is not critical	NASA Program	
21	Hughes Aircraft Co	Rotary Transformer	Qualified - launch in 1970 scheduled	Signal level	Feasible	Can be designed for 95 to 97% efficiency if weight is not critical	Part of the Intelsat IV Despin Bearing and Power Transfer Assembly Personal Communications	
22	Massachusetts Institute of Technology	Rotary Transformer	Design study by E E Landsman	N/A	Feasible	Can be designed for 95 to 97% efficiency if weight is not critical	Design procedures derived	MM 2-3

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4 2 4 Lubrication

Existing technology of lubricants for space applications will be reviewed under two categories as follows 1) lubricants for bearings, gears, and other mechanical devices, and 2) lubricants (both solid and liquid) for electrical brushes and contacts Matrix charts for these two categories are headed "Lubricants" and "Brush Materials", respectively, and the former are further classified as "Oils", "Greases", and "Solids"

Successful spacecraft lubrication, both mechanical and electrical, has been accomplished in the face of severe environmental conditions. The absence of oxygen and water vapor has required that lubricants be specifically incorporated into brush compositions to avoid rapid brush wear, and the hard vacuum of space has limited the selection of bearing and gear lubricants to low volatility oils and greases and to solid lubricative films and self-lubricating solids

The requirements of ODAPT will impose some additional limitations on lubricant selection. The long anticipated life and minimum maintenance requirement may possibly mean that at least the mechanical lubricants will be selected from among those which can be replenished periodically through feed lines or supplied continuously from adjacent reservoirs

The following paragraphs are concerned with the lubricants and brush materials which appear to have application to ODAPT After a discussion of most of the materials known to be used in similar applications the ones which are the most promising are listed Testing is now underway which will aid in making a final selection

4 2.4.1 Bearings and Gear Lubricants

Space lubrication technology has advanced during the past decade with regard to more effective lubricating fluids and solids, improved understanding of sliding and rolling phenomena, and increased experience (successes and failures) with space and vacuum chamber lubrication

Fluorine-containing fluid compounds have been developed, such as the flurosilicones and perfluoro ethers, which possess chemical stability at higher temperatures and improved load-carrying properties, the concepts of elastrohydrodynamic lubrication have provided much better understanding of rolling contact bearing lubrication, and successful satellite systems operational for periods of up to three to four years have greatly increased confidence in the correlation between vacuum test performance and actual space vacuum experience.

An indication of the advances in space lubrication technology is reflected by the entries in the "Lubricants" matrix charts, both those related to successfully flown spacecraft and those related to carefully controlled hard vacuum evaluation tests. Significant lubricant space experience and vacuum chamber evaluations shown in the matrix charts are discussed below.

- <u>Oils</u>

  General Electric Versilube F-50 lubricating oil (methylchlorophenyl silicone) has probably been more widely used in spacecraft bearings than any other single lubricant (FF-24) It has flown on such programs as Ranger, Mariner, Nimbus, and Mercury, setting a good success record in each case. The choice of F-50 has undoubtedly been due to its all-around good lubricant characteristics, such as low pour point ($< -100^{\circ}F$), wide useful temperature range (-100 to $+400^{\circ}F$), relatively low volatility, and inherently effective boundary lubrication properties.

  One of the longest periods in the space environment (and still operational) has been accumulated by Vac Kote lubricated bearings on OSO III (three and two-thirds years as of November 1970).

Oils (cont'd)

The Vac Kote oil (FF-25) used in this and other OSO satellites has a very low vapor pressure (6×10^{-9} torr at 25°C) and is fortified to provide the boundary lubrication properties required in slow speed ball bearings. Both Vac Kote and F-50 have been subjected to extensive vacuum chamber testing

Winsorlube L245X (FF-26) is not an especially low volatility oil; but in spite of loss by evaporation, an effective reservoir of oil-impregnated porous nylon in close proximity to bearings in Nimbus and Tiros served to maintain an adequate supply of oil This technique has been widely used in other spacecraft, supplemented frequently with porous ball retainers and labyrinth seals.

The Apiezon oils "J" and "K" (FF-27 and -31) have been proven to be very effective ball bearing lubricants in space vacuum applications and vacuum chamber tests These are molecularly distilled petroleum base oils having very low vapor pressures (10^{-9} to 10^{-10} torr for oil "K") but which, unfortunately, have high viscosities and high pour points. The chart entry for oil "J" shows it to have a viscosity of 50,000 SUS at 70°F compared, for example, with 1,250 SUS at 70°F for Vac Kote used in OSO. The viscosity of oil "K" is even higher, nevertheless, as shown in the oil chart, this oil was successfully used in OGO ball bearings where its viscosity was not detrimental. Both oils "J" and "K" gave excellent long-life test bearing lubrication in the LMSC vacuum chamber test program Another oil which exhibited excellent bearing lubrication in this test program is Mobil XRM 141 C (FF-30). Its base oil is similar in nature to the Apiezon oils, but it contains additives to enhance oxidation stability and load-carrying properties. After 4.5 years in the vacuum bearing test, oil was still present, which is an indication of low volatility

The Dow Corning fluorosilicone fluids FS-1265 (FF-32 and -33) represent a significant improvement in silicone lubrication characteristics Both low volatility and good load-carrying properties are reflected in the bearing test results obtained in the LMSC vacuum bearing test program, epsecially for the 250 cs fluid, which was still present in well-lubricated ball bearings after 5 5 years. Another Dow Corning fluid, DC-7024, a high-phenyl content silicone (FF-34), gave equally good performance for 4.3 years in the LMSC test program.

o Greases

The improvements in liquid space lubricants over the past decade have been paralleled by impressive developments in greases. This is primarily the result of having the improved liquids, since greases are but liquids which have been thickened with metal soaps or finely divided solids, but the variety of advanced thickeners now available to aerospace grease compounders, as reported by Christian (Ref Bib UU 2-1), has vastly increased the versatility of greases which can be made from the new synthetic fluids.

Fortunately, at the beginning of the space age, General Electric Versilube G-300 (F-50 plus lithium soap thickener) was an available, effective, low-volatility grease and has been utilized successfully on a number of spacecraft systems, such as Mariner, Ranger, Gemini, and Nimbus (FF-35). As noted on the drive system chart (AA-8), Nimbus I suffered an early bearing lubrication failure using Versilube G-300, but careful failure analysis and verification tests showed (Ref Bib GG 1-4) that the problem was ultimately caused by improperly designed heat removal and dissipation features This experience points up an important consideration in designing space lubrication systems, i e , that heat removal provisions must be included as

a necessary part of every drive system (bearings and gears) where detailed heat balance and prototype vacuum testing reveal that lubricant temperatures will reach unacceptably high levels Although G-300 has claimed operating range of -100 to +400°F, the LMSC vacuum bearing test program showed that effective lubricant life is significantly reduced when the bearing operating temperature range is increased from 130-230°F to 290-300°F (see entry (h) of FF-35 on the Lubricant chart)

Other greases successfully used in spacecraft bearings and gears have been Aeroshell 7, an extreme pressure diester grease (FF-36), Aeroshell 15, a silicone base grease (FF-37), and Dow Corning FS-1290, a lithium-soap-thickened flurosilicone (FF-39) This last grease is one which incorporates the effective FS-1265 fluid discussed previously, however, experience in the LMSC vacuum chamber bearing test program has shown that thickeners other than lithium soap may produce greases with improved bearing lubrication properties. For example, the FS-1290 grease showed signs of degradation after only 1.6 years, although the bearings were still operating satisfactorily, by comparison, the fluorosilicone fluid thickened with arylurea (FF-42) and with ammeline (a triazine compound) (FF-43) produced greases which ran for 4.4 years in bearings exposed to 10^{-6} to 10^{-9} torr. The tests were terminated while the bearings were still in excellent condition with grease present.

Other fluorine-containing fluid compounds have been formulated into grease compositions and subjected to vacuum bearing tests A perfluoro ether thickened with fluorinated ethylene-propylene copolymer (FF-47) ran for 39 days before failure in a ball bearing turning at 1750 rpm and exposed to 10^{-7} to 10^{-8} torr. The same fluid thickened with ammeline (FF-48) was run in bearings under similar test conditions for periods ranging from 45 to 302 days before failure, and four bearings with this grease were still

running after periods of 160 to 190 days These or similar grease compositions have also been vacuum tested in ball bearings at the Air Force Materials Laboratory The ammeline-thickened greases (Grease "A" and Grease "B," FF-49 and -50) appeared to provide longer bearing performance than those thickened with fluorinated ethylene-propylene (Grease "C" and Grease "D," FF-51 and -52) but insufficient data were obtained to distinguish clearly between the relative performance levels of perfluoro polymeric fluids #1 and #2 used in these greases. On the other hand, the data does indicate a very marked effect of test temperature on bearing life with Grease "A" At ultrahigh vacuum levels (10^{-9} to 10^{-11} torr), bearings with Grease "A" ran for 583 hours at 400°F and longer than 7500 hours at 300°F Estimated bearing life at 200°F was $\gg$ 50,000 hours.

- Solids

Fortunately, MoS_2, unlike graphite, exhibits lower frictional properties in vacuum than it does in normal air atmospheres This makes it a very desirable ingredient in most solid film lubricant formulations Nevertheless, lubrication of bearings and gears in hard vacuum with solid film lubricants is generally limited to slow speed applications if long life is a requirement. Otherwise, solid films have been successfully used on single-operation or intermittently-operated spacecraft mechanisms such as deployment devices (Pegasus, Mariner, and Nimbus), hinges and latches (Surveyor, Nimbus, and Mercury), and shutter and thermal-louver pivots and shafts (OAO and OGO) In some applications, dry lubricants are absolutely necessary in order to avoid impairment of optical instruments.

With regard to dry film lubricated bearings and gears, dry Vac Kote lubricant (mechanically applied MoS_2) (FF-1) was used

successfully on OSO I and OAO ball bearings and supplemented with ball retainers made of filled Teflon-Rulon A plus 5 percent MoS_2 (FF-3) and Bartemp (FF-10) The self-lubricating retainers function as solid dry lubricant sacrificial reservoirs whereby gradual wear of the ball pockets provides a continual replenishment of solid lubricant (Teflon and MoS_2) Other solid films without binder (i e , no organic or inorganic binder ingredient, per se) include CLD 5940 (FF-5), a multi-component vacuum-processed film used on some Gemini ball bearings, and burnished-on MoS_2 (FF-6), used to supplement gold-plate on bearings for the OGO orientation drive mechanism and as sole lubricant for some Pegasus and Nimbus bearings and gears

Several bonded solid film lubricants utilizing the good vacuum lubricating properties of MoS_2 have been applied to spacecraft bearings and gears Electrofilm 4396 (FF-2) employs an organic (phenolic) binder as also, perhapes, does Drilube (FF-11), depending on the particular Drilube composition (unidentified in bibliography reference, GG 2-2). These were gear lubricants for Ranger and Mariner mechanisms Inorganic (inert) binders are contained in Everlube 811 (FF-7), Molykote X-15 (FF-19), and Microseal (FF-23) The first two contain sodium silicate binder and were used to lubricate bearings and gears of Pegasus spacecraft, while another unidentified sodium-silicate-bonded MoS_2 lubricant (FF-12) film was used on Gemini. Microseal was used extensively on Surveyor bearings, gears, and other sliding parts

Teflon thin films (FF-16) and bushings (FF-4) (which quickly transfer thin Teflon films to mating shafts) were found to be suitable spacecraft lubricants for certain ball bearings and shafts of Explorer, Pegasus, Mariner and Surveyor. Aside from Teflon films transferred by rubbing, thin pure Teflon films must be formed by fusing finely dispersed Teflon particles

This requires a high curing temperature (~ 700°F) which is prohibitively high for many substrate materials, viz , aluminum alloys Otherwise, Teflon lubricative films may be applied as finely divided particles in a binder matrix, as are MoS_2 bonded films Which method was used to apply Teflon to Mariner and Surveyor bearings was not disclosed in the bib reference GG 2-2.

Thin gold and silver electro-deposited films (FF-13 and -14) have served lubricating functions on various parts of ball bearings used on Pegasus, Advent, and OGO spacecraft As mentioned above, the OGO ball bearings also had MoS_2 burnished on as supplementary lubricant The chromium-plated OGO gears (FF-15) utilized this hard coating primarily for wear reduction rather than for friction reduction

A particularly promising gear lubrication technique is represented by the Westinghouse-developed composite materials (FF-20 and -21) Unlike the sintered bronze/MoS_2 composite (FF-18) gears used for the OGO wabble drive, Bowen and his co-workers at Westinghouse (Ref Bib. WW 1-5) performed extensive vacuum testing to develop composites for use as lubricative idler gears which function in a manner similar to the filled-Teflon bearing retainers discussed above. In fact, the Westinghouse metal/Teflon/WSe_2 composites have proven to be just as effective retainer materials for dry lubricated bearings as they have idler gears for dry lubricated gears. The lubrication mechanism for a pair of loaded drive gears involves the transfer of solid lubricants (i.e , Teflon and WSe_2) to the teeth of one of the drive gears from an idler gear made of the composite The idler gear teeth are pressed into those of one of the drive gears by means of load springs. Suitable metals in the composites are silver and copper, but when the metal was omitted in one test series (FF-22) catastrophic gear wear and failure occurred.

The development program was aimed specifically at providing a dry lubrication system for heavily loaded gears and bearings used in handling equipment of a large AEDC space-vacuum environment test chamber, but the resulting lubricative composites would have obvious application to long-lived space missions

In considering likely candidates, the following conditions must be kept in mind.

- Static bearing and gear pressures One major ODAPT requirement is that the bearing and gear lubricants provide adequate metal separation (e g., at ball/race contact spots) during an extended period of static load condition when the orientation drive mechanism is in a locked position This condition will tend to squeeze out oils and greases and may require the additional application of thin lubricative solid or soft metal films, such as MoS_2 and gold plate In any case, loaded bearing or gear storage tests in vacuum will be needed on candidate oils and greases to determine their ability to withstand long-term static loading

- Ground Test Conditions
  Oxidation, high humidity, salt spray, and particulate contamination are conditions to which ODAPT will likely be subjected before launch. Candidate bearing and gear lubricants must be prepared to survive these conditions without impairing their space mission qualities or quantities. Effective seals on bearings and gears would, of course, reduce the importance of the prelaunch environment, but the ability of candidate materials to withstand such conditions must be determined by suitable tests.

- Ten-year life requirement Evaporation of oils and greases is the primary consideration for selecting candidate lubricants for the unusually long ODAPT life. Greases would become stiffer with evaporative loss of their oil components, and oils would tend to become more viscous as their more volatile constituents distilled off. Seals and reservoir systems would largely offset the volatility problem, or solid lubricants, if otherwise satisfactory, would avoid the problem. Thus, the ten-year life requirement in itself would not necessarily rule out any of the space-proven/vacuum-proven lubricants which may not have accumulated that much time in space or vacuum chamber tests. Nevertheless, evaporation rate determinations on candidate oils and greases would be required.

- Wear Life. Although ODAPT is required to operate ten years in orbit, the corresponding bearing and gear wear life requirement per se is relatively mild. This is due to the very slow rotary and oscillatory speeds which the bearings and gears will experience It is believed that the primary bearing and gear lubricant problem, as discussed above, will be that of maintaining an effective lubricant film in static load conditions rather than in preventing gear and bearing wear during rotation. However, the low wear life requirement will bring solid film lubricants and solid self-lubricating materials into consideration as candidate lubricants for the orientation drive bearings and gears, and for such materials, an adequate wear life will have to be assured by means of accelerated but realistic vacuum chamber tests

With the above ODAPT operational considerations in mind, the existing lubrication technology which appears to be applicable is quite extensive, and as indicated above, the absence of knowledge is associated more with screening candidate lubricants for operation under the specific ODAPT conditions rather than requiring the development of new materials or new

lubrication technology The oils, greases, and solids which appear to be potential candidates are discussed briefly below

- Vac Kote oils A low volatility petroleum base oil has been proven in space applications, and low volatility synthetic ester and ether base oils have been vacuum chamber tested

- Versilube F-50 oil and G-300 grease These lubricants have been used extensively in space mechanisms and evaluated in vacuum chamber tests

- Fluorosilicone oils and greases. These lubricants, especially the 250 cs oil and the arylurea and ammeline greases, gave excellent results in the LMSC vacuum chamber tests

- XRM 141 C paraffin-base oil This Mobil Oil Company product appears to warrant further evaluation because of its excellent bearing lubrication results in the LMSC tests

- DC-7024 high-phenyl silicone oil Again, excellent bearing lubrication in the LMSC tests makes this oil a potential candidate, in spite of its being a silicone

- Perfluoroether and perfluoropolymeric fluid greases. These lubricants are the ones shown on "Lubricant" charts FF-48 through -52 Those thickened with ammeline appear to be likely candidates

- Vac Kote dry lubrication These processes have been proven with space applications, and continuing vacuum chamber tests on bearings and gears have extended the confidence in their performance

- Bonded solid film lubricants. Products such as Electrofilm 4396, Everlube 811, and Molykote X-15 have had space applications which proved their durability for use on gears or bearings or both. These and other film products listed in bibliography ref. MM 3-2 should also be considered, especially for gear lubrication.

- Electroplated gold and silver. The successful use of thin soft metal films for certain space mechanisms has been demonstrated, and, as mentioned above, may be useful in combination with oils and greases in preventing cold welding of bearing and gear surfaces in the ODAPT static operation mode

- Teflon/MoS_2 composites. Teflon filled with inert materials (for added strength) and MoS_2 (for added lubricity) has been successfully used as ball bearing retainer material in space and in vacuum chamber tests.

- Metal/Teflon/WSe_2 composites. These Westinghouse-developed self-lubricating composites show promise as both bearing retainer materials and as lubricant-supplier idler gears for loaded drive-gear pairs.

LUBRICANTS FF

NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
	SOLIDS			
1	Vac Kote dry MoS_2 applied mechanically (proprietary process) Ball Brothers Research Corp	a) OAO	a) Lubricant for ball bearings, thrust bearings, and sliders	GG 2-2 BB 1-39
		b) OSO I	b) Lubricant for solar array despin mechanism and elevation axis bearings	BB 1-18
		c) Vac Kote vacuum evaluation test	c) Bearings for vacuum drive device Ran for 2210 hours at 10^{-6} torr and 6-120 rpm No bearing degradation (Rulon A with 5% MoS_2 retainers)	BB 1-16
		d) Vac Kote life test in vacuum at higher speeds	d) Bearings for motor test Ran 200 hours at 102 rpm and 100 hours at 360 rpm, both at 10^{-7} torr Retainers Rulon A (5% MoS_2) Bearings in good condition	BB 1-16
		e) Vac Kote vacuum evaluation test	e) Slip ring support bearings having Rulon A (5% MoS_2) retainers Ran 190 hours at 6 rpm and 1820 hours at 10 rpm, both at 10^{-7} torr Bearing performance was satisfactory	BB 1-12
2	Electrofilm 4396 Phenolic bonded MoS_2 and graphite Electrofilm Corp	a) Ranger 1	a) Gear lube	LL 2-27
		b) Mariner 2	b) Gear lube	LL 2-27
		c) A F Type I & II - LMSC	c) Gear lube	
3	Rulon A Teflon plus inert filler and 5% MoS_2 Dixon Corp	a) OSO I	a) Ball bearing retainers	BB 1-18
4	Teflon Polytetrafluoroethylene Du Pont Corp	a) Explorer 14, 15	a) Bushing material for stepper device	LL 2-27
		b) Explorer 26	b) Bushing material for solar panel deployment shaft	LL 2-27
		c) Pegasus 1 and 2	c) Bushing for wing hinge pins	LL 2-27
5	CLD 5940 MoS_2, Ag, and Cu applied by proprietary vacuum process CBS Laboratories Inc	a) Gemini	a) Ball bearing lubricant	LL 2-27
		b) OAO	b) Shutter pivot bearings	LL 2-27
6	MoS_2 dry film Applied without binder by burnishing	a) OGO 1	a) Applied to gold-plated ball bearings of orientation drive mechanism of solar panel array	LL 2-27
		b) Pegasus	b) Used on needle brgs of gear and pinion shafts	LL 2-27
		c) Nimbus 4	c) Applied to gear head bearings	

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LUBRICANTS FF

NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
	SOLIDS CON'D			
7	Everlube 811 Sodium silicate bonded MoS_2 and graphite Everlube Corp	a) OGO 1	a) Lubricant on aluminum alloy shaft of thermal louvers and on Elgiloy springs	LL 2-27
		b) Pegasus 1 and 2	b) Lubricant for gears and bearings of deployment mechanism	LL 2-27
8	Bonded MoS_2 film MoS_2 applied with unspecified binder	a) Mariner 3 and 4	a) Lubricant for solar panel actuator	LL 2-27
		b) Nimbus 1	b) Lubricant for panel deployment hinge pins	LL 2-27
		c) Mercury	c) Lubricant for heat shield release mechanism	GG 2-2
9	Nylatron Nylon filled with solid lubricant The Polymer Corp	a) Mariner 3 and 4	a) Bushing material for solar panel pivots	LL 2-27
10	Bartemp Filled Teflon Barden Bearing Company	a) Tiros and OAO	a) Ball bearing self-lubricating retainer material	GG 2-2
11	Drilube Bonded MoS_2 and perhaps, other solid lubricants Drilube Company	a) Ranger	a) Lubr for slow speed stepping motor actuator on antenna hinge, antenna drive	GG 2-2
		b) Mariner	b) Gears on instrument mount	GG 2-2
		c) Surveyor	c) Lubr for hard anodized surfaces, hinges, latch mechanisms	GG 2-2
12	Sodium silicate bonded MoS_2 (Mfgr not identified)	a) Gemini	a) Lubr for bearings, rollers gears and sliders	GG 2-2
13	Electroplated Gold (plating conditions not specified)	a) OGO	a) On ball bearings and gears of solar array device	GG 2-2
		b) Pegasus	b) On 52100 steel ball bearing races	GG 2-2
		c) Advent	c) Electroplated hard gold on radial ball bearing (full ball complement) for solar array shaft	
14	Electroplated Silver (plating conditions not specified)	a) OGO	a) On ball bearing retainers	GG 2-2
15	Chromium plate (plating method and conditions not specified)	a) OGO	a) On gears	GG 2-2

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NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
	OILS			
24	Versilube F-50 Methylchlorophenyl Silicone General Electric Company	a) Ranger 1	a) Lubr for antenna drive ball bearings	LL 2-27
		b) Mariner 2	b) Lubr for antenna drive ball bearings	LL 2-27
		c) Mariner 3 & 4	c) Scanner mechanisms	LL 2-27
		d) Ranger 6-9	d) Actuator bearings, bushings, and shaft bearings	LL 2-27
		e) ARENTS	e) Lubr for test ball bearings	GG 2-2
		f) Nimbus	f) Impregnated into sintered bronze bushings	GG 2-2
		g) Mercury	g) Lubr for gyro bearings, sliders, elsewhere	GG 2-2
		h) Vacuum bearing test program (LMSC)	h) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-6} -10^{-9} torr Bearing failures occurred at 0 5 to 2 7 years operation at 160° to 250° F Some bearings were exposed to gamma radiation, evidently without marked effect on life	LL 2-15
25	Vac Kote wet Low volatility oil applied by proprietary process Ball Brothers Research Corp	a) OSO II-VI	a) Lubr for solar array despin mechanism and elevation axis bearings Vac Kote oil on all bearing parts including impregnation in phenolic laminated retainers	BB 1-34
		b) Vac Kote evaluation test in vacuum	b) Bearings for slip ring and torque motor No bearing degradation after 1339 hours at 10^{-8} torr and 120 rpm	BB 1-33
		c) Vac Kote vacuum evaluation test	c) Motor bearings were run 1795 hours at 120 rpm at 10^{-8} torr No bearing degradation was observed	BB 1-29
		d) OSO II bearing test	d) Bearings with phenolic laminated retainers Ran 1840 hours at 60 rpm and 10^{-8} torr No signs of lubrication failure	BB 1-34
		e) OSO II bearing test	e) Bearings with steel retainers Ran 1840 hours at 60 rpm and 10^{-8} torr One bearing with Vac Kote functioned normally, a second bearing without lubricant operated erratically	BB 1-34
		f) OSO II qualification test	f) Bearings with phenolic retainers and steel ribbon retainers running at 60 rpm for 4200 hours at 10^{-7} torr Performance in both cases was entirely satisfactory. The bearings with steel retainers were tested further at 1000 rpm (10^{-6} torr) for 45 hours without signs of degradation	BB 1-34
26	Winsorlube L-245X Diester synthetic oil F E Anderson Oil Company	a) Nimbus 1 and Tiros	a) Lubr for radiometer bearings Porous nylon impregnated with the oil served as lubr reservoir surrounding the shaft	LL 2-27
		b) ARENTS	b) Ball bearing lubricant	GG 2-2

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NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
	SOLIDS CON'D			
16	Teflon thin film (Application method and mfgr not specified)	a) Mariner	a) Coated on bearing balls and bushings	GG 2-2
		b) Surveyor	b) Coated on bearing balls and bushings	GG 2-2
17	Rulon C Teflon with inert filler Dixon Corp	a) OAO	a) Sleeve bearings	GG 2-2
		b) Pegasus	b) Ball bearing retainers	GG 2-2
18	MoS_2 in Sintered Bronze (Mfgr not identified)	a) OGO	a) Wabble drive gear material	LL 2-27
19	Molykote X-15 Sodium silicate bonded MoS_2 and graphite Dow-Corning Corp	a) Pegasus 1 and 2	a) Used on gears and bearings of deployment mechanism	LL 2-27
20	Silver/Teflon/WSe_2 Composite Westinghouse Electric Corp	a) Vacuum test program	a) Composite was used in ball bearings as retainer material Tests conducted at 10^{-6} to 10^{-9} torr and -160 to +300° F Hertz stresses were 150,000 - 200,000 psi No other lubricant was present Lubrication was satisfactory	WW 1-5
		b) Vacuum test program	b) Composite was used as an idler gear bearing against one of a pair of loaded gears and serving to provide dry lubricant Hertz stresses were 90,000 - 120,000 psi Lubrication was satisfactory	WW.1-5
21	Copper/Teflon/WSe_2 Composite Westinghouse Electric Corp	a) Vacuum test program	a) Same test conditions as used with silver/Teflon/WSe_2 composite, (a) and (b) above Bearing and gear lubrication was satisfactory	WW 1-5
22	Teflon/WSe_2 Composite Westinghouse Electric Corp	a) Vacuum test program	a) Composite was used as idler gear to lubricate a pair of loaded test gears as in above (b) gear tests with silver/Teflon/WSe_2 composite Catastrophic wear and failure occurred	WW.1-5
23	Microseal Proprietary dry lubricant thin film Microseal Corp	a) Surveyor	a) Applied to various ball bearings, gears, and other parts	LL 2-27

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LUBRICANTS FF

NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
	OILS CON'D			
27	Apiezon "K" Low volatility hydrocarbon Apiezon Products Ltd	a) OGO b) Vacuum bearing test program (LMSC)	a) Lubr for ball bearings, having oil-impregnated laminated-cloth-phenolic retainers b) Used in motor ball bearings at 8000 rpm and 10^{-7} -10^{-8} torr Bearings still good after 2 3 years	GG 2-2 LL 2-15
28	NPT-4 Synthetic ester oil Bray Oil Co	a) Nimbus 4 and OGO	a) Lubr for main support and gear head bearings and gears Made into grease product with silica (Cabosil) thickener and applied as thin grease plate by thinning with xylene solvent	
29	Terrestic V-78 Paraffinic oil plus additives Humble Oil and Refining Co	a) Vacuum bearing test program (LMSC)	a) Lubr for motor ball bearings subjected to 10^{-6} to 10^{-9} torr and run at 8000 rpm to failure Bearing failures occurred after 1 6 to 2 5 years Two were still running after 2 9 years, including 2 years gamma radiation exposure	LL 2-15
30	XRM 141C Paraffinic oil with additives Mobil Oil Co	a) Vacuum bearing test program (LMSC)	a) Lubr for motor ball bearings running at 8000 rpm and in vacuum of 10^{-7} to 10^{-8} torr Bearings still in excellent condition after 4 5 years Oil still present	LL 2-15
31	Apiezon "J" Low volatility molecularly distilled petroleum oil Associated Electronics Industries, Ltd	a) Vacuum bearing test program (LMSC)	a) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-6} -10^{-9} torr Test discontinued after 4 7 years, bearings still in excellent condition with oil still present Not a probable candidate oil for ODAPT since oil is very viscous (50,000 sus/70° F) and has high pour point (+45° F)	LL 2-15
32	Fluorosilicone FS1265, 250 cs fluid Dow-Corning Co.	a) Vacuum bearing test program (LMSC)	a) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-3} -10^{-8} torr Bearings still in excellent condition with oil present after 5 5 years	LL 2-15
33	Fluorosilicone FS1265, 1000 cs. fluid Dow-Corning Co	a) Vacuum bearing test program (LMSC)	a) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-3} -10^{-8} torr Bearing failed at 2 0 years, another still OK at 2 0 years	LL 2-15
34	DC-7024 (MLO 61-97) High phenyl content silicone oil Dow Corning Corporation	a) Vacuum bearing test program (LMSC)	a) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-6} -10^{-7} torr Bearings still in excellent condition with oil present after 4 3 years	LL 2-15

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LUBRICANTS FF

NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
	GREASES			
35	Versilube G-300 Methylchlorophenyl silicone with lithium soap thickener General Electric Company	a) Gemini b) Mariner 3&4 c) OGO d) ARENTS e) Nimbus f) Ranger g) Mercury h) Vacuum bearing test program (LMSC)	a) Gyro bearing lubricant b) Scanner mechanisms bearings c) Bearings in experimental package d) Lubr for test ball bearings e) Solar array drive ball bearings and gears f) Self-aligning monoball g) Gyro bearings, sliders, elsewhere h) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-5} -10^{-9} torr Failures occurred after 1 1 to 2 7 years at test temperatures of 130-230° F and after 0 5 year at 290-300° F	LL 2-27 LL 2-27 LL 2-27 LL 2-27 LL 2-27 LL 2-27 LL 2-27 LL 2-15
36	Aeroshell 7 Soap thickened diester Shell Oil Co	a) Ranger 6-9	a) Lubr. for antenna drive worm gears	LL 2-27
37	Aeroshell 15 Silicone fluid thickened with synthetic organic dye Shell Oil Co	a) ARENTS b) Vacuum bearing test program (LMSC)	a) Lubr for ball bearings b) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-3}-10^{-8} torr Failures occurred at 2 2-2 3 years without radiation and at 0 6 year with about 0.5 year exposure to gamma radiation	GG 2-2 LL 2-15
38	Apiezon "L" Low volatility hydrocarbon base grease Apiezon Products Limited	a) OSO b) Vacuum bearing test program (AEDC)	a) Lubr for hinge pins b) Lubr for three tapered roller bearings (support bearings for test machine), heavily loaded, turning at 100 rpm in vacuum of 10^{-7} -10^{-9} torr Bearing temperature of 120-180° F caused grease to migrate and contaminate test bearings, which were dry lubricated Test stopped at 36 hours - grease lubricated bearings were satisfactory	GG 2-2 BB 1-18 AA 2-5
39	FS-1290 Fluorosilicone fluid (FS-1265) with lithium soap thickener Dow-Corning Co	a) Apollo b) Vacuum bearing test program (LMSC)	a) Lubr for Service Module main engine gimbal actuator b) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-5} -10^{-8} torr Both bearings still OK but grease showed signs of degradation Test discontinued after 1 6 yrs Program terminated	LL 2-27 LL 2-15
40	Supermil AS. #31052 Silicone oil thickened with arylurea American Oil Co	a) Vacuum bearing test program (LMSC)	a) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-7} -10^{-8} torr Failures occurred at 2 4 and 3 3 years of operation	LL 2-15

FOLDOUT FRAME 2

NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
	GREASES CON'D			
48	MCG-64-40 Perfluoro ether thickened with ammeline Supplied by Air Force Mtl's Lab	a) Vacuum bearing test program (SWRI)	a) Lubr for test ball bearing running at 1750 rpm in a vacuum of 10^{-8} torr for 35 days without failure Another bearing completed 13 days without failure	UU 2-5
		b) Vacuum bearing test program (SWRI)	b) Six test bearings lubricated with this grease ran at 1750 rpm in a vacuum of 10^{-6} -10^{-7} torr The above two bearings failed after 302 and 45 days, respectively, while four others were still running after periods of 160 to 190 days	UU 2-5
49	Test Grease A Perfluoro polymeric fluid #1 thickened with ammeline Air Force Mtl's Lab	a) Vacuum bearing test program (AFML)	a) Size R-4 bearings with Grease A lubricant ran at 10,000 rpm and 400° F for 1457 hours at 10^{-7} torr and 583 hours at 10^{-9} torr This compares with a reference silicone grease (ammeline-thickened high-phenyl silicone) which ran for 395 hours under the same conditions	UU 2-6
		b) Vacuum bearing test program (AFML)	b) Same test conditions as above except at 300° F, bearings with Grease A ran longer than 7500 hours at 200° F, estimated bearing life is 50,000 hours	UU 2-1
50	Test Grease B Perfluoro polymeric fluid #2 thickened with ammeline Air Force Mtl s Lab	a) Vacuum bearing test program (AFML)	a) Fluid #2 is more volatile and less thermally stable than Fluid #1 above In same test conditions as for Grease A, above, bearings ran for 1216 hours at 10^{-7} torr and 694 hours at 10^{-9} torr	UU 2-6
51	Test Grease C Perfluoro polymeric fluid #2 thickened with fluorinated ethylenepropylene Air Force Mtl's Lab.	a) Vacuum bearing test program (AFML)	a) Same test conditions as for Grease A, above Bearings ran for 437 hours at 10^{-7} torr and 245 hours at 10^{-9} torr	UU 2-6
52	Test Grease D Perfluoro polymeric fluid #1 thickened with fluorinated ethylenepropylene Air Force Mtl's Lab	a) Vacuum bearing test program (AFML)	a) Same test conditions as for Grease A, above Bearings ran for 261 hours at 10^{-9} torr	UU 2-6

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NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
	GREASES CON'D			
41	EG-509 Silicone oil with organic thickener and solid lubricant Marlin Rockwell Corporation	a) Vacuum bearing test program (LMSC)	a) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-5} -10^{-8} torr One bearing failed after 3 9 years, but another was still satisfactory	LL 2-15
42	MLG 61-92 Fluorosilicone oil (1000 cs) thickened with arylurea Supplied by Aero Sys Div USAF	a) Vacuum bearing test program (LMSC)	a) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-6} -10^{-9} torr Bearings still in excellent condition and grease still present after 4 4 years	LL 2-15
43	MLG 62-142 Fluorosilicone oil (1000 cs) with ammeline thickener Supplied by Aero Sys Div USAF	a) Vacuum bearing test program (LMSC)	a) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-6} -10^{-9} torr Bearings still in excellent condition and grease still present after 4 4 years	LL 2-15
44	EG-429 Silicone oil with organic thickener and solid lubri Marlin Rockwell Corporation	a) Vacuum bearing test program (LMSC)	a) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-8} torr One bearing failed and one still satisfactory after 1 5 years	LL 2-15
45	DC-40 Silicone fluid with metallic soap thickener Dow Corning Co	a) Vacuum bearing test program (LMSC)	a) Lubr for motor bearings running at 8000 rpm in vacuum of 10^{-5} -10^{-8} torr Bearings still in excellent condition and grease still present after 1 6 years	LL 2-15
46	Apiezon "H" Low volatility hydrocarbon base grease Apiezon Products Limited	a) Vacuum bearing test program (AEDC)	a) Lubr for three tapered roller bearings (support bearings for test machine), heavily loaded, turning at 100 rpm in vacuum of 10^{-7} -10^{-9} torr Bearing temperature reached 140° F and lubrication was satisfactory without grease migration	AA 2-5
47	MCG-64-39 Perfluoro ether thickened with Fluorinated ethylenepropylene Supplied by Air Force Mtl's Lab.	a) Vacuum bearing test program (SWRI)	a) Lubr for test ball bearings running at 1750 rpm in a vacuum of 10^{-7} to 10^{-8} torr for 38 days without failure	UU 2-5
		b) Vacuum bearing test program (SWRI)	b) Lubr for test ball bearing running at 1750 rpm in a vacuum of 10^{-7} to 10^{-8} torr Above bearing, OK at 38 days, failed at 39 days	UU 2-5

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4.2.4.2 Brush Materials and Lubricants

Metal strips or multiple wire bundles (literally, brushes) were originally used (ca 1870) to transfer electrical power across rotating connections, either to or from slip rings and commutators of motors and generators Although they were commonly lubricated with petroleum oil, mechanical and electrical wear rates were extremely high, and this imposed severe restrictions on motor and generator development The introduction of carbon- and graphite-containing sliding blocks or "brushes" (ca. 1885) in place of wire bundles constituted a revolutionary development in electrical power transfer machinery, for wear rates decreased to almost negligible levels. However, occasionally, very high brush wear rates were encountered with machinery operating in extremely dry-air conditions, and this led to initiation of some fundamental studies of graphitic brush sliding properties in the 1930's.

Investigators found that carbon and graphite brushes depended on the presence of absorbed moisture for their lubricating properties. World War II added emphasis to the problem because of rapid brush wear in electrical machinery of high-flying aircraft caused by low pressures of water vapor at high altitudes. The brush compositions developed to alleviate this "high-altitude brush problem" formed the basis for brush compositions usable in space vacuum environments. Since MoS_2 was found to possess better frictional properties in vacuum and inert atmospheres than in air, it has been widely used as a brush ingredient for aircraft and space application.

Unlike graphite, however, MoS_2 is not an electrical conductor, and this fact has led to some high-resistance problems when unusually heavy MoS_2 films have been built up on slip rings and commutators when using brushes with high MoS_2 concentrations. Fortunately, research into other dichalcogens having the same lamellar crystal structure as MoS_2 produced some which were good electrical conductors as well as good lubricants in vacuum. One of the best of these is niobium diselenide,

$NbSe_2$, and its use in vacuum brushes -- especially those for long-life applications -- will probably increase. Liquid-lubricated brushes, such as those used in OSO satellites, represent another promising direction of development for space vacuum brushes.

The "Brush Materials" charts, GG, contain entries of successful spacecraft brush applications as well as the results of brush tests conducted in vacuum chambers. Significant experience from both of these areas is discussed herein.

As mentioned above, the OSO brushes, both the ones used for slip rings and the ones for torque motors, are impregnated with a low-volatility liquid lubricant (Vac Kote). This lubrication technique has been found to be extremely effective in minimizing brush wear regardless of the brush composition. For example, Stackpole ES-340 (GG-1) contains 5 percent MoS_2 as a solid lubricant constituent, but without Vac Kote lubricant, heavy wear occurs on both the brushes and the slip rings. Vac Kote also greatly reduces the level of electrical noise (i.e., the rapid fluctuation of brush contact resistance due to brush bounce). Silver/graphite brushes (80:20) (GG-1) without Vac Kote exhibited an average noise level of 0.5 volt, but after treatment with the Vac Kote, the noise level decreased to 0.02 volt.

The silver/graphite OSO motor brushes, RS-S2 (GG-2) are also Vac Kote lubricated. An indication of their low wear rate in vacuum is provided by their longevity in space, where OSO III motors (and slip rings) are still operable after 3-2/3 years. In vacuum chamber tests, these brushes exhibit wear rates in the range of 10^{-9} to 10^{-11} inches of wear per inch of travel. By comparison, other brush wear rates shown for some of the brush materials in the GG charts (under a variety of test conditions) are in the range of 10^{-7} to 10^{-10} inches per inch of travel. Vacuum test results on another Vac Kote lubricated silver/graphite brush are listed at GG-8.

(8)

Dry lubricated brushes for vacuum use have steadily improved over the past decade, and some of the significant vacuum chamber test results are tabulated in the matrix charts One of the most important is the silver/copper/MoS_2 composite (GG-5) developed by Clauss et al, at LMSC - Ref. Bib LL. 2-4. This brush material was successfully used as slip ring brushes on the Nimbus 4 spacecraft and has been extensively evaluated in vacuum chamber tests. Even at high sliding speeds (318-424 inches/minute) and very high current densities (for vacuum applications) of 229-300 amperes/square inch, the maximum wear rates were only 1.3 to 1.5×10^{-9} inches/inch of travel A related brush composition (GG-11) which was part of the LMSC development program was tested in vacuum against silver and gold-plated slip rings for comparison purposes This composite had Ag/Cu/MoS_2 in the ratio 85 5.10, and, under the particular set of test conditions employed, brush wear against gold was alsmost twice that against silver. average wear rates were 7.8×10^{-10} and 4.05×10^{-10} inches/inch of travel, respectively. This and other similar results indicate that gold-surfaced slip rings have no advantage over silver-surfaced ones and may be somewhat poorer from the standpoint of brush wear.

The LMSC brush development program included many brush compositions, but, for illustrative purposes, only some have been tabulated in the "Brush Materials" charts. In addition to the Ag/Cu/MoS_2 compositions, the charts also show the following: 80 Ag/20 graphite (GG-9), 90 Ag/10 graphite (GG-10), and 75 Ag/15 Mo/10 MoS_2 (GG-12).

An interesting comparison was made by Moberly and Johnson at Westinghouse (Ref. Bib. LL. 1-4) between two dry lubricants in silver base brushes. Vacuum slip ring tests were conducted at 85 Ag/15 $NbSe_2$ (GG-6) and 85 Ag/15 MoS_2 (GG-7) sliding on coin silver rings (90 Ag/10 Cu) at the slow speed of about 3.4 inches/minute. Their maximum wear rates did not significantly differ, being 1.2×10^{-8} and 1.0×10^{-8} cu. in./rev, respectively (equivalent to approximately 2.9×10^{-10} and 2.3×10^{-10} inches wear/inch of travel), but the relative contact resistances of the two brush compositions reveal the decided advantage of niobium

diselenide over molybdenum disulfide as a dry brush lubricant, as discussed previously The average voltage drops (directly proportional to contact resistances) were 0 04 and 0 07 volt, respectively, and, in addition, the magnitude of the variation in these voltage drops (noise) was four times higher than the MoS_2 lubricated brushes than for those with $NbSe_2$ lubrication. This latter comparison reflects either lower frictional characteristics or the lower resistivity of $NbSe_2$ or both.

New developments in the transfer of electrical power across rotating connections by means other than slip rings have been discussed in Section 4 2 3 2 above (Chart entries EE-14 and EE-17) The two involving transfer across contacting surfaces, power clutches and rotary connectors (meshing gears), necessarily incorporate electrical contact materials. Since brushes, per se, are not involved, the contact materials for these devices are not included in the "Brush Materials" charts. Nevertheless, the devices do constitute significant developments, and the contact materials deserve comment.

All mating gears in the rotary connector evaluated at MIT were gold-plated oxygen-free copper. The outer ring was electroplated with a hard gold and the several inner rings with a very soft gold (24 carat), the thickness of both being 0.0005 inch. As might be expected with gold-versus-gold contacts in such a device, the contact resistance and electrical noise were minimal.

The Boeing power clutch utilized the Boeing Compact 045-46 as the contact material for the stator clutch facings. This material is composed of 75 percent MoS_2 plus 25 percent metals (mostly Mo and Ta). Identity of the mating rotor clutch material was not given in reference (BB. 3-3) but was most likely silver or gold plate, or perhaps copper. In any case, no electrical performance characteristics were presented so that evaluation from the standpoint of materials is not possible.

Compared with all previous spacecraft, the orbiting space lab for which ODAPT is intended will consume a large amount of power -- up to 100 kilowatts. Thus, no previous spacecraft experience is directly applicable to ODAPT from the standpoint of the level of power transferred, and, in

addition, this is also the case with regard to physical size. On the other hand, the ODAPT application will require very slow sliding speeds (up to three inches/minute for brush/slip ring assemblies, for example) and a relatively short total sliding distance

Brushes sliding on slip rings (if used in ODAPT to transfer power) would slide slightly less than 16 million inches on a seven-foot diameter slip ring turning at one revolution every 90 minutes for a ten-year period. In comparison, industrial types of rotating electrical machinery commonly have brushes sliding at 5000 ft/min, at which rate they cover 16 million inches in 4 5 hours. Brush wear in ODAPT slip rings would obviously pose no serious problem, however, the very slow sliding speeds and static conduction conditions could pose other problems, such as electrical pitting or erosion of slip ring surfaces and, possibly, minute welded metal bridges across the contact interface if metal-containing brushes are used. The static condition has been examined for short periods with dry lubricated brushes (GG-5) but longer term tests of candidate materials should be carried out Likewise, for liquid-lubricated brushes, no static conduction experience at all has been reported, and tests will be required.

With regard to applicable liquid-lubricated brush materials, the consistently successful experience of OSO satellites with liquid Vac Kote impregnated brushes (GG-1 and GG-2) provides a sound basis for considering this lubrication technique to be a prime ODAPT candidate. Wear rates for these brushes in vacuum indicate that total brush wear in ten years at a sliding rate of three in./min would amount to less than 20 mils per brush. The exposure to space vacuum for ten years would possibly require the provision of porous Nylon Vac Koted reservoirs in the vicinity to maintain a suitable lubricant atmosphere. This aspect of liquid-lubricated brushes would require some vacuum evaporation weight loss tests on brushes of a size which might be used on ODAPT slip rings -- say 0.5 square inch cross section and about two inches long. Data from such tests would enable reservoir requirements to be established.

An important parameter in evaluating the liquid evaporation rate of liquid-lubricated brushes is the brush operating temperature. Factors de-

termining brush heat buildup include current density, brush resistivity, and brush holder design. The ability of the holder to remove I^2R heat from the brush will largely determine brush temperature, and as a consequence, the liquid evaporation rate.

Dry lubricated brushes avoid the potential problems of liquid evaporation and are, therefore, attractive candidates for ODAPT. Probably the most applicable dry brush technology is provided by the vacuum brush development program at LMSC where the highly successful silver/copper MoS_2 composition was developed (GG-5). The brush/slip ring assembly for that program was designed to transmit in vacuum 800 kilowatts of power at sliding speeds up to 424 in./min., both of which parameters are several-to-many times more severe than the ODAPT requirements. At the LMSC test current densities of 229-300 amps/sq. in., measured brush wear rates covering several hundred hours of operation would, under the ODAPT conditions, result in brush wear of only 20-30 mils during the ten-year life. Besides the vacuum test experience, the $Ag/Cu/MoS_2$ composition was also used for slip ring brushes in Nimbus 4.

The approximately optimum ratio of ingredients for the LMSC brush is represented by the ratio shown for Stackpole SM376 -- 85 silver/2.5 copper/12.5 MoS_2. This particular composition resulted from vacuum tests on a large number of variations in ratios of the three components. Best performance was found when the brush was sliding on silver-surfaced slip rings.

Other likely dry-lubricated brush candidates are silver/MoS_2 and silver/$NbSe_2$ (GG-4, GG-6 and GG-7). The success of the former as brush material for Nimbus 1-3 slip rings cannot be overlooked, and the vacuum test program at Westinghouse revealed the advantages in contact voltage drop of substituting $NbSe_2$ for MoS_2 as the dry lubricant ingredient. The wear rates measured under the conditions of the Westinghouse test indicate that only about 5 mils of brush length would be worn away during the ten-year ODAPT life, whichever dry lubricant is used. The Westinghouse test parameters of approximately 3.4 inches/

min sliding speed, 80 amps/sq in. current density, and 4 psi brush pressure are very close to those which might be encountered in the ODAPT application. For this reason, the Westinghouse vacuum test results on Ag/MoS_2 and $Ag/NbSe_2$ composite brushes are very applicable.

In Sections 4.2.3.2.2 and 4.2.3 2 3 contact materials used in experimental power clutch and rolling contact electrical transfer devices were mentioned. The contact materials themselves, gold plate and Boeing Compact 045-46, have been widely used and evaluated in electrical contact application and, hence, are possible candidates for these devices if their further development for ODAPT appears warranted. In addition to these materials, others should also be tested, including electro-plated silver for the conducting gears (with and without $NbSe_2$ lubricant) and various successful vacuum brushes versus silver for mating power clutch facings Brush materials would be $Ag/NbSe_2$, Ag/MoS_2, and $Ag/Cu/MoS_2$ Such tests in hard vacuum would be required in order to determine, for each candidate material pair, the critical performance characteristics needed for design - current densities, equilibrium materials temperatures, and wear or other forms of surface degradation affecting performance.

BRUSH MATERIALS GG

NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
5	Stackpole SM 376 85% Silver 2 5% Copper 12 5% MoS_2 Stackpole Carbon Company	a) Vacuum test program on large environmental chamber	a) Power slip ring brushes sliding on silver rings at 229 amps/in² Wear was (max) 1 5 x 10^{-9} in wear per in travel at 318 in/min. sliding speed No deletorious effect of static conduction for 40 hours	AA 2-3
		b) Brush test development program at LMSC for above chamber	b) Power slip ring test program Brushes sliding on silver rings carrying 300 amp/in² at a sliding speed of 424 in/min Wear rate (max) = 1 3 x 10^{-9} in/in travel No effect on performance of static conduction (10 hrs)	LL 2-4
		c) Nimbus 4	c) Slip ring brushes	
		d) Lockheed/DOD program	d) Slip ring brushes sliding on coin silver rings and additionally lubricated with F-50 silicone fluid	
6	Silver/Niobium Diselenide 85% Ag 15% $NbSe_2$	a) Brush/slip ring test program in vacuum	a) Tests conducted at 10^{-8} torr with current density of 80 amp/in² Brushes sliding on coin silver rings Wear rate = 1 2 x 10^{-8} cu in/rev (max) Double contact resistance = 0 04 volt	LL 1-4
7	Silver/Molybdenum Disulfide 85% Ag 15% MoS_2	a) Brush/slip ring test program in vacuum	a) Test conditions same as above Wear rate = 1 0 x 10^{-8} cu in/rev (max) and double contact resistance = 0 07 volt	LL 1-4
8	Silver/Graphite 75% Ag 25% Graphite	a) Vacuum slip ring/brush test	a) Wear and noise test, brushes sliding on coin silver and Vac Kote lubricated Noise levels and wear were satisfactory	BB 1-24
		b) TAC COMSAT test program	b) Vacuum test of power type assembly Brushes sliding on coin silver rings at 100 rpm, 30 gm brush force, 150 amp/in² Vac Koted	BB 1-14
		c) Vacuum test of brush lubricant (Vac Kote)	c) Brushes (Vac Kote lubricated) sliding on coin silver rings Wear of brushes and rings was minimal	BB 1-33
		d) Vacuum test of brush lubricant (Vac Kote)	d) Brushes (Vac Kote lubricated) sliding on coin silver rings Wear of brushes and rings was minimal Concluded Vac Kote suitable for OSO application	BB 1-34
		e) Slip ring feasibility study (vacuum test)	e) Brushes Vac Kote lubricated and run on silver rings Low noise Ring and brush wear negligible Successful test	BB 1-32
9	Silver/Graphite 80% Ag 20% Graphite	a) Brush test development program at LMSC for large environmental chamber (AEDC) for hard vacuum	a) Brush sliding on electrodeposited silver in vacuum test Result was severe ring wear and brush wear Brush wear (avg) = 4 5 x 10^{-7} in/in of travel	LL 2-4
		b) Vacuum slip ring test	b) Brushes sliding on thenium plated rings. Untreated noise level was 0 5 volt; after Vac Kote lubrication, noise was 0 02 v	BB 1-37

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BRUSH MATERIALS GG

NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
1	Stackpole ES-340 75% Silver 20% Graphite 5% MoS_2 Stackpole Carbon Company	a) OSO I-VI	a) Slip ring brushes Vacuum impregnated with low-volatility oil plus 5% special additive (Proprietary BBRC Vac Kote process)	BB 1-18
		b) Vacuum qualification test for OSO Second Source Slip Ring Assembly	b) Brushes sliding on coin silver rings Vac Kote lubrication was satisfactory but wear of brush and ring was higher than normal due to unusual brush and ring geometry (button brush in U-groove ring)	BB 1-21
		c) Vacuum slip ring test	c) Brushes sliding on rhenium plated rings Untreated noise level was 0 4 volt; after Vac Kote lubrication, noise was 0 005 volt	BB 1-37
		d) Vacuum lubrication development test	d) Unlubricated (no Vac Kote) brush/slip ring assembly Six brushes on silver plated rings, six on gold rings Heavy wear of brushes and rings, though less wear of silver rings compared with gold	BB 1-36
		e) Vacuum lubrication development test	e) Unlubricated (no Vac Kote) brush/slip ring assembly Brushes sliding on coin silver rings Heavy wear of brushes and rings	BB 1-36
		f) Vacuum lubrication development test	f) Brushes sliding on coin silver rings Six Vac Kote lubricated brushes showed virtually no wear Six unlubricated (no Vac Kote) brushes were heavily worn	BB 1-32
		g) Vacuum lubrication development test	g) Brushes and rings were Vac Kote lubricated Coin silver rings Rings and brushes showed minimal wear	BB 1-32
2	RS-S2 50% Silver 50% Graphite plus HA-12 altitude treatment Metallized Carbon Company	a) OSO I-VI	a) Torque motor brushes vacuum impregnated with low volatility oil plus 5% special additive (Proprietary BBRC Vac Kote process)	BB 1-18
3	Stackpole 566 Electrographite with lithium carbonate altitude treatment Stackpole Carbon Company	a) Nimbus	a) Brushes for iris drive motor	GG 2-2 LL 2-27
4	Silver/MoS_2 88% Silver 12% MoS_2 (Mfgr not identified)	a) Nimbus 1-3	a) Slip ring brushes sliding on rhenium plated rings	LL 2-27

FOLDOUT FRAME 2

BRUSH MATERIALS GG

NO	IDENTIFICATION	APPLICATION	REMARKS	BIBLIO NO
10	Silver/Graphite 90% Ag 10% Graphite	a) Brush test development program at LMSC for large environmental chamber (AEDC) for hard vacuum	a) Brush sliding on electrodeposited gold Severe ring and brush wear Brush wear (avg) = 1 5 x 10^{-8} in/in of travel	LL 2-4
11	Silver/Copper/ MoS_2 85% Ag 5% Cu 10% MoS_2	a) Brush test development program at LMSC for large environmental chamber (AEDC) for hard vacuum	a) Brush sliding on electrodeposited silver Low brush and ring wear Brush wear (avg) = 4 05 x 10^{-10} in/in of travel	LL 2-4
		b) Brush test development program at LMSC for large environmental chamber (AEDC) for hard vacuum	b) Brush sliding on electrodeposited gold Wear of brushes greater than above (about twice as much) but ring wear about the same Brush wear (avg) = 7 8 x 10^{-10} in/in of travel	LL 2-4
12	Silver/Molybdenum/MoS_2 75% Ag 15% Mo 10% MoS_2	a) Brush test development program at LMSC for large environmental chamber (AEDC) for hard vacuum	a) Brushes sliding on electrodeposited silver Moderate ring wear Brush wear (avg) = 1 73 x 10^{-9} in/in travel	LL 2-4
13	Paliney #7 Palladium alloy containing Ag, Au Pt, Cu, and Zn The J M Ney Co	a) Vacuum slip ring test program	a) Wire brushes sliding on electroplated silver gave low signal noise Brushes and slip rings were Vac Kote lubricated Wire brushes have poor applicability to ODAPT for the transfer of electrical power	BB 1-12
14	Neyoro 28A Gold-silver alloy containing other metals The J M Ney Co	a) Vacuum slip ring test program	a) Wire brushes sliding on electroplated silver gave low signal noise Brushes and slip rings were Vac Kote lubricated Wire brushes have poor applicability to ODAPT for the transfer of electrical power	BB 1-12
		b) Vacuum qualification test for OSO Second Source Slip Ring Assembly	b) Wire brushes sliding on 24K gold with Orotherm flash Vac Kote lubricated Low noise and wear Completely successful	BB 1-21

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4 2.5 Continuous Drive vs Reset Systems

In order that the array reset versus continuously rotating power transfer device determination could be made, it was necessary to find out the time history of the two gimbal angles for the five different orbits and the two space station flight modes, i.e., X-POP and Y-POP The X-POP mode means that the space station X-axis is maintained perpendicular to the orbit plane. In this mode the station Z-axis is controlled so that it points down local vertical The Y-POP mode means that the space station X-axis is maintained perpendicular to the orbit plane, and in this mode the X-axis is held inertial.

A Y-POP mode has been considered where the Z-axis is held to local vertical, but this requires that the station turn about its largest moment of inertia as well as rotating the solar arrays. This control mode would no doubt be prohibitively costly in attitude control fuel. It is worth noting that in the X-POP mode the space station turns about its smallest moment of inertia and the solar arrays are not rotated.

The gimbal configuration considered is where the inner gimbal is concentric with the space station X-axis and the outer gimbal at right angles and rotates with the inner gimbal. This gimbal pair can be considered an azimuth-elevation (az-el) configuration, and since the azimuth, or inner, axis has continuous rotation capability, the maximum rotation required by the outer gimbal is $\pm 90^{\circ}$ to point to anywhere in the celestial sphere.

This is easy to see if an ordinary searchlight is considered. It is apparent that the light can be pointed anywhere in the upper hemisphere by an azimuth rotation followed by an elevation rotation of 90° or less. This is exactly the situation with the ODAPT gimbals. Of course, the rotation about the line of sight to the Sun cannot be controlled, but this is not important when the task is to collect solar energy.

The az-el configuration experiences gimbal lock when the Sun is at either the positive or negative X-axis As long as the gimbals are computer controlled, the gimbal lock condition is no problem once the computer program is completed. If the array is controlled by a sensor mounted on the array, then gimbal lock becomes troublesome but the solution is well known.

From the preceding discussion, it has been shown that flex cables are quite feasible power transfer devices for the outer gimbal, and they are at present the prime candidate for the job.

A computer study was made to determine the time-angle relationships of the two gimbals for the several possible orbits and the two control modes. Figure 4-10 shows the outer gimbal angular excursion as a function of time for the X-POP control mode, and it shows that the outer gimbal makes one cycle ($\pm$ 90° max.) per year. The inner gimbal makes one revolution every orbit. Fig. 4-11 shows the outer gimbal angular excursion as a function of time for the X-POP control mode, and it also shows that the outer gimbal makes only one cycle ($\pm$ 90° max.) per year The inner gimbal in this mode makes only one revolution per year. This information is summarized below.

	X-POP	Y-POP
Inner Gimbal	One rev. per orbit (≈ 6000 rev. per year)	One rev. per year
Outer Gimbal	1 cycle per year	1 cycle per year

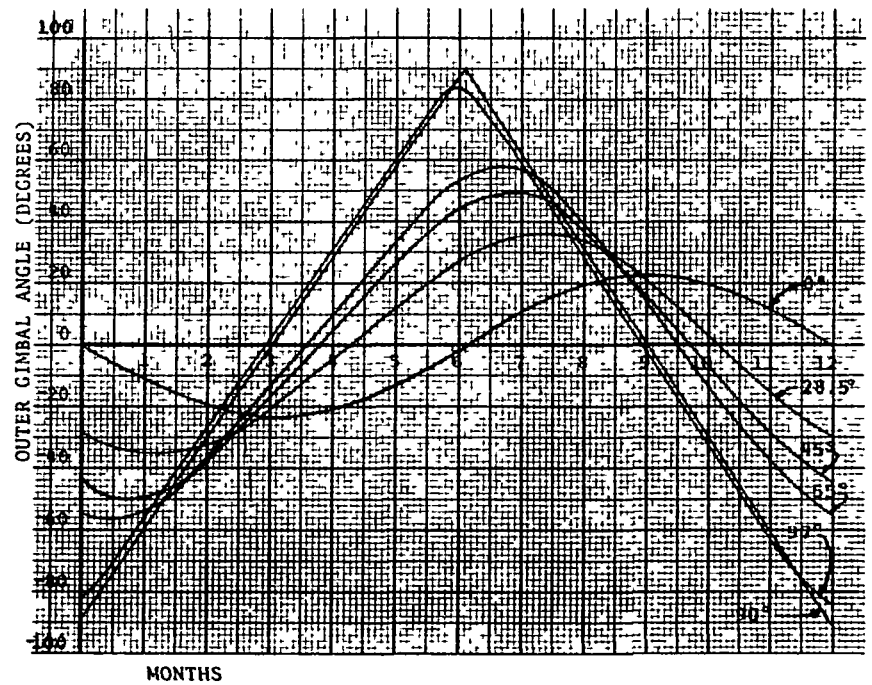

Fig. 4- 10 Outer Gimbal Angle as a Function of Time - X-POP Control

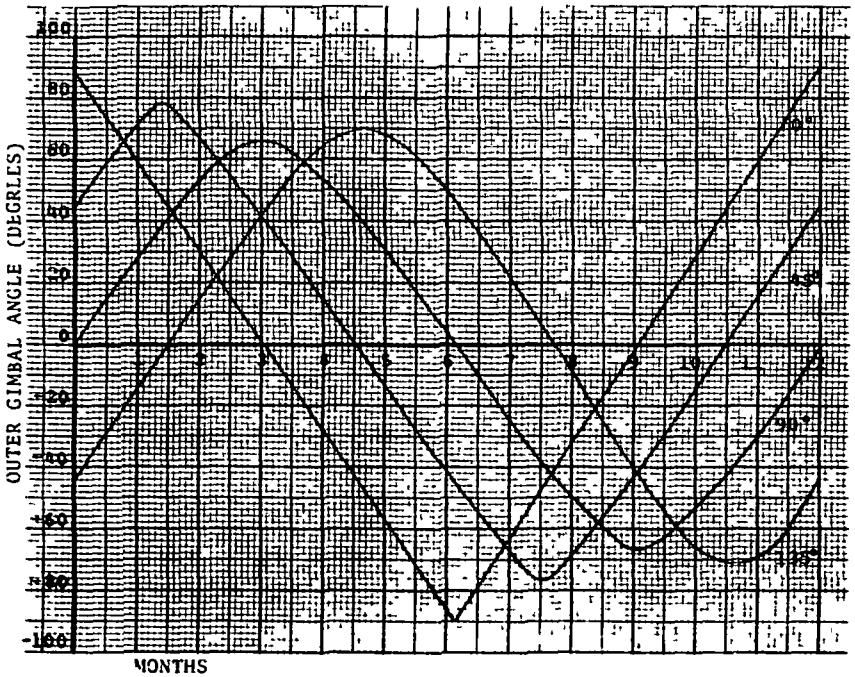

Fig. 4-11 Outer Gimbal Angle as a Function of Time - Y-POP Control

Since the inner gimbal makes one revolution per satellite orbit on the X-POP case, flex cables cannot be considered as the total power transfer mechanism. This follows from the consideration that resetting the two extremely large arrays to keep cables from winding up is not a desirable procedure, either from a power or dynamics standpoint A better solution for resetting is to reset the flexible cables with some sort of power clutch arrangement rather than the entire array. Slip rings and rotary transformers are still candidates for the power transfer job across the inner gimbal.

Section 5

RECOMMENDED TECHNICAL EFFORT

The purpose of this Technology Evaluation phase of the Space Station Solar Array Program is two-fold

- To search out, summarize, and evaluate data and approaches that can be used in development of a Space Station solar array structure, orientation, and power transfer system.
- To identify areas in the technology where more work needs to be done, and to suggest approaches for accomplishing these tasks in time to support technology readiness or to provide improvements later in the development cycle

This section of the report covers the latter portion of the objective. Since the state-of-the-art in the various technology areas has been discussed previously, no attempt is made here to repeat the evaluations; however, the appropriate matrices are referenced extensively in the individual program plans.

5.1 SUMMARY OF RECOMMENDATIONS

To better organize the material, both for understanding and utility, the program plans have been separated into three categories and are presented here in separate subsections. The categories are not meant to indicate level of priority but the nature of priority. The three categories are defined below and their time spans are summarized in Figs. 5-1, -2, and -3.

CATEGORY I – Projects Planned Under This Contract There are fourteen projects, representing the key hardware testing and analysis planned to be completed under the Space Station Solar Array Program In most cases, the problems addressed are, to a major extent, Space Station mission-peculiar They fall into one of two sub-categories – generation of data or analyses without which the baseline design cannot proceed, or testing

of typical major hardware elements in order to evaluate or demonstrate technology readiness. The tasks presented are primarily expansions on overall proposed tasks As a result of the design and analysis phase of this program, the upcoming task emphasis may change As an example, the solar array drive system trade-offs will determine the type of power transfer concept to be selected (reset or continuous tracking), which will then determine the relative emphasis on Flexible Cable Evaluation (Project 5.2.13) as well as emphasis on the complexity of the Full Scale Power Transfer Test (Project 5.2 14).

CATEGORY II – Additional Projects Recommended to Ensure Technology Readiness. The resources available for the Space Station Solar Array Program preclude complete development of all contributing technologies critical to technology readiness Further, the program duration is not long enough to allow adequate life testing in some areas. The ten projects were included in this category for one of three reasons:

- Program is long-term in nature and independent enough of Space Station array configuration to allow valid independent testing and analysis.
- Program provides extension of life tests started under Space Station program or provides further testing on Space Station array hardware.
- Program is a parallel effort providing a backup approach in an area of high technical uncertainty. As a general rule, these parallel projects were differentiated from Category III in that their primary impact is on reliability as opposed to dollars, volume, weight, or performance.

CATEGORY III – Projects Recommended to Provide Significant Down-stream Improvements. This category could easily contain several hundred items if the various programs were not screened with respect to the size and payoff of the potential improvement. The ground rule used was that the proposed program must have a substantial potential improvement in terms of measurable quantities such as dollars, cubic feet, pounds, etc.

In some cases these projects are currently underway and no change in goal or augmentation of effort is recommended. In such cases, this is stated. In some cases several projects can be combined into one integrated program For instance, elements of

Flexible Interconnect Development (Project 5.3.2), Solderless Joining Techniques (Project 5 3.3), and Teflon Solar Cell Cover Development (Project 5 4 1) currently have a high probability of being combined into a single flexible array assembly development having extremely high potential in temperature cycle performance, low cost, and radiation protection. However, where possible, program elements of this type were separated to provide maximum versatility with respect to both funding center and contractor selection. Thus, a minimum number of these projects are related to a single center or contractor.

The following sub-sections present these project descriptions.

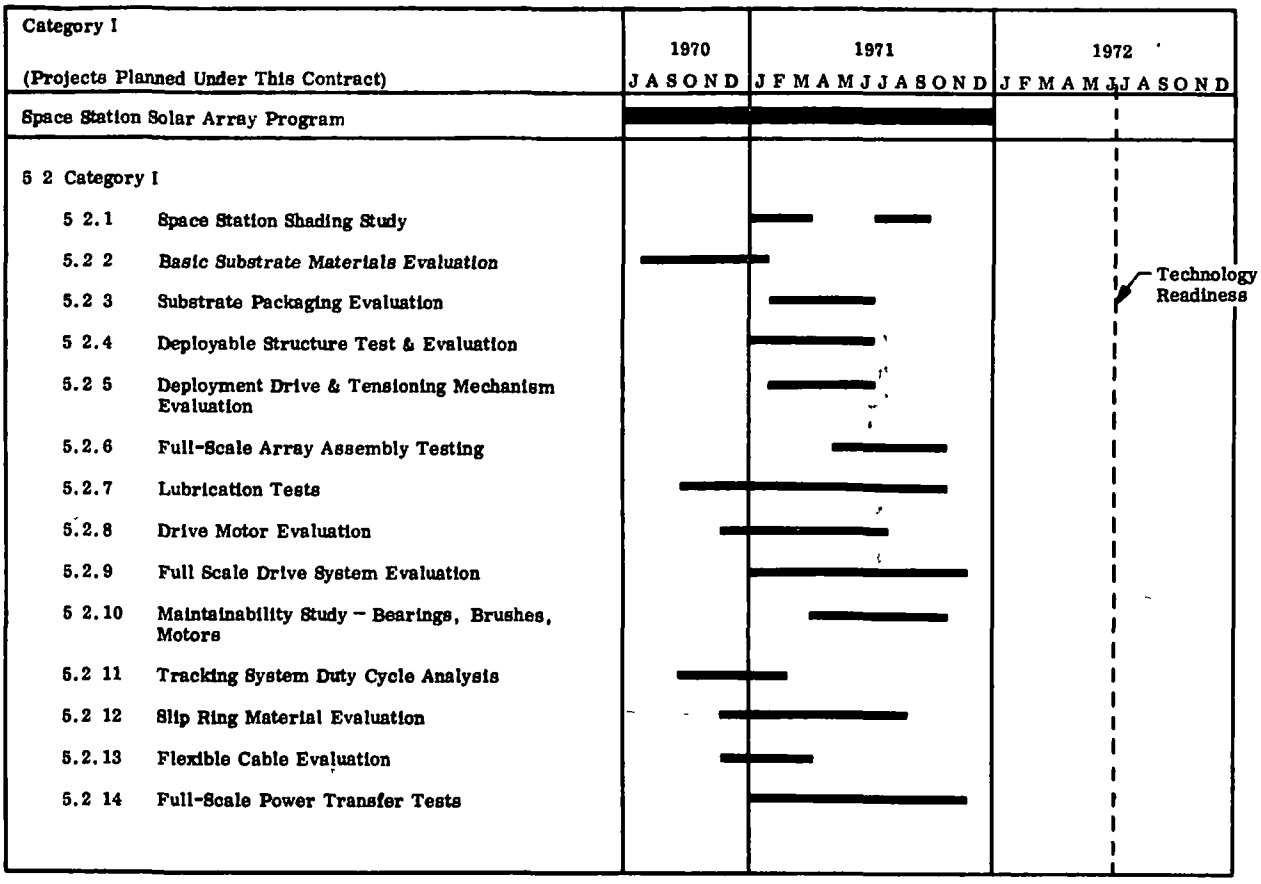

Fig. 5-1 Summary of Recommended Projects

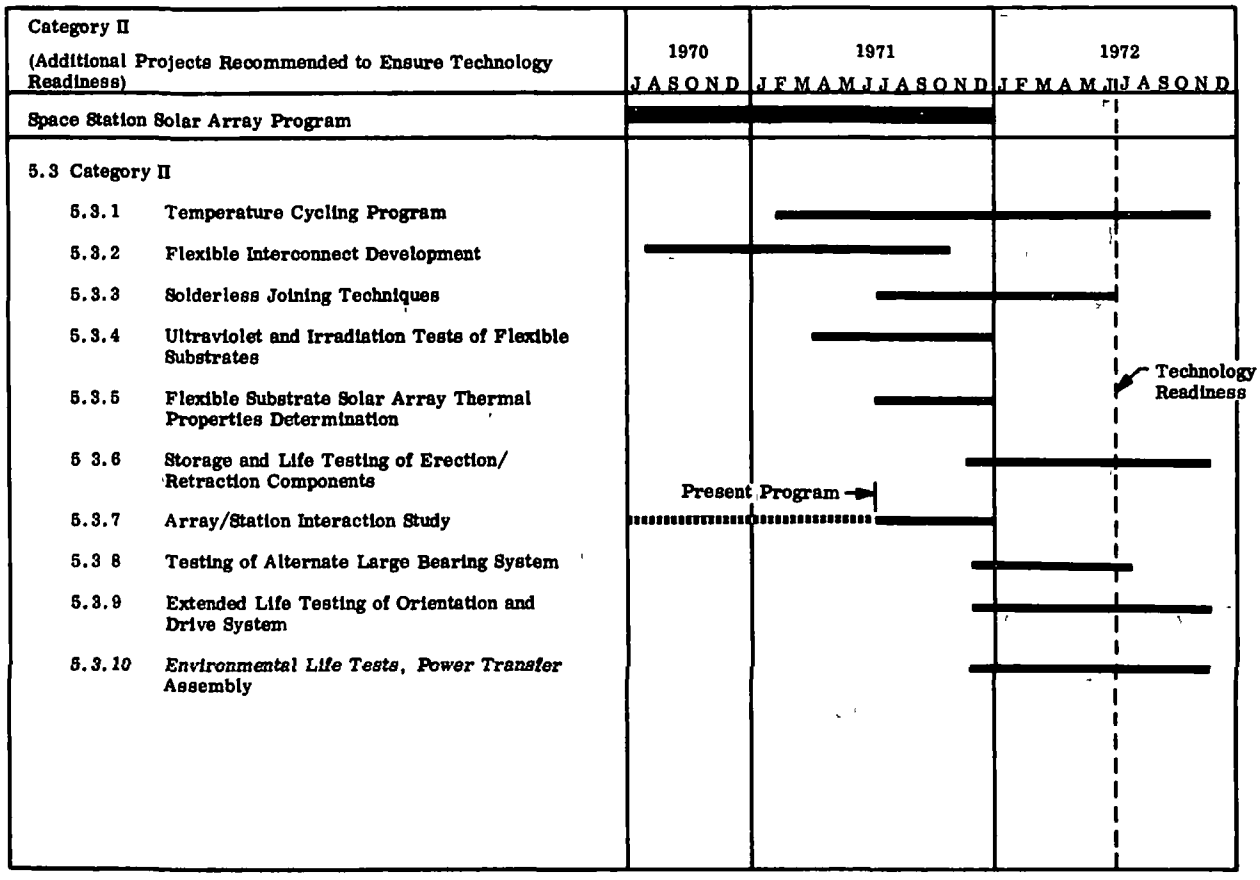

Fig 5-2 Summary of Recommended Projects

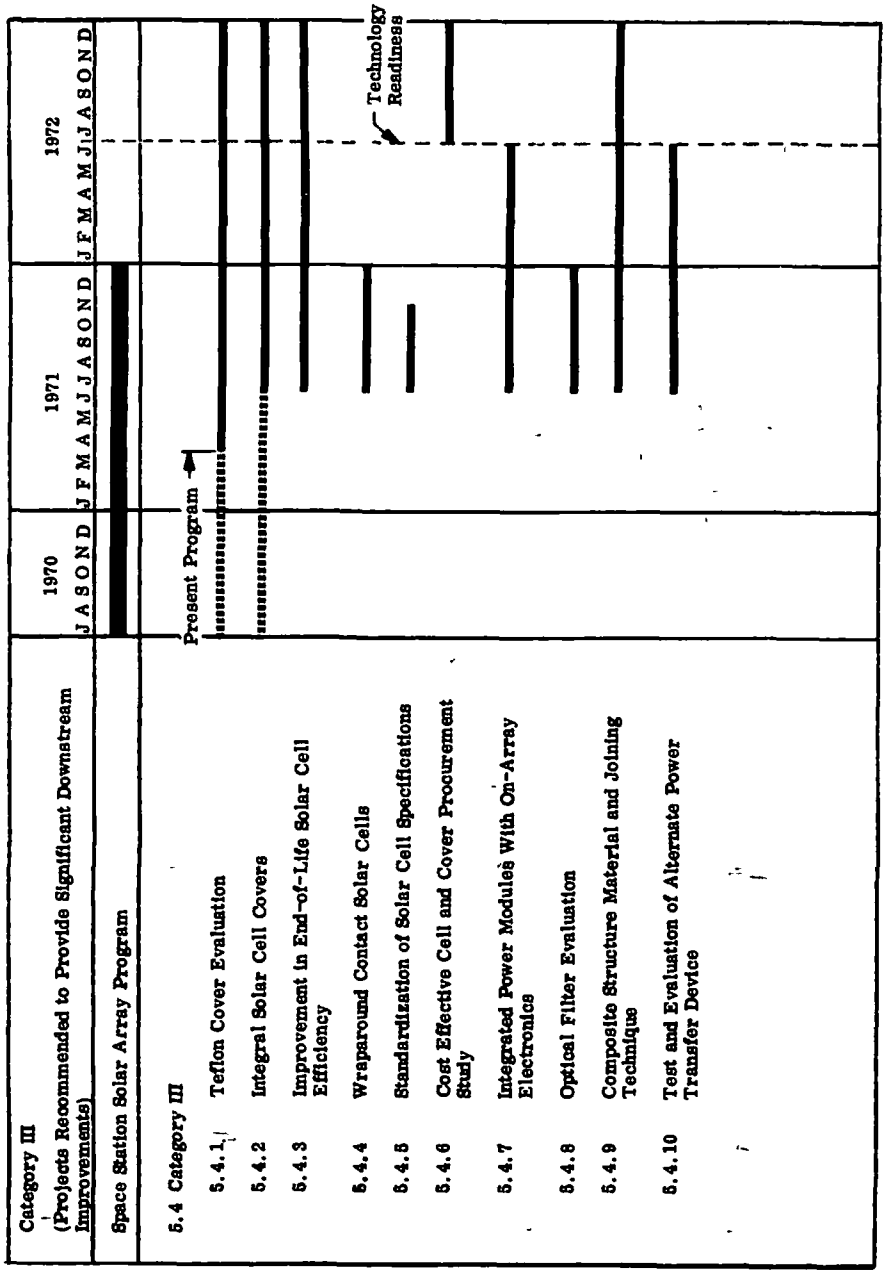

Fig. 5-3 Summary of Recommended Projects

5 2 1 Project Title Space Station Shading Study

Priority

Category I This study is incorporated in the current MSC/Lockheed program to define various station configuration shading effects on power analysis and to evaluate magnitude of array shading problems in terms of power output loss, and potential negative thermal effects The analytical methods derived will be adaptable to all station/array and independent experiment module/array configurations, and can be employed for inputs to Space Station thermal control design

Reference

1 Space Station Solar Array Program Plan LMSC A976081, NAS9-11039, page 60 and 61

Statement of Problem

Background - Virtually every satellite system which contains solar arrays has been subjected to a shading study analysis and their value as an electrical design tool is generally recognized A shading study is especially pertinent in manned systems to evaluate vehicle on array and array on vehicle shade factors as a basis for radiator location and design

Desired Output - Anticipated outputs of this study include vehicle on solar array shading patterns as a function of inclination angle and vehicle position in orbit, optimized circuit layout relative to shade sweep direction, evaluation of solar cell size relative to shade effects determination if highly shaded areas should be void of cells, evaluation of bypass diodes use in moderately shaded areas, and determination of possibility of hot-spot problems on array

The study becomes a valid design tool in assessing integrated power output as a function of orbit ephemeris and in assessing advantages of one configuration over another in minimizing shading effects The results will be employed in the array design and will be published in parametric form in the Design Handbook

Timing - These studies, based on the three existing Space Station configurations, will be conducted during the first quarter of 1971 and refined during the third quarter prior to full scale array fabrication

Recommended Program Elements

The project will include the following tasks

(1) Computer shading analysis of candidate station/array configurations

(2) Preliminary electrical output calculations for aspect ratio trade-offs

(3) Photographic shading analysis of models of selected configurations.

(4) Optimization of solar cell sizes and patterns and evaluation of bypass diode utilization

(5) Refined shading tests of selected configuration

5 2 2 Project Title Basic Substrate Materials Evaluation

Priority

Category I The mechanical properties (tensile strength, creep rate) of many of the candidate flexible substrates (particularly the laminates) are not available over the required design temperature range Further, the changes in properties when exposed to UV, vacuum, and prolonged temperature cycling are not known An excessive creep rate could, over a ten year period, result in significant dimensional change, which must be designed for in the mechanical tensioning system Since the material design data compiled from the Technology Evaluation is insufficient to form a basis for baseline selection, this work is planned under the Space Station Solar Array Program

References

1 This Report, Basic Substrate Material, Section 4 1 3 1

2. Substrate Evaluation Test Plan, LMSC A976179 Rev A, 9-22-70

Statement of Problem

Background - A test plan for creep and tensile (strength and tear) of flexible substrate candidate materials, laminates and joints, to obtain design data for selection of a final baseline substrate design was submitted August 1970, and initiated in September 1970 The test specimen matrix submitted with this Test Plan identified some 40 elevated temperature specimen creep tests and approximately 30 tensile tear propagation specimen tests (Document LMSC A976179 Rev A) These test specimens include laminates of Kapton/FEP, Kapton and Fiberglass (Teconic), module assemblies (some with integral and others with surface bonded cell interconnects) of Kapton/FEP, Kapton/Epoxy and resin impregnated Fiberglass Three identical specimens of any substrate laminate or assembly are being tested in the initial program which is directed at obtaining the worse case elevated temperature creep rates which are most vital to preliminary design.

Desired Output - This program will provide sufficient elevated temperature (up to 160°F) creep data to accommodate preliminary design and comparative data for final baseline substrate selection

Timing - This program was initiated almost immediately after the start of the contract in an effort to generate some data in time for initial baseline design selection in late 1970 Creep tests will continue through 1971, and results will be included in the Design Handbook

Recommended Program Elements

The program should include the following key tasks

(1) Obtain substrate creep and tensile specimens from material vendors and leading flexible solar array manufacturers

(2) Conduct creep, tear, and tensile tests on sample materials before and after U-V exposure, concentrating on obtaining early results at maximum anticipated orbital temperatures to provide timely worse case design data

(3) Repeat tests on laminates and material joints.

(4) Continue long term creep testing to obtain parametric life data

5 2 3 Project Title Substrate Packaging Evaluation

Priority

Category I The Space Station Solar Array System has a total deployed area of 10,000 square feet and contains approximately 2,000,000 2 x 2 cm solar cells Much of the mechanical complexity associated with flexible solar arrays is associated with the launch packaging of these cell assemblies and particularly with their automatic re-packaging during retraction For the Space Station, the added requirements for replaceability will be superimposed At least three basic packaging methods - roll-out, fold, and flat spindle must be traded-off to select a baseline approach A typical module must be fabricated to evaluate the feasibility of the concept to demonstrate technology readiness with respect to handling and packaging solar cell assemblies forty times larger than have ever previously been assembled Since this scale-up capability must be developed and demonstrated to provide technology readiness, it has been included as a task in the present program

References

1 This Report, Existing Solar Array Systems, Section 4 1 1 1

2 This Report, Basic Stowage Methods and Variations, Section 4 1 2 2 2

3 This Report, Extension/Retraction Methods, Section 4 1.2.2 3

Statement of Problem

Background - As yet there has been no flight experience on flexible solar arrays, and no test experience above 250 square feet in size, which is 1/40th the size of the Space Station Solar Array Extensive experience exists with rigid "fold out" panels and more experience will be obtained from the Skylab system, but the packaging techniques are totally inapplicable to lightweight flexible arrays Existing ideas for flexible array packaging include drum rollers or spindles with integral or separately packaged padding, as well as flat fold outs with integral or separate padding and with no padding provided except for temporary launch protection These approaches have yet to be screened by design iteration for application to very large solar arrays and tested under launch and retraction conditions

Desired Output - This project will provide (1) documented design trade-offs of the candidate packaging concepts for the Space Station application, (2) comparative thermal and structural test data on several alternate padding configurations including test evaluation of the feasibility of eliminating padding during on orbit array retraction, which would result in major design simplifications, (3) demonstration of the feasibility of packaging and deploying a full scale array module

Timing - The preliminary trade offs and small scale testing must be completed prior to test prototype design freeze and the full scale module test must be completed during the present program to demonstrate technology readiness

Recommended Program Elements

The following tasks will be accomplished under this project

(1) Analysis and trade off of candidate concepts against typical Space Station requirements

(2) Design evaluation of several selected approaches

(3) Small scale thermal and vibration testing of selected padding configurations for both launch and retraction modes.

(4) Design selection

(5) Design, fabrication, and vibration test of selected array module design

(6) Employment of the array module with array structure in later deployment tests

5 2 4 Project Title Deployable Structure Test and Evaluation

Priority

Category I This project is being given high priority in the Space Station Solar Array program because the technology readiness of the deployable boom system is fundamental to the credibility of solar array technology for the Space Station application The combination of size (greater than 80 ft per section), "g" loads (0 to 1 0 g) and supported mass (10,000 square feet of solar array and structure) is orders of magnitude beyond the capability of past system design concepts

References

1. This Report, Deployment and Retraction Structure Review, Section 4 1.2 2

2 This Report, Evaluation of Extensible Structure for Large Space Station Applications, Section 4 1 2 3

Statement of Problem

Background - Present state of the art in flexible solar arrays includes primarily the employment of tubular SPAR type booms in sizes up to 2" in diameter to support flexible arrays up to 250 ft^2 in size and loadings of a maximum of 0 1 g and normally down in the order of 0 01 g, with negligible stiffness requirements for deployed shock loadings Preliminary evaluations, (see above) show requirements for boom cross sections up to 48" to handle the anticipated loadings associated with the Space Station solar array The weight of penalty variation due to boom selection can be in the thousands of pounds range as shown in the references Further, the capability of fabricating, testing, handling, and deploying space structures of this size in lightweight configuration has not been demonstrated

Desired Output - The outputs of this project will be (1) a set of design trade-off results leading to selection of a boom type suitable to the anticipated spectrum of space station requirements (2) parametric load deflection prediction and thermal analysis results for future sizing of the selected boom type (3) structural and thermal test results on boom sections (4) full scale structural test results (5) boom hardware for the full scale system deployment Resulting

Desired Output - (Continued)

design and test data will be included in parametric form in the Design Handbook, and actual boom weights and structural parameters can be employed in Space Station designs This data will include information on extension capabilities, unloaded erection alignment, stiffness, buckling due to lateral and column loads, tolerance buildup and packaging volume

Timing - This project must be completed during the present program to insure technology readiness Parametric analyses and selection will be completed prior to test prototype hardware design

Recommended Program Elements

The following key tasks will be accomplished

(1) Analytical design, evaluation, and selection of boom candidates vs structural analysis

(2) Development of latching mechanism, hinge mechanism, selection of basic materials and joining techniques

(3) Evaluation tests of boom elements and sample sections including thermal shading element temperature gradient measurement, static bending tests, buckling tests, and preliminary tolerances buildup evaluation

(4) Fabrication of full scale boom element and bending, torsion and alignment test in the 180 feet LUMF water tank facility

(5) Employment of the same boom hardware in system deployment tests.

5.2.5 Project Title Deployment Drive and Tensioning Mechanism Evaluation

Priority

Category I This task, incorporated in the current MSC/Lockheed program, includes design, fabrication and evaluation testing of candidate devices for controlling boom deployment, array segment retraction and providing uniform substrate tensioning under anticipated variable orbital loading conditions Since deployment drive and tensioning system design has not yet been attempted for flexible arrays of this size, nor has any tensioning system of any size been required to perform over the 0 to 1 "g" range, the limiting problems must be defined and resolved through design and test of key components in order to evaluate technology readiness of large flexible solar arrays for Space Station application.

References.

1. This Report, Deployment and Retraction Structure Review, Section 4.1.2.2.

2. This Report; Testing Performed on Flexible Array Systems, Section 4.1 1 2.

Statement of Problem·

Background - The deployment drive and tensioning system for a flexible solar array provides the stored energy necessary to deploy and/or retract the boom as well as to apply controlled tension to the substrate to accommodate thermal expansion, creep, and variable on-orbit static and dynamic loads while maintaining reasonable alignment of the total array structure. In presently developed flexible solar arrays, designed in sizes up to 250 square feet for loads significantly less than 0.1 g, the total dimensional change in the substrate due to the above combined effects is in the order of inches, and is normally handled by means of a simple negator spring system, and even here design compromises to accommodate retraction and launch loads prove difficult (Reference 2) In the Space Station Array design, a misalignment of 1 degree means a 21 inch boom tip deflection or a 7 inch lower support deflection. Tensioning up to 50 lbs per foot of substrate width must be maintained while compensating for up to 18 inches of substrate length variation due to combined thermal growth and creep in a 0 to 1 "g" field. The problems associated with these requirements must be defined and solved.

Desired Output - The outputs of this task will be (1) definition of the scale-up problem as it relates to mechanism design (2) Tradeoff data defining the "cost" in weight and complexity of the artificial "g" and retraction requirements (3) Design tradeoff data on candidate drive and tensioning systems (4) Test data on a prototype proof of principle set of hardware employed in array deployment tests Supporting data will be published in the Design Handbook

Timing - The deployment mechanisms for erecting the boom and tensioning the substrate must be designed, tested, and reconfigured as required in time for incorporation into full scale quadrant testing. Substrate creep data must be available to complete component design

Recommended Program Elements

This project will include the following elements·

(1) Analysis of tensioning loads and length compensation requirements

(2) Design tradeoff

(3) Detailed design of selected hardware

(4) Hardware performance tests

(5) Redesign and rework as required

(6) Array system quadrant test

5 2 6 Project Title Full Scale Array Assembly Testing

Priority

Category I Full scale test evaluation of the major solar array components is necessary to evaluate design concepts and analytical procedures used in design and to assess problems in fabrication, assembly and test of a 10,000 ft^2 solar array for a typical Space Station This task is planned for accomplishment in the present Space Station Solar Array program, and constitutes the final test to evaluate technology readiness of the selected baseline system

References

1. This Report, Existing Solar Array Systems, Section 4 1 1 1

2. This Report, Structure Environmental Test, Section 4 1 1 2

Statement of Problem

Background - To date the largest flexible substrate arrays to be designed and tested have been 250 ft^2 in extended area This is 1/40 of the Space Station wing presently being studied The handling and test techniques of a 10,000 ft^2 array must also be scaled up with the size of the arrays to determine feasibility of using an array of this size The effects of artificial "g" loads on a flexible panel have never been demonstrated, nor has the capability to design and build lightweight retractable solar array structures in this size been evaluated or demonstrated.

Desired Output - This project will·

(1) Demonstrate assembly inter-relationships and function

(2) Prove solar array segment deployment and alignment in typical Space Station sizes

(3) Demonstrate retraction mechanism capability

(4) Provide simultaneous evaluation of

(a) Ground handling methods
(b) Mechanical acceptance test techniques
(c) Electrical acceptance test techniques

Desired Output - (Continued)

(d) Recommended erection, deployment, retraction rates

(5) Determine necessary tension levels to eliminate wrinkling or the tension necessary to minimize wrinkling and still maintain sufficient power levels during the artificial "g" mode.

(6) Provide assembly static deflection data for system analysis

These outputs will form the key background for the final design specification, and the development program plan, and will provide valuable insights for future design and development efforts

Timing - This testing is required to determine technology readiness and/or where additional development is necessary. This test will be initiated after all substrate, mechanism, and structure component testing is complete, since it is planned to reuse these components in this final full scale test

Recommended Program Elements

The key program tasks are

(1) Design a 10,000 ft^2 array that satisfies known space station requirements

(2) Fabricate a 2500 ft^2 section of the Space Station array containing all major elements, packaging, extension, devices, etc

(3) Assemble major solar array and test components and test fixtures

(4) Extend and retract solar array system.

(5) Determine tension necessary to minimize or eliminate panel wrinkling under artificial g loading, and compare against predicted values

(6) Evaluate and document critical handling, test, and checkout problems and recommended procedures for incorporating in the development and qualification plan

5.2.7 Project Title Lubrication Tests

Priority

Category I. One of the critical determinants of lifetime of the Solar Power System will be the selection and application of space-qualified lubricants. Three and one-half years is the maximum known useful lifetime of lubricants in a space application. No previous system has required a 10 year design life. Tests are underway on another program to qualify 5 year lubricants. However these are continuous rotation applications. The Space Station requirements demand stop and start operation for this time period. Due to these unique demands, this testing has been included as a task in the Space Station Solar Array Program.

References:

1. This Report, Drive Systems; Section 4.2.2.

2. This Report, Lubricants, Section 4.2.4.

Statement of Problem

Background - As shown on the "W" matrix charts in Section 4, a large number of candidate lubricants are available. Tests are required and will be performed on the MSC program to pick the proper lubricants for this specific application. The drive system could use bearings from a small size (2" dia) up to an extremely large size (6' dia), as well as a similar size range for gears. It is improbable that any one lubricant can perform properly for all required applications. Tests are required to select the best lubricant for each requirement. For example, one operating mode will result in the bearings being stationary for extended periods of time. This condition would tend to squeeze liquid lubricants, if used, out from loaded ball/race interfaces. Evaporation to a more viscous fluid residue around the contacting load areas is another, though less important, factor. Cold welding and increased viscous drag could be the result, and increased starting and running torques (besides surface degradation of bearing elements) would be the consequence.

Desired Output - It is the intent of this task to test lubricants to provide input wear and chemical degradation data for design support and tradeoff analysis to help select the lubricants to be used for the major hardware tests. This does not eliminate the need for further lubricant testing, because the final results of the major hardware

5 2 7 Continued

Desired Output (cont'd)

tests will determine if the proper lubricants were selected Additional tests may be required during the Development Program

The test results will be applicable in part to all space programs and can also be used for other systems on the Large Space Station, where intermittent tracking is a requirement.

Timing - Lubricant testing should be initiated as soon as possible so that specific applications can be evaluated. Tests will continue through 1971 to obtain degradation data.

Recommended Program Elements

In order to obtain needed data not presently available on potential lubricants, laboratory tests should be conducted on bearing and gear lubricants considering (1) Static bearing and gear pressure, (2) Ground test conditions, (3) Life requirements and (4) Serviceability.

Some lubricants recommended for tests are

(1) Vac Kote oils - low volatility petroleum base, synthetic ester, and ether base oils

(2) Versilube F-50 - Methylchlorophenyl silicone

(3) FS-1265 - Fluorosilicone oil

(4) XRM 141C - Paraffin base oil

(5) DC-7024 - High-phenyl silicone oil

5 2 8 Project Title Drive Motor Evaluation

Priority

Category I A broad base of drive motor technology is available for solar array tracking applications However, special requirements of the Space Station will necessitate evaluation of the drive motor for (1) Continuous bi-directional torque capability proportional to the current input, (2) Stall torque capability sufficient to overcome brush and bearing friction plus array inertia in acquisition and tracking modes, plus (3) 10-year operational life This study will be a part of the design support testing conducted on the Space Station Solar Array Program.

References

1 This Report, Drive Systems, Section 4 2 2

2. This Report, Motors, Section 4. 2. 2. 2

Statement of Problem

Background - Large industrial-type motors of the rating required for this system are, of course, readily available from commercial sources. However, the ten-year vacuum operation requirement will impose limitations upon the applicable technology. Periodic maintenance and component replacement will be a major consideration for the design. The selection of the motor which will meet all the design and performance requirements must be made during the tradeoff study. Both brush and brushless type motors have been used in previously spacecraft. None of the spacecraft have used an "on-axis" *motor with a large bore through its center.* One of the largest motors of that type is an Inland DC permanent magnet torque motor, No. T-36001 which has a 25.625 inch bore and 41 inch outside diameter. A direct scale-up to a motor having a five foot diameter bore is questionable. Therefore, most probably an "off-axis" motor will be selected which drives through a gear reduction.

Desired Output - Tradeoff data will be obtained on candidate motor design approaches for the baseline Space Station Array System. Performance data on the selected motor type will be employed as inputs to array interaction analysis and Space Station controls analysis. Life testing will continue throughout the program to evaluate endurance capability under typical Space Station cycles.

Timing - Design, selection, procurement, and performance testing must be completed during the first half of 1971 in order to finalize drive system design. The test motor will be employed in drive system testing in late 1971

5 2.8 Continued

Recommended Program Elements

The following tasks are currently planned

(1) Design tradeoffs and candidate drive motor selection

(2) Functional performance testing in air

(3) Thermal vacuum testing

(4) Design modifications as required

(5) Incorporation into drive system test.

The extent of test effort to be applied to this task will depend upon final design selection Should the use of a space qualified drive motor prove practical in the overall design, this testing will be reduced in favor of increased emphasis on less well-defined aspects of the system design.

5.2 9 Project Title Full Size Drive System Evaluation

Priority

Category I A drive system capable of automatic 2-axis orientation of a 10,000 ft^2 solar array, with manual over-ride provisions, accommodation of vehicle maneuvering, and operation in a fixed position for periods up to 30 days while absorbing loads resulting from 4 RPM Space Station rotation represents a combination of problems not previously encountered by drive system designers Evaluation of full scale components under predicted loading conditions is necessary to achieve and demonstrate technology readiness for the drive system

Reference

1. This Report, Drive Systems, Section 4 2 2

Statement of Problem

Background - Drive systems are designed to accommodate specific spacecraft structures and orbit parameters, but some insight can be derived from past development with respect to general approach and component selection All systems developed to date, except for the 10 ft diameter Apollo Telescope Mount roll axis drive, which has not yet been qualified or flown, are much smaller in size than the Space Station system. No drive system has been required to sustain loads in a high artificial "g" field.

Desired Output - This task is expected to provide design trade-off data on alternate approaches to overall drive system design, an assessment of the design impact of the large array inertia and the artificial "g" loadings, performance test data on the selected drive system, and endurance test data under critical loading where appropriate. These results will be published in parametric form in the Design Handbook, and insight with respect to handling and test techniques and anticipated critical development problems will be reflected in the Development Plan.

Timing - An attempt will be made to provide updated baseline design inputs to the Array Interaction Study - (Langley/Fairchild Hiller) in early 1971. All testing will be completed by the end of 1971

Recommended Program Elements.

Design trade-offs will be conducted to select a baseline approach, with final design selection hopefully based on an evaluation of the effect of drive motion on the Solar Array structure as determined by the Space Station Solar Array Interaction program. The following simulations will be performed with the test model

5 2.9 Continued

Recommended Program Elements (cont'd)

- Docking stress
- Spin mode stress
- Launch loads
- Tracking and gear dynamics studies

Design modifications will be made as required and test iterations completed. Recommendations will be made for further design improvements and future development test program emphasis.

5 2.10 Project Title Maintainability Study - Bearings, Brushes, Motors

Priority

Category I Much of the technology already developed for bearings and motors is definitely applicable to the basic Space Station drive design The problem is to select a specific approach and insure reliable performance in the absence of test data relevant to ten year vacuum operating life. In order to maximize the probability of success, a key element in the design approach will be the employment of man's presence to provide at least backup maintenance support to this system Since very little thought has previously been applied to maintainable space drives in the past, this effort will represent a key element in the Space Station Solar Array Program

References

1. This Report, Bearings, Section 4.2.2.1,
2. This Report, Motors, Section 4.2.2.2

Statement of Problem:

Background - The longest continuous flight history available on drive systems is 42 months (as of Nov. 1970) on the OSO vehicle, which represents about 1/3 of the required life of the Space Station System. In addition, it is a lightly loaded application of much smaller size. Short duration missions such as this have demonstrated the feasibility of conventionally designed motors and bearings for continuous rotation - primarily at higher rotating speeds, but the problems of 10 year operation at intermittent rates differ greatly from these past applications. This lack of background makes an effective maintenance/replenishment philosophy mandatory, and this must be established and reflected in the Space Station drive hardware designs.

Desired Output - Results of evaluation of candidate maintenance/replacement modes will be published in the design handbook including degradation, failure mode analyses, design complexity assessments, and weight penalties.

Timing - Trade-off analyses should be completed by the first quarter of 1971, and an approach selected, since this aspect of the problem will, to a large extent, govern the system design. Maintenance procedures must be demonstrated on test hardware prior to December 1971

5.2.10 Continued

Recommended Program Elements

Design studies will determine which maintenance/replenishment features should be included in the drive and power transfer test hardware During hardware testing, these approaches will be evaluated as part of the various test programs. No special extra test hardware or fixtures are anticipated at this time.

5 2 11 Project Title Tracking System Duty Cycle Analysis

Priority

Category I. This effort involves a computer analysis of the various possible Space Station flight modes to determine the total travel and rate requirements of the two axis drive system. This task is fundamental to the generation of design requirements for the drive system. This program will also provide key inputs to the Solar Array Shading Studies (5.2.1) and to the Langley/Fairchild Hiller array/space station dynamic interaction evaluation study

Statement of Problem

Background - Preliminary Space Station studies show that the Space Station might fly in either of two basic orientation (X-POP) and (Y-POP) during zero "g" operation. Further, a range of inclinations from 28.50° to polar is specified, although some flight peculiar pre-orbit adjustment may be possible on specific flights to accommodate the planned inclination. The impact of this range of requirements on drive and power transfer hardware design, and the impact of various mission modes on design complexity has not been evaluated.

Desired Output - Parametric data will be generated on drive rates and position vs time for the various orbital inclinations.

Timing - This task must be completed by January 1971 to provide inputs to drive design. Preliminary inputs are now available for updating the baseline design in December 1970.

Recommended Program Elements

Preliminary computer runs have already been made to define travel limits in both axes, and results indicate that there is a definite possibility for flexible cable power transfer in at least one axis. Parametric curves covering all inclinations of interest will be generated and published in the Design Handbook for future use. Using this same data, an evaluation will be made of the operational feasibility of an all-flexible cable/reset system, including maximum required reset rate (minimum shade time) and power penalties associated with this approach.

5 2.12 Project Title Slip Ring Material Evaluation

Priority

Category I With the exception of flexible cables, which can be employed only on missions where reset is not a problem, slip ring technology is the only method used extensively to date for transferring power across a rotating joint. Although a large amount of vacuum testing has been done on slip ring materials, very little of this has been based on the 0-6 degree per minute range associated with the Space Station design. Since the basic failure mode of brushes changes with rotating speed, candidate materials must be screened specifically for Space Station application and wear rates measured for use in design and life prediction.

References:

1. This Report, Slip Rings, Section 4 2.3.1

Statement of Problem

Background - The largest slip ring flown to date is the 8 inch diameter ring on TACSAT, which carried 3 0 kW peak power across the rings. The typical Space Station application for which the ODAPT system is being designed is expected to generate up to 100 kW in the solar arrays. Transferring power at this rate across sliding contacts in space under both static conditions and slow sliding speeds coupled with the ten year life requirement with minimum maintenance presents a unique design problem.

Desired Output - The major output of this test series will be a determination of the effect of static and slow speed sliding performance of power-type brush/slip ring combinations in vacuum in terms of brush voltage drop, noise, surface damage, and temperature rise. The effects of speed variation over the range of 0-6 degrees per minute will also be measured.

These data will be published in the Design Handbook, along with extrapolations to ten year operation. Another program output will be an evaluation of the critical failure modes and risk penalties associated with the employment of slip rings in this application. This will be valuable for final system design recommendations and Development Planning.

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5.2.12 Continued

Timing - Some test data is desirable before the first quarter of 1971 to facilitate trade-offs between slip rings and flex-cable reset systems. Life tests will continue throughout the program. Because of the need for early data, this test is already underway

Recommended Program Elements

The tasks to be performed include (1) selection of a minimum of two candidate brush/slip ring combinations based on the Technology Evaluation, (2) testing of these combinations over a range of brush pressure, current density, lubricant types, and speeds from 0 to 6 degrees per minute, (3) determination of friction, wear rate and brush voltage drop under this slow oscillatory motion and (4) analytical extrapolation of these parameters to 10 year life

5 2.13 Project Title Flexible Cable Evaluation

Priority

Category I A preliminary computer analysis for the orientation drive system duty cycle based on the orbits specified by North American Rockwell shows that the total angular excursion for the outer gimbal is + 90 degrees, making a flex cable a leading candidate for power transfer across it Further, the power clutch is an attractive, alternate power transfer device which requires flex cables for power transfer across the inner gimbal.

Test information relating to the use of flex cables alone or in combination with various power transfer devices is critical to the basic design.

Therefore, preliminary evaluation of flex cable material, conductors, and insulators, will be accomplished under this program.

Reference.

1. This Report, Electrical Power Transfer Devices (other than Slip Rings), Section 4.2.3.2

Statement of Problem.

Background - Flexible cables have been employed in combination with up to 360° reset drives for power transfer on most tracking solar arrays flown to date, including Air Force arrays with power inputs up to 1500 watts. Increasing power, thickness or number of cables causes configuration problems. Further, the effects of the longer life of 10 years on insulation and fatigue have not been evaluated for the Space Station application.

Desired Output - It is desired that the following questions be answered with respect to flex cable system for Space Station application:

(1) How can the stiffness of cabling carrying up to 100,000 volt-amperes be minimized in a configuration such that torque, power consumption, and cooling requirements are not prohibitive?

(2) What maximum life limiting factors are there for such a system in a vacuum?

(3) What insulation should be employed if the cable is exposed to UV and what degradation modes can be expected?

5 2 13 Continued

Timing - Design analysis will be accomplished in late 1970 and early in 1971 to provide a flexible cable option for the Space Station UV and life tests will be initiated only after configuration selection has been made and the likelihood of use of flex cables has been established

Recommended Program Elements

This task will involve the following elements

(1) Employing results of the tracking mode computer program runs (5. 2. 11), a design of flexible cable tracking options will be carried out including analysis of stiffness, cooling requirements, and reset dates

(2) Vacuum cycling ± 180 degree flexure tests will be initiated on the candidate cable configuration selected.

(3) If extensive exposure seems probable and flexible cables are selected in the baseline, a separate test will be initiated to evaluate insulation flexibility under UV exposure of 10 sun years

5 2 14 Project Title Full Scale Power Transfer Test

Priority

Category I This task constitutes the final step in determination of power transfer technology readiness, which is the major goal of the Space Station Solar Array program Since the key problems associated with power transfer involve scale up of power transfer capability and physical unit size coupled with extended 10 year life, the proposed design must be tested at full loads for an extended period

References.

1. This Report, Power Transfer, Section 4 2. 3.

2 This Report, Electrical Power Transfer Devices other than Slip Rings), Section 4 2. 3. 2

Statement of Problem

Background - The ATM has a power transfer requirement across a large diameter (10 ft) ring, but neither its current density nor its duty cycle or life requirements are anywhere near as severe as those of the Space Station Each power transfer system employed in the past (flexible cables, slip rings, or combinations) has been a unique, vehicle peculiar design with very little beneficial basic data fallout except in the lubrication area.

Desired Outputs - This full scale model test is expected to demonstrate or measure our ability to hold proper tolerances and successfully fabricate and operate a full scale slip/ring power transfer system. Basic design data will be generated over the range of operating speeds (bi-directional) for the selected configuration, including thermal characteristics, power dissipation, wear, drag and noise.

Timing - The task will be initiated in the second quarter of 1971 after design and analysis is complete and a major portion of the associated small scale testing (5 2 12 and 5. 2. 13) has been completed

Recommended Program Elements

A power transfer model having full scale current density capability and thermal configuration consistent with the final selected design will be fabricated Thermal vacuum tests will be run to determine configuration-dependent effects such as friction drag, temperature rise, power dissipation, wear and electrical noise along with effects of static and slow oscillations in system operation. Results will be factored into final design specifications and insights gained will be employed as a basis for this portion of the Development Program Plan

5 3 1 Project Title Temperature Cycling Program

Priority

Category II. The Space Station Solar Array must survive over 58,000 temperature cycles in low earth orbit over the ten year design life Although no major on-orbit power degradation in the past has been traced to thermal effects, this large number of required cycles, coupled with the need for comparative data on candidate cell assemblies to withstand this environment must be demonstrated before the Space Station array can be considered technology ready Limited convective temperature cycling (less than 1000 cycles) is planned under the present program for screening purposes on 3-6 candidate cell assemblies, but no long term low orbit test programs exist A program of this type would be of value to all low altitude programs, and the associated facilities would be equally applicable to high altitude missions.

References

1 This Report, Thermal Cycling Tests of Flexible Substrates, Section 4 1.3.8

2 This Report, Substrate Thermal and Optical Properties, Section 4.1.3.7

Statement of Problem:

Background - The low mass of flexible solar arrays results in on-orbit rates of change of temperature which are 3-4 times greater than for conventional honeycomb panels on which most prior temperature cycling has been performed. On the other hand, the flexible substrate applies less stress to cells and interconnects than does the rigid substrate, and the low altitude results in a less severe shade environment than high altitude missions due to albedo. The net effect of these opposing parameters is unknown as is the effect of other variables such as interconnect material, substrate tension, joining method, solder thickness, interconnect material thickness, and interconnect geometry Although almost all of the candidate interconnect-cell combinations have been temperature cycle tested to some extent almost none have been cycled more than 4,000 cycles and flexible substrates have not been cycled beyond 1800 cycles. Of perhaps more importance, in no case have more than one type of flexible assembly been evaluated in the same test under the same conditions, so that even crude screening of approaches is not possible.

Desired Output - This program should provide (1) A high test sample capacity temperature cycling facility capable of "in situ" output measurement (2) An "open ended" test service where candidate samples can be inserted at any time without disturbing on-going tests

5 3 1 Continued

Desired Output (cont'd)

(3) Comparative low orbit temperature cycle data on candidate flexible solar cell assemblies for up to 60,000 cycles. (4) Validation of accelerated and low cost testing methods such as convective cycling (5) An understanding of basic failure mechanisms, and, ultimately, the ability to analytically model and predict failure modes.

Timing - This program should be initiated as soon as possible, at least to the extent of comparative testing of candidate assemblies The baseline concepts and perhaps several alternates should, if possible be tested to 60,000 cycles prior to the technology readiness date In the present program, the selected design approach will take into consideration possible downstream changes in substrate/interconnect design in selecting structural and packaging approaches. Thus, long term cycling results from this program can be factored into the Space Station array design well into the development phase.

Recommended Program Elements

The program should include as key elements (1) A preliminary or parallel analytical effort to define basic failure modes and to evaluate convective vs. radiative testing effects. (2) A parallel radiative and convective test program to attempt to validate (or invalidate) the less expensive convective techniques. (3) Fabrication of a high capacity open-ended test facility with capability for "in situ" electrical output measurement. (4) Early initiation of flexible assembly testing to temperatures and rates as determined by Space Station solar array thermal analysis. (5) Continued addition of candidate assemblies as they become available. (6) Detailed failure analysis of samples. (7) Continuous analytical support for data analysis and failure mode refinement.

This testing should be operated continuously with test samples being procured and placed under test as they become available in a manner similar to the NAD Crane battery cell test program, with test space made available to all companies and centers who care to submit samples. This dictates that the work should probably be done in a government lab or by a test contractor who is not in the business of producing solar panels, cells, or interconnects.

An estimated 300 to 500K in men and materials would be required through final facility completion, which could be in one year, with high priority tests being initiated within one month using existing facilities. Continuing test and analytical effort beyond this initial phase could cost less than 100K per year with proper test automation.

5 3.2 Project Title Flexible Interconnect Development

Priority

Category II. The Space Station Solar Array Program will concentrate on copper and kovar printed circuit interconnects which appear to be adequate for the Space Station application, although this has not yet been demonstrated by life tests. Some investigators, in anticipation of of temperature cycling problems in long life systems, recommend alternate approaches such as expanded mesh, molybdenum or aluminum materials, or employment of ultra-thin sheet Should present approaches prove inadequate, alternate approaches must be made available to guarantee technology readiness

References

1 This Report, Interconnectors, Section 4.1.3 2

2. This Report; Thermal Cycling of Flexible Substrates, Section 4.1 3.8

Statement of Problem.

Background - A variety of interconnect designs employing copper, kovar, and (more recently) molybdenum have been employed on rigid and flexible solar arrays. Each company and agency which designs or builds solar panels has its own favorite approach which it considers uniquely advantageous, but comparative tests and evaluations have seldom been done except to support adequacy for specific vehicle applications having much less severe life requirements than the Space Station Solar Array.

Desired Output - Comparative data on candidate interconnects including high and low temperature fatigue data and tensile test results for various material and geometry combinations applied both to adhesive bonded and integral printed circuit flexible substrate assemblies. Comparative cost data on various approaches. Since the alternative to developing a proven ten year life interconnect is more frequent module replacement at $25,000,000 per solar array plus logistics costs, there is a high incentive to invest in approaches which may reduce this frequency.

Timing- Early results from this project could be employed as inputs to final baseline selection. Since overall array structural design and interconnect type are not strongly interdependent, advanced interconnect concepts could be adapted to the Space Station array late in the development cycle provided the substrate material remained the same. However, development should be initiated early to allow temperature cycle evaluation (5.3.1).

5 3 2 Continued

Recommended Program Elements

This program should include high and low temperature fatigue and tensile tests of candidate materials and geometries both separately and in combination with substrates (adhesive and pressure bonded) Consideration should be given to application to both conventional and wrap around electrode solar cells. Geometries should include wire, mesh, and thin etched foils Materials should include copper, kovar, molybdenum, aluminum, aluminum-4% copper, and silver, with low cost plating process development proceeding concurrently where required for joining compatibility such as is the case with molybdenum. Promising approaches should be confirmed, using appropriate joining methods (5. 3. 3), and flexible solar cell assemblies, fabricated for inclusion in the temperature cycle testing program (5 3 1).

An effective screening program could be accomplished for under 100K per year excluding production process development, which should wait until final selection of a preferred approach.

5 3 3 Project Title Solderless Joining Techniques

Priority

Category II This program is recommended in order to investigate and compare alternative metal joining techniques with those of controlled soldering techniques prior to final selection of a specific method for Space Station Solar Array production No standardized test programs have been run to date, nor are there task objectives oriented toward development and comparative testing of solderless interconnection methods under the present program With some reported adverse thermal cycling effects of solder upon solar cell surfaces at temperatures of -200° F and below, extensive work is needed in this area to provide reliable alternatives to soldering in the event that their use proves necessary on the Space Station Solar Array Results and facilities from this program could then be applied to any satellite mission

References

1 This Report, Interconnects, Section 4 1 3.2

2. This Report, Solar Cells, Section 4 1 3 3

Statement of Problem

Background – Solderless interconnection methods data is scattered and sparse Only two sources reported extensive use of resistance welding – both are European-British (BAC) and Telefunken Neither source provided test data with any degree of uniformity of standardization between them. Thus effective evaluation, based on their data, would not be sufficiently reliable or adequate to base a design decision The same can be said for ultrasonic and thermo-compression bonding data which is also sparse In addition, no data exists on proposed techniques such as using silver bearing conductive epoxy/polyurethanes for interconnect joints, or sandwiching cells and interconnects between layers of FEP Teflon/Kapton for pressure contact joints as was recently proposed by NASA LeRC As approaches are developed, they should be compared under similar test conditions, and this is seldom done.

All bibliographical references (particularly those advocating use of welded/brazed or ultrasonically bonded joints) avoid mention of repair techniques It is difficult, if not impossible to conceive how a contractor, no matter how skilled, can build a 10,000 square foot solar array without breaking a few solar cells during the processing Soldering, to date, is the only interconnection process which enables one to potentially remove a damaged cell and replace it with a good cell without degrading the circuitry system An extensive study of repair techniques for all types of joints is therefore needed

Desired Output – Developed methods and techniques for repeatedly making high quality solderless interconnections to solar cells and comparative data on these techniques against conventional soldering

5 3 3 Continued

Trade-off study results to simultaneously compare relative technical and economic merits of each interconnection system as above methods and techniques are developed Final interconnection system selection could therefore be based, not only on technical excellence of a particular system for LSSSA application, but also on its merits with respect to high quality, economical manufacture (particularly its adaptability to reliable low cost, high volume production)

Timing – Early results would be used for screening approaches Long term results can be later applied to alter baseline data during later development, except in the case of the Lewis approach of sandwiching cells and substrate between FEP Teflon/Kapton layers This FEP Teflon concept, if found to be the best, would impact the development plan, because its adoption would negate all the joining methods and render less important the interconnect material used Therefore, data on this system would be needed before final design is started

Recommended Program Elements

Candidate solar cell assembly techniques to be developed should apply to candidate interconnects from 5 3 2 and include brazing, welding, ultrasonic bonding, and thermo compression bonding, all of which are currently receiving some development attention, and all of which share the common problem of repair difficulty This must be investigated along with development of production techniques. Also to be emphasized are approaches which appear to have high potential either for cost reduction or ease of repair such as conductive epoxy/polyurethane adhesives or integrated FEP sandwich assemblies with compression joints Techniques should be comparatively evaluated using identical test techniques including high and low temperature pull and shear tests, and thermal shock at the single cell level. Promising methods should be selected for employment in flexible cell assemblies and incorporation into temperature cycling tests (5.3.1).

Initially, multiple approaches should be funded at low levels (25-50K) until some screening has been performed The more expensive follow-on process development should proceed only after screening tests indicate a preferred approach.

5 3 4 Project Title UV and Irradiation Tests of Flexible Substrates

Priority

Category II. The Space Station Solar Array must survive 10 years of low earth orbital environment Of major concern are the long term effects of combined vacuum, ultra violet, and penetrating radiation on the structural and thermal properties of the polymeric substrate materials which, in this flexible solar array application, become a major structural component in that deployed structural properties such as stiffness and damping depend upon the tensioned substrate. A test program in this area would be of value to all programs anticipating the use of flexible solar arrays A small test effort to provide creep, tear and tensile data for preliminary design is currently underway under the Space Station Solar Array program, but long term effects on these properties must be evaluated to insure technology readiness.

References

1 This Report, Candidate Substrate Materials, Section 4 1 3.1

2 This Report, Substrate Thermal/Optical Properties, Section 4 1 3.7

Statement of Problem:

Background - Although an abundance of radiation-effects studies have been performed on polymeric materials (Reports - Radiation Effects Information Center of Battelle Memorial Institute) these investigations were aimed mainly at electrical and thermal degradation (i.e , insulation properties) while the present application requires strength characterization as a function of environmental stress

Previous proposed applications of flexible solar arrays were for much shorter mission duration and for very, very low levels of stress in the substrate material. For example the G E. /JPL design had a stress level of only 20-30 psi in comparison to the artificial gravity induced stresses of approximately 2000 psi on the Space Station In addition the long term effects will affect the physical properties. For example preliminary testing has revealed no creep for the substrate at 200°F and 100 psi loading after 720 hours of test, but the relationship between creep and combined environmental effects is completely unknown Because of the small dollar volume in the solar array market, thin film suppliers have small incentive to conduct this testing

5 3 4 Continued

Desired Output - Data on the combined effects of UV, penetrating radiation and vacuum on the structural and electrical properties of the candidate substrate materials

Timing - Worst case (high temperature) creep and tensile data is being developed now in support of preliminary design Data on UV and particle irradiated material is needed before technology readiness can be demonstrated for the selected substrate material

Recommended Program Elements

This program should include several candidate substrate materials such as Kapton, FEP, Fiberglass and laminates of these materials The following tasks should be included

(1) Prediction of degradation in properties based on available data

(2) Creep and tensile testing in the -250°F to +200°F range.

(3) Particle radiation and U V. exposure to ten equivalent years (samples at five or six intermediate exposure levels would be desirable)

(4) Post-radiation tensile and creep testing

(5) Employment of irradiated samples for thermal properties determination under project 5.3 5

5.3 5 Project Title Flexible Substrate Solar Array Thermal Properties Determination

Priority

Category II. The Space Station Solar Array must survive over 58,000 temperature cycles in low earth orbit during the life of the Space Station. In order to fully understand the thermal stresses within the substrate and substrate to cell interface, the material and thermal optical properties must be known as a function of temperature and environmental exposure At the low end of the anticipated temperature range, these properties are not completely known. The ability to select the desired properties which minimize the thermal extremes would greatly enhance our ability to meet the total thermal cycling requirements, since the number of cycles to failure is a function of stress level which is a function of Tmax and Tmin.

A high priority is assigned this effort since realistic thermal predictions are required for the design and thermal cycling program Until these data are available, thermal predictions and therefore thermal cycle testing will have little meaning.

References

1. This Report; Substrate Thermal/Optical Properties, Section 4.1 3.7

Statement of Problem.

Background - The low thermal mass of flexible solar arrays results in on-orbit temperature differences of approximately 200°C at heating and cooling rates up to four times those of conventional honeycomb panels.

The low temperatures reached by flexible substrates must be estimated based on the material property change as a function of temperature. At these cryogenic temperatures the material properties are changing and for thermal modeling and predictions these property changes are very critical. The ultimate thermal stress and thermal cycling requirements are dependent on accurate values of thermal properties at cryogenic temperatures. Such basic data as the thermal expansion coefficient of P type silicon at low temperatures is not now available.

A small test program is currently underway at Lockheed to provide low temperature data on their flexible solar array component materials, but more extensive testing is needed

5 3 5 Continued

Desired Output - This program should provide design information on (1) Thermal properties as a function of temp, (coefficient of thermal expansion, conductivity, specific heat, phase relationship), (2) Optical properties as a function of temperature (emissivity, absorptivity, reflectivity, and transmissivity), (3) An understanding of and the effect of these property changes on stress, life, and on-orbit temperatures

Timing - Low temperature thermal data could be employed now for Space Station orbital temperature predictions and modeling of the baseline system. Such data will be mandatory before initiation of thermal cycle life testing either under the Space Station program or under project 5.3.1.

Recommended Program Elements

This program should include measurement of emissivity, absorptivity, transmissivity, reflectivity, specific heat, coefficient of thermal expansion, and thermal conductivity as a function of temperature down to -300°F. These measurements should be repeated for samples after environmental exposure (5.3.4). Materials to be tested include candidate interconnect metals (5.3 2) substrate materials (5.3 4), solar cells, and solders. This program is potentially expensive, since measurement of some of the above properties at cryogenic temperatures requires sophisticated equipment and instrumentation, which could require non-recurring expenditures as high as 500K to develop and validate test equipment and techniques. Actual sample testing is short term in nature and would require less than 100K per year for a high volume test program. This program could logically be combined into a single effort with the Radiation Program 5.3.4

5.3 6 Project Title Storage and Life Testing of Erection/Retraction Components

Priority

Category II Data must be made available on materials and components to design a solar array system which can be stored for a period up to one year with a minimum of handling and which can be retracted after being extended in a vacuum for periods up to 2 1/2 years

References

1 This Report, Evaluation of Flexible Array Packaging, Extension and Tensioning Mechanisms, Section 4 1.1.3

Statement of Problem

Background - Solar Array systems will undergo periods of storage between their final systems test and flight which in some cases may be up to 1 year. The systems presently require preloads for ascent protection of solar cells and structures. The preloads related to storage of solar cells are necessary to prevent slippage during ascent. Depending on the ascent loads and orientation to these loads may be 1/2-1 lb./in². The preloads are provided by tensioning the substrate as it is being stored in drum systems and by compression between structural covers in flat fold systems. Both systems use some type of padding which will be compressed for a period of time during which significant relaxation may occur in the ascent preload This could be serious in drum concepts since this preload adjustment requires re-extension and retraction. Padding material elastic property variation with time are not known for this type of application

Long term storage may also increase edge curl tendencies in the assembled panels resulting in power degradation.

Retraction of structural components such as springs or cables erected in the space environment for periods of 2 1/2 years or longer may involve serious design problems Substrate or structural material changes as well as material interface changes due to loading without movement for long periods of time may prevent retraction.

Desired Output - The outputs which would be required include compression vs. time data on a variety of padding materials up to periods of 1 year, effects of multiple application of preload on material physical properties, edge curl effects on extended panel as a function of storage time, and definition of spring systems and bearing/lubricant combinations required for applications where they are loaded without movement for long periods of time in the low earth orbit environment and then require operation

5 3.6 Continued

Desired Output (cont'd)

This project would provide important design data for the development phase of the Space Station Solar Array and determine if it is necessary to design backup release systems for resupply of solar arrays

Timing - This information is required prior to final array development to design/develop a solar array system and to define operation and load requirements. At least some extrapolatable degradation data is required to demonstrate technology readiness to initiate a final packaging design with confidence.

Recommended Program Elements·

The program should include as key elements·

(1) Padding material test effort to evaluate long term (up to 1 year) compression at load levels comparable to expected preloads. New padding techniques and materials should be added as they are developed.

(2) Effort to determine permanent set in substrate materials due to long term storage Edge curl for drum configurations and creases for flat-fold. In addition, time at environmental conditions to eliminate the effects if they can be eliminated.

(3) Test variety of bearing sizes/materials and lubricants to determine if there are weldment problems with bearings in this type of operation.

(4) Test long term storage and orbital environment effects on spring motors and electrical motors.

Some of this effort, particularly items 1 and 2 may be recommended for inclusion in the Space Station Solar Array effort since they are simple and inexpensive tests. After the planned full scale testing under the program, the prototype hardware could be used, again inexpensively, to obtain further life/storage data.

5.3.7 Project Title Array-Station Interaction Study

Priority

Category II. One of the demonstrations of technology readiness will be a determination of dynamic compatibility, based on a model simulating the Space Station structure, the solar array structure, and the Space Station Guidance and Control System. In the absence of a final Space Station configuration, the baseline solar array should at minimum be dynamically modelled and an analytical determination made that a typical flexible solar array system can be employed with Space Station configurations with no potential instabilities. This model can later be employed as a key design tool for the Space Station structure and control system.

References

1. Discussions with personnel at JPL, Fairchild Hiller, and Langley Research Center.

Statement of Problem:

Background - A study aligned to this problem is presently being conducted by Fairchild-Hiller in Germantown, Maryland. The program is investigating zero "g" modes of space station operation only, for both rigid and flexible array systems. That program does not include the artificial gravity mode which may be the major structural design requirement affecting the Space Station solar array. The majority of designs being presently investigated under that program do not address the original requirement that the solar array first mode natural frequency be less than .1 Hz during the artificial G mode. To date, only out-of-plane modes have been modeled under this program, but Ross of JPL is currently developing an in-plane model in conjunction with G. E flexible solar array tests, and this work will be made available to Fairchild-Hiller. Baseline design information on the Space Station Solar Array is being fed to Fairchild-Hiller as it is generated, but the timing of the two programs makes it difficult for either program to efficiently employ the results of the other.

Desired Output - The immediate desired output is a computerized model which can be employed for dynamics simulation of the present baseline solar array, considering zero and artificial "g" loads including solar array tracking system characteristics

Timing - Present Lockheed programs are adequate for the current analytical requirements which are limited to evaluation of candidate structural designs with respect to natural frequency and to establish substrate tensioning requirements. By late 1971, a program should be available which is capable of analysis of all in-plane and out-of-plane motions of the Space Station Solar Array design.

Recommended Program Elements

The total program should include the following steps

(1) Development of a basic dynamic model to be employed in Space Station Solar Array analysis

(2) Continual improvement in modeling, including evaluation where possible of model predictions against solar array dynamic test data is currently being done by JPL.

(3) Dynamic modeling of the Space Station Solar Array using test program results including measured boom stiffness, mass properties, substrate tensions, and actual tracking drive properties.

(4) Ultimate inclusion of this model or a part of the overall Space Station dynamic model.

The first two tasks are currently underway at Fairchild-Hiller and JPL, respectively. The third and fourth tasks should be initiated in late 1971, probably by MSC or MSFC in conjunction with one or both of the Space Station contractors working with the solar array design team.

5.3.8 Project Title Testing of Alternate Large Bearing System

Priority

Category II. The main (large) drive axis will be the heart of the orientation and drive system. This 5' to 10' bearing or roller system will transmit total dynamic loads between the 10,000 square foot solar array/structure and Space Stations weighing up to 120,000 lbs The critical importance of this component assembly to the overall system success together with lack of design background on large bearings makes this backup testing highly desirable. One of the least known things about the rotating system is maintainability It is impossible to predict maintainability based on the manufacturers catalogs or test results not directly related to this application. Since this system must perform for ten years, it is necessary to find out which type of rolling contact system is best, so the correct decision can be made for the Development Program.

References

1. This Report; Bearings, Section 4.2.2.1.

2. This Report, Drive Assemblies, Section 4.2.2

Statement of Problem.

Background - Large bearings are available for ground application, but the largest ball bearing used in space had less than a 6" bore.

As a part of the MSC program, a full scale model of the drive system will be built and tested. A part of this drive system is the item or items that provide the rolling contact between the two large cylinders. These items will be either large bearings or small rollers. The decision as to which item to use for the full scale model of the drive system for this program will be made as a result of the trade-off analysis.

If it were required to make a choice today, the choice would of necessity be bearings because more data exists on bearings. The choice should be made on which one works best, not which one has been used the most in the past.

Desired Output - Test results on an alternate main drive bearing approach on which to base a final development decision.

Timing - It appears at this time that this program should be conducted after completion of the present program to insure proper application of lessons learned in evaluating the chosen drive system approach.

5.3.8 Continued

Recommended Program Elements

(1) Design prototype test unit using bearing type (roller or ball) not used in baseline.

(2) Fabricate full scale bearing and drive structure for application of flight loads.

(3) Test and evaluate rolling friction, starting torque, wear, etc., similar to primary bearing approach.

(4) Compare results of both bearing approaches and recommend configurations for Development Program

An estimated 6 man months would be required for design, analysis, and fabrication support plus 10 man months for test performance and support. Hardware fabrication costs would be approximately $15,000.

A recommendation as to timing will be made to MSC after the Design and Analysis phase is complete.

5.3.9 Project Title Life Testing of Drive System

Priority

Category II Basic bearing and lubricant data is available to design for a 10 year life time, however there is no life test history on even small continuously operated drive systems in space environments To increase confidence, and to turn up unpredictable operational anomalies, an extended life test is necessary to evaluate technology readiness with respect to 10 year life and to provide some technical basis for formulation of maintenance and replacement procedures Since test components will be available, their tests should, at minimum, be extended to provide some limited life data prior to initiation of development

Statement of Problem

Background - In recommending a long term test of bearing lubricant, the primary consideration is that of lubricant degradation mechanisms which cannot be predicted or extrapolated based on short term tests Once the loads and speeds are known, lubricants can be selected which will provide good bearing lubrication so long as the lubricant remains present in adequate quality and quantity

Lubricant can be added periodically to the general area of a bearing, but lubricant quality at the ball/race interface is another matter, and accelerated tests can give very misleading results. Lubricant properties can be affected by complex interactions of temperature, bearing stress level, shear rate, evaporation loss, metal-catalyzed low-rate degradation reactions, and long life. Since no set of accelerated test conditions can accurately compensate for the time factor by exaggerating the other factors, a long term (10 year) test of lubricated bearings is highly desirable.

Desired Output - Several means of continuous life test data on the prototype drive including wear rates, drag, and lubricant degradation data. Recommended maintenance schedules and procedures

Timing - Testing should continue without interruption at the end of the present program.

Recommended Program Elements

This program would be a continuation of testing which will be going on at the close of the present program.

This life testing can be conducted on hardware developed under the present program with minimum manpower levels for data analysis and failure mode analysis report If it were desirable to build additional hardware for life testing, fabrication of a drive system from the established design and testing for one year would cost approximately $200,000

5 3 10 Project Title Environmental Life Tests, Power Transfer Assembly

Priority

Category II Five year lifetime extrapolations have been made on slip rings with considerable confidence since actual satellite experience is approaching that period, but extrapolations for twice that period require extended life tests Tests on slip rings will be initiated in the existing program, but are short term due to the program span Extended or augmented testing will provide correlation for more accurate total life prediction on the Space Station and associated programs

Reference

1 This Report, Slip Rings, Section 4 2.3.1

Statement of Problem

Background - No data on power transfer testing in the size or current density regimes of the Space Station array have been conducted. All flight data has been with much smaller units A full scale device will be placed on test under the present program and, at minimum this test should be extended in time

Desired Output - Long term data on lubricant and material stability will be obtained. Extended data on liquid vs. dry lubricated brushes will be made available as an extension to the existing program.

Timing - The results of this project will add confidence and validity to selection of the long term baseline power transfer selection. This project should be initiated in October of 1971 and continue to at least mid 1972 and preferably until failure.

Recommended Program Elements

Slip ring/lubricant combinations are being built up under the existing program The suggested project will extend the tests of the existing program without the extravagance of test specimen and test set up shut-down and disassembly. Greatly increased accuracy in operational performance prediction will result as a result of additional test time.

Assuming a continuation of existing tests without initial test termination, the augmented testing task can be conducted for approx. 40K per year total. Task elements are as follows

(1) Monitor operational functions.

(2) Record and report major findings.

(3) Maintain test setup and ancillary equipment as required.

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5.4.1 Project Title Teflon Cover Evaluation

Priority.

Category III. Cost savings of 80% and weight savings of 75% over presently considered coverglass configurations may result from the development of teflon cell covers for the Space Station array. Teflon cell cover studies are now being conducted by NASA Lewis/LMSC under contract NAS3-14388. That effort is considered adequate at this time and supplemental work is recommended only if present environmental tests show promise. Satisfactory results realized in the use of teflon as a coverglass material will be applicable to any size power systems design with an equal savings potential. Further evaluation under extreme temperature/radiation/time conditions could possibly allow its consideration as a universal cell cover.

References

1. This Report, Cover Glasses, Section 4 1.3.4

Statement of Problem·

Background - Teflon is a newcomer for use as a coverglass material, and as such, processes and production technique optimization and adequate environmental testing has not occurred. Early investigation indicates studies should continue, but areas of radiation testing and temperature cycling need much more effort.

Teflon covers if qualified can result in an extremely profitable cost savings. For example Heliotek (under contract 952560 with JPL) reports an average cost for conventional cover installation using fused quartz 7940 and microsheet 0211 of approximately $3.50 and $2.50 per cover respectively. It is estimated that teflon will cost about .50 per cover. This represents a total cost savings to one Space Station vehicle of $6 million.

Weight savings can also be substantial. Based on 2×10^6 cover filters, as required in the Space Station baseline, the material weight comparison of 12 mil fused quartz, 6 mil microsheet and 3 mil teflon is 1280 lbs, 775 lbs and 295 lbs respectively, including adhesives Additional potential payoffs of a successful development include added cell protection from physical damage, humidity protection, and edge protection from radiation.

Desired Output - The major program outputs should be early determination of any apparent drawback to the use of teflon for covers, measurement of degradation levels of teflon covers as related to particle and UV radiation, process data on application to cells and cell groups, and, if this testing is successful, a developed proven application process would be the final output.

5 4 1 Continued

Timing - At the present time the Lewis program scope is felt to be adequate to determine a go-no-go status of teflon covers. Variables would possibly be introduced which were not compatible with the existing program plan if further study were to begin now without the benefit of the results from the study in progress. It is recommended that follow-up testing begin as soon as definite conclusions are reached This should occur by March of 1971.

Recommended Program Elements

The recommendation is to initiate further work based on fruitful results of the present study. These tests should include·

(1) Further substantiate degradation levels of teflon covers as related to particle and UV radiation at environments determined for the Space Station.

(2) Establish effect of temperature (rate, range and duration) on teflon covers.

(3) Perfect processes relative to multiple cell application.

(4) Refine process for production capability.

(5) Determine relationship of thickness to application/environment

(6) Supplement work established by the basic study.

The total program could be completed for 300-400K, including process development. If the technique continues to look good, some samples should be included in initial temperature cycle testing (5. 3. 1).

5 4. 2 Project Title Integral Solar Cell Covers

Priority

Category III. Conventional coverglasses must be 6 mil minimum thicknesses to keep costs reasonable. Integral covers can be 1-2 mils, resulting in significant weight reduction and elimination of the need for adhesive Further, significant cost reductions ($1-$2 per cell) may be realized No work in this area is planned under the Space Station Solar Array Program beyond defining thickness needed and procurement of available covers. This project would be applicable to most solar power applications, the exception being very short life (under 6 month) applications where thick covers are optimum

References·

1. Correspondence - W Cherry to W. Dusenbury, 2 October 1970

2. This Report, Cover Glasses, Section 4. 1. 3. 4

Statement of Problem:

Background - Application of integral covers is not yet compatible with present cell manufacturing techniques Materials and processes must be evaluated and selected. Production capability does not exist. Potential savings for a single Space Station vehicle would be 2. 6 to 3. 0 million dollars if this technique were proven out and brought to production status.

Desired Output - A production process with proven ability to apply low cost, reliable integral covers in thicknesses of 1-2 mils

Timing - Will take approximately 2-1/2 to 4 years to provide mass production capability. This technology cannot be ready for technology readiness deadlines, but can be incorporated at any time up to flight hardware production. Heavy process development expenditures should not be made until this approach is compared with the competing teflon covers (5. 4. 1) and a decision on relative merit is made.

Recommended Program Elements

The following estimated efforts are required to reduce integrals covers to production status

Phase I - Development of processes and material for use with standard cell manufacturing techniques - $150, 000.

Phase II - Development of production capability - $200, 000 - $300, 000.

Phase III - Evaluation and qualification of production products - $75, 000 to $100, 000.

5 4.2 Continued

Recommended Program Elements (cont'd)

Based on evaluation of potential payoffs it presently appears that this effort should not proceed beyond Phase I unless teflon covers prove undesirable.

5.4.3 Project Title Improvement of End of Life Solar Cell Efficiency

Priority

Category III. The large number (over 2 million) of conventional solar cells required for the baseline Space Station solar array system provides more incentive than ever before for end-of-life solar cell efficiency improvements. For example, an increase of only 5% in end-of-life power output, either from average cell efficiency increase or from reduction in cell degradation with time, results in a cost reduction for cells alone of 5 to 1.0 million dollars per Space Station. Further, such improvements would be of benefit to all Satellite programs employing solar photovoltaic power There is therefore a large incentive to support effort in this area.

Reference:

1. This Report, Solar Cells, Section 4.1.3.3

Statement of Problem:

Background - Some investigators believe that improvements of 100% can be realistically realized in AMO solar cell efficiency. Dr Martin Wolf, for instance, concludes that efficiencies up to 22% can be expected according to a recently completed study. Of equal or greater importance than efficiency is the amount of electrical degradation which takes place in the solar cell due to UV and particle radiation as well as repeated temperature cycles. Reductions in radiation degradation may be possible if proposed improvements such as lithium doping which is currently under development can be proven out. In view of the large payoff of even a small part of these predicted improvements, an augmentation of present efforts is justified. Prior and present efforts in these areas have been numerous and under the cognizance of a number of Army, NASA, and Air Force centers with little central direction and much overlap.

Desired Output - A more thorough understanding of the physical phenomena governing solar cell performance leading to inherent radiation stability and higher efficiency demonstrated in production solar cells for 10 year life in the low orbit environment. Combined improvements in radiation damage and cell efficiency could realistically result in up to 25% power output improvement.

Timing - Since improvements must be demonstrated for long life in the low orbit environment prior to employment in an operational system, present efforts in this area should be augmented now in order to allow adequate testing. Assuming that improved cells can be shown to be mechanically similar to present cells, they can be substituted late in the development program. Thus, this program need not be constrained by the technology readiness date, but should be a continuous iteration of cell development and life testing of promising approaches.

5.4.3 Continued

Recommended Program Elements

A single, centrally directed program should be initiated with multiple approaches being directed and evaluated by a single NASA center based on thorough analysis of the basic mechanisms of power conversion and damage mechanisms. Although cell development should be the subject of multiple contracts, testing and evaluation should be done in one central facility to minimize test peculiar conclusions, and provide valid comparative data. Areas to be investigated should include gettering, +P backside contacts, use of varied resistivities, diffusion control and junction depth effects, reduction of surface recombination velocity, minority carrier lifetime improvements different from gettering and basic research on radiative and non-radiative recombination along with improvements in material and process control.

If testing and evaluation results in end of life performance improvements, process specs should be written and extensive testing done on a large statistical sample of production lots to insure that the gains are realizable in practice. Based on potential payoff, expenditures of 500K per year in this area would not be unreasonable.

5.4.4 Project Title. Wrap Around Contact Solar Cells

Priority.

Category III. The development of backside contact cells and modules would result in up to 5% area/weight reductions, better packaging factors, and cost reductions of up to $200/ft^2 by reducing the complexity of panel assembly, thereby resulting in a more reliable panel as well The MSC program will include application tradeoff analysis evaluating potential use of backside contact cells. This effort will include only small scale assembly or testing. The availability of backside contact cells could be beneficially applicable to any flexible substrate array, but development of a production capability is required.

References.

1. This Report, Solar Cells; Section 4.1.3.3

2. This Report, Interconnectors; Section 4.1.3.2

Statement of Problem.

Background - In the mid 60's, all of the domestic cell vendors fabricated small pilot runs of wrap around contact cells and attempted to solicit industry acceptance. The major objection at that time was that no joint inspection could occur after panel assembly. This objection was negated with the advent of flexible substrates, primarily kapton or laminates thereof, and joint visibility after assembly is now possible, either with substrates which incorporate the circuit or with independently interconnected solar cells if transparent adhesives are used.

The series connection to the top electrode has been a major problem area in solar array systems to date. For example:

- Top side electrodes make generous stress relief series tabs mandatory, complicating panel assembly.
- Series spacing to accommodate series tabs increases cell spacings.
- Virtually all temp cycling testing has identified the series tab as a potential failure mechanism.
- Proper stress relieved series tabs protrude above the cell/cover surface complicating and compromising stowed padding methods.
- Both flight and ground tests have confirmed accelerated cell radiation degradation due to N bus gap problems.

5.4 4 Continued

Background (cont'd)

Thus the incentive exists to reduce the back electrode or wrap around electrode cell to production practice.

Desired Output - At least two qualified sources exist in the U. S. for production of back electrode solar cells. Availability of production cells for the Space Station program would result in

- Fully automated assembly of flexible substrates. Parallel and series contacts could be made simultaneously resulting in up to $\$200/ft^2$ savings.
- Reduction of series spacing to 10 mils with area reduction of 166 ft^2 based on a Space Station array.
- Use of an in-plane stress relief interconnect design with the majority of the interconnect properly encapsulated and supported increasing temperature cycle life.
- Reduction in padding thickness and weight along with elimination of tab deformation and padding hang-ups during deployment
- Use of multi cell covers (teflon, for example) and reduction in cover dimensional criteria.

Timing - Small quantities (under 2000) cells will be required for small sample testing under the present MSC program.

Production lots should be available by late 1972 for inclusion in candidate assemblies for temperature cycle testing (5. 3. 1)

Recommended Program Elements:

The following three phases could be completed in one year and should be initiated in early 1971

(1) Production process development (50K per supplier).

(2) Cell mechanical, electrical and contact testing (20K per supplier).

(3) Fabrication of cells for temperature cycle modules - (1,000 cells per supplier at $10 per cell).

Following selection of a baseline cell for the Space Station, further process refinement and automation might be recommended based on production cost analysis.

5 4 5 Project Title Standardization of Solar Cell Specifications

Priority

Category III Cell suppliers have stated that cell cost reductions of up to 15% may be effected by reduction of cell mechanical and cosmetic requirements which they feel have little relationship to power output or mechanical strength of the cell For the Space Station Solar Array, this would amount to a cost reduction in excess of $1,000,000 per power system A joint NASA/Industry study of this problem is therefore highly desirable

References

1 Conversation with K Ling, Centralab

2 Conversation with E. Ralph, Heliotek.

3 This Report, Solar Cells, Section 4 1 3.3

Statement of Problem

Background - Historically some of the requirements specified in cell procurement specifications are cosmetic in nature, directed towards cell appearance rather than proven performance criteria These requirements align to the philosophy that "if the cell looks better, it will work better " Indiscriminate relaxation of these requirements, however, could lead to lower cell quality unless the nature and source of the defect in question is thoroughly understood

Therefore, there is a need for specific performance data on cells as a function of the following - contact or ohmic strip width, chips and nicks, grid line discontinuity, contact pinholes and color variations Also needed, once the above data is known, is the development and distribution of suggested modified cell standards. If mechanical requirements now imposed have no valid relation to cell environmental stability and can be relaxed, this could result in substantial savings for a space station solar array. It could lead to greater uniformity and predictability in cell performance by identifying the correlation of specific performance/fabrication/inspection factors

Desired Output - A realistic, cost effective solar cell specification which identifies and controls critical parameters without excessive cost penalties

5 4 5 Continued

Timing - Major recommendations should be available by the third quarter of 1972 for inclusion in the Development Program Plan

Recommended Program Elements

A review committee of leading NASA and industry solar cell users should be convened to obtain an aggregate of procurement experience, to summarize recommendations, and to review results of a test and evaluation program conducted at the cell suppliers under NASA direction

This test program should be started by taking categorized cells which are rejects, from production runs These cells should then be subjected to the standard electrical, mechanical and environmental tests which class A cells experience After publication and review of the test results, representative cells, from lower level of acceptance screening should be included in downstream temp cycle testing. It is estimated that starting in July 1971 and continuing thru December, that such a program could be accomplished for 60K.

Based on these results, a Space Station cell procurement specification should be prepared and possibly applied to other NASA programs as well

5 4 6 Project Title Cost Effective Cell and Cover Procurement Study

Priority

Category III There is a valid opportunity to increase production personnel competence and reduce cell costs by pre-programming cell production spans for Space Station Solar Arrays The usefulness to the user and the cell vendor of such a program have often been discussed, but the potential size of the Space Station array cell procurement makes such planning virtually mandatory to avoid excessive facility costs and insure availability The methods derived from this study could aid in all NASA cell or cover orders

References

1 Technical discussions with engineering and marketing personnel at OCLI, Centralab and Heliotek

2 This Report, Solar Cells, Section 4 1 3 3

Statement of Problem

Background - Cell and cover procurement has consistently been in a "peaks and valleys" category to the extent that on several occasions the vendors have had to reassign or lay off key production personnel This has meant rehiring, retraining, increase in operator error and rejects resulting in increased product costs A study should be conducted to assess the feasibility of intermittent quantity and delivery programming of components over flexible time spans up to a fixed completion date. Such a study will aid the vendor via more uniform facility and personnel use and will result in a lower cost, higher quality product. It would aid the government in providing lower costs of solar cell procurements for all programs Application of programmed cell procurement coupled with standardized cell procurement specification (5.4.5) by NASA across the board could result in more impact on cost and reliability than many of the more exotic R&D programs currently under contract

Desired Output - The ideal result would be an all NASA and Air Force programmed solar cell production schedule administered by a central procurement officer to a common procurement specification At minimum, a study of cost saving potential based on production projections for the next 10 years should be done

5 4 6 Continued

Timing - Cost and delivery figures should be generated prior to the third quarter of 1972 so that the results can be reflected in the Development Program Plan

Recommended Program Elements

This study should initially assess the shelf life factors associated with cells and panels (Much data is available from the ATM arrays and the Lockheed/Lewis SERT arrays with regards to shelf life) Arbitrary random pattern cell procurement plans should be quoted by the vendors Then cost impact of stop-start cell receipt for the panel fabrication process should be assessed based on past experience The final output of the study should be an early start date procurement plan for at least the Space Station and preferably NASA-wide It is estimated that such a study can be conducted for 20K.

5.4.7 Project Title Integrated Power Modules with On-Array Electronics

Priority

Category III The concept of voltage regulation, voltage limiting, or fault isolation through employment of multiple electronic modules mounted directly on solar array modules has several potential advantages including reduction of power transfer requirements, reduction of power dissipation in the spacecraft, and reduction of the probability of large percentage power losses due to individual circuit failure. This technology is an integral part of the solar array module design problem and although not an absolute necessity for technology readiness demonstration, it deserves major emphasis in developing downstream improvements to the baseline Space Station array flexible module. Limited design and exploratory test work conducted under the present program will form a basis for follow-on efforts

References:

1. This Report, On-Array Electronics, Section 4. 1. 3. 9

2. Discussions with Grumman concerning Space Station Battery System Design

Statement of Problem.

Background - Only very simple on array electronics concepts have been flown to date including by-pass diodes and Zener diode voltage limiters. On the Space Station, assuming a nominal 112 volt system unregulated voltage, excursions above 200 volts will occur at low array temperatures. Further, the preferred approach to battery charge control includes on-array switching, and solar array oversizing to to provide redundancy as well as a radiation degradation margin will result in the dissipation of up to 27 KW in excess array power during periods of low usage. These requirements make the ultimate use of some form of on-array power conditioning or heat dissipation a virtual certainty.

Desired Output - Under the present program, tradeoffs will be performed leading to a baseline electrical design selection, and test prototype panels will be fabricated with results of analyses and tests reported in the Design Handbook. Follow-on programs, based on this effort, should aim at improved circuit designs and life testing of full panel modules to evaluate life characteristics of advanced panel modules. The final output would be a life qualified building block power module for the operational Space Station.

5.4 7 Continued

Timing - Since the basic flexible module is not likely to be structure-peculiar, design and development iteration and life testing could be continuous up to final operational Space Station array design freeze. New circuits as well as new cell and cover assembly technology (5.3.2, 5.3.3, 5 4.1, 5.4.2, 5 4.3, 5.4.4, 5.4 8) can be factored into the design as they become available. Follow-on efforts should proceed starting in late 1972.

Recommended Program Elements

Based on the tradeoffs and testing under the present program, early augmented effort should concentrate on comparative testing of circuit elements and testing of alternate concepts recommended during the trade-off studies Electrical testing should be conducted on the panel module level, with early attention directed at heat rejection which has proven to be a limiting problem in past flight systems. The more promising configurations should be subjected to thermal cycle and radiation testing to simulated Space Station life cycles. In view of the central importance of the basic power module to the overall Space Station power system problem, added expenditures of as much as 400K per year appear justified beyond 1972 if enough promising component improvements come along under the other projects

5.4.8 Project Title Optical Filter Evaluation

Priority

Category III. A program is required to determine if the blue filter used on conventional coverglasses is actually needed to protect the present day, UV resistant adhesives. If not, there are possible savings of approximately 11% in the cost of coverglasses and power increases of over 8% are possible if a non-degradable "red' filter is developed. There are no plans to conduct an investigation of this nature under present programs. Any positive results of the above investigations would be applicable to all solar arrays flown in the future.

References.

1. This Report, Coverglasses, Section 4.1.3.4

Statement of Problem:

Background - Almost all solar arrays flown to date have had A. R. /blue filters. Exotech in its Handbook of Space Environmental Effects on Solar Cell Power Systems indicated that after only 735 sun hours, a blue filter experiences a 2.2% loss in transmission. After 2000 sun hours, Sylgard 182 adhesive with no primer experiences no loss in transmission. These test times by no means approach the Space Station life but they do indicate that a blue filter may not be needed. It should be investigated.

Also, there is a lack of information available in the literature indicating whether or not the existing AR coating applied to the coverglass is an optimum one with respect to reflectance, transmission, or degradation. This should be investigated. In addition, an investigation should be conducted to find a pure "red" filter that would not degrade in the space environment. (The basic transmission loss and degradation of present day "blue-red" filters make their net total effect negligible). The JPL report on an Improved Solar Cell Module shows that an ideal red filter would reduce cell operating temperature by 17.6°C.

Desired Output - If development were successful, the following gains might be realized:

- A blue filter may add as much as $0.32 to the cost of a coverglass If it could justifiable be eliminated, there are potential savings of $640,000 per Space Station in the cost of covers alone.
- The elimination of this degradable filter will produce perhaps a 2% increase in end of life power. This means 2% or approximately 40,000 less required solar cells on the SSSA if all other factors are constant. This is a savings of approximately $140,000.

5 4 8 Continued

Desired Output (cont'd)

- The addition of a non-degradable "red" filter would produce over 8% increase in power and therefore, 8% or 160,000 fewer cells would be required for the array if other cell factors are constant. This is a savings of approximately $560,000.

Timing - Some initial experimental data and cost information would be desirable in time to influence the Development Program Plan in late 1972. Complete environmental life data is required two years prior to qualification of flight panels to provide economic lead times for procurement.

Recommended Program Elements.

The initial program must involve generation of data in four areas to determine whether or not a blue filter is required.

- Transmission losses - the basic transmission loss of the cover experienced when a blue filter is applied should be determined.
- Cell operating temperature - it should be determined what effect the blue filter has on cell operating temperature, i.e., does it in fact give a cooling effect and if so, how much does it affect the power output.
- Degradation - the transmission losses due to degradation of the adhesive alone and of the blue filter-adhesive combination should be determined for exposures to ultraviolet radiation and possibly to low energy protons and electrons for periods of 5 to 10 years.
- Cost - the specific per-cell-production cost of adding a blue filter to a coverglass should be determined to evaluate cost savings.

A parametric study of all possible AR coatings should be conducted to find the optimum one with respect to low reflectance, high transmission and low or no degradation in the space environment.

Finally, investigations should be conducted to find a "red" filter that would reflect all light energy above 1.2 microns in wavelength. Work should be directed toward finding a filter that degrades little if any and has a high transmission. This filter would produce lower operating temperatures and thus higher cell power.

The above investigations would involve 3-4 man years of contractor effort.

5 4.9 Project Title Composite Structure Material and Joining Techniques

Priority

Category III. The attractive combination of strength and mass properties peculiar to advanced composites make this class of materials prime candidates for construction of the Space Station Solar Array deployment structure. High strength, high stiffness, low thermal expansion and low density - characteristic of graphite/organic advanced composites - are desirable properties for space systems. Weight savings in the range of 1,000 lbs per space station could be realized on the basis of replacement of aluminum structures with graphite epoxy. In addition, stiffness, (one of the major design parameters) could be increased 5 times providing excellent alignment potential for extension and retraction of the large array system Thermal deflection would be reduced to an absolute minimum with the extremely low coefficient of expansion (approximately 1×10^{-6} in/in°F).

Based on present evaluation of state-of-the-art, these materials will not be employed in the present space station program, except that design studies will identify possible downstream applications of this technology in the hope that downstream improvements in weight and stiffness can be realized.

References:

1. This Report, Structural Materials, Section 4.1.2.1

Statement of Problem

Background - Prior to 1977 launch, much of the mechanical properties data for advanced composites will have been established by expanded use in aircraft and spacecraft. However, solar array structure designs will employ composites in much thinner gauges than normally used for structural applications. Development of properties in thin sections (2-3 mil range) are difficult to test, but must be verified. Durability of organic matrix materials in orbit must be reliably predicted. Verification testing for long duration life times must be initiated as soon as possible.

Compatibilities with conductive and insulative coatings, longevity of each, means of repair or replacement in space are other considerations which must be evaluated for successful utilization of a graphite/organic material system or any other system under consideration.

Creep fatigue effects from temperature cycling (up to 60,000 cycles) in the space environment should be a long-term advanced study for these materials, and the bonding methods used to join them.

5 4.9 Continued

Background (cont'd)

There are also problems in standardizing the materials between manufacturers and quality control over batches of graphite epoxy.

Desired Output - Sufficient graphite composite materials data for design of solar arrays structures using thin sections in low earth orbits for periods up to 10 years, including strength degradation due to fatigue, radiation, temperature, and outgassing.

Timing - Results should be available to include this material in the solar array development phase beginning in late 1973.

Recommended Program Elements·

In addition to the generation of the basic properties stated above, shapes should be fabricated based on the baseline Space Station array designs. These shapes should be tested structurally and thermally and, assuming that the basic creep and radiation degradation properties prove satisfactory, improved structural elements (boom sections, etc.) should be fabricated and tested to the same conditions as the baseline structure and, if successful, incorporated as an improved baseline. In view of the high potential payoff in weight and stiffness, added expenditures of the required 100K-200 per year in this area appear justified.

5.4.10 Project Title Test and Evaluation of Alternate Power Transfer Device

Priority

Category III. Slip rings and flex harnesses are both being considered for Space Station Solar Array baseline design approaches. Potential reliability advantages have been identified with alternate devices such as power clutches and rotary transformers, but very little basic work has been done on such devices on which to base a power transfer system design. Potential payoffs in reduced maintenance or logistic requirements justify further experimental effort in these areas.

References

1. This Report; Power Transfer Devices other than Slip Rings; Section 4.2.3.2

Statement of Problem.

Background – Currently slip rings or flex harnesses are the only flight demonstrated methods of power transfer across a rotating joint. Flex harnesses are restricted to reset or limited rotation. It has been determined that continuous rotation slip rings are required in one and possibly two axis. Because of the mandatory scale up in both size and current carrying capacity, it is deemed critical to evaluate backup transfer systems such as power clutches or rotary transformers for the Space Station array application. The MSC/Lockheed program will evaluate duty cycles and current density on slip rings. However, it is beyond the scope of this program to adequately test potential backup devices.

Power clutches and rotary transformers for space applications are relatively new devices. As yet no operational testing or reliability testing has occurred on power clutches. Power clutches built to date are in the demonstration model or mockup category.

In power clutch operation, the holding pressure can be much higher than could be considered using a slip ring because of the excessive ring and brush wear resulting from the high pressure. This higher pressure means that the contact resistance is lower than that possible from slip rings. Hence less energy is lost in this interface and power transfer efficiency is high. A rotary transformer has many potential advantages including no wear or wear products, no arcing, negligible friction, no viscous drag from liquid contact, and energy transfer relatively unaffected by the presence of oil, water, or other contaminants, but further experimental work is needed to determine the practicality of such devices for high power application.

Desired Output – The major area where technology does not exist for development of the power clutch is with face plate materials and lubricants. Much that is known about switches, relays and contractors is directly applicable to power clutches. The degree of applicability needs to be evaluated and related to feasible face plate designs. The capability should be developed to state the design impact that use of power clutches or rotary transformers would have.

5.4.10 Continued

Recommended Program Elements

The initial efforts should include

Power Clutch

(1) Perform conceptual design to determine scale up feasibility and weight.

(2) Perform parallel contacted, face plate tests to determine the extent if any of make before break arcing.

(3) Construct development model and run tests similar to planned slip ring tests.

Rotary Transformer

(1) Perform conceptual design to determine scale up feasibility and weight.

(2) Determine the complexity associated with mandatory power conversion equipment on the array root.

(3) Determine the space allocation impact associated with conversion and transformer components.

(4) Construct development model and run tests similar to planned slip ring tests.

The above represents an 18 month to 2 year effort of approximately 200K. Following this effort, one approach should be adopted and a full scale prototype built and placed on life test as a backup for the baseline power transfer system.

Section 6

BIBLIOGRAPHY OF SOLAR ARRAY TECHNOLOGY

The bibliography section is made up of the following three parts.

- Part 6.1, a description of the bibliography content, code for looking up referenced documents, and method of determining value of listed documents for use on this program.
- Part 6.2, list of documents reviewed and used in preparing the Solar Array/Structure portion of the report.
- Part 6.3, list of documents reviewed and used in preparing Orientation/Power transfer portion of this report.

6.1 DESCRIPTION OF BIBLIOGRAPHY

The bibliography is divided into two major subject categories, (1) Solar Array and Structures and (2) Orientation and Power Transfer. Report content made it imposs ble to categorize further by subject; therefore, in each of the major sections the documents are listed in alphabetical order by company or by Government Center if no outside contract was involved. Listings are coded with a one letter, two number, group such as A.2.3 which designates the following A refers to all companies whose name starts with A; 2, refers to the second company in the A listing; 3, refers to the third document in the listing under that company. In each listing documents are identified by contract number or by conference, symposium, or journal number and by title, month, and year of publication. In addition, a brief abstract of the subject matter treated in the document was added to the bibliography.

To maximize the usefulness to the power system designers, a code was used to indicate whether or not a document had information regarding a specific subject and whether or not it was applicable to the Space Station. The code is as follows

(1) A solid black dot in a column means that the report information concerning that subject is directly applicable to Space Station power system design.

(2) An open dot means the information is useful but not directly applicable.

(3) No dot indicates the document is not considered applicable at this time.

Bibliography coding was designed to be open-ended to allow addition of documents in every area.

TECHNOLOGY EVALUATION – BIBLIOGRAPHY

DOC NO.	ORIGINATOR/DOCUMENT IDENTIFICATION	DATE	BRIEF ABSTRACT	DESIGN SUPPORT FLT SCIENCES	ARRAY BLANKET: SUBSTRATES	ARRAY BLANKET: CELL COVER	ARRAY BLANKET: CELL INTER-CONNECT	ARRAY BLANKET: SOLAR CELLS	ARRAY BLANKET: POWER CONDITIONING	ARRAY STRUCTURE: STOWAGE METHOD	ARRAY STRUCTURE: PROTECTIVE PADDING	ARRAY STRUCTURE: DEPLOY / RETRACTION	ARRAY STRUCTURE: END SUPPORT	ARRAY STRUCTURE: SUPPORT STRUCTURE	ARRAY STRUCTURE: POWER TRANSFER	ARRAY STRUCTURE: EXTENDIBLE STRUCTURE
	AEG TELEFUNKEN															
A 1-1 & A 1-2	Contract ESRO 459/67A Title Study on Development of Improved Interconnected Techniques for Silicon Solar Cell Arrays 1st & 2nd Quarterlies & F R.	May 68 thru Jun 69	Developed a solderless contact which allows for using welded interconnections in cell modules - based on the electro-mechanical passivation of Ti/Ag contacts by means of a Pd interlayer Corrosion of standard Ti/Ag contacts explained.				●	●								
A.1-3	Manufacturers Publication Title Covered Silicon Solar Cells for Space Applications	No Date	Passivated titanium-palladium-silver contacts and high-power output Ti-02 antireflection coatings on qualified production cells. Electrical characteristics, I-V curves & spectral response reported.					●								
A 1-4	Company Publication Title: Informations Space Activities Solar Arrays	No Date	Brochure giving history of solar cell activities in this company New type solar cell contacts and coatings described, including techniques for interconnects.				●	●								
A.1-5	7th Photovoltaic Spec Conf. Title New Aspects for the Choice of Contact Materials for Silicon Solar Cells	Nov 68	Passivation of contacts by shifting the electrochemical exchange potential of Ti-Ag couple into positive direction by addition of Pd. Withstand temp and are compatible with solderless interconnection schemes.					●								
A 1-6	8th Photovoltaic Spec Conf. Title Influence of Controlled Lifetime Doping on Ultimate Technological Performance of Silicon Solar Cells	Aug 70	Theoretical & experimental studies correlating the electrical performance of 10 ohm-cm n/p cells with thickness and minority carrier diffusion length New post-process getter step innovated regenerating carrier lifetime in base region.					●								
A. 1-7	8th Photovoltaic Spec Conf. Title Silicon Solar Cell Technology of the Seventies	Aug 70	Improvement of cells by incorporating new technologies such as passivated Ti (Pd) Ag contacts together with a rp-back contact. Cells survive storage at elevated temps or in humid atmosphere. New wrap around contacts and cover glass techniques are discussed.			○		●								
	AF-AEROSPACE RESEARCH LABS															
A.2-1	Contract: F04701-68-C 0200 Title Low-Energy Proton Effects on IDCSP/A Solar Cells	Aug 68	Technical operating report IDCSP/A (Initial Defense Communication Satellite Program Augmentation) Cells representative of phase on program tested in proton environment (synch altitude) 10-year equivalent exposure. Reduced power level only 1%.					●								
A 2-2	Contract: F04695-67-C-0158 Title: A Technique for Estimating Space Power Systems Cost	Oct 67	1968 DOD Space Power Study used for data employed in costing Cost-scaling factors for integrating each type of power system into a payload. Details of estimating procedure are given.													

LEGEND-

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A.2-3	6th Photovoltaic Spec Conf Title Solar Cell Power Systems for Air Force Satellites	Mar 67	Work under contract AF 04 (695)-1001 Attempt to give solar cell specialists an understanding of practical considerations important to program engineers				●	○								
A.2-4	Contract F04701-70-C 0039 Title: Micro-creep of a Polymetric Adhesive	Jul 70	Adhesive Epekote 816 was subjected to creep test at 30°C under torsional shear load for 6 months. Test fixture design & assembly described. Creep measured with an automatic autocollimator-linear sensitivity of $5x10^{-8}$ in.													
A.2-5	8th Photovoltaic Spec Conf Title: Low-Energy Proton Irradiation of Solar Cell Back Contacts	Aug 70	Work under contract AF-F04701-69-C-0068 Experimental investigation using n/p solderless cells 1x2 cm, 15 mils thick. Irradiation by monoenergetic protons, energies from 0.6 to 2.0 Mev Measurements of current voltage relationship reported.					●								
A 3-1	AF-APL WRIGHT-PATTERSON Internal Rept. AFAPL TR-69-17 Title Radiation and Angular Response of Experimental Solar Cells in A 2000 Nautical Mile Polar Orbit	Jun 69	Experimental cells (ion implanted Si CdS thin films, cadmium telluride, dendritic Si and drift field) modules flight tested to determine environmental resistance, define operational problems and the severity of the environment over a one-year period.					○								
A.3-2	IECED Paper Title: An Analysis of Low Orbital Drag Constraints of Orbit- and Sun Oriented Solar Cell Arrays	Aug 67	Low earth-circular orbits of 100 to 700 nm selected. Arrays sized at 22.8 lb/kW and 100 ft²/kW Drag makeup system computed for each array concept in line with AF effort to develop a flex 20 kW array	○												●
A.3-3	5th Photovoltaic Spec. Conf. Title. Progress on Cadmium Telluride Thin Film Solar Cells	Oct 65	Work under contract AF 33(657)-10601 & 33(615)-2655 with GE Technology for economical fabrication of efficient lightweight radiation resistant thin film cells. Progress toward larger cell areas & improved efficiencies is reported. Prelim. test results presented.					○								
A.3-4	6th Photovoltaic Spec. Conf. Title. Integral Covers for Solar Cells	Mar 67	Preliminary solar cell performance & spectral response measurements, in addition to vacuum - UV and thermal cycling tests on integrally coated cells. NRL made performance measurements before & after 400 Kev proton irradiation.			●										

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A 3-5	7th Photovoltaic Spec. Conf Title Hardened Solar Cells	Nov 68	3 new cell types hardened against nuclear weapons effects investigated. p/n cells n/p cells and multilayer solar cells. Cell designs rationale for designs, program results and future effort discussed.													
A 3-6	7th Photovoltaic Spec. Conf. Title: Large Retractable Solar Cell Array	Nov 68	Demonstrates flex array concept in multi-kilowatt range Hughes aircraft contracts AF 33(615)-2750 and F 33615-68-C-1678 are reviewed & evaluated. Flight test plan described.									○		○		○
A 3-7	Internal Doc. Tech. Rept. 32-1321 Title: Mariner Venus 67 Solar Panel	Apr 70	Describes the design, manufacture assembly, testing and performance used on this system. Remarks on adequacy of the design and recommendations for future missions of this type.					●	●							
A 4-1	ALPHA METALS INC Electronic Packaging & Production Article Title: The Case for Solder Preforms	Dec 68	Shaped as required with or without flux, these handy manufactured solder configurations help produce superior points Although higher in cost the preforms allow fully automated assemblies at reduced cost.				●									
A.5-1	AMERICAN ELECTRONICS LAB Machine Design Article Title. The Silver Migration Problem	Jun 70	Silver-plated electronic hardware and humid environments are incompatible. Problem is silver migration. Possible solutions to the problem are presented.				●									
A.6-1	AMF CO. Contract AF33(615)-1853. Title: Design of Tubular Extendible Booms for Structural Applications	Jun 65	Criteria for design procedures and allowables reported. Investigation of beryllium-copper as best suited material. 20-foot length and diameters up to 2 inches tested. Models of reeling mechanisms constructed and tested.	●												●
B.1-1	BELLCOM INC Annual Aviation & Space Conf. Title: Solar Array Performance as A Function of Orbital Parameters & Spacecraft	Jun 68	The effects of all parameters of a circular earth orbit on array performance is studied. Several combinations of a passively-stable local-vertical attitude and either a fixed array or an array with a single incremental degree of freedom are compared with a sun-oriented array	○												

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B, 2-1 thru B 2-3	BRITISH AIRCRAFT CORP Contract. ESRO No. 623/68 sl Title A Study of Advanced Solar Array Design 1st, 2nd, and 3rd Quarterlies	Jun 69 thru Nov 69	Evaluation of improvements in solar array technology with respect to stowage volume and power-to-weight ratio Built and tested two flexible arrays, one for qualification and the other for acceptance testing. Subjects treated: flexible substrates, cell cushioning & adhesives, cell attachment and interconnection stowage & deployment system, dynamic characteristics of array & spacecraft		●		●	○		●	●	●	●	●	●	●
B, 2-4	CNES Symposium Paper Title. The Structure of UK-3	Jun 65	Third in a series of joint Anglo-American scientific research satellites. Launched at WTR end of 1966 Three-year design development, manufacturing, & test program reviewed. Shape, body design and boom erection analysis reported.													○
B, 3-1 thru B, 3-4	BOEING Contract. JPL 951653 Title: Large Area Solar Array – Phase I 1st, 2nd and 3rd Quarterlies and Final Report	Sep 66 thru Nov 67	Follow-on to the Feasibility Study 20 watt/lb contract which included prel. design (baseline selection) of a 47 4 kW-folding modular array using beryllium structure. Power source for (electric propulsion & outboard) mass fly-by probe Phase I was a detail design effort, analytical verification, detail design and partial experimental verification of the 1250-ft panel assembly included detail design of ground support equipment and critical items for Phase II.		○		●	●		○	○	○		○	●	●
B, 3-5 thru B, 3-8	Contract: JPL 951934 Title Large Area Solar Array Phase II 1st, 2nd and 3rd Quarterlies (2) and Final Report	Sep 67 thru Oct 68	Advance technology in lightweight electrical power systems (50 kW) for interplanetary spacecraft flights during 1970s and 1980s. In Phase II developed manufacturing technology by fabricating one subpanel, developed zero-g deployment test equipment & procedures. MTA-1 (major test article) subpanel fabricated & tested (8 x 13 ft). Dynamic response for MTA-1 determined by vibration test in air and vacuum. Manufactured G, S, E.	○	○		●	●		○	○	○		○	○	

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B 3-9	Contract JPL 952371 Title Lightweight Solar Panel Development Final Report No Quarterlies	Jul 69 thru Jul 70	LASA Phase III indefinitely postponed because Mars electrical propulsion mission was eliminated This contract called for design fabrication and test of a solar panel for Mars orbital mission (Viking backup) Use LASA technology (20 watts/lb) for a 1 kW solar array on 1973 Mars flight. Prepared procedures and processes for lightweight solar panels Determined zener diode characteristics when installed on solar panel Complete test results discussed – acoustic sinusoidal vibration thermal/vacuum shock, power output and substrate frequency	○	○		●	●								
B,3-10	Contract. NAS3-8995 (LeRC) Title High Voltage Solar Array Electrical Config Study F R.	Apr 70	Increase reliability and reduce weight of high-voltage solar-cell power systems 15 kW 2 to 16 kV integrally regulated array Computer controlled shunting of modules and switching approaches described.	●			●	●	●							
B,3,11	Raumfahrforschung article Title Technology of Large (1 to 5 Kw) Solar Arrays	Mar 65	Fallout from contract JPL 951934 Paper describes techniques for packaging interconnections cover glasses structures & assembly Future trends outlined.		○	○	○	○								
B,3-12	Aerospace Structures Design Conf. paper Title Structural Design Experience on Beryllium Solar Array	Aug 69	Fallout from contract JPL 951934 Paper discusses beryllium structure bonding columns and tensile stresses, fabrication techniques and some test results.							○	○	○		○	○	
B,3-13	Contract. NAS 9-1659 (Hdgs) Title Investigation into the Mechanism of Degradation of Solar Cells with Silver-Titanium Contacts	Jul 70	Physical measurements by electron micrographs x-ray diffraction mass and internal reflection spectroscopy Electrochemical tests included polarization, rest potential and chemical environment-effects measurements.				●	●								
B,3-14	IECEC Paper Title Discussion of Power Systems for Solar Probes – Solar Photovoltaic Concepts	Sep 66	Passively cooled solar cell systems rather than conventional flat panels, are possible for probes 0 closer than 0 2 AU to the sun. Such concepts as the sawtooth, optical reflector elevated absorbing filter etc are analyzed.													

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B 3-15	IECEC Paper Title Structural Problems Associated with Development of Large Deployable Solar Cell Arrays	Aug 67	Fallout from JPL contracts 951653 & 951934 Discusses selection of materials Compares candidate materials for prime structure substrates & thermal control coatings Some evaluation test requirements briefly covered	○								○				○
B 3-16	IECEC Paper Title Development of Electrical Design Concepts For Large Area Solar Array	Aug 67	20 watt/lb (4900 ft^2) solar array for electric-propulsion-type Mars-bound spacecraft Magnetic effects power losses & diode losses are discussed Testing of cells interconnects and buses is described				○	○	○						●	
B 3-17	IECEC Paper No 699065 Title A Technique for Identifying the Cause of Performance Degradation in Cadmium Sulfide Solar Cells	Sep 69	Effect of changes in five physically meaningful parameters on the I-V curve of a CdS solar cell is calculated. Calculated and performance data are compared. The parameter that changed to cause degradation is identified					○								
B 3-18	IECEC Paper No 699095 Title Lightweight Large Area Solar Arrays	Sep 69	Comparison of features of drum rollout flat foldout and flat rollout solar array concepts Discussion of future applicability & potential							●		●				
B 3-19	6th Photovoltaic Specialists Conf Paper Title Cadmium-Sulfide Solar Cells in A Deployable Array Composed of Rigid Frames	Mar 67	Three basic deployment methods compared CdS cells on flex membrane rollup, cells on membrane deployed by inflatable structure and cell substrate on rigid frames coupled by hinges springs cables etc		○		○	○						○		
B 3-20	5th Photovoltaic Spec Conf Paper Title: A 50 kW 20 Watt/Pound Solar Cell Array Feasibility Study	Oct 65	Fallout from contract JPL 95132 (Feb-Dec 1965). Array configuration studies semi-rigid fiberglass substrate and rectangular panel shaped joined by hinges Description of prototype interface and development problems													
B 3-21	5th Photovoltaic Spec Conf Paper Title High Voltage Solar Array Operation in the Ionosphere	Aug 70	15 kW 2 to 16 kV ion thrusted spacecraft that spirals from 100 nm out to synchronous in 3 months High voltage solar array loses power if leakage current flows through plasma. Several solutions to this problem are discussed.					●								
B 3-22	Contract NAS3-10445 Title Develop. of Solar Panel System for Thermally Annealing Radiation Damaged Solar Cells First Quarterly	Oct 67	Design & build two operable 1 ft^2 panels to withstand 10 thermal annealing cycles 20 to 450°C Thermal diffusion bonding process developed Thermal analysis to evaluate heating methods & prelim panel design reported													

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B 3-23	Contract NAS3-6008 Title Simulated Space Environmental Tests on Cadmium Sulfide Solar Cells F R	Feb 69	Environmental tests of cells manufactured in 1967 & 1968 Pressure less than 10^{-8} Torr UV and thermal cycles between -100°C & 60°C Degradation of characteristics at 500 and 2000 cycles reported					○								
B 3-24	2nd Aerospace Mechanisms Symposium Title New Closed Tubular Extendible Boom	May 67	Development of MAST (Multiple Application Storage Tube) collapsible tube which can be used to transport fluid and transmit torque Design guide data presented Development work described.													●
B 3-25	1st Power Conditioning Conf Title A Regulated Solar Array Model – A Tool for Power Systems Analysis	Apr 70	Mathematical models of key elements of digitally regulated solar array system is presented. Used for performance evaluation of interface between source and load. Permits easy incorporation of source performance changes						●							
B 3-26	8th Photovoltaic Spec Conf Title The Fundamental Mechanism of Humidity Degradation in Silver-Titanium Contacts	Aug 70	Silver layer promotes capillary condensation of water when humidity exceeds critical value Varies with manufacturer. Titanium reacts electrochemically with water to form hydrogen & titanium oxides Halogen contaminants accelerate the process					●								

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	BROWN UNIVERSITY, R I															
B 4-1	Contract JPL-952386 Title Investigation of the Effects of Sub-Threshold High Energy Electrons on Properties of Silicon Photov Cells (F R)	Feb 70	Measurements of photovoltaic characteristics of p/n lithium doped p/n conventional and n/p cells Damage rates compared for electron radiation at 90°K A deflection circuit to produce a scanned electron beam pattern is described					○								
	CALIFORNIA INST OF TECH															
C 1-1	Title Coverplate for Solar Cell Panels Patent Application	Jan 70	Invention to control the illumination of cells as mission progresses from earth to sun Object origin and summary of three inventions are presented													
	CARA CORP															
C 2-1	Contract NAS 8-1732 Title The Relation Between Solar Cell Flight Performance Data & Mfg Data	Apr 70	Examined flight performance data (1957-67) for satellite solar systems and related differences in performance to materials and manufacturing factors Data retrieval was cumbersome & costly Ended up designing a data gathering & storage system for the future	○												
	CENTRA LAB (GLOBE-UNION/HOFFMAN)															
C 3-1	Contract NAS3-3557 Title Integral Glass Coatings for Solar Cells (F R)	Nov 64	Research investigation varying glass layer thickness from 2 microns to 20 mils Applicable only to missions where passive thermal control & low energy radiation dominate Production feasibility demonstrated			●										
C 3-2	5th Photovoltaic Spec Conf Title Integral Glass Coatings for Solar Cells	Oct 65	Centrifugally deposited ground glass powder fused to silicon Thickness control & hydrofluoric acid dip for higher thermal emittance achieved. Tests for radiation resistance reported			○										
C -3	6th Photovoltaic Spec Conf Title Experience with & Future of Lithium Containing Silicon Solar Cells	Mar 67	Work under contract NAS 5-10271 Two methods of doping discussed. lithium suspension in oil or wax deposited on silicon & heated to diffuse in the lithium lithium metal thermally evaporated & subsequently heated I-V characteristics presented					○								

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DOC NO	ORIGINATOR/DOCUMENT IDENTIFICATION	DATE	BRIEF ABSTRACT	DESIGN SUPPORT FLT SENSORS	ARRAY BLANKET: SUBSTRATES	ARRAY BLANKET: CELL COVER	ARRAY BLANKET: CELL INTER-CONNECT	ARRAY BLANKET: SOLAR CELLS	ARRAY BLANKET: POWER CONDITIONING	ARRAY STRUCTURE: STOWAGE METHOD	ARRAY STRUCTURE: PROTECTIVE PADDING	ARRAY STRUCTURE: DEPLOY/RETRACTION	ARRAY STRUCTURE: END SUPPORT	ARRAY STRUCTURE: SUPPORT STRUCTURE	ARRAY STRUCTURE: POWER TRANSFER	ARRAY STRUCTURE: EXTENDIBLE STRUCTURE
C 3-4	Internal Document - copyrighted Title. Solar Cell Space Manual	66	Inner working of a semiconductor cell both electrically and mechanically described Modules & arrays regarding design and fabrication techniques environmental effects and measurement method complete the manual			●		●								
C 3-5	7th Photovoltaic Spec Conf Title Effects of Lithium on Solar Cell Properties	Nov 66	Survey of effects of lithium on solar cell properties Results of measurements performed on cells fabricated with varying amounts of lithium are reported Present understanding of pre-irradiated properties can help explain post-irradiation performance					○								
C 3-6	8th Photovoltaic Spec Conf Title: Improved Silicon Solar Cell Anti-reflective Coatings	Aug 70	Both monochromatic and achromatic coating treated theoretically and experimentally AMO short-circuit current spectral reflectance and AMO response measurements are reported					●								
C 3-7	ASME Paper Title How Mechanical Requirements Affect Solar-Cell Costs	Jun 70	Describes typical present day specifications and discusses how cell costs could be reduced with no loss of output or reliability If some of the mechanical and visual requirements were relaxed Mechanical electrical and environmental test tolerances are discussed					●								
C 3-8	8th Photovoltaic Spec Conf Title Increased Output from Silicon Solar Cells	Aug 70	Describes high output cells (exceeding 14 mw/cm² in space sunlight) Discusses the probable impact upon the state-of-the-art both for practical applications and in providing an even closer approach to the theoretical maximum output					●								
	CENTRE NATIONAL DE LA RESEARCHE SCIENTIFIQUE (PARIS)															
C 4-1	7th Photovoltaic Spec Conf Title Photovoltaic Effects in Graded Band Gap	Nov 65	Theoretical presentation of effects in non homogeneous semiconductors taking into account variations of band gap effective masses mobilities majority carrier concentration and pair lifetime					●								
C 4 2	7th Photovoltaic Spec Conf Title Contributions to CdS-Cu_2S Solar Cell Studies	Nov 65	Investigation of CdS resistivity Cu_2S layer thickness effecting characteristics of this cell Work supported by CNES contract N /459 development of this polycrystalline solar cells at SAT lab					●								
	CLEVITE CORP															
C 5-1	Contract AF33(615) 5324 Title Research on the Mechanism of the Photovoltaic Effect in High Efficiency CdS Thin Film Solar Cells	Oct 69	3 years research Clevite solar cell model is described Objections to specific parts of model and alternate schemes are discussed. Data on autoMonochromatic spectra response is reported X ray crystallographic & optical transmission data included					○								
C 5-2	Contract F33615-6?-C 1152 Title Improvements in CdS Thin-Film Solar Cells	Mar ?	Results of flight experiments panels on OV 1-13 & OV 1-1 satellites reported also modules aboard 6 -64-69 JPL balloon flights Developmental effort for improving the stability and efficiency of these cells is reported					○								

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C 5-3	5th Photovoltaic Spec Conf Title The Thin Film CdS Solar Cell	Oct 65	Summarizes the progress made since understanding the functioning of the component parts of the cell The construction of design improvements present problems and future possibilities are discussed					○								
C 5-4	5th Photovoltaic Spec Conf Title Thin Film Plastic Substrate CdS Solar Cells	Oct 65	Large area cell efficiencies greater than 7% obtained Design of plastic substrate cells and methods of processing are described along with indications of present problems and anticipated improvements					○								
C 5-5	6th Photovoltaic Spec Conf Title The Status of the Clevite CdS Thin Film Solar Cell	Mar 67	Summary of development from wall cell of both plastic and copper foil substrate given Recent changes and further improvements discussed. Stability characteristics under shelf storage humidity and high temperature described.					○								
C 5-6	7th Photovoltaic Spec Conf Title The Mechanism of the Photovoltaic Effect in High Efficiency CdS Thin Film Solar Cells	Nov 68	A tentative Cu_2S/CdS heterojunction model was studied by electrical optical & chemical measurements Results verify essential features of the model Cell efficiency increased by improvement in electron lifetime in Cu_2S					○								
C 5-7	LeRC Symposium on CdS Thin Film Solar Cells Title Progress in the Fabrication of CdS Thin Film Solar Cells	Apr 70	Two major difficulties to overcome output drop off with cell age and humidity sensitivity Major change in cell fabrication to increase efficiency and lifetime are described New Clevite facilities are presented					○								
	COMSAT															
C 6-1	7th Photovoltaic Spec Conf Title Low Energy Proton Damage in Silicon Solar Cells	Nov 69	Report on cell current degradation at fixed voltages to nominal 10 ohm-cm cells with coverslips which are irradiated by 1-0 and 270 kev protons Damage is dependent on exposed area and proton energy					●								
C 6-2	8th Photovoltaic Spec Conf Title Statistical Analysis of One Mev Electron Irradiation of Silicon Solar Cells	Aug 70	Van-de-Graaff accelerator used Float zone refined silicon performed best Cells covered with TiO_2 and SiO_2 anti-reflective coatings. All n/p cells had same efficiency after $3x10^{-14}$ (1 Mev) electrons/km^2					●								
C 6-3	IECEC Paper 699091 Title Evaluation of the Performance of Solar Arrays on Intelsat Spacecraft at Synchronous Altitude	Sep 69	Discusses performance on Early Bird, Intelsat II F-3 and F-4 Data indicates 21% degradation on Early Bird (4 year orbit) 19% on INTELSAT II and F-3 (2 year orbit) Data indicates degradation due to low energy protons similar to lab experience													

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C 6-4	1st Power Conditioning Spec Conf Title Communications Satellite Power Conditioning Systems	Apr 70	Review of power-conditioning systems on INTELSAT I through IV Ni-Cd batteries during eclipse operation Different methods for battery charging charge control voltage regulation and power management on each vehicle Advantages & disadvantages discussed	○												
C 6-5	7th Photovoltaic Spec Conf Title. Irradiation Studies on State-of-the-Art Cadmium Sulfide Cell	Nov 68	Work sponsored by Intelsat Proton (energies 250 Kev to 5 0 Mev) irradiation of cells and Kapton coverslides Data provided on short circuit current open-circuit voltage maximum power & current also Kapton transmission data			●										
C 6-6	Int J Solar Energy Soc Conf 1970 Title Solar Cell Research at Comsat	Mar 70	Data from studies of low energy proton irradiations on partially shielded silicon cells 1 Mev electron irradiations and thermal cycling of cadmium sulfide cells Support work for the International Satellite Consortium					○								
	DEHAVILLAND AIRCRAFT-CANADA															
D 1-1	Contract AF33(615)-2724 Title Boom Attachment System	Aug 70	Astronaut work outside spacecraft entails difficulty to maneuver and keep station A rigid boom attachment device (evaluation model) based on STEM was carried out. Detailed hardware description presented													○
	DENVER RESEARCH INST.															
D 2-1	Contract JPL-952533 Title The Effects of Space-Particle Bombardment on Solar-Cell Materials	Mar 70	Effects of proton bombardment of silicon cells by electronic measurements, electron microscopy and x-ray topography Experimental approach and results of the latter two techniques are discussed.					●								
	DYNACHEM CORP															
D 3-1	Dynachem Tech Data Bulletin Title. Dynaplate Electroless Tin-Lead EBS 250	Jul 70	EBS 250 represents a major breakthrough in chemical plating technology This is a tentative operating instructions bulletin.				●									
	ELECTRO-OPTICAL (EOS)															
E 1-1	Contract JPL952485 Title Res & Dev of Electroformed Aluminum Solar Cell Contacts & Interconnects	Oct 69	Results of studies in photo-resistant masking optimization of the plating process and effects of sintering are reported. Production of electroformed aluminum contact cells with >10% AMO efficiency reported				●	●								

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E 1-2	Contract NAS3-10187 Title Lightweight Solar Panel Interconnects F R	Aug 67	Developed technology to electroform silver or copper interconnections between wrap-around silicon cells with Ag Ti sintered contacts Developed mandrels and masking for single cell tabs two cell interconnects four cell modules Interconnections process spec included				●	○								
E. 1-3	Contract: JPL 952035 Title Planetary Solar Array Development	Jan 68	Selection of four promising array concepts and comparison of their characteristics Solar cell circuit & substrate design and materials study results Heat balance & structural analysis presented	○												
E. 1-4	5th Photovoltaic Spec Conf Title: Status of Advanced Solar Cells at Electro-Optical Systems Inc	Oct 65	Work under contract NAS 5-3560 Development of silicon drift field & thin (0 004 in. single crystal cell having 8-10% efficiency Radiation resistant cell employing a built-in electrostatic field described Open circuit voltage degradation discussed					○								
	ESRO (EUROPEAN SPACE RESEARCH ORGANIZATION)															
E. 2-1	Title Integration of Solar Cells into Modules	Aug 70	Problems associated with layout and construction of cell modules and module mounting techniques are discussed Review of interconnector and contact materials Transmittance degradation of cover slips & adhesives by irradiation discussed			○	○									
E 2-2	Title Increased Solar Cell Output by Improved Optical Matching Part I Theoretical Considerations	Mar 69	Derivation of formulas for reflection phenomenon including outer space sunlight distribution and spectral response of cells Optimum anti-reflection layer for covered & uncovered cells calculated Calculated & measured reflection compared	○		○		○								
E. 2-3	Title Design of Solar Cell Arrays and Their Performance in Space	Aug 69	Description of parameters important in design of solar generators Review of characteristics of fixed and oriented arrays and their mechanical design Electrical interconnection methods shadow effects & reliability considerations presented				○									
E 2-4	Title Advanced Solar Cell Array Concepts	Aug 69	Areas of potential improvements determined. Power-to-weight ratio increased to 40 watt/kg New designs for structure of array panels discussed Design basic problems reviewed. Thin film solar cell developments described					○						○		
E 2-6	Sixth ESRO Summer School Proc. Title Space Power Systems Photovoltaic Energy Conversion	Nov 69	Papers Photovoltaic Effect Solar Energy Conversion Solar Cell Performance Thin Film Solar Cells Cell Calibration & Solar Cell Testing Problems					○								
E. 2-7	7th Photovoltaic Spec Conf Title The Photovoltaic Effect in the Cu-Cd-S System	Nov 68	Critical examination of models of proposed photovoltaic cells Spectral response measured and calculated for model in which Cu_2S layer plays a role are discussed Cross-over of dark and light I-V characteristics described					○								

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E 2-8	7th Photovoltaic Spec Conf Title Photoconductivity Study of Annealing of Radiation Defects in Lithium-Doped Silicon	Nov 68	Single crystal wafers containing various concentrations of oxygen phosphorus and boron irradiated by 2 Mev electrons Photoconductivity at longer wavelengths than the silicon absorption edge were measured Annealing at 300°K described					○								
	ESRTC															
E 3-1	8th Photovoltaic Spec Conf Title Environmental Study of European Silicon Solar Cells with Improved Anti-reflection Coatings	Aug 70	Silicon cells from four European suppliers compared for recently innovated titanium oxide and conventional anti-reflection coatings Small worthwhile improvement by replacing silicon monoxide with titanium oxide coatings					●								
E 3-2	8th Photovoltaic Spec Conf Title Status of Welded Solar Cell Module Technology at ESTRO	Aug 70	Development of welding techniques for cell modules is reviewed Design requirement established Welded (resistance welding) joints show resistance to keep thermal cycling to -180°C or lower				●									
	EXOTECH INC															
E 4-1	Contract NAS-no number Title Solar Cell Performance Mathematical Model 1st Quarterly only	Jun 69	Effort to prepare a computer program for silicon cell performance in space environment Previous model reviewed in light of current research activity for improvement & alternative techniques	○												
E 4-2	Contract NASW-01345 Title Handbook of Space Environmental Effects on Solar Cell Power System	Jan 68	This volume revises updates and expands the July 1963 handbook It is a single source of analytical methods & experimental data for design engineers Space-radiation and meteroid effects are discussed			●		●	●							
	FAIRCHILD-HILLER															
F 1-1 thru F 1-4	Contract JPL 951969 Title Fabrication Feasibility Study of A 30 Watt/Pound Rollup Solar Array 1 2 & 3 Quarterlies and Final Report	Oct 67 thru Aug 68	Array area-250 square feet Design analyses and description of major components Three candidate structural systems evaluated in depth for weight minimization Trade study for selection of deployment/retraction mechanism reported Description of array panel composition and results of full scale model tests presented	●	●	○	●	○		●	●	●	●	●	●	●

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F 1-5 thru F 1-7	Contract NAS5-9649 Title Positive Deployable Solar Array Development Program Phases I, II & III Reports	Jun 66 thru Jul 68	Fabrication and testing of an array for spin-oriented spacecraft application. Developed and tested a 2 16 ft. wide by 9 20 ft long flex array Humidity vibration tension-fatigue and thermal cycling tests are described Design analysis and system components described in detail Dynamic equations presented in appendix	○	●	○	●	○		●	●	●	●	●	○	○
F 1-8	Journal Spacecraft Article Title Solar Deflection on Thin-Walled Cylindrical Extendible Structures	May 70	Derivation of analytical expression describing steady state deflection of tubular structure with a locked overlapped cross section subjected to solar heating in zero g Results presented in graphical form for engineering design A specific example is discussed.	○												○
F 1-9	Title Investigations of a 12-16 Kw Rigid Deployable Solar Array	No Date	Study tailored to Saturn orbital work ship configuration The design both structural & mechanical Structural analysis and electrical design are described in detail													○
F 1-10	Contract NAS9-21202 Title Final Report - Study of Deployment/ Retraction Techniques for Flexible Roll-up Solar Arrays	Jan 69	Determination of optimum deployment system for 40 KW (e) array on SIVB dry Workshop System component structural and thermal analysis are reported Selection trade studies used throughout	○						○		○				
F 1-11	Contract NAS8-21202 Title Bibliography - Solar Arrays and Associated Technologies	Apr 68	Covers literature from 1960 to 1968 Lists of title author source & brief synopsis (Section I) Technical category cross reference is given in Section II													
	FRANKFURT UNIVERSITY, GERMANY															
F 2-1	7th Photovoltaic Spec Conf Title Impurity Photovoltaic Effect in Silicon	Nov 68	Gold donor level observed. Spectral response of open circuit voltage measured with lock-in technique No improvement in efficiency by doping with deep traps - overcompensation by an enhanced minority carrier recombination					○								
	GENERAL ELECTRIC SYRACUSE															
G 1-1	Electronic Packaging & Production Article Title IC Chip Interconnection Replacing the Flying Lead	Dec 69	Recent developments are countering the inherent weaknesses of the flying lead interconnection method These advances (beam lead & flip chip) have been followed by others using batch processing techniques described here				●									

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	GENERAL ELECTRIC VALLEY FORGE															
G 2-1 thru G 2-4	Contract JPL 951970 Title Feasibility Study of 30 Watts Per Pound Rollup Solar Array 1st, 2nd, 3rd Quarterlies and Final Report	Sep 67 thru Jun 68	Preliminary design and analysis of 250 ft² array Fabrication of model to demonstrate deployability Trade studies and preliminary design of baseline configuration Specifications for deployment boom selection and for slip ring assembly Blanket curling investigation Fabrication of deployability demonstration model described in detail	●	●	○	●	○		●	●	●	●	○	●	
G 2-5 thru G 2-9	Contract JPL 952314 Title Rollup Sub-solar Array 1st 2nd, 3rd and 4th Quarterlies and Final Report	Sep 69 thru Oct 70	Description of detail design of components and performance analysis Fabrication of prototype test model parts and of array substrate reported Test and support test equipment identified and described Mechanical assembly of prototype test model discussed. Planning of system tests	●	●	○	●	○		●	●	●	●	●	○	
G 2-10	J Spacecraft Article Title Thermally Induced Vibration & Flutter of A Flexible Boom	Aug 69	Analytical study of satellite boom oscillations thermally induced in passing from Earth's shadow into sun Viscous fluid damper added at tip of boom to prevent thermal flutter	○										○		○
G.2-11	Contract NAS 3-9997 Title Study of High Voltage Solar Array Configuration with Integrated Power Control Electronics	Jun 70	To provide regulated dc power directly to loads array mounted power conditioning discussed Regulation by binary coded digital switching system to short circuit series connected solar cell groups	●				○	●							
G.2-12	IECEC Paper 699070 Title The "Hot Spot" Failure Mode for Solar Arrays	Sep 69	Local heating phenomenon producing high temperatures is more probable in non-metallic substrates (flex) Caused by small fault in series elements Connected by control of I-V characteristic using bypass diodes	●				○								
G.2-13	IECEC Paper 689073 Title A Design Concept for a 30 watt pound Rollup Solar Array	Aug 68	250 ft² system Trade studies and analyses for selection of configuration discussed Determination of substrate preload by analytical model reported Major component designs described.	○	●					●	●	●	●	●		
G 2-14	IECEC Paper 699041 (P600) Title Methods for Fabricating CdS Thin Film Solar Cell Modules	Aug 69	Two methods for series and parallel interconnection Sample submodules tested dynamics, tensile vac-thermal cycling Soldered and bonded modules-process and tooling developed.				○	○								

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G.2-15	Contract NAS 7-547 (OART) Title Nimbus 2 Photovoltaic Power Systems on Flight Spacecraft #68SD4222 (first of a series)	Feb 68	Comprehensive description of the design and performance of the power system in Nimbus 2 spacecraft. Complete environmental tests qual and acceptance tests Technical problems discussed.													
G.2-16	Title Failure Analysis & Design Report of Nimbus 1 Solar Array Drive Failure	Aug 66	Due to deterioration of grease (G-300 silicon lube) in solar array drive system at high temp condition (300 F) Complete post-flight failure mode analysis													
G 2-17	Photovoltaic Specialist Conf Paper Title Cadmium Telluride Thin Film Solar Array Technology	Mar 67	Sponsored by contract AFAPL 33 (615) -2835 production of large cells fab & thermal cycling of 28 volt modules Design and fab of an array concept module. Analysis of applicability of array module in the 1 25 to 40 kW range				○	○								
G 2-18	Photovoltaic Spec Conf Paper Title New Work on CdTe Thin Film Solar Cells	Mar 67	Clues to failure mechanisms were sought by examining spectral response of single crystal and thin film cells resulting from thermal treatment and electron bombardment New barriers forming technique (sputtered platinum) and integrated array fab techniques are also presented													
G.2-19	IEEE 21st Nat'l Aerospace/Electronic Conf Title Power Distribution Characteristics for Overload Protection	May 69	Overload protection guidelines are developed for power subsystem servicing multiple loads by common bus Source and protective device characteristics are discussed. Static and electromechanical breakers compared.						○							

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	GOODYEAR AEROSPACE CORP															
G 3-1	3rd Aerospace Expandable & Modular Struc Conf Title Gas-Cured Urethane Resin Syst. for Space Structure	May 67	Archer Daniels Midland Co (ADM) urethane resin material applied to 10-ft diam parabolic collectors and 4-ft diam by 8-ft long cylinders Emphasizes work on the solar-collector program namely the Airmat technique													●
	GULTON INDUSTRIES															
G 4-1	1st Power Conditioning Spec Conf Title High Efficiency Solar Cell Array Peak Power Tracker and Battery Charger	Apr 70	Coupling in Airlock Vehicle for Skylab between SIVB workshop and Apollo spacecraft Array power converted by a switching regulator, charges battery & supplies loads Peak array power varies from 70 to 258° watts Open circuit voltage as high as 120 volts						○							
	HARSHAW CHEMICAL															
H 1-1	Contract NAS3-6464 Title Development of Optical Coatings for CdS Thin Film Solar Cells (F R)	Dec 65	Investigation of optical properties of high infrared emittance optical films Materials were selected and deposited by sputtering and thermal evaporation measurement made of emittance & cell stability in humid atmosphere	○												
H 1-2	6th Photovoltaic Spec Conf Title Further Considerations of the Model for the CdS Solar Cell	Mar 67	Model proposes n-type CdS in and on which p-type Cu_2S is grown with the rectifying junction changing geometry & characteristics due to ion motion Device is described and properties of CdS and Cu_2S are discussed.													
	HAWKER - SIDDELEY															
H 2-1	Journal of the British Interplanetary Soc Title Design Description of the Power Supply Subsystem for the TD1/TD2 Satellites	69	Description of the operation performance and method of construction of each major component of the system Significant results including choice of battery charge control, method of controlling the solar array battery connection method etc are discussed.	○												

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	HELIOTEK															
H 3-1 thru H 3-4	Contract JPL 952560 Title: Development of An Integrated Lightweight Silicon Solar Cell Array 1st 2nd & 3rd Quarterlies (Final Report to be published)	Jul 69	To provide design data to develop lighter and less expensive flex arrays Solar cell cost effectiveness comparison preliminary and detailed analysis of a continuous process cell Ultra-thin cover installation cell interconnect stresses and ribbon substrate are treated Interconnector flexure/tensile and thermal cycling study is presented Wrap-around interconnected module feasibility and cost study is reported.	●	●	●	●	○								
H 3-5	Contract F33615-65-C 1198 Title: Lithium Doped Hardened Solar Cell Optimization (F R)	May 70	Part I - Method of depositing integral cover of interconnecting cells and design of flex array and automatic test system presented. Part II - radiation damage effects on hardened cells by high-energy particles & laser light			○	●	○								
H 3-6	Contract JPL 952547 Title Development of Lithium Diffused Radiation Resistant Solar Cells (3rd Quarterly)	Apr 70	TiPdAg and Al contacts systems on p/n cells were evaluated for strength and humidity resistance New lithium evaporation process developed. Data comparing cell output as a function of lithium application is presented.					●								
H 3-7	IECEC Paper Title: Solar Cell Development Survey	Aug 68	Description of conventional space qualified single crystal silicon cells & typical performance characteristics for various cell designs presented. Influence of large area cells on parameters is discussed. Status of new work reported.					●								
H 3-8	6th Photovoltaic Spec Conf Title: Performance of Very Thin Silicon Solar Cells	Mar 67	Provides engineering design data on power weight parameter and on cell performance as thickness is decreased over a wide range of temperature					○								
H 3-9	5th Photovoltaic Spec Conf Title: Preflight Calibration & Matching of Solar Cells for a Band Pass Filter Experiment	Oct 65	Pre-flight program to provide complete standard units of identical cell characteristics cell spectral response & cell current output at load point at various temperatures Cells matched within ±1% Predictions of space performance reported					○								
H 3-10	6th Photovoltaic Spec Conf. Title: Status of Lithium Doped P N Solar Cells	Mar 67	Experiments performed to determine the optimum lithium cell design are described. Advantages and limitations of the annealing effect are presented.					○								

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H.3-11	7th Photovoltaic Spec Conf. Title: Solar Arrays Utilizing Large Area Silicon Solar Cells	Nov 68	Special considerations and engineering guidelines for design of arrays using large area cells Theoretical analysis of thermal phenomena experimental verification of mathematical calculation, and practical considerations of panel assembly treated.	●			○									
H. 3-12	Int's Colloquim on Solar Cells Title: Silicon Solar Cell Interconnections for Low Temperature Applications	Jul 70	Generalized stress equations developed for "no fatigue" interconnector Experimental test program verifying failure modes of interconnectors is reported. Modules survived several thousand temp. cycles between 450°C and -170°C				●									
H.3-13	8th Photovoltaic Spec Conf Title: Silicon Solar Cell Lightweight Integrated Array	Aug 70	Attempt to improve the power to weight ratio by use of thinner cells on the blanket. Design factors for the array and components (interconnector coverglass, substrate) are presented to show how optimum could be realized.		○	●	●									
	HEWLETT-PACKARD															
H 4-1	McGraw-Hill Publication 12607 Title: Printed Circuits Handbook Section 4 - Soldering	67	Design requirements for good soldering and chapter 12 - materials selection for soldering including chemical composition requirements of solder are presented.				●									
	HONEYWELL INC															
H 5-1	Suppl IEEE Transactions Aerospace & Electronics Systems Title: Adaptive Power Conditioning for Solar Cell Arrays	Nov 66	Description of a design technique which insures optimal power transfer from array to load. Concept forces cell to operate at max power point despite environment impedances or changes in source volt-ampere characteristics.												○	

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	HUGHES AIRCRAFT															
H 6-1 thru H 6-6	Contract AF33(615)-2750 Title. Flexible Integrated Solar Cell Array 1st 2nd 3rd 4th and 5th Quarterlies and Final Report	Sep 65 thru Aug 67	Development of technology to fabricate a large area lightweight low-stowed volume flexible array @ 0 5 to 20 kW power range Qualification tests on dendritic cells and cell-substrate-composite design of interconnects. Used a de Havilland STEM Array segment temp shock & vibration tested 50 ft² demo model (500 watts) using 1x30 cm dendritic cells assembled and tested	●	●	○	●	○		●	●	●	●	●	○	○
H 6-7 thru H 6-13	Contract. AF33 (615)-68-C-676 Title: Flexible Rolled Up Solar Array 1st 2nd 3rd 4th 5th 6th and 7th Quarterlies Final Report due November 1970	Oct 68 thru Apr 70	Baseline configuration - two 177 by 67 inch panels 8 inch diam drum four booms driven by ac motor slip rings for power transfer Design analysis, fabrication and test of all major components Requirements and interface documents submitted Complete power subsystem breadboard test program Analysis of failure modes maintainability and reliability SAMSO (SESP program-LMSC) meeting for Agena interface definition	●	●	○	●	○		●	●	●	●	●	○	○
H.6-14	Annual Aviation and Space Conf Paper Title Some Design Aspects of Solar Electric Propulsion Spacecraft	Jun 68	Highlights design requirements of large solar arrays - packaging stowage deployment for interplanetary vehicle ion engine/solar array/power conditioning configuration constraints presented.						○	○		○				
H 6-15	8th Photovoltaic Spec Conf Paper Title- Pulsed Xenon Solar Simulator System	Aug 70	Simulator system integrating optics and data acquisition for testing single cells cell groups and solar panels Solar simulation for large panels not previously possible-uniform intensity high performance system					○								
H.6-16	Contract. NAS5-3823 (Goddard) Title ATS-F1 Power Subsystem Radiation Effects Study	Dec 67	One month task force study to analyze anomalous 20% degradation of solar arrays & effects of synchronous environment on several types of solar cell assemblies - trapped electrons solar flare protons - correlation with coverglass thickness			○	○	○								
H 6-17	5th Photovoltaic Spec Conf Paper Title- Recent Developments in Large Area Solar Cell Arrays (Ref documents 19 thru 21 above)	Jan 66	Sponsored by AFAPL 33(615)-2750 and NAS 5-3989 Research and development of deployable large arrays Six packaging systems including flex arrays for Spinning Satellite Design analysis and demo model for feasibility of flex drum - stowed array are presented.							●	●	●	●	●		○
H 6-18	6th Photovoltaic Spec Conf Paper Title: Development of A Flexible Deployable Solar Array (Ref documents 21 thru 24 above)	Mar 67	50 ft² - 500 watt demo model environmental test results discussion. Investigation of growth potential and reasonable extension of demo concept				●	○		●	●	●	●	●		○

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H 6-19	6th Photovoltaic Spec Conf Paper Title- Computer Simulation of Solar Array Performance	Mar 67	Mathematical model based on original equivalent circuit of M Prince was investigated for accuracy under various environmental conditions Mismatch losses and significance of cell reverse-bias operation are discussed					●								
H 6-20	Contract NAS3-8996 Title: High Voltage Solar Array Configuration Study	Jul 70	Conceptual design study of HV solar arrays with integral power conditioning (15 kW 1 to 16 kV) Power-subdivision regulation power transfer mechanization components performance and problem areas described.						●							
H 6-21	Contract NAS2-4975 Title- Engineering Study of Elevated Temperature Solar Cell Panel Fabrication Techniques	Aug 70	Materials and process techniques for fabricating an array operating over temp range -100° to 210°C Interconnects are high temp solder and copper mesh and/or aluminum foil ultrasonically bonded. 1 ft² panel tested environmentally	○			○									
H 6-22	8th Photovoltaic Spec Conf Title- Electron Spectrum Irradiations of Silicon Solar Cells	Aug 70	Work under contract NAS 7-100 (JPL) Spectrum simulated the synch altitude trapped electron environment Effects of cell output as a function of coverslide thickness cell manufacturer, backside cell irradiation is reported (U S. & foreign cells)	○		○		○								
	IMPERIAL CHEM. INDUSTRIES, LTD.															
L 1-1	S. P E. 27th Annual Tech Conf Title: Uniaxial Creep of Polytetra Fluoroethylene	May 63	Description of effort to improve standardize the plastics creep test methods and system of product testing by the Plastics Design Data committee. PLC/38 of the British Standards Institution		○											
	INTEGRATED CIRCUIT ENGINEERING															
L 2-1	The Electronic Engineer Article Title- Integrated Circuits Course - 5 Parts	Mar 67	These articles discuss the importance of IC yield to engineers IC processing problems photo masks - the tooling for ICs epitaxial growth in IC fabrication and new techniques of breadboarding				●									

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	ION PHYSICS															
I 3-1	Annual Aviation & Space Conf Title Solar Cell Integral Coverslips	Jun 68	Improves cell overall performance Particulate radiation (Van Allen region-protons/electrons) increases optical absorption of coverslips Thermal control effect of slips is an emissivity enhancement Fused silica & sapphire sheets are discussed			●										
I. 3-2 thru I 3-9	Contract NAS 5-10236 Title Solar Cell Cover Glass Development 1 2, 3 4, 5 6 7, & 8 Quarterlies	Jan 68 thru Apr 69	Refinement and economic optimization of fabrication techniques for thick integral coverslips on silicon solar cells Integral coverslip cells show definite superiority over conventional glued coverslip cells Improvements have been achieved in reaction sputtering and electron beam evaporation processes for integral SiO_2 coverslips Testing with ultra violet & electron irradiation for degradation of coverslips reported			●										
I 3-10	5th Photovoltaic Spec Conf Title Ion Implantation as A Production Technique	Oct 65	For production of n/p solar cells Recent developments in ion implantation techniques for dendritic material cells reported Investigation of fused silica integral coverslips and compatible anti-reflection coatings discussed			●		●								
I 3-11	6th Photovoltaic Spec Conf Title The Application of Implantation to Thin Silicon Cells	Mar 67	Dendritic cells including the filet and dendritic regions as well as the web have been studied. Method of avoiding leakage losses at edge material developed. Reflecting back thin single-crystal cells also developed													
I 3-12	7th Photovoltaic Spec Conf Title Aluminum Contact Deposition and Testing for Silicon Solar Cells	Nov 68	Ion beam sputtering and evaporation of aluminum investigated Interconnections by ultrasonic bonding peel & pull tested. Aluminum contacted solar cells thermal cycled (458°C and -195°C) 30 minutes.				●									
I. 3-13	8th Photovoltaic Spec Conf Title: Low Stress Integral Cover Slips	Aug 70	10-mil thick borosilicate glass (7070) coverslips deposited by high vacuum ion beam sputtering The as-deposited stress can be reduced by annealing or by cerium doping during deposition Manufacturing cost reduction discussed			●										
	JAPAN															
J 1-1	8th Int l Symposium Tech & Science Title Lithium-Doped Silicon Solar Cells	Aug 69	Results of development & reliability tests described Temp cycling in vacuum & high & low temp annealing tests reported.					●								

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	JOHNS HOPKINS APPL. PHYS. LAB															
J 2-1	Contract NOW 62-0604-C Title Bending in An Extendible Boom Subject to the Influence of A Gravitational-Centrifugal Force Field	Nov 63	Analysis to determine magnitude of bending expected in long extendible booms on earth-oriented satellites The bending is demonstrated for a specific configuration	○												○
J 2-2	Contract NOW-62-0604-C Title Solar Panel Test Set	Feb 70	Description of testing solar-cell panels in artificial sunlight (equiv intensity 140 m W/cm²) using iodine-quartz (tungsten) lamps as radiant energy source Methods of calibrating test set described.					○								
J 2-3	Contract. NOW-63-0604-C Title- A Practical Solution to the Problem of Thermal Bending in Spacecraft Extendible Booms	Jun 67	New fabrication techniques and surface treatments to reduce bending due to spacecraft movement in and out of sunlight, are presented Development of shroud (sunshield) to encase the boom as protection from extreme thermal changes discussed,													○
J 2-4	Contract. NOw-62-0604-C Title- Design & Analysis of Solar Array Configurations for Vertically Stabilized Spacecraft - Near Earth Orbit	Aug 69	Design principles & analysis techniques developed from basic solar cell performance characteristics Predictable solar orientation patterns orbit environment effects irradiation degradation & earth albedo influence are discussed	○				○								
J 2-5	IECEC Paper (with Heliotek) Title- Radiation Damage to Thin Silicon Solar Cells	Aug 67	Development of membrane substrates for attaching 0 004 inch thick silicon solar cells may be attached. Unfurlable deployable arrays may require bending of silicon wafers requiring a thickness like 0 004 inch Experimental test results discussed.		○		○	○								
J 2-6	3rd IFAC Symposium Title- Gravity Gradient Stabilization Studies with the Dodge Satellite	Mar 70	Launched July 1967 near synchronous orbit. First satellite with three axis stabilized (gravity-gradient) Discussions of design aspects boom configurations damping system angular momentum flywheel are given	○												○
	KAMAN-AVIDYNE															
K 1-1	AIAA Structure Spec Conf Title- Minimizing Spacecraft Structure/Control System Interaction	69	Work under contract NAS 12-613 Various methods discussed by means of examples from each category of three basic structural configurations Design improvements based on flight experience are emphasized	○												○

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	LTV AEROSPACE CORP.															
L 1-1	1st Power Conditioning Spec Conf Title: Solid State Power Controller Circuits and Their Effect Upon Power Conditioning Requirements	Apr 70	New system concept for electrical distribution systems called SOSTEL (SOlid STate Electric Logic) is described Power bus and AC load controllers are discussed DC load controller and load monitoring also included						○							
	LITTON SYSTEMS, INC.															
L 2-1 and L 2-2	Contract NAS5-11595 Title: Solar Cell Contact Development 1st & 2nd Quarterly	Jun 68 thru Dec 69	Contact degradation within the TiAg contact Exposure of Ti (unprotected and coated with evaporated film of Ag) to various gases and solutions reported. Auger spectroscopy to detect contaminants Sectioned cells examined by electron mirror microscope					○								
	LOCKHEED ELECTRONICS CO.															
L 3-1	Internal Document Title: Advanced Design Solar Cell Panel	June 67	Development program to design flex interconnect system to use in fabricating arrays on honeycomb substrate Engineering model fabricated to generate data Test panel of 36 6-cell submodules fabricated. Description of sunlight test data				○	○								
	LOCKHEED MISSILES & SPACE COMPANY															
L 4-1	IEEE Transactions article Title An Analysis of Non-Uniform Proton Irradiation Damage in Silicon Solar Cells	Oct 66	Experimental data on degradation of the short-circuit current in 1 ohm-cm N/P cells irradiated by low energy 0 1-3 0 MEV protons Damage constant in analytically derived expression increases with decreasing proton energy					●								
L 4-2	Company funded Research Title: Solar Cell Module-Fabrication by Induction Heating	Oct 65	Investigation of soldering of shingled and parallel connected subpanel configurations by induction heating Electrical output compared favorably to modules soldered by hot plate method No environmental tests				●	○								
L 4-3	Independent Development Program Title Solar Power Development Study-196- F R	Dec 67	Two major efforts systems design data generated for advanced flexible and rigid modules development tests to provide basic design data and to determine environment limiting factors due to new processes and devices		●	○	●	●	○							

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L 4-4	Letter report - SAT to LMSC Title: Thermal Cycling Test of Lockheed Supplied Test Module	Jul 70	INTELSAT 5 sample submitted for test had cell edge overlap by coverslides with some in edge to edge contact Visual examination with binocular lenses and electrical output measurement before and after cycling		●		●	○								
L 4-5	Machine Design article Title Designing for Space	May 70	Discussion of aerospace mechanism designers special problems and challenges along with methods of handling them - particularly in the areas of launch shock vibration acoustic pressures and thermal variations	○												○
L 4-6	Independent Development Program Title: 760-Inch x 40-Inch Tri-Extender Boom Stiffness and Strength Analysis	Jul 69	Summary of analyses on the extended version of a lazy tongs boom structure using the Space Truss computer program Establishes feasibility of such a design	●								○				●
L 4-7	Independent Development Program Title Tri-Beam Devel Structural Test Eval	May 67	Bending, torsion, compression test results on tri-beam mag specimen being developed for ATS-F&G Preliminary structural analysis presenting strength stiffness and damping characteristics of this design	○												●
L 4-8	Aerospace Mechanisms Series Vol 3 Title Passive Gravity Gradient Libration Dampers	Aug 69	Sponsored by NASA Electronics Research Center Presents design and flight experience with all existing dampers - single-part spherical ball-in-tube magnetic hysteresis and lossy spring dampers Recommended practices for prevention of failure	○												
L 4-9	AF Satellite Prog - presentation Title Flexible Solar Array Design Review	Oct 69	Trade studies requirements electrical & mechanical and systems analysis for this system are reviewed viewfoil charts Development & evaluation tests also		●		●	●							●	
L 4-10	AF Satellite Prog presentation Title Block II-Flex Solar Array Improvements	May 70	Panel substrate & cell electrical interconnection configuration modifications for improved performance decrease in weight presented in viewfoil from charts		●		●	●								
L 4-11	Contract AF04(695)67-C-0022 Title Solar Array Wing Power Systems & Characteristics Test	Oct 68	Complete document of test instructions test data & results performed at NTB for Program 770					○								

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L 4-12	5th Photovoltaic Spec Conf paper Title Solar Cell Coatings	Oct 65	Integral cell cover in the form of a coating spray applied to preheated solar-cell panel is then oven cured at 250°F is compared to the conventional Corning-7940 Vacuum & UV tests prove it superior			●										
L 4-13	7th Photovoltaic Spec Conf paper Title Accelerated UV Degradation to Solar Cell Coatings	Nov 68	Two types of integral covers on groups of cells (marks coating & Texas Instr quartz) and bare control cells were exposed to UV rad (1-6 suns for period of 60 days) I-V curves in situ measurements were made to determine degree of degradation			●										
L 4-14	IECEC paper Title: Flight Experience with Large Area Solar Array Systems	Aug 67	Twenty-five solar array systems flown Lessons learned are being applied to current advanced array panels of rigid and flexible type A flex circuit sub-module & spray-on cell cover promising concepts are presented.		○	○	○	○								
L 4-15	IECEC paper No 689080 Title Development of Interconnectable Solar Panels for Large Array Systems	Aug 68	Building block approach to solar panel design – 50 watt increments up to 2 kW for Agena satellite missions cell interconnect and panel design considerations stowage and deployment mechanisms described. Simulator testing.			○	○	○		○		○				
L 4-16	Contract F33615-67-C-1739 Title Space Materials Handbook Third Edition	Jul 68	Part 2 of this volume effect of space environment on materials especially chapters 7 9 12 Thermal control mtls Lubrication applications organic structural mtls respectively are applicable to space station solar array design	○	○						○	○	○	○		○
L 4-17	IECEC paper Title Flat-Pact Flexible Solar Cell Array	Aug 68	Flex solar array stowage & deployment method different from drum types is described. Thermal conductance tests on assemblies forming flat pack modules Radial deployment concepts are presented		●	○	●	○		○	○	○	○			○
L 4-18	1st Aerospace Mechanisms Symposium Title An Extendible Structure for Solar Electric Power in Space	May 68	The system requirements the type of mechanism used and the ascent support structure for the system are described. Structural ground 1-g tests results including 200 extension cycles are reported.	○								●		○		○
L 4-19	Independent Development Program Title Solar Power – 1968	Nov 68	Effort expended chiefly in two areas Flexible substrate development and flat pack solar array Technology culminated in construction of an engineering development model Other work on unique sun-tracking system reported.	●	●	○	●	○		●	●	●	●	●	●	○

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L 4-20	Internal Mfg Research Monthly Title Solar Cell Thermo-Plastic Film Cover Installation	Apr thru Sep 70	LMSC Research Laboratory investigation of use of FEP Teflon as cover material for solar cells Processes tests and problem areas are described Special tooling design & fabrication techniques reported			●										
L 4-21	Internal Research Brief TP-3033 Title Sprayed-on Flexible Solar Cell Covers	Apr 70	Sprayed-on fluorinated plastic coatings for cell-radiation protection & temperature control is described Favorable cost weight and fabrication simplicity advances the state-of-the-art of array manufacturing			●										
L 4-22	Contract AF33(615)-3709 Title Space Linkage System Analytical Study & Preliminary Design	Apr 67	Determination of problems associated with tethering a sun-oriented power system to earth-oriented vehicle Computer program for control system design developed Selection of Ryan-type deployable boom or folding type linkage described	○												●
L 4-23	Independent Development Program Title Laboratory Test Report on Tri-Beam Boom	Nov 67	Determination of maximum deflection of tri-beam boom when subjected to controlled temp/altitude environment (HIVOS facility) Deflection measurements by four linear position transducers recorded on Honeywell Visicorder	○								○				●
L 4-24	1st Aerospace Mechanisms Symposium Title Extendible Boom Device	May 66	Development of unique device which forms a beam from three rolls of metal tape with edges joined by Velcro tapes and snap fasteners Mechanism designed fabricated and successfully tested as reported									○				●
L 4-25	Subcontract NAS3-11497 (SPO 33002) Title Large Telescope Experiment Program (LTEP) F R.	Jan 70	Final report summarizing results of LTEP spacecraft support study of Phase 3 definition program Refinement of attitude control & stability analysis outgassing effects evaluation structural & dynamic analysis & lifetime potential evaluation reported	○												
L 4-26	Contract AF33(616)-6022 Title Study & Design of Unfurlable Antennas	Nov 60	Possible unfurling techniques are discussed Pressure erection techniques used to overcome size limitations in mechanical methods of unfurling are also covered A number of antennae models are presented													●
L 4-27	Contract NAS5-26004 Title Investigation of Transient Degradation/Contamination of Thermal Coatings (LMSC-1st Quarterly-3rd monthly)	May thru Aug 70	Literature review and evaluation describes guidelines resulting from compilation of ground & flight test data presented Predictions based on correlation of data initiated	○	●											

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	MARTIN-MARIETTA															
M 1-1 thru M 1-2	Contract NAS2-5983 Title: Low Energy Proton Effects on Solar Cell Cover Glass Material Vol I & II F R	Nov 69	Evaluation of spectral transmission stability of cover glass materials under simulated solar wind & proton environment Specimens were 0211 microsheet and 7940 fused silica with & without MgF2 anti-reflective coatings Optical stability measurements reported Tabulated raw data in appendices (Vol II) Surface contamination effects described			●										
M 1-3	IECEC Paper Title: Particle Radiation Effects on Solar Cells for Near-Sun Missions	Aug 68	Effects of solar-flare protons & alpha particles on n/p solar cells for a 0 2-AU solar probe mission is a function of fused silica cover glass thickness Mathematical model described by equations Results plotted in curves			○		○								
M 1-4	IECEC Paper Title Power Systems for the Apollo Applications Program (Sky Lab I & II)	Sep 69	Description of solar array/battery systems for ATM and OWS include design consideration of spacecraft attitudes vehicle configurations & power requirements Power conditioning regulation & distribution are discussed						●							
M 1-5	7th Photovoltaic Spec Conf. Title: Integrated CdS Solar Cell Array	Nov 68	Discussion of an array consisting of four CdS cells deposited on a single sheet of Kapton electrically connected in series & mylar covered Pneumatic deployment technique and electrical/mechanical properties presented.					○								
M 1-6	8th Photovoltaic Spec Conf Title: An Evaluation of the Methods of Determining Solar Cell Series Resistance	Aug 70	Two methods based on single exponential lumped constants model for determining lumped series resistance of cells are compared and theoretical methods also briefly analyzed Series resistance should be treated as variable a function of current light intensity and cell temperature				○	●								
M 1-7	IECEC Paper Title: ATM Solar Cell Module Performance Testing	Sep 69	One million sq. cm of cells on a module deployable array Largest ever flown. Electrical performance testing of the array a 360 individual 20 x 24 inch modules under simulated sunlight is reported					○								
M 1-8	ASME 10th Structure Conf Title: Observations on the Mechanism of Thermal Torque Instability	69	Spacecraft booms develop thermally-induced oscillatory instability (bending & twisting) Rederivation of the thermal torque equation With the new formulation a finite twist is predicted.	○												○

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	MCDONNELL DOUGLAS ASTRONAUTICAL															
M 2-1	IEEE Transactions Vol AES-6 No 2 Title Integration of Large Power Systems into Manned Space Stations	Mar 69	Essential design factors and system characteristics are explored Impact of mission requirements upon selection of power system is discussed with power levels from 3 to 50 kWe(e) four to nine-man crews Rigid and rollout solar arrays are analyzed							○						
M 2-2	Contract NAS5-25140 Title: Space Station Definition Vol V - Subsystems Book 1 - Electrical Power	Jul 70	Solar array EPS (Electrical Power System) selection and trade study presented Fairchild-Hiller array description and operational characteristics are described. Results of solar panel and array optimization is presented.	○	●	○	●	●	○	○	○	○	○	○	○	○
	MESSERSCHMITT-BOLKOW-BLOHM SPACE DIV.															
M 3-1	Title: Development of A Deployable & Self-Rigidizing Solar Cell Array in the Multi-Kilowatt Range	Aug 70	Development of array with small stowage volume & favorable power to weight ratio Combination of rigid & flex arrays deployed by an arrangement and inflated by pressure gas Tested under environmental conditions -20m² panel		○		●									●
	MIT (LINCOLN LABS)															
M 4-1	Contract AF19(628)-5167 Title Prel Results from Les - 6 Solar Cell Experiment	Apr 70	Thirty cells of various types flown at synchronous orbit on LES - 6 satellite (x2 cm) Experiment took I-V curves for each over one year period Lithium doped p n cells high degradations All current results tabulated	○				○								
M 4-2	8th Photovoltaic Spec Title: Structural Failures in Lightweight Solar Cell Arrays Under Thermal Cycling	Aug 70	Small silicon solar cell arrays of different types mounted on honeycomb panels and on flex substrates subjected to long term cycling between -150°C and 60°C Observation of fracture modes contact failure silicon fracture etc compared		●	○	●	○								
M 4-3	5th Photovoltaic Spec Conf Title Impurity Photovoltaic Effect in Cadium Sulfide	Oct 63	Work under NASA Grant NsG 436 Spectral response of CdS cells (fabricated by evaporating thin Cu layer on single crystal n-type CdS) enhanced in the infrared Transient measurements of emptying & filling of impurity states were made					○								

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M 4-4	7th Photovoltaic Spec Conf Title Solar Cell Calibration Experiments on LES-6	Nov 68	Lincoln Laboratory Experimental Satellite in synchronous orbit Sept 68 30 cells of different types thicknesses & covers Initial orbital results compared to ground calibration done at Kitt's Peak near Tuscon Ariz.			○		○								
M 4-5	7th Photovoltaic Spec Conf Title Solar Cell Degradation Experiments on LES-4 and -5	Nov 68	LES-4 orbited Dec 65 (highly elliptical) LES-5 quasi-synchronous July 67 Each carried 10-ohm cm silicon cells with 20 & 6 mil cover slides 2 CdTe and 2 CdS thin film cells Degradation effects measurements reported.			○		○								

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	MULLARD MITCHAM MULLARD LTD.															
M 5-1	Internal Report CML1072 Title Effects of Radiations on Various Cover Glasses & Cover/Solar Cell Assemblies	Sep 69	Comparison of cover glasses containing cerium oxide with conventional multilayer covers Exposure to protons electrons and UV Measurements of spectral transmission and electrical/performance reported			●		○								
	NASA-AMES															
N 1-1	8th Photovoltaic Spec Conf Title Engineering Study of Elevated Temperature Solar Cell Panel Fabrication Techniques	Aug 70	Work under contract NAS 2-4876 Materials and process techniques investigation for fabricating an array to operate over temperature range -100 to 310°C Honeycomb-sandwich substrate (epoxy-novolac-fiberglass with aluminum core) Cylindrical section fabricated and tested													
N 1-2	Internal Document A-552-69-144 Title The Effects of Solar Radiation Pressure on the Radio Astronomy Explorer (RAE) Satellite Booms	Apr 69	Developed a technique to determine times when the RAE satellite boom & sun are in direct line-of-sight. Planar motion of boom element analyzed and first order solutions obtained and described													○
N 1-3	8th Photovoltaic Spec Conf. Title A Comparison of Gallium Arsenide and Silicon Solar Cells for A Solar Mission	Oct 65	Close-run mission-as close as 0 1 AU desired (perhelion) Search for thermal control of solar array (like Pioneer-spinning cylindrical structure with cells on outside) Results of investigation to substitute gallium arsenide cells is presented.					○								
N 1-4	8th Photovoltaic Spec Conf Title Silicon Solar Cells for Near-Sun Missions	Mar 67	Using basic Pioneer spacecraft to penetrate interplanetary space as close as 0 2 AU (25 suns) Concepts evolved despun heat shield with adjustable width slots for temp. control or highly reflective coatings and selective interference filters	○		○										
N 1-5	7th Photovoltaic Spec Conf Title An Exploratory Study of the Interplanetary Environmental Effects on Solar Cell Cover Glasses	Nov 68	Feasibility of predicting cell cover responses so that optimum system can be selected for specific missions Measured effects of 3 Mev protons on Corning 0211 microsheet Corning 7940 silicon, antireflection coatings blue and blue-red interference filters	○		●										
	NASA-GODDARD															
N 2-1	Internal Document (X-716-69-383) Title Evaluation of Integral Covers on Silicon Solar Cells	Sep 69	Description of most promising techniques used in integral coverslip development delineates problems encountered, presents test results, and outlines direction of effort Two types of sputtering-radio frequency & high-vacuum-ion-beams are described			●										

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N 2-2	Internal Document (X-710-65-474) Title Solar Cell Radiation Damage on Satellites Relay I & Relay II	Dec 65	Perigee & apogee bracketed inner Van Allen belt-heavily damaging region Thirty 1 x 2 cm cells mounted on a damage panel operated in short-circuit condition Voltages cell temp. solar aspect angle & carrier lifetime signals were telemetered and recorded													
N 2-3	Internal Document (X-716-65-369) Title Investigation of Resinous Materials for Use as Solar Cell Cover Glass Adhesive	Sep 65	Various polymeric adhesives (bonding protection cover glass) subjected to temperature storage vibration thermal shock and cycle thermal vacuum and irradiation Comparative degradation effects shown by transmission-loss curves			○										
N 2-4	Internal Document (X-710-65-195) Title Radiation Damage Shielding of Solar Cells on A Synchronous Spacecraft	May 65	Experiment aboard ATS-1 spacecraft - synchronous orbit using conventional n/p 10 ohm-cm silicon boron-doped cells with various radiation shields - Corning 7940 fused silica of different thickness Complete voltage-current data telemetered.			●		○								
N 2-5	Internal Document Title A Lightweight Folding Boom for Accurately Placing Scientific Experiments Up to 25 Ft From Large Spacecraft	Sep 65	Isolation of experiments susceptable to contamination or interference by subsystems or other experiments Boom-operation configuration locks drive motor etc are described Experimental model discussed													○
N 2-6	Internal Document (TND-5310) Title Thermoelastic Instability of Open-Section Booms	Dec 69	Differential thermal expansion in hollow cylindrical space boom generates thermal bending-moment Dynamic out-of-plane motion produces twist Two mathematical thermoelastic models developed OGO-IV unstable thermally induced oscillations discussed	●									○			●
N 2-7	Internal Document (TMX-63730) Title Geometric Modeling of Folded Booms of IMP-1	Oct 69	Laws derived and all expressions reduced to seven laws dependent upon a geometrical scale factor One-half scale model tests of IMP-1 booms calculated Construction feasible but zero gravity simulation not practicable													●
N 2-8	AIAA Guid Ctrl & Flt Dyn Conference Title Satellite Attitude Control Using a Torqued 2-Axis Gimballed Boom as the Actuator	Aug 68	Precision attitude control by gravity-gradient boom and small momentum wheels Results of linear analysis, computer simulations and hardware tests are presented Gimballed boom designs and configurations described													

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N 2-9	5th Photovoltaic Spec Conf Title Preliminary Results of the Explorer XXVI Solar Cell Experiment	Oct 65	Preliminary results of an engineering experiment consisting of 4 series strings of 1 ohm-cm and 10 ohm-cm cells on Explorer facet to determine integrated-radiation effects Six mil and 60 mil glass shields Precision resistor across each string Voltage-current measurements reported.			○		○								
N 2-10	6th Photovoltaic Spec Conf Title Solar Power Systems for Satellites in Near-Earth Orbits	Mar 67	Several types (IMP NIMBUS II & ATS-J) solar conversion/energy storage power systems described System block diagrams solar array configuration features presented	○					○							
N 2-11	6th Photovoltaic Spec Conf Title A Survey of the Trapped Radiation Environment	Mar 67	Various models of space environments radiation belts described. Discussion of inner zone/outer zone electrons High energy/low energy protons illustrated. Environment models based on observational data produced.	○												
N 2-12	6th Photovoltaic Spec Conf Title Present Status of Lithium Diffused Silicon Solar Cells	Mar 67	Two models of the mechanism of spontaneous annealing of Li-diffused solar cells one to compensate defects the other to form metastable defects are presented.					○								
N 2-13	7th Photovoltaic Spec Conf Title. Solar Cell Radiation Damage on Synchronous Satellite ATS-1	Nov 68	Continued monitoring of solar cell experiments aboard ATS-1 Conclusions presented. (See N 2-4 above)			●		○								
N 2-14	Internal Doc TND-3996 Title Damping Behavior of DeHavilland Stem Booms	Jun 67	Damping behavior discussed in terms of boom orientations boom length and the mechanism responsible for boom dynamics. Experiments conducted to measure vibration-decay rates under vacuum using strain guage techniques.	○												●
N 2-15	Internal Doc X-716-67-522 Title The Effects of Ammonium Hydrogen Sulfide and Freon 14 on Silicon Solar Cells	Oct 67	Electrical output & mechanical condition of cells with titanium silver grids and contacts in $NH_4 - H_2S$ and Freon - 14 gas atmospheres @ +20 to -20°C investigated No short-term degradation of cells observed.													
N 2-16	1st Power Conditioning Spec Conf Title A Buck-Boost Main Bus Voltage Regulator for A Solar Array Battery Space Power System	Apr 70	Design approach for the switching regulator analysis of its operation definition of characteristics & functional performance are presented. This regulation technique employing one series circuit offers increased efficiency & flexibility for optimization						○							

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	NASA HEADQUARTERS															
N 3-1	ASME Winter Annual Mtg Title Status of Photovoltaic Power Technology	Dec 68	Review of state-of-the-art over four years 1964-68 Describes solar-cell power systems, improvements in silicon solar cells, large solar array technology and cadmium sulfide thin film solar cells					●								
	NASA - JPL															
N 4-1	JPL Space Programs 37-60 Vol III Sect XIII Matls Title Tape Type Temp. Control Coatings Application	Dec 69	List of types of pressure-sensitive tapes and uses Gold on Kapton, aluminized Kapton Film-adhesive substrates (laminates) interfaces behavior in space radiation environments tested and reported	○												
N 4-2	Internal Doc (No 900-270) Title Survey & Study for an Improved Solar Cell Module	Aug 69	Initial phase survey to determine state-of-the-art of silicon solar cells Remaining phase improvements to be made Advanced planning in materials fabrication methods and processes presented Recommendations for future programs			●	●	●								
N 4-3	Internal Doc (JPL 320-31601-2-3420) Title Summary of Work Accomplished in the Area of Photovoltaic s Supporting Development	No Date	Comprehensive electrical and mechanical characteristics of solar cells as a function of cell temperature and solar intensity experimentally obtained over simulated sun-probe distance, corresponding to Venus and Jupiter missions	○				○								
N 4-4	Internal Doc (TECH. REPT 32-1424) Title Results of the 1968 Balloon Flight Solar Cell Standardization Program	Dec 69	Cell array terrestrial calibration measurement difficulties minimized by use of high altitude balloons Also furnished means of lifting radiometers above Earth's atmosphere to measure solar constant.					●								
N 4-5	Internal Doc (TECH. REPT 33-125) Title: Effects of Solar Proton Flares on the Power Output of Solar Cells Having Various Configurations.	Feb 68	A technique for predicting the degradation of solar-cell output for p/n and n/p silicon solar cells for two solar flare models is presented. Results of an experiment testing the validity of the technique are presented.	○				●								
N 4-6	Internal Doc (TECH REPT 32-1362) Title Effects of Environmental Exposures on Silicon Solar Cells	Jan 69	Batches of silicon cells having titanium-silver contacts were environmentally tested (with & without solder coating) to determine effects on electrical & mechanical properties of cells - humidity, elevated temperature, & thermal cycling.					○								

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N 4-7	JPL Space Programs Summary 37-60 VOL III Title Tops Boom Deployment Mechanism	No Date	RTS's and science platform mounted on hinged rigid booms Summarizes progress in analysis & development of deployment booms Generated a variety of applicable concepts and developed an analog model for a generalized swinging boom													○
N 4-8	Aerospace Structures Design Conf Title Deployment Techniques Developed for Large Area Roll-Out Solar Arrays	Aug 69	In stowed configuration lightweight flex arrays occupy a minimum of area within stowed envelope Proposed deployment mechanisms for the 30-watt/ lb array booms are compared Manufacturing technology limited													○
N 4-9	IECEC Paper Title A Structural View of Solar Array Developments	Aug 67	Reviews structural criteria analysis approval and development experiences of Mariner programs This background is then related to potential structural and dynamic problem areas in large lightweight array development.													●
N 4-10	IECEC Paper Title Solar Cell Submodule Design and Assembly	Aug 67	Mariner Mars ('64) Mariner Venus (1967) and Surveyor (SC-5, -6, and -7) spacecraft solar-cell submodule-design fabrication and evaluation features are described. Automatic conveyor soldering oven included.				○									
N 4-11	IECEC Paper 659020 Title: Electrical Characteristics of Silicon Solar Cells as a Function of Cell Temp & Solar Intensity	Aug 67	Specially designed thermal-vacuum test facility with a filtered xenon solar simulator used in evaluating 2x2 cm n/p and p/n devices over sun distances corresponding to Venus and Jupiter Parametric performance presented.													
N 4-12	IECEC Paper 659069 Title: Electrical Power System Design for A Jupiter Solar Electric Propulsion Mission	Aug 65	900 day mission low thrust propulsion engine power consumption profile with solar panel maximum power - point tracker. Includes an evaluation of irradiation and micrometeroid damage to array performance													
N 4-13	IECEC Paper 689070 Title: Transit & Lunar Performance of the Surveyor-V Solar Panel Assembly	Aug 65	Launch Sept. 1967-86 watts usable power 3-day transit and 30-day lunar surface. Solar panel assembly electrical configuration, flight acceptance tests described													
N 4-14	IECEC Paper 699093 Title: Solar Array Configurations & Performance on the Martian Surface	Sep 69	200-watt system - three feasibility models described. High impact tests for hard lander on Mars surface Conceptual design for both soft and hard landers described (conical, articulated, single-panel and two-panel concepts)													

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N 4-15	6th Photovoltaic Spec Conf Title: Mariner Mars 1964 Power System Design & Flight Performance	Mar 67	Launched Nov 1964 flew by planet July 1965 Four solar panels active area 70 ft Design philosophy and actual design and operation of mechanization system described. Flight performance presented.				○								
N 4-16	5th Photovoltaic Spec Conf Title: A Method for Predicting Solar Cell Current-Voltage Curve Characteristics as Function of Incident Solar Intensity & Cell Temp	Mar 67	Refinement of existing computer program to predict cell performance over Mars/Venus mission distances The equations use a point-by-point extrapolation technique. Experimental & predicted digital data are correlated.	○											
N 4-17	7th Photovoltaic Spec Conf Title: Status of Lithium Solar Cell Development	Nov 65	Philosophy general considerations present investigations and overall objects of several subcontracts monitored by JPL are reviewed. Singular optimum cell design does not yet exist.					○							
N 4-18	ASME Winter Meeting Paper Title Analysis of Performance Characteristics and Weight Variations of Large Area Rollup Solar Array	Nov 63	Development of program for calculating the weight, structural member sizes, and deployed vibration modes for single boom array concept. Program designed for modifications to other configurations by addition or deletion of subroutines	○											●
N 4-19	Internal Doc Tech. Rept. 33-1321 Title: Mariner Venus 67 Solar Panel	Apr 70	Description of design, manufacture, assembly testing & performance of the array given. Remarks on adequacy of array design & recommendations for future designs also included.					●	●						
N 4-20	8th Photovoltaic Spec Conf Title: Temperature Effects on Silicon Solar Cell Short-Circuit Currents	Aug 70	Quantitative analysis for short-circuit current variations with temp Developed expressions to account for band-gap width, photon absorption coefficients & diffusion length. all temperature-sensitive parameters Comparisons made between tabulated & measured results					●							
N 4-21	8th Photovoltaic Spec Conf Title: Performance Characteristics of Ti-Ag Contact N/P and P/N Silicon Solar Cells	Aug 70	Cells illuminated with filtered Xenon solar simulator at 25-degree increments between +60 and -140 C in vacuum at sun-distances corresponding to Jupiter/Venus missions Parametric-performance characteristics presented & discussed.					○							
N 4-22	8th Photovoltaic Spec Conf Title Status of Lithium-Doped Solar Cell Investigation at JPL	Aug 70	Author's interpretation of results of industry programs - improvement of cell processing techniques and experiments for theoretical understanding of the action of lithium in irradiated silicon. Suggestions for future work are made					○							
N 4-23	8th Photovoltaic Spec Conf Title: Defect Structure and Behavior in Electron Irradiated Lithium Diffused Silicon Solar Cells	Aug 70	Review of recent work on understanding the nature of microscopic complexes formed in irradiated lithium diffused silicon cells The complexes role in radiation damage and annealing mechanism is discussed along with the approach of the general research program					○							
	NASA-LANGLEY														
N 6-1	Langley Working Paper LWP-669 Title: The Effect of Radiation on Cerium Doped Glass Solar Cell Covers	Mar 70	Feasibility of producing an inexpensive radiation-resistant cover glass replacing synthetic fused quartz Cerium doped samples irradiated with 1 Mev electrons and 50 Mev protons Spectral wide-band transmittances measured			●									

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	NASA LeRC														
N 6-1	Internal Doc (TMX-1687) Title Comparison Between Cemented and Soldered Cover Glass for Silicon Solar Cells	Nov 68	To compare spectral responses, transmission factors for the cover glass were determined in range from 0 4 to 0 95 micron, by using a filter wheel solar simulator Commercial cells with anti-reflection coating used in measurements			○									
N 6-2	Internal Doc (TMX-1905) Title. Transmission Effects on Plastic Films Irradiated with UV Light, Electrons and Protons	Oct 69	UV-light in vacuum irradiation by 1 Mev electrons of plastic films used for covers on thin film CdS solar cells One film bombarded by 80 Kev protons Effects on plastics transmission (0 35 to 1 2 μm) measured			●									
N 6-3	Internal Doc (TN D-2932) Title: Radiation Damage to Cadmium Sulfide Solar Cells	Jul 65	Results of irradiation of 70 cells some by 2 5, 1 0 & 0 6 Mev electrons, others by by 2-10 Mev protons at different accumulated doses Three types of plastic encapsulant used polyethylene terephthalate, polyvinyl fluoride & polyimide					○							
N 6-4	Internal Doc (TM X-52874) Title Improvements in Silicon Cell Cover Glass Assembly & Packaging using FEP Teflon	Jul 70	Two techniques described: one using teflon as adhesive for cementing cover glass to cell the other using teflon as the cover and as adhesive of cell to substrate. Fabricability and characteristics of both are discussed.			●	●								
N 6-5	Internal Doc (TM X-1619) Title A 23 4 Square Foot Cadmium Sulfide Thin-Film Solar Cell Array	Apr 68	Exploration of construction problems associated with assembly Extended vertically from storage drum by self-extending booms Complete retraction capability Demonstration model extended/retracted 500 times, no damage												●
N 6-6	Internal Doc (TMX-1913) Title Conceptual Design and Structural Model of A 500-Watt Thin-Film Solar Cell Array	Oct 69	188 ft^2 active-area array of CdS cells designed for SERT-II flight test. Work concentrated on structural problems Surveys of general design constraints on the configuration for Agena vehicle Deployable, not retractable.	●											●
N 6-7	Internal Doc (TND-3788) Title Comparison of Solar Direct-Energy Conversion Systems Operating Between 1 0 & 0 1 AU	Feb 67	Flat-plate thermoelectric/, thermionic/ solar concentrator and uncooled silicon cell arrays compared for the mission. Specific weight, and power output variation - basis for comparison												
N 6-8	IECEC Paper Title Status of the Cadmium Sulfide Thin-Film Solar Cell	Aug 68	Cells not yet acceptable because of degradation and instabilities under thermal cycling Performance levels are summarized along with degree of reproducibility and yields obtained Improvements in design & performance discussed.					○							

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N 6-9	5th Photovoltaic Spec Conf Title Behavior of Bombarded Solar Cells Made from Various Silicon Materials	Oct 65	Comparison of post-bombardment of aluminum and boron-doped cells Further comparison of the two types after annealing shows the stabilized values of diffusion length to differ					○								
N 6-10	6th Photovoltaic Spec Conf Title Mechanism of Cadmium Sulfide Film Cell	Mar 67	Complete version TN D-3949 Produced single crystal cell with sunlight efficiency of 5 percent Advances in film cell technology reported Discussion of cell structures junction-barrier height energy band structure spectral response					○								
N 6-11	6th Photovoltaic Spec Conf. Title Environmental Testing of Thin-Film Solar Cells	Mar 67	Preliminary screening by thermal cycling tests Effects of long-term thermal cycling studies. Facilities and tests both at Boeing & LeRC described. Temperature limits discussed.	○												
N 6-12	6th Photovoltaic Spec Conf. Title Annealing of High Energy Proton Damage in Silicon	Mar 67	Results of irradiation of n/p type silicon by 22 40 and 15[illegible] Mev protons at 100 200 and 300 C reported Flux and energy dependence reported. Discussion of effect of increasing/decreasing minority carrier lifetimes observed during isothermal annealing					○								
N 6-13	6th Photovoltaic Spec Conf. Title The Performance of N/P Silicon and CdS Solar Cells as Affected by Simulated Micrometeoric Exposure	Mar 67	Shielded and unshielded cells bombarded by clouds of SiC particles (6μ diam) accelerated to hypervelocities in a shock tube Degradation determined by measuring current-voltage characteristics before & after bombardment	○				○								
N 6-14	6th Photovoltaic Spec Conf. Title Comparison of Lithium Containing P/N Silicon Cells with N/P Silicon Cells	Mar 67	Comparison of radiation damage resistance of different cells using cell current as a criteria is misleading Effects of original lithium concentration profile and method of contact fabrication in the evaluation of bombardment degradation are discussed.					○								
N 6-15	7th Photovoltaic Spec Conf. Title Impurity Profile & Energy Band Diagram of the Cu_2S-CdS heterojunction	Nov 68	Impurity profile in CdS layers determined from capacitance measurements and on Hall and electron micro-probe on the Cu_2S layer A band structure was assembled. This supports a model which has Cu_2S contributing to red response													
N 6-16	7th Photovoltaic Spec Conf Title Solar Cell Performance at Jupiter Temperature and Solar Intensity	Nov 65	Simulated Earth & Jupiter conditions applied to 2 CdS cells and 5 flight-type silicon cells to obtain photovoltaic properties Technique for mounting cells to permit measurements at low temp developed. Measured electrical cell characteristics presented.					○								

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N 6-17	7th Photovoltaic Spec Conf Title: Observations on CdS Solar Cell Stability	Nov 68	Cells thermally cycle tested recently are more stable – tighter specs and quality control responsible Thermal cycling is not a primary cause of cell degradation, but electrical loading during test is Load effect is responsible for differences observed					○								
N 6-18	Internal Doc TMX-1503 Title Design and Performance of Two Vacuum Chambers and Solar Simulators for Solar Cell Research	Feb 68	Description of facility and support equipment Vacuum levels in the 10^{-8} to 10^{-9} torr range Information regarding a test apparatus and solar-cell installation included.					○								
N 6-19	Internal DOC TND-4331 Title: Theoretical Temperatures of Thin-Film Solar Cells in Earth Orbit	Jan 68	Analysis including equations and charts to calculate temperatures of opaque thin flat plates in a sun-planet system. Analysis accounts for albedo direct sunlight, earth radiation and orientation. Plate surface absorptance and emittance required. Applied to three cadmium sulfide cells					○								
N 6-20	5th Photovoltaic Spec Conf. Title: Calibration of Solar Cells Using High-Altitude Aircraft	Oct 65	This technique measures short-circuit current of cells at different attitudes and plots them logrithmically as a function of air mass Extrapolation to air mass zero yields outer space short-circuit current. Aircraft used is B-57B with cells mounted in aft fuselage collimating tube – no window					○								
N. 6-21	8th Photovoltaic Spec Conf Title: Improvements in Silicon Solar Cell Cover Glass Assembly and Packaging Using FEP Teflon	Aug 70	Two methods presented: one uses teflon as adhesive between cell & cover glass eliminating UV filter; the other uses teflon both as cover material and as adhesive between cell and flex substrate, achieving cost reduction in fab.			●	●									
N 6-22	8th Photovoltaic Spec Conf. Title: The Effect of Electrons, Protons and Ultraviolet Radiation on Plastic Materials	Aug 70	Aclar, Kapton and Teflon-FEP irradiated with UV, electrons and protons. Mylar with Astro Epoxy irradiated by UV and mylar with electrons, protons FEP adhesives combinations subjected to UV. Equipment procedures & results described.		●	●										
N 6-23	Space Power Syst. Adv Technology Conf Title Conventional & Thin-Film Solar Cells	Aug 66	Only work of special interest to LeRC is discussed namely, radiation damage to solar cells, thin film cells and high power arrays					○								

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	NAVAL RESEARCH LABS															
N 7-1 thru N 7-3	JPL Subcontract 5056 Title Semi-Annual & Annual Reports for Solar Cell Research	Oct 69 to Apr 70	Lithium diffused silicon irradiated 1 Mev electrons and CO-60 gamma results reported Computer program written to obtain diode parameters of cell by a least-squares fitting of I-V data to solar cell equation.	○												
N 7-3	Navy Space System Activity Title: Space Power Supply Study	May 68	Collection organization and presentation of data relating to "prime space power supplies for future missions Power load configurations for future possible mission requirements included													
N 7-4	Internal Doc Tech. Rept NSSA-R-40-69-4 Title: Space Electrical Power Systems for the Mid-1970's	Sep 69	Comparison of potential power systems capable of meeting mission requirements. Circular polar orbit at 225 nm for one year lifetime (1-5kW) Mass volume and cost figures presented													
N 7-5	IECEC Paper 659015 Title: One Mev Electron Damage in Silicon Solar Cells	Aug 65	Damage from 1 Mev electrons was studied in 14 kinds of n/p silicon cells Current-voltage characteristics measured under solar simulator (140 MW/cm²) Irradiation in air at room temp No difference between aluminum & boron doped cells					○								
N 7-6	5th Photovoltaic Spec Conf. Title: Status of Silicon Solar Cell Radiation Damage	Oct 63	Presentation of radiation damage data to solar cells in a manner useful to designers and users for comparison purposes at radiation dose of 10^{16} electrons/cm² - 1 Mev and at cell temperatures of 25°C-30°C Solar simulators are identified.					○								
N 7-7	5th Photovoltaic Spec Conf Title: Status of Solar Cell Cover Material Radiation Damage	Oct 63	Determination of the nature of degradation and the effects on power efficiency of the cell. Summarizes most important results achieved by researchers in past few years - shielding filters & adhesives treated.			○										
N 7-8	6th Photovoltaic Spec Conf. Title Thermal Annealing of Proton-Irradiated Silicon Solar Cells	Mar 67	N/P cells irradiated by 4 6 Mev protons. Flux levels of 10^{10} to 10^{12} protons/cm² at room temp (1 5 and 10 ohm-cm base resistivity with solderless Ag-Ti electrodes) Proton damage annealing in two stages 50-150°C and 350-450 C					○								
N 7-9	7th Photovoltaic Spec Conf. Title Characteristics of Solar Cells at Low Temperature	Nov 68	1 ohm-cm p/n,1 ohm-cm n, p and 10 ohm-cm n/p types investigated at temp from 82 to 300 K and light intensities 1 mW/cm² to 140 mW/cm² simulating planet Jupiter missions Trends in cell behavior reported					○								

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	NORTHROP CORP LABS															
N 8-1 thru N 8-2	Contract JPL 952523 Title Study of Dopants for Radiation Resistant Silicon 2 Quarterlies	Jul 69 thru Jan 70	Uniform samples prepared by diffusing lithium into blanks of ~ 160 ohm-cm P-doped material Past studies show that aluminum doped silicon under some circumstances is radiation resistant Investigation of degradation by Co-60 gamma radiation in bulk silicon containing aluminum boron or diffused lithium Attempt to resolve the contradiction that Li and Al doped silicon are more sensitive to gamma than B-doped	○				○							
	NORTH AMERICAN ROCKWELL															
N 9-1	Contract NAS9-8953 Title Solar Powered Space Station Definition Vol III - Subsystem Definition Part 2 Electrical Power	Jul 70	Space station power requirements candidate primary power systems are described. Trade study for solar photovoltaic/battery system selection is presented Summarizes selected systems (GE) flex roll-up performance and design characteristics	○	●	○	●	●	○	●	○	●	●	●	○	●
	OPTICAL COATING LABORATORY, INC															
O 1-1	Internal Document Title General Spec Guide for Solar Cell Covers	Jan 68	Changes in quality level and production yields are reflected in this spec Uniformly high quality at reduced cost due to new and better coating techniques and tooling methods Spectral & mechanical parameters of all covers presented.			●										
	UNIVERSITY OF PENNSYLVANIA															
P 1-1	8th Photovoltaic Spec Conf Title The Formation & Degradation of TiAg & Ti-Pd Ag Solar Cell Contacts	Aug 70	Structure of these cell contacts evaluated by transmission electron microscopy and electron diffraction before & after 50°C 85% relative humidity exposure Improvements in present contacts and evaluation are discussed.					●								
P 1-2	8th Photovoltaic Spec Conf Title A New Look at Silicon Solar Cell Performance	Aug 70	Loss mechanisms in present cells reexamined and process dependence losses studied for affects on collection efficiency voltage factor and curve factor Reduction of surface recombination velocity increase in minority carrier lifetime and reduction of base region resistivity for efficiency improvement are discussed.					●								
	PHILCO-FORD															
P 2-1	Contract NAS7-409 Title Experimental Study of Coatings for Temperature Control of Solar Cells	June 66	Analytical & experimental program using selective interference filters & highly reflective coatings Measurement of filter-adhesive-cell composite performance under equilibrium temperature Studies to predict cell temperature and performance under various coatings	●		●	●	●								

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P 2-2	Patent Appl NASA-NPO 1111- Title Mechanically Extendible Telescoping Boom	Feb 70	Pivotally supported boom (crane type) having telescoping boom assembly including axially extended conduit elongated & contracted as boom assembly is extended and retracted													●
P 2-3	5th Photovoltaic Spec Conf Title Solar Cells from Epitaxial Gallium Arsenide on Germanium	Oct 65	Find methods of putting down thin layers of GaAs on suitable substrates Germanium obvious choice as substrate Techniques of preparation & characterization evolved in producing higher quality GaAs on germanium are described													
P 2-4	5th Photovoltaic Spec Conf Title Beta Irradiation of Lithium Doped Solar Cells	Nov 65	40 cells of 3 basic types irradiated for 118 days with Strontium 90 radioisotope almost matching Earth s trapped electron environment. Spontaneous recovery at varying rates Float zone silicon superior to Iopex and crucible					○								
P 2-5	Journal Spacecraft (Vol. 2 No 3) Title Pointing Error in Passively Stabilized Spacecraft Caused by Thermal Bending	May-Jun 65	Equations are derived for determining the bending radius for a long thin walled cylinder that points from spacecraft at all times to earth The no-stress and general cases are treated for cylinder exposed to the sun.	○												○

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	RCA (RADIO CORP OF AMERICA)															
R, 1-1	8th Photovoltaic Spec Conf Title: Room Temperature Stability & Performance of Lithium Containing Solar Cells Evaluation	Aug 70	Work done under contracts JPL-952249 & 952555 Results of investigation into recovery and post recovery behavior of lithium containing p/n silicone cells irradiated by 1 Mev electrons to fluences 1×10^{14} to 3×10^{15} e/cm^2					●								
R, 1-2	SAMPE Symposium Vol 15 Title: Erectable Structures and Meshes for Space Applications	- 69 -	New techniques in fabricating, stowing & deploying these extendible spacecraft structures. Formulas for analysis & design and techniques for mounting & deploying are given.	○												●
R, 1-3	Contract: JP 952555 Title: Study to Determine & Improve Design of Lithium-Doped Solar Cells	Mar 70	Effort to understand the cell damage & recovery mechanism when exposed to particle radiations (1 Mev electron beam - RCA Van de Graaff generator) "Hall-bar" silicon bars, float-zone, Lopex and crucible grown cells in the experiments at room temperature or below					●								
R, 1-4	IECEC Paper Title: Solar Cells Today	Sep 66	Continued improvements being made in solar cell capability Results on solar cell arrays, thin film and radiation resistance are discussed. Predictions for the future are included					●								
R, 1-5	IECEC Paper Title Thermal Restraints on Lightweight Solar Cell Arrays in Synchronous Orbit	Aug 67	At -120° C lunar orbiter array is flight qualified. Defines reasonable lower limit temp goal & establishes relationship between low temp extreme & significant electrical/mech parameters for large area oriented arrays.	○												
R, 1-6	IECEC Paper Title: Design of Multi-Kilowatt Photovoltaic Power System for Manned Space Stations	Aug 67	Design features of a 5 kW system for a 200 nm, 28 5 inclination mission orbit. 1720 ft^2 array has total system weight of 4026 lb Drag, gravity-gradient forces etc , are evaluated. Saturn envelope constraints are presented.	○												
R, 1-7	5th Photovoltaic Spec Conf Title: Wrap-Around Contact Solar Cells	Oct 65	Work under contract NAS5-3812 Developed a silicon solar cell with a wrap-around contact and a module by bonding such cells on a printed circuit board. Cell fabrication modifications described Tables of electrical characteristics given.					●								
R, 1-8	5th Photovoltaic Spec Conf Title: GaAs Thin Film Solar Cells	Oct 65	Comparison of electrical & optical properties of sputtered, flash evaporated, and vapor grown GaAs films. Covers film formation on various substrates, junction formation, cell structures and results obtained.													

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R 1-9	5th Photovoltaic Spec Conf Title Thin Film Cadium Sulfide Solar Array on Plastic Substrate	Oct 65	Arrays consist of two or four CdS cells (total area 11 cm²) Thermal vacuum cycling and vacuum storage of these samples discussed Irradiation tests conducted DuPont-Kapton plastic film as substrate					○								
R 1-10	5th Photovoltaic Spec Conf Title: The Effect of Lithium on Radiation Damage in Silicon Solar Cell Devices	Oct 65	Research under contract NAS 5-9131 diffusion length degradation in lithium doped silicon investigated by electro-voltaic effect requiring rectifying contacts All units irradiated with 1 Mev electrons in air at 30°C					○								
R 1-11	6th Photovoltaic Spec Conf Title: Progress in Thin Film GaAs Solar Cells	Mar 67	Research under contracts AF33 (616)-3486, NAS 3-6456 & NAS 3-8510 Two cell types evolved. One has substrate molybdenum, barrier layer of platinum & antireflection layer of SiO the other has aluminum substrate barrier layer of cuprous selenide. Greatest problem - low open circuit voltage.													
R 1-12	6th Photovoltaic Spec Conf Title: Calculation of 1 Mev Electron Flux & Irradiation Degradation of Solar Cell I-V Curves by Computer	Mar 67	Method for calculating the equivalent 1 Mev electron flux for a given charged particle environment and for degrading the cell I-V curve to account for the flux. Two digital subroutines (PHI and DEGRADE) flow diagrams and curves presented.					○								
R 1-13	6th Photovoltaic Spec Conf Title: Neutron Damage in Silicon Solar Cells	Mar 67	Interaction of lithium with more complex damage clusters produced in solar cells by neutrons. Information required for design of solar cell power systems exposed to weapon bursts or spacecraft using both nuclear & solar power supplies. Results of 14 Mev and fusion neutron bombardment reported.													
R 1-14	7th Photovoltaic Spec Conf Title Long Term Stability of Lithium Doped Solar Cells Irradiated with Electrons, Protons or Neutrons	Nov 68	Work under contract. JPL 953259 Irradiations by 1 Mev electrons, 16 5 Mev protons or 14 Mev neutrons - monitoring of cells for periods from 7 mos. to 2 yrs. Lithium doped p/n cells have higher resistance to all type radiations than standard p/n or n/p cells					○								
R 1-15	7th Photovoltaic Spec Conf Title: Injection-Level Effects in Irradiated Lithium-Containing Solar Cells		Work supported by contract NAS 5-10239 Results of an investigation of injection level effects on minority-carrier lifetimes in lithium doped solar cells irradiated by 1 Mev electrons and reactor neutrons Defect complexes formed in these tests are not in stable equilibrium at room temperature for days or even months					○								

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R.1-16	Applied Physics Letters Vol 9 No 1 Title Lithium-Doped, Radiation Resistant Silicon Solar Cells	Jul 66	Floating zone silicon boron & lithium diffused cells (p/n) irradiated with 1 Mev electrons and their electron and photovoltaic properties compared to standard cells. Diffusion length curves and table included					○								
R.1-17	Contract: NAS 5-10239 Title Recovery from Radiation Damage in Solar Cells Doped with Lithium (Annual Report)	Jun 67	Achieved a better understanding of the effect of lithium in producing cell recovery Recommendations for optimization radiation-resistant cells and suggestions for future study are included Speed & extent of cell recovery depends on amount of free and unpaired lithium available					○								
R.1-18	Contract NAS W-1427 Title Review and Evaluation of Past Solar Cell Development Efforts (Interim Report)	Dec 67	Contains bibliography of literature examined, a historical account of research on photovoltaic effect and devices used for power generation (from 1940 to 1967)					●								
R.1-19	Contract. NAS W-1427 Title: Review and Evaluation of Past Solar Cell Development Efforts	Jun 68	Literature survey time span increased (1839-1940) expanding the historical account. Additional evaluation and analysis in specific areas to help solve present and foreseeable problems in solar devices are reported.					●								
R.1-20	IECEC Paper Title Mechanical Thermal & Dynamic Considerations for A Photovoltaic System for Manned Space Systems	Aug 67	Description of a design concept of a PSM (power system module - solar array/power conditioning) Design considerations for orbital configuration of array-spacecraft are discussed Correction for orbital perturbation are included.	●			○			○				○		●
	ROME AIR DEVELOPMENT CENTER															
R.2-1	Research & Technology Briefs AFSCRP 80-1 P15 Title Rapidly Deployable Lightweight Antenna & Mast	Apr 69	Unique mast configuration, designated "ASTROMAST™" - a three-sided lattice column fabricated of high strength corrosion-resistant stainless steel, is described. 100 ft mast fully retracts to package height of 41 inches.													●
	RAE ROYAL AIRCRAFT ESTABLISHMENT															
R.3-	Title Recent Developments in Silicon Solar Cells	No Date	Development trends in solar cells, cell covers, flex array substrates and structures are reviewed and reported. State-of-the-art specific weight & specific area curves are presented		●	○	●	○								

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R 3-2	RAE Tech. Report 68137 Title: Developments in Solar Cell Performance Measurement	May 68	Procedure for measuring the orbital photoelectric performance of cells. Techniques and equipment for greater accuracy described. Checking methods for assembly test phases and pre-launch checkout are discussed.													
R 3-3	RAE Tech. Report 67305 Title: Thin Silicon Solar Cells for Larger Flexible Arrays	Nov 67	Evaluation of performance characteristics of n/p silicon cells 100 to 400 microns thick following irradiation by 1 MeV electron fluxes up to 10^{16} e/cm^2 Reduction of specific mass from 20 kg/Kw is described					○								
R 3-4	ECOSEC Paper (Toulouse) Title: An Advanced Lightweight Solar Array	Jul 70	50 watts/kg. (500 watt) experimental array for prototype testing. 5-mil silicon cells, 4-mil special glass coverslips on 2-mil Kapton panels & flat pack stowage. Progress in main problem areas reviewed, future plans outlined.		●	○	●	○		●	●	○		●		○
R 3-5	RAE Tech. Report 68191 Title The Ion Engine and Large Solar Array for XB Spacecraft	Aug 68	Description of the ion engine and the 530-watt deployable solar array for Black Arrow-XB spacecraft. Problem areas are discussed and present state of development.		○		○			○	○					
R 3-6	RAE Tech. Report 65019 Title: Large Solar Cell Array	Jan 65	Possible methods of stowage deployment and support of large deployable arrays. Using 100 micron thick n/p cells the arrays would weigh less than 20 kg per kW extending about 12 m^2 per kW Discussion of problem areas included.		○		○			○	○					
R 3-7	RAE Tech. Report 68052 Title: The Ariel 3 Power System	Mar 68	Novel features, technological problems and techniques for adequate performance for this satellite solar cell/battery system are described Selection and flight acceptance test procedures are outlined.													
R 3-8	RAE Tech. Report 68218 Title: Mass Spectrometer Analysis and Tensile Testing of Irradiated Materials for Satellite Applications	Aug 68	Gamma irradiation under vacuum of sheet plastic material and "Loctite", sealant. Measured outgassing and analyzed gas composition. Tensile strength measured before and after irradiation		○											
R 3-9	7th Photovoltaic Spec Conf Title: Environmental Assessment of Thin Silicon Cells from Pilot Production	Nov 65	Feasibility of using 4 mil Si cells on large flex arrays Both conventional & wrap-around cells with solderless evaporated TiAg contacts & solderless plated Ni-Co-Au contacts evaluated Subjected these cells to environmental conditions					●								
R 3-10	7th Photovoltaic Spec Conf Title: Large Solar Array Development in U K	Nov 65	Development of 560-watt deployable array some novel feature discussed Concertina-fashion folded Kapton and pneumatically-actuated telescopic masts. 8 m^2 array - 22 3 watt/lb at 55 C		●	○	●	○		●	●	○		○		○

LEGEND

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R 3-11	6th Photovoltaic Spec Conf Title Progress in Advanced Solar Array Development	Aug 70	Review of a low-cost lightweight deployable array of silicon solar cells Stowage system and telescopic mast described Array used 12 μm cells with wrap around contacts and cheap radiation resistant coverslips		●	●	●	○		●	●	○		●		●
R 4-1 thru R 4-4	RYAN AERONAUTICAL Contract JPL 951107 Title Deployable Large Area Solar Cell Array Tech presentation summary final design and test reports 1st, 2nd, 3rd Quarterlies and Final Report	May 68 thru Aug 69	Three-phase study design and fab program to develop the concepts and technology required for a deployable large area solar array structure using a minimum shroud volume Phase I - concept selection was a roller drum-extendable beam having inherently good self-damping qualities in stowage Phase II - designed a four-element 200 ft^2 deployable array structure - weight objective 0 6 lb/ft^2 half for deployment, structure & substrate & half for cells filters wiring and cable Phase III-fabricated 50 ft^2 element of design concept to demonstrate feasibility compatibility with environmental and flight requirements	○			○	○		●	●	●	●	●	●	○
R 4-5 thru R 4-8	Contract JPL 951971 Title Feasibility Study 30 Watts Per Pound Rollup Solar Array 1st, 2nd, and 3rd Quarterlies and Final Report	Jul 67 thru Jun 69	Design trade studies analysis and development verification test conducted to select the most promising solar array configuration Detailed preliminary design of the selected configuration was performed Detailed stress dynamic thermal & weights analyses were performed A full size drum with six substrate panels (mass loaded to simulate the 250 ft^2 panels) was tested to sinusoidal launch environment Full scale model fabricated to demonstrate deployment/retraction	○	●	●	○	○		●	●	●	●	●	○	●
S 1-1	SANDIA CORP - LIVERMORE LAB Electronic Packaging & Production Article Title On the Quality of Soldered Joints	Jun 69	Parallel-gap soldering has [illegible] of silicon integrated circuit flat packs for making connections between silicon integrated circuits (SIC) and printed wiring boards is discussed				●									

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	SELENIA CO ITALY															
S 2-1	Tech. Report Title PAS Transfer Orbit Solar Cell Energy as Function of Launch-time	Apr 69	Solar cells on the surface of cylindrical PAS satellite Report gives the documented electric energy per orbit of transfer for 80 different launch times Also included are the eclipse times for the different launchings													
	SOCIETE ANONYME DE TELECOMMUNICATIONS															
S 3-1	5th Photovoltaic Spec Conf Title Antireflecting Silicon Solar Cells with Titanium Dioxide	Aug 70	Significant quantities of cells processed to allow comparison of results on average basis. Theoretical and experimental results are presented					●								
S 3-2	Title Lockheed Supplied Test Module-Thermal Cycling Test	Jul 70	Results of thermal cycling test on LMSC flex substrate presented. Conditions at ten year synchronous orbit applied		●	●	●									
	SPAR AEROSPACE PROD LTD															
S 4-1	Advanced Aerospace Tech Symposium (Toronto) Title Deployable Booms for Gravity Gradient Stabilization	Mar 69	STEM (Storage Tubular Extendible Member) description and flight history presented Design of interlocked bi-stem boom is included.													○
	SPECTROLAB															
S 5-1	Int l Colloquium on Solar Cells (France) Title Solar Array with Integral Diodes	Jul 70	Shadows across a series element eliminates the circuit Discussion of the Integral Diode Solar Cell (patent applied for) as an alleviation to the disproportionate losses resulting from shadow problems.	○			●	○								
	STANFORD UNIVERSITY															
S 6-1	7th Photovoltaic Spec Conf Title Photovoltaic Effect at Cu_2S - CdS Heterojunctions	Nov 64	Study of the depletion layer width diffusion lengths and spectral response by a light microprobe electron mirror microscope and etch techniques													

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	SYLVANIA															
S 7-1	Contract COMSAT CSC-ED-17 Title Dynamics of Deployment of Extendible Booms from Spinning Space Vehicles (J Spacecraft Article)	May 68	Developed general equations of motion Using the simplifying assumption of rigid booms the equations are solved for the cases of unrestrained extension and constant-velocity extension Interesting characteristics of motion for a sample problem are discussed	○												○
S 8-1	Electronic Design 22 article Title: Chip Bonding Promises and Perils (Special Report)	Oct 69	Beam-leaded chips chips with silver-tin bumps and spider bonding are discussed as to relative production merits for packaging and forming hybrid circuits				●									
	TEM-PRES/RESEARCH/CARBORUNDUM															
T 1-1	Contract F33615-69-C-1221 Title Hydrogen Impregnated Glass Covers for Hardened Solar Cells	Mar 70	Experimentally demonstrated that hydrogen impregnation significantly reduces darkening of cell glass covers Corning 7050 Clay Adams A-1409 & Corning 1723 successfully treated Levels of H_2 impregnation for various dose levels reported			○										
	TEXAS INSTRUMENTS															
T 2-1	Contract NAS5-10319 Title Solar Cell Integral Cover Glass Development	Nov 68	Applying integral cover glass coatings to cells by radio frequency sputtering Techniques used to deposit insulator films on silicon & theory & experimental details of radio frequency sputtering discussed. Environmental testing reported			●										
T 2-2	Contract: NAS5-11612 Title Solar Cell Contract Deposition Study (1st Quarterly)	Nov 68	6 months study to improve vacuum deposition of TiAg contacts on silicon cells Evaluated effects of various evaporation substrate temps 9 C to 200°C Data indicates TiAg contacts with smallest grain size exhibit high degree of humidity resistance					●								
T 2-3	5th Photovoltaic Spec Conf Title Development of Epitaxial Structures for Radiation Resistant Silicon Solar Cells	Oct 65	Use of built-in electric fields in solar cells used to enhance their performance after irradiation by high energy particles Exponential is ideal distribution for optimum field, approximated by using co error distribution function Cell fabrication and test results discussed					○								
T 2-4	6th Photovoltaic Spec Conf Title Lithium Doped Radiation Resistant Silicon Solar Cells	Mar 67	Investigation of three Lithium diffusion techniques Radiation annealing behavior of lopex, float-zoned and quartz crucible made cells compared Integral quartz covers applied to cells					○								

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	THOMSON-RAMO-WOOLDRIDGE SYS INC															
T 3-1	Contract NAS5-11551 Title Fast Response Solar Array Simulator F R	Oct 65	Performed trade studies to determine design requirements for power system (range 20 watts to 3 kW) Generated static/dynamic characteristics through forward biased solar cell as analog reference Variation of characteristics with time programmed by digital technique	○				○								
T 3-2	Contract JPL 9523-4 Title Study & Determination of an Optimum Design for Space Utilized Lithium Doped Solar Cells	Apr 70	This 3rd Quarterly Report presents the measured effects of irradiation on lithium doped quartz-crucible lithium compensated p-type silicon and bismuth/tin doped, cells to determine defect complexes formed and post-annealing. Better groups tested for radiation resistance					●								
T 3-3	IECEC Paper Title Computer Simulation of Satellite Electric Power Systems	Jul 69	Describes computer program concept for electrical analysis and transient thermal analysis of system composed of solar array batteries & power controls Program plots curves of voltage currents temperatures & energy balance for one or more orbits	○												
T 3-4	Contract NAS3-10496 Title Study on Fluid Dampers for Booms	Jul 65	Investigation of feasibility of using rings and spheres filled with viscous fluid for damping an oscillating boom. Only ring and spherical dampers were analyzed in detail and compared for performance characteristics	○												
T 3-3	Gravity Gradient Attd Ctrl Symposium Title Solar Flutter of A Thin Walled Open-Section Boom	Dec 64	Mathematical model was formulated to demonstrate thermally - excited oscillation in long boom antennas Results presented are typical of OGO-IV flight boom which exhibited a non-planar coupled bending-torsion oscillation excited solely by incipient solar radiation.	○												

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T 3-6	IECEC Paper 689076 Title: Thin-Film Multikilowatt Solar Arrays	Aug 68	Two wing (folded) 2 3 kW solar array using CdS solar cells studies in detail Deployment by extendible mechanical booms & actuators At 1 AU 20 watt/lb realized using CdS cells of 3 6% AMO efficiency at 25 C	●				○							●	●
T 3-7	IECEC Paper 689077 Title Lunar Surface Solar Array Characteristics	Aug 68	Silicon cell arrays both oriented and non-oriented compared. Array size performance structural designs & materials selection are considered. Passive thermal control concept is presented Array temperature sensitivity discussed.	●												
T 3-5	IECEC Paper 689075 Title Large Solar Arrays for Multi-Mission Lunar Surface Exploration	Aug 68	Power profiles in high energy requirements regime (10 to 300 kW) Solar arrays in conjunction with fuel cells and/or batteries as power supply for various surface missions Impact of lunar environment emphasized.	○												
T 3-9	IECEC Paper 699081 Title Temperature Cycling Effects on Solar Panels	Sep 69	Soldered silicon cell assemblies with copper kovar and molybdenum interconnectors exposed to more than 300 temp cycles down to -173°C Wide range of failures depending on materials thicknesses. Solder fatigue failure rate presented.	○			●									
T 3-10	IECEC Paper Title OGO Solar Array Design Fab & Flight Performance	Aug 67	Describes design, fabrication, and flight performance of mis sun oriented deployable solar arrays 3 OGOs successfully launched (5 years total time) Describes electrical design. Excellent performance-qual test program discussed													
T 3-11	IECEC Paper Title Multifaceted Solar Array Performance Determination	Aug 67	Two computer programs for multifaceted spinning or non-spinning body-mounted or paddle mounted solar arrays described. Output of programs - tabulated panel/array voltage current & power from short-to-open-circuit plot & graphs.	○												

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T 3-13	IECEC Paper Title: The Solar Array for the Pioneer Deep Space Probe	Aug 67	Description PIONEER VI & VII solar array power systems Cylindrical body mounted (37 in diam 36 in long) Engineering model ground tests & design data compared to flight data Photographs illustrations showing design construction and tests				○									
T 3-13	5th Photovoltaic Spec Conf Paper Title: Low Energy Proton Degradation in Silicon Solar Cells	Oct 65	Experimental technique and resulting data from bombarding 10 ohm-cm 1 x 1 cm p/n silicon cell in STL 2 Mev proton Van de Graaff at energies from 0 2 Mev to 1 9 Mev to determine radiation induced changes in I-V characteristics					●								
T 3-14	5th Photovoltaic Spec Conf Title: A Theoretical Model for Low Energy Proton Irradiated Silicon Solar Cells	Oct 65	Model generated for low carrier injection levels - solution presented in closed form in terms of physical and geometrical parameters Short-and open-circuit voltage calculated and compared to experimental results					●								
T 3-15	6th Photovoltaic Spec Conf Title: Annealing of Radiation Damage in Lithium Doped Silicon	Mar 67	Initial effort in a program for clarifying the role of lithium in irradiated silicon specimens Irradiated with 1 Mev electrons Results on floating zone and crucible silicon cells are presented					○								
T 3-16	6th Photovoltaic Spec Conf Title: Effects of Base Resistivity on the Characteristics of N-on-P Silicon Solar Cells	Mar 67	Investigation of electrical characteristics of silicon cells with base resistivities in 1- to 25-ohm-cm range Experimental measurements made on N/P cells of various base resistivities in TRW Van de Graaf generator (1 Mev electrons at various fluxes)					●								
T 3-17	7th Photovoltaic Spec Conf Title: Electrical Output of Shadowed Solar Arrays	Nov 68	Current voltage characteristics of solar cell circuits effected by shadow studies for development of mathematical models Shadowing factor for analyses of large arrays permits analyses by digital computer using empirical input data	●				●								
T 3-18	7th Photovoltaic Spec Conf Title: Temperature & Humidity Effects on Silicon Solar Cells	Nov 68	Determination of degradation in power output with time of silicon cells stored at room or elevated temperatures with high humidity (with AgTi contacts with and without solder) Periodic measurement of short circuit current of specimens					●								

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T 3-19	IECEC Paper 699094 Title: 40 Watts/Pound Spacecraft Solar Array	Sep 69	Description of deployable silicon cell solar array with self-rigidizing folded panels - flexible substrates Analysis and test show capability of 40 w/lb and 1 3 kW 1 to 3 of stowage volume Single extendible boom presented		●	○	○	○		●	●	●	○			○
T 3-20	Contract NAS5-10243 Title: Final Report for Nimbus Solar Array Drive Sub-system	Feb 70	Design development manufacture & test of four solar array drives 2 engineering models & two prototypes Hardware description design configuration description and equipment specification are covered												○	
	UNIVERSITY OF TORONTO															
T 4-1	Journal Spacecraft Title: Explanation of the Anomalous Spin Behavior of Satellites with Long Flexible Antennas	Sep 67	Spin behavior is shown to be a consequence of the joint action of solar-heating-induced bending of the antennae and solar radiation pressure Means of preventing spin by use of tip plates perpendicular to antennae explained	○												
	WELLS ELECTRONICS INC															
W 1-1	Electric Packing and Production Article Title: Multiple-Lead Reflow Soldering Techniques	Oct 67	An assembly technique for flat packs said to be 18 times faster than hand soldering is presented Components such as capacitors, transformers, and relays are available in flat packs permitting increased ministurization					●								
	WESTINGHOUSE															
W 2-1	Contract: AF33 (615)-5462 Title: High Voltage Solar Cell Array Segment (Interim report)	Sep 67	Twelve-inch long silicon web processed Longest cell tested consisted of 43 unit continuous array Power conditioning network capable of converting 50 vdc to 1000 vdc (10 watts power) developed 46 watts/lb breadboard circuit.					○	●							
W 2-2	Contract. AF33 (615)-5198 Title: 4 kW Solar Photovoltaic Power System Design Study (F R)	Jan 62	Intended for use on a stationary equatorial communication satellite 2 paddles each paddle 4 frames (13 x 7 6 feet) p/n silicon cells covered by 0 030 in. sapphire Presents configuration analysis, design specification & data for prototype													
W 2-3	Contract. F33615-68-C-1616 Title: Solar Cell Neutron Damage Investigation (F R)	May 70	Fast neutron irradiation of multi-layer cell specimens (epitaxially-fabricated) and conventional n/p cell specimens Neutrons from test reactor-fluence range 10^{10} to 10^{14} n/cm^2 Efficiencies and short-circuit currents reported.					○								
W 2-4	Contract: NAS 5-10130 Title: Gravity Gradient Stabilization System Elements & Antenna Structures (Long Booms for ATS)	May 66	Interim Report - Development of a deployer and scissoring assembly to fit ATS vehicle Produced an engineering model deployer fitted with a 150 foot boom and assembled in a scissoring mechanism													○
W 2-5	IECEC Paper Title: Drift Field Solar Cells on Silicon Web	Sep 66	Optimization of solar cells for radiation resistance Fabrication of epitaxial growth techniques to obtain graded layers resulting in drift field structure Improved "solderless" cell is also discussed along with test results					○								

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				MOTORS	GEARS	BEARINGS/ ROLLERS	LUBRICATION SYSTEM	SLIP RINGS	ROTARY TRANSFORMERS	LUBES/ SEALS	FLEX CABLE
	ARO INC (cont)										
AA 2-3	Performance Test of Power Transmission Slip-Rings in Vacuum Environments - D L Adkins		Results in this report are also included in AD-457 356 Tested brushes of "CLD Alloy" (82 5 - 85 % Ag +2 5% Cu +12 5 - 15% MoS_2) on silver rings at 6 and 10 psi brush pressure carrying 40 and 74 amps (75 amps equiv to 229 amps/in^2) in vacuum of 10^{-8} - 10^{-9} in wear per inch travel at 318 in/min No deleterious effects were caused by 40 hours of static conduction at 75 amps					●			
AA 2-4	Operational Evaluation of Dry Thin Film Lubricated Bearings and Gears for use in Aerospace Environmental Chambers - T L Ridings	2/65	This report contains the results of a test program set up to determine the operational characteristics of dry, thin film lubricated bearings on gears uniquely adapted for operation in a simulated space environment Results indicate that dry thin film lubricants and soft metal plating lubricants can be applied satisfactorily to certain types of bearings and gears and are capable of sustaining heavy loads at slow speeds in space environments		○	○	○				
AA 2-5	Tests of Dry Composite Lubricated Bearings for use in an Aerospace Environmental Chamber - T L Ridings	3/65	This report contains the results of a test program set up to determine the operational characteristics of dry composite lubricated bearings Two different bearing types were tested Tapered roller bearings and ball bearings Four dry composite lubricants and two low vapor pressure greases were tested Results indicate that the dry composite lubricants were more successful when used with ball bearings than when used with tapered roller bearings All four composite lubricants provided low system torques (40 to 60 lb-in) under heavy loads (3000 lb/bearing) for the scheduled 100 hours Best results were obtained using CU (copper) and PTFE (Teflon) and WSE2 (Tungsten Diselenide) and a silver alloy + PTFE + WSE2 One low vapor pressure grease was successful as a lubricant at room temperature but migrated at temperatures above room temperature The other low vapor pressure grease was successful at temperatures up to 140°F with no migration		○	○	●				

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				MOTORS	GEARS	BEARINGS/ ROLLERS	LUBRICATION SYSTEM	SLIP RINGS	ROTARY TRANSFORMERS	LUBES/ SEALS	FLEX CABLE
	ARO INC (Cont)										
AA 2-6	Tests of Dry Composite Lubricated Gears for use in an Aerospace Enviornmental Chamber - T L Ridings	3/65	This report contains the results of a test program set up to determine the operational characteristics of dry composite lubricated gears Two diametral pitch sizes, 7 and 12, and two gear materials, nitralloy steel and nodular iron were tested Three dry composite lubricants and one low vapor pressure grease were tested All three dry composite lubricants provided adequate lubrication for periods of up to 300 hr at 100 rmp with very little wear of either load gears or lubricating idlers The MoS_2-fortified, grease lubricated failed after 40 hr of operation		○		○				
	BALL BROTHERS RESEARCH CORPORATION										
BB 1-1	Acceptance Report - Torque Motor Elevation OSO-D P/N 19.73-.. - Williams	8/65	Report is about the behavior of a specific motor type under varying environmental conditions General behavior pattern may be extracted	●			○				
BB 1-2	Design Study Report Lubrication System for Comsat ITS-3 Antenna Despin Assembly - Mayer	6/68	The report gives design calculations for bearing lubricant requirements and loss rate to meet operations over a 5 year period			○	○				
BB 1-3	Determination of Life Expectancy of Vac-Kote Processed Bearings for Aerospace Allocations - B Perrin	2/66	The report contains a review of the theoretical basis for Vac-Kote lubrication systems Included are calculations on bearing life lube loss rate radiation damage etc Report concluded that bearings with Vac-Kote and Nylasint reservoirs would meet 5 year life requirements with 92% reliability at 90% confidence level			○	○				
BB 1-4	Effects of Thin Oil Films on Bearing Torque - Christy	7/64	A test method is presented with its mathematical basis for determining torques of ball bearings Torques are calculated from run-down time Test results are given to show the torques of a given ball bearing as a function of Vac-Kote oil film thickness			○	○				

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				MOTORS	GEARS	BEARINGS/ ROLLERS	LUBRICATION SYSTEM	SLIP RINGS	ROTARY TRANSFORMERS	LUBES/SEALS	FLEX CABLE
	BALL BROTHERS RESEARCH CORP (Cont)										
BB 1-5	Electrical Properties of Vac-Kote 108 - Roller	5/62	This document develops the theory for measuring the electrical conductivity and the dielectric constant of Vac-Kote 108 materials A practical method for making these measurements is discussed, then the actual measurements are presented along with a discussion				●	●			
BB 1-6	Flexprint Vacuum UV Irradiation Test - A Kay	5/65	This is probably not helpful to our job because it is specialized UV tests on small conductors If we end up with flex cables exposed to UV, then we should look at this again - otherwise not								●
BB 1 -	Investigation of a Dry Lubricant Surface Treatment for Bearing - A Kay		The report gives test data showing advantages in glass bead peening followed by application of MoS_2 over other non-bonded methods of applying MoS_2			●	●				
BB 1-3	Mechanical Design Analysis Antenna Control and Drive System - J Hinricks		Contains stiffness and deflection analysis and resonant frequency calculation for bearings and structure Thermal analysis over temperature range of 20° C to +80° C Shows equivalent beam and node model, computer outputs for deflections at different nodes and stiffness matrices			●					
BB 1-8	OSO D Acceptance Report Slip Ring Assembly P/N 16093 - Williams	8/65	This document is the Acceptance Test report for the OSO-D slip ring assembly The test specification is included along with filled out test procedures for two slip ring assemblies					●			
BB 1-10	Reliability Analysis for TRW Despin Mechanical Assembly - Halbert		Describes the methods and formulas used to arrive at a final reliability figure for the TRW Despin Mechanical Assembly The information contained herein is not applicable at this time to the ODAPT Program								

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	BALL BROTHERS RESEARCH CORP (Cont)										
BB 1-11	Slip Ring Noise Tests in Vacuum - K" Roller	3/67	This report presents the results of electrical noise testing performed on slip ring assemblies in a vacuum The primary purpose of the testing was to measure the low frequency (8 Hz to 60 kHz) and high frequency (150 kHz to 400 MHz) noise generated by the slip rings and DC torque motor brushes Additional data includes brush wear, contact resistance, and brush temperature The devices were operated at either 30 or 150 rpm, brush forces ranged from 10 to 60 grams, and the test current from 0 2 to 5 amperes Brush wear is shown to be dependent in the sliding velocity and independent of the current in the range tested Contact resistance is low at high brush forces but varied unpredictably at light forces Brush temperatures were affected more by sliding velocity than by conducted current				●			
BB 1-12	A Summary of Slip Ring Test A - Christy		Some wear information on slip rings A vacuum life test on various materials that were lubricated with Vac-Kote Fine silver and hard gold was used as ring material and Palinoy No 7 and Moy Oro 28A was the brush wire material Test was for 2000 hours Moy Oro 28A on hard gold was the best combination				●	●			
BB 1-13	Technical Report - Vac-Kote Process Treatment - Dunipace		Report contains summary tabulations of results from vacuum lab tests and S-16 satellite performance on torque motors and slip rings lubricated with Vac-Kote lubricants							●	
BB 1-14	Test Report Electrical Contact Ring Assembly 95 Day Life Test - Hinricks	4/69	This document reports on the vacuum life test of a Hughes Aircraft Co slip ring assembly treated with Vac-Kote The rotor was driven at a nominal 55 rpm for the entire 95 day test Test currents ranged from 100 milliamps to 36 amps Noise measurements were made weekly Wear measurements are given The results indicate a very high probability that this unit will meet the 5-year life objective					●			

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	BALL BROTHERS RESEARCH CORP (Cont)										
BB. 1-15	Tests of Dry-Lubricated Gears and Bearings-Rector		Report gives vacuum test results on dry Vac-Kote gears and bearings operating in a test fixture Endurance of lubricative film is shown to exceed that of the gear teeth themselves; i e though the gear teeth failed by plastic flow, the dry Vac-Kote was still intact on the deformed surfaces		O	O	O				
BB. 1-16	Torque Motor Life Test - Frank		Data sheets of brush type DC torque motor running time in vacuum References photographs which might come in handy should question of brush wear arise	●							
BB. 1-17	OSO-G Qualification Test Report, Cable Assembly, Flexible - K Pykkonen	7/69	This document reports on the Qualification Tests of the OSO-G flex cable assembly The test specification is included along with a filled-out test procedure								O
BB. 1-18	Orbiting Solar Observatory (S-16) Final Report		Final Report on first OSO satellite	●	●	●	●	●		●	●
BB 1-19	Statistical Analysis of OSO Slip Ring Noise	2/68	This document is a theoretical noise study augmenting the OSO second source qualification tests on the Poly-Scientific slip ring assembly					O			
BB. 1-20	Technical Report Analysis and Correction of Slip Ring Problems	3/63	This report documents the history of the slip ring problems encounted by Aerojet General Corp This is a case history of a particular problem								
BB. 1-21	Orbiting Solar Observatory (OSO) Slip Ring Qualification Test Report	1/68	Report gives detailed test data on three slip ring assemblies being qualified for use in OSO's					O			
BB. 1-22	OSO-E1 Acceptance Report Slip Ring Assembly P/N 16093-1	4/66	This document is the Acceptance Test report for the OSO-E1 slip ring assembly The test specification is included along with the filled out test procedure					O			
BB. 1-23	OSO Acceptance Report Slip Ring Installation P/N 15491-1 S/N 11	11/67	This document is the Acceptance Test report for a flight slip ring assembly The test specification is included along with the filled out test procedure					O			

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	BALL BROTHERS RESEARCH CORP (Cont)										
BB. 1-24	Vacuum Test of Slip Ring/Motor Assemblies and Bearings	11/63	This report discusses a 200 hr vacuum test on 4 motor-slip ring-bearing assemblies The tests were performed for Lockheed Missiles and Space Co The purpose was to determine the performance of two Inland Motor Corp slip ring assemblied and Bardan Corp ball bearings when treated with Vac-Kote The tests were successful	O		O	O	●			
BB. 1-25	Slip Ring and Torque Motor Noise Measurements - O J Simpson	7/65	This document describes the slip ring and torque motor noise tests on OSO type slip rings and torque motors lubricated with Vac-Kote Most testing was done at ambient conditions since experience seemed to indicate that the noise is the same whether in vacuum or room ambient Current up to 15 amps were used in some tests					O			
BB. 1-26	Slip Ring Noise Study		This document describes some 1961 vacuum tests on several slip ring and brush material combinations Iron Fireman ELDEC and Breeze, assemblies were tested Silver and Coin Silver rings were used with silver graphite and Pelmey No 7 brushes Noise measurements were the primary reason for the tests					O			
BB. 1-27	Interim Technical Data on Slip Ring Test Assemblies ET2040-1 and ET2040-2 - Mayer; Hindricks	7/69	This report contains information on materials used on Comsat (Company confidential)					O			
BB 1-28	Space Mechanism Lubrication - Perrin and Mayer	5/68	Paper reviews M M Fulk's theoretical lubrication model and the successful Vac-Kote lubrication of various spacecraft								
BB. 1-29	Results of Vacuum Environmental Test of a DC Motor Prepared by the Vac-Kote Process	8/61	Vac-Kote lubricated Inland DC motor (T-4006B) ran for 1795 hours and longer without appreciable mechanical or electrical changes	O							
BB 1-30	Vac-Kote Process Treatment - Dunipace	1/63	The report presents test data to illustrate the improvement in performance characteristics of torque motors and slip rings which may be expected from the use of the Vac-Kote process				O				

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	BALL BROTHERS RESEARCH CORP (Cont)										
BB 1-31	Thermal Vacuum Test on Flex Cable - R Christy	2/68	Company Private Data - This test measures the torque and life of six types of flex cable, operating in thermal vacuum Test samples selected cover the range of flex cables typically used on gimbaled axes in spacecraft pointing systems From the data obtained, flex cable torques and torque variations for given applications can be predicted by extrapolation								●
BB 1-32	TRW/STL Slip Ring Feasibility Study - B J Perrin	7/65	This is a thorough review of Vac-Kote lubricated brushes and slip rings Both OSO flight experience and vacuum test data are presented in support of a proposal to use OSO-type slip rings on a one rev/day synchronous satellite					●			
BB 1-33	Results of Vacuum Environmental Tests: On Slip Ring (TM61-47 A), on Bearings (TM61-38A, on DC motor (TM 61-48A), all Treated with Vac-Kote		The object of the test was to determine the degradation of the mechanical and electrical performance of slip rings operated in a high to ultrahigh vacuum at a known temperature.	●		●	●	●			
BB 1-34	Qualification Report Lubrication, S-17 Orbiting Solar Observatory -	1/63	Report contains long-term tests of Inland torque motors in vacuum with grease and oil lubricants				●				
BB 1-35	Friction Torque in Lightly Loaded Ball Bearings with Vac-Kote Lubrication	11/66	The purpose of this study was to compile some of the torque data available at BBRC and to organize these data in a manner which facilitates torque predictions for different bearings in new applications			○					
BB 1-36	Test Procedure for Test Sequence B - Roller	3/62	Report describes details of materials and procedure to be conducted on a number of potential brush/slip ring combinations					●			
BB 1-37	Subcontract No 28-457 to Lockheed Missile and Space Co - Mayer	10/62	Report is on contract work to develop slip ring assemblies which will operate in a space environment Current conduction is on a signal level					●			
BB 1-38	Development of Slip Rings for Space Application - Mayer		Report is a general overview of the contract work without much of specific results See progress reports for details					○			

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	BALL BROTHERS RESEARCH CORP (Cont)										
BB 1-39	Thermal Vacuum Testing of Star Tracker Components - Mayer	1/64	Report gives information on preparation and testing of components for use on a space drive system			○	○	○			
BB 1-40	STL Component Feasibility Test Tests 1, 2 and 3		A thermal vacuum test was performed for STL Antenna Control and Drive System (ACDS) components This was an initial feasibility test to evaluate components and lubrication considerations These documents report the test procedure and results of these feasibility tests			●	●	●			
BB 1-41	OSO-F Qualification Report - Filter Choke Cable Assembly - Johnson	12/68	This report documents tests performed to demonstrate qualification of the OSO-F Filter Choke Cable Assembly for Flight use								
BB 1-42	OSO-G Qualification Report - Cable Assembly, Flexible - Pykkonen	8/69	This report documents the qualification tests performed on Flex Cable Assemblies and shows that they meet the qualification test requirements								
BB 1-43	Qualification Test, OSO S-17		This report gives OSO Qualification Test information on Upper Azimuth Bearing and Lubricant Performance								
BB 1-44	OSO Bearing Qualification Test		A report on OSO component Qualification Tests in Azimuth and Elevation Drive Bearings								
BB 1-45	Recommended Procedures for in Orbit Operation of the OSO B-2		This report is a procedural document which describes the technique to be used for in-orbit operation of the OSO B-2 spacecraft								

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	BARDEN CORP										
BB 2-1	Investigation of Unconventional Bearings John J Murphy, Et Al		The investigation of unconventional approaches to the problem of providing a dynamic support in an aerospace environment is the object of this research contract Current work by other investigators and original concepts and their potential are discussed The report covers solid liquid gaseous and metallic lubricants, rolling element, journal and gas bearings, electric and acoustic force field supports, seals, cooling and means of preserving lubricants and surfaces Several systems utilizing a combination of operating principles or devices are proposed which meet the aerospace environmental conditions One system the gas bearing with molecular pump seal is recommended as most likely of success An extensive bibliography is included			O					
	BOEING CO., SPACE DIV.										
BB. 3-1	Maintainability of Manned Spacecraft for Long-Duration Flight, Volume 1		This report evaluates the maintainability of long-term manned space flights								
BB. 3-2	Maintainability of Manned Spacecraft for Long-Duration Flights Volume 2		This document pertains to design requirements and philosphy of maintainability Reliability should read it for use in their part of the program later on Applies to maintainability considerations (See 2 2 for specific study conclusions)								
BB 3-3	Rotary Relay for Space Power Transfer- II Theron Baynie	6 70	The power clutch presented in this paper was designed for the transfer of electrical signals and power across rotating joints Radio noise, friction and wear are virtually eliminated The design, construction, and applications are presented This clutch eliminated the need of recycling solar arrays once each orbit by recycling only a low-inertia component of the power system					●			

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	DEFENSE DOCUMENT CENTER										
DD 1-1	Lubricants for use in the Space Environment Volume I		A DDC Bibliography, DDC No AD-702 550								
DD. 1-2	Lubricants for use in the Space Environment, Volume II	3/70	A DDC Bibliography DDC No AD-867 903								
DD. 1-3	Solar Cells and Solar Panels Volume I & III		A DDC Bibliography, DDC No AD-700 500								
DD. 1-4	Solar Panels Volume III of III Volumes		A DDC Bibliography, DDC No AD-866 201								
	DEFENSE METALS INFORMATION CENTER BATTELLE MEMORIAL INSTITUTE										
DD 2-1	Surface welding in the Space Environment R M Evans Et Al	6/66	In this memorandum, the available reports in DMIC which are concerned with welding of metal surfaces in space environments whether this welding is desirable or undesirable, are reviewed The phenomenon of surface welding in the space environment is of interest to many for various reasons Some hope to use the phenomenon for the completion of attachment joints or repairs to spacecraft Some are concerned because of the possible malfunction of moving components such as bearings valves and electrical contacts However, no effort has been made to correlate and analyze the data that are presented A section on fundamental studies also is included, along with an annotated bibliography which covers references dealing primarily with lubricants, lubrication coatings and test equipment			O					
DD. 2-2	Electrical Contact Materials for Space Applications -		Report deals primarily with precious metal contacts and slip rings for signal-level currents					O			

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	DESIGN NEWS PUBLICATION										
DO. 3-1	Sintered Skeleton Sweats Lead to Control Friction - T Balmer	11/70	"Bishiraloy" a slider material for high-speed Japanese trains conducts 150 amps at 25 000 volts 60C Hz, to supply power for driving trains at 130 mph Service life is 10 000 miles compared with <1,000 miles for previous unspecified material Material is lead-impregnated sintered ferrous alloy It functions by oozing melting lead when frictional heat causes temperature to rise Lead composition can range from 10 to 30 percent depending on application					●			
	DORNIER SYSTEM GMBH										
DO. 4-1	Development of a Bearing for the Despin Antenna of a Spin Stabilized Satellite Part 1, Basic Investigation	10/67	Report is in German but a summary in English indicates that various bearing types and lubricants were tested under vacuum conditions and resulted in selection of the best combination for use in a bearing system for the despin antenna of a spin-stabilized communications satellite			●					
	DOW-CORNING CO.										
DO. 5-1	Testing Solid Lubricants - Bani T Azzam	8/69	This paper discusses the problems involved in the investigation of the friction and wear complex and describes some of the techniques available today for the meaningful evaluation of solid lubricants				●				

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	ELLIOT BROS. LTD. ELLIOT SPACE & WEAPONS RESEARCH LABORATORIES										
EE. 1-1	Vacuum Effects on Spacecraft Materials Lawrence R Greenwood, Et Al		Describes the effects of hard vacuum on the properties of various materials (mechanical & thermal) This report concerns itself with materials which would not be considered in the ODAPT design (i e , Parachute material, solid rocket fuel and ablative material)				●				
EE. 1-2	Vacuum Evaluation of Lubricants and Techniques for Space-Exposed Components - C L Harris		The paper shows that lead-plated ball bearings give long-lived vacuum operation at slow speeds Also, showing promise were MoS_2-filled grease, and carbon-fibre filled Delrin				●				
	EUROPEAN SPACE TECHNOLOGY CENTRE										
EE. 2-1	Short Survey of European Work on Lubrication in Vacuum H M Briscoe & J Dauphin		Paper reviews European and some Russian literature on vacuum and space lubrication, some of the references reviewed in this survey are in the ODAPT files One item of interest is the promising performance of lead-coated ball bearings for vacuum use.				●				
	G E. - GENERAL ELECTRIC CO.										
GO. 1-1	Advanced Reaction Wheel Controller for Spacecraft Attitude Control - C F Auclair AIAA Guidance, Control, and Flight Mech Conference - August 1969		This paper describes tests undertaken at GE to find efficient methods of driving a reaction wheel Compares AD motors vs DC brush torque motors vs DC brushless torque motors commutated by Hall effect devices	●			●				
GO. 1-2	Dynamic Shaft Seals in Space		The final report for this project could be of interest							●	

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	G E - GENERAL ELECTRIC CO (Cont)										
00. 1-3	Survey of Aerospace Requirements for Bearings and Lubricants - D G Flom	5/64	Report discusses the natural and induced environments which bearings, lubricants, etc will experience in orbiting earth satellites and other space vehicles Report contains no lubrication recommendations or data	O			O				
00 1-4	Nimbus Meteorological Satellite Integration and Testing Materials Report No 8	7/65	Failure analysis on Nimbus A noted that after 26 days in orbit, its solar array drive ceased rotating Concluded that area of failure was probably the size 8 motor gearhead (MGB) assembly Motor stalled due to increased frictional drag probably caused by increased viscosity of the G-300 bearing lube		●	●	●				
00 1-5	Final Report - Failure Analysis and Design Report of Nimbus I Solar Array Drive Failure - W D Simpson	8/66	The Nimbus I Weather Satellite was launched August 28, 1964 After 26 days of successful operation, Nimbus I prematurely stopped operating due to the failure of the Solar Array Assembly to maintain its proper orientation with respect to the sun This document summarizes the Failure Analysis and Design Improvement action instituted to resolve this failure			●	●	●			
	G.E. - GENERAL ELECTRIC CO. MISSILE & SPACE DIV										
00. 2-1	Friction of Tungsten Disulfide Sliding in an Ultrahigh Vacuum System - A J Haltner	11/67	A study of tungsten disulfide, which crystallizes in a layer lattice identical to molybdenite, has been undertaken in ultrahigh vacuum in an effort to learn more of fundamental sliding mechanisms in lamellar solids The friction of WS2 was found to be nearly as high at 10 to the -9th power torr as in air where the presence of water vapor affects friction levels When condensible gases were admitted to the chamber to raise the pressure from 10 to the -9th power torr to the region of 10 to the -6 power to 10 to the -5th power torr, the friction dropped sharply and was found to be strongly influenced by sliding speed This new vapor lubrication effect may be related to the synthetic origin of the lubricant powder					●			

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	G E - GENERAL ELECTRIC CO MISSILE & SPACE DIV (CONT)										
00 2-2	Lubricants for the Space Environment - Flom, Et Al	3/68	A thorough and competent review of theory and practice of space lubrication Table 8 contains brief notes of satellite flight experience for various lubricants and classes of lubes	O	O	●	●	●			
	G E - GENERAL ELECTRIC CO ORDANCE DEPT.										
00 3-1	Qualification Test Report of Slip-Ring Assemblies	7/63	This report describes the procedures and results of qualification tests performed on slip-ring assemblies manufactured for use on the Polaris FBM Guidance System, MK 2 Mod 0 These assemblies conform to BuWeps drawings 2317723 (the 32-circuit unit) and 2317724 (the 72-circuit unit)					O			
	GODDARD SPACE FLIGHT CENTER										
00 4-1	Evaluation of Space Lubricants Under Oscillatory and Slow Speed Rotary Motion - Charles E Vest, Et Al	4/68	This paper describes vacuum tests using slow speed and oscillating bearings and commutator brushes Long-term lubrication was obtained with retainers of Teflon + Fiberglass + MoS_2 (Vol % = 59 + 39 + 2, respectively); and tachometer brushes of precious metal alloys were successfully lubricated with low noise with burnished films of MoS_2 A gold inlay technique was also tested but gave somewhat greater electrical noise					O			
00. 4-2	Rolling Element Slip Rings for Vacuum Application - E J Devine	4/64	Electrical slip rings employing rolling contact elements (balls and raceways) were tested in a hard vacuum environment Low noise operation was achieved at speeds up to 5000 rpm Slip rings lubricated with MoS_2 operated with lower noise and had a longer life than slip rings employing solid metal film lubrication The final configuration operated in a vacuum of 2×10^{-9} torr at 2000 rpm for over 100 million revolutions at a noise level of 0 002 ohm rms			O	O				

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	GRUMMAN RESEARCH DEPT. GRUMMAN AIRCRAFT ENGINEERING CORP.										
GG 5-1	Friction and Wear Behavior of Molybdenum Disulfide in Air, Vacuum, and Dry Nitrogen - William Wolkowitz	6/66	Anodized 7076-T6 aluminum alloy, coated with three different molybdenum disulfide solid film lubricants was slid against uncoated, unanodized 7075-T6 aluminum alloy Friction and wear data were collected for each type of lubricant film Two different anodizes, H2SO4 and CR2O3 were used and the tests were conducted in air and a vacuum of 4 x 10 to the minus eighth torr A limited amount of testing was done in dry nitrogen A load of 16 3 lbs (75 psi) and a sliding speed of 35 in per minute were used Tests were terminated at the end of 112 feet of sliding				O				
	H.A.C. - HUGHES AIRCRAFT CO.										
HE 1-1	Accelerated Vacuum Testing of Long Life Ball Bearings and Slip-Rings - Meeks, Christy, and Cunningham		Report contains very general review of vacuum tests on 1 Bearings lubricated with F-50 and a hydrocarbon oil plus additives 2 Slip-rings with brushes containing several dry lubricants Emphasis in the report was not method of test; not detailed or comparative results			O	O	O			
HE 1-2	Despin Bearing Technology and Applications for Communications Satellites - F A Glassow - AIAA 3rd Com Sat Systems Conf		Describes methods of mounting bearings and material choices to achieve 10 year life goal Describes lubrication methods and lubricant properties (Lubricated by BBRC)			O					

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	H A C - HUGHES AIRCRAFT CO (Cont)										
HE 1-3	Flexible Rolled-Up Solar Array - George Wolff, Et Al	1/70	The main activities on the flexible rolled-up solar array (FRUSA) program during the sixth quarterly reporting period consisted of completion of the detailed drawings of all the FRUSA components Most of the drawings have undergone stress and dimensioning checks and have been released to manufacturing for procurement or fabrication of components and parts The supplier of the boom actuator mechanism has completed final tests of the development test unit prior to shipment of the unit The solar cell manufacturer has fabricated the cell qualification log; and the average power output is slightly higher than the specified value Test and development programs on various system components including panel roll-up, cushion, panel thermal shock, and battery/charge controller have been successfully completed Design reviews on each of the FRUSA subsystems were held prior to initiation of the qualification model drawing release phase which was initiated during this reporting period	●	●	●	●				
HE 1-4	Flexible Rolled-Up Solar Array, George Wolff, Et Al	4/70	The main activities on the flexible rolled-up solar array (FRUSA) program during the reporting period consisted of drawing release of all the FRUSA subsystem components, with the exception of the power electronics and storage, and startup of manufacturing of the development/qualification model The solar cells required for the qualification model have been received and wired into the required cell groups ready for bonding, together with the blanks, to the solar panel The storage drum is in the final stage of fabrication, and the small and large housings for the orientation mechanism are ready for final processing prior to start of assembly								
HE 1-5	TACSAT I Nutation Dynamics - C R Johnson AIAA 3rd Com Sat Sys Conf		Describes nutation damping and stabilization methods used in Hughes Tacsat I Satellite This sattolite utilizes the Hughes BAPTA drive Describes ways of bearing mounting to overcome sattolite nutation								

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				MOTORS	GEARS	BEARINGS/ ROLLERS	LUBRICATION SYSTEM	SLIP RINGS	ROTARY TRANSFORMERS	LUBES/SEALS	FLEX CABLE
	H A C - HUGHES AIRCRAFT CO (Cont)										
HH 1-6	OLSCA - Orientation Linkage for a Solar Cell Array	7/68	A 12 month program was conducted to develop the technology for actively orienting 1/2 to 20 kw solar cell arrays on actively and passively stabilized earth oriented satellites with mission lifetimes of 3 to 5 years A detailed design for a linkage capable of carrying a 5 kw array was developed	●		○	○	●			
	J.P L - JET PROPULSION LABORATORY										
JJ 1 1	Behavior of Materials in Space Environments- L D Jaffe, Et Al	11/61	Quantitative effects of space environments upon engineering materials are discussed Most metals will be unaffected by vacuum except for slight surface roughening Among organics, polysulfides, cellulosics, acrylics, polyvinyl chloride, neoprene, and some nylons, polyesters, epoxys, polyurethanes, and alkyds break down at low temperatures in vacuum Polyethylene, polypropylene, most fluorocarbons, and silicone resins do not decompose significantly in vacuum below 250°C Except for plasticized materials significant loss of engineering properties in vacuum is unlikely without appreciable accompanying sublimation or decomposition Certain low vapor pressure oils and greases, tetrafluoroethylene, and thin films of MoS_2, AU, and AG can probably provide adequate lubrication The particles of the earth s radiation belts will cause radiation damage to organics and optical properties of inorganic insulators Semiconductors affected by solar flare emissions				○				

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	J P L - JET PROPULSION LABORATORY										
JJ 1-2	Evaporation Effects on Materials in Space - L D Jaffe Et Al	10/61	Sublimation of inorganic materials in the vacuum of space can be predicted accurately from knowledge of their vapor pressures and for compounds of their free energies Among the elements CD, ZN, and SE are readily lost near room temperature and HG at elevated temperatures Selective loss at individual grains and at grain boundaries can produce some surface roughening Evaporation rates of low-molecular-weight single-component oils can also be calculated from vapor pressures most are rather high Polymers lose weight in vacuum by decomposition; nylon, acrylic polysulfide and neoprene show high decomposition rates near room temperature Many other polymers including polyethylene and isoprene are stable to high temperatures in vacuum Engineering properties are, in general little affected in vacuum unless appreciable loss of mass occurs				○				
JJ 1-3	Proceedings of the 4th Aerospace Mechanism Symposium		This report describes the Hughes Beta Drive which was assembled and lubricated by BBRC Of particular interest are slip-ring and motor brush wear test descriptions There was a failure in the original design of the slip-ring - the failure mode is described here and the resulting redesign effort	●			○	●			
	LEWIS RESEARCH CENTER (NASA)										
L 1-1	Effect of Inert Reducing, and Oxidizing Atmospheres on Friction and Wear of Metals to 1000 Degrees F - Donald H Buckley, Et Al	10/61	Friction and wear characteristics were studied for various bearing metals in inert, reducing, and oxygen controlled atmospheres at temperatures to 1000°F A hemispherically tipped rider (3/16-in rad) under a 1000-G load slid on a rotating disk at a surface speed of 35 FPM The absence of oxides on metal surfaces resulted in excessive wear and high friction of metals In some instances where surfaces were devoid of oxides (electrolytically pure CU), mass welding of the specimens occurred The presence of extremely small quanitites of O (in the atmosphere) for some metals (0 03 vol-% O2 for 440-C stainless steel) was found to be sufficient to provide adequate surface protection of the metal by oxide				○				

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	Lewis Research Center (NASA) (CONT)										
LL 1-2	Lubrication and Bearing Problems in the Vacuum of Space - Edmond E Bisson		Report contains a general review of space lubrication considerations and methods: solid lubricants, ball bearing lubrication, fluid lubricant loss and containment, and other aspects			●	●				
LL 1-3	Lubrication and Bearing Problems in the Vacuum of Space - Edmond E Bisson		A review paper presenting data on volatility friction and wear of various greases, oils solid lubricants and metal alloys Various problems of space lubrication are presented			●	●				
LL 1-4	Lubrication of Sliding and Rolling Element Electrical Contacts in Vacuum - J Przybyszewski	5/68	Sliding electrical contact problems in vacuum recent experiments in this field are reviewed in regard to the lubricants used Attention is given to the relationship between surface contamination and the wear of graphite			●	●	●			
	LOCKHEED MISSILES & SPACE CO										
LL 2-1	Behavior of Slip Rings in a Space Environment - F J Clauss, Et Al	8/62	Tested several slip ring assemblies in vacuum (10^{-6} torr) for noise. Tested Paliney 7 on gold-plated silver chromium-plated Paliney 7 brushes on gold-plated silver; silver-graphite (80:20) on Ag; and Ag-MoS_2 brushes (88 12) on silver, copper, rhenium plate, and rhodium plate					●			
LL 2-2	D C Motor Brushes for Hard Vacuum Applications		Test report for a test program of high current density brushes Sixteen brush materials (LMSC proprietary information) were tested Material "H" was the only material that met the test objective wear rate of 0 021 inches per hour of operation	●			●				
LL 2-3	Electrical Contacts in Space Environment - George E Owens		Very old biblio and slanted mainly toward signal level applications					●			
LL 2-4	Electrical Transmission Components for a Large Aerospace Environmental Chamber - Francis J Clauss		Very thorough document Gives design parameters on rotary transformers Treats flex cable nicely Clip rings won Report considered three methods (in vacuum) of transferring 800 KW across rotating joint: rotary transformer flex cable, slip rings Concluded that slip rings were best under the circumstances					●	●		●

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	LOCKHEED MISSILES & SPACE CO (Cont)										
LL 2-5	Evaluation Tests of Solar Array Drive Assembly - P/N 1310386 - J H Fairman	11/60	The objective of these tests was to prove the design integrity of the Solar Array Drive Assembly by subjecting it to environments of vibration shock, acceleration, humidity, temperature shock, high temperature, and altitude temperature	●		●	●				
LL 2-6	Evaluation Test of Solar Array Flex Harness Type I - R. L Beard		Same information of flex cables but not so much								●
LL 2-7	Evaluation Test - Orientation Motor, Solar Array 1062659	4/60	The object of this test was to prove the design integrity of the motor under environments of High Temperature, Altitude and Temperature, Vibration, Acceleration, Shock Humidity, and Thermal Shock	●							
LL 2-8	Gears, Bearings, and Lubricants for Aerospace Allications - Helen V Abbott		An annotated bibliography								
LL 2-9	Heliotrope Solar Array 698BX		The purpose of this paper is to describe the design features initial concepts and power capabilities of the 698BX Heliotrope Solar Array								
LL 2-10	Zombie 2-Axis Suntracking System		A study of a Two Axis Solar Servo System capable of aligning solar arrays toward the sun The arrays are to provide power for Zombie experiments This preliminary design study established the feasibility of such a system and recommended a design approach	●		●	●				
LL 2-11	Lubricants and Self-Lubricating Materials for Spacecraft Mechanisms - F J Clauss		Report gives tabulated test results on a wide variety of oils, greases, solid lubes, plastics, and self-lubricating solids subjected to vacuum tests Included are not only LMSD test data, but also data from reports and personal contacts of other workers active in the space lubrication field Versilubes F-50 and G-100 were found to provide long-life lubrication for ball bearings in vacuum Others also were promising				●				

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	LOCKHEED MISSILES & SPACE CO. (Cont)										
LL 2-12	Lubricants for the Space Environment - Francis J Clauss	11/65	A paper reviewing literature on space lubrication techniques, including the Lockheed vacuum bearing life tests and their Ag + Cu + MoS_2 slip ring brush composites				O				
LL 2-13	Lubrication Evaluation Francis J Clauss	4/66	This is an earlier report of Lockheed's vacuum tests of lubricants the final report of which is MRI 503 02 This last "Final Report" includes all the earlier test data				O				
LL 2-14	Lubrication Evaluation H I Silversher	9/67	Report gives vacuum test results on motor bearings lubricated with oils greases, bonded solid films, and self-lubricating retainers	O		●	●				
LL 2-15	Lubrication Evaluation Final Report - H I Silversher, Et Al	4/68	In addition to lubes listed in MRI 503 01, greases made from fluorosilicone oil (Fs-1265) were still lubricating bearings after up to 4 years 4 months of operation in motors These are designated MLG 61-92 and MLG 62-142	O		●	●				
LL 2-16	Lubrication of Ball Bearings for Space Applications - W C Young Et Al		This paper is based on early results from LMSD vacuum bearing tests - some motors had run for slightly over one year using bearings lubricated with Apiezon K and for about 10 months using bearings with F-50 Bonded MoS_2 films did not hold up well in ball bearings tested in vacuum but G-300 and Aeroshell 15 greases showed promise			O	O				
LL 2-17	Lubrication Under Space/Vacuum Conditions - Francis J Clauss		This is an early wide-ranging study of vacuum lubrication of bearings and slip rings Some of the more prominent results were as follows 1 Apiezon K oil and versilube F-50 gave good ball bearing lubrication for the longest operating periods 2 Versilube G-300 and Aeroshell 15 greases gave good long performance 3 Bonded MoS_2 films were generally poor in ball bearings 4 Duroid 5813 and Rulon C retainers gave best performance 5 Best brush slip ring performances were given by silver-MoS_2 brushes on fine silver and on rhodium plate			O	O	O			

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	LOCKHEED MISSILES & SPACE CO (Cont)										
LL 2-18	Materials Evaluation Under High Vacuum and Other Satellite Environmental Conditions - P H Blackmon Et Al	1/62	This is an early report of progress in testing bearings gears and contacts in vacuum chambers Preliminary results are given of tests on which much more data are given in later LMS reports This report is devoted mostly to description of test equipment		O	O	O	O			
LL 2-19	Passive Solar Array Orientation System (Thermal Heliotrope)		This document reports the procedures and results of a 9 month study to evaluate the feasibility of thermally actuated sun tracking devices To avoid complex linkages and gas systems the approach given herein uses bimetallic elements in the form of flat wound helicoil which produces rotational deflection and force								
LL 2-20	A Brief Study of the Transfer of Electrical Power Through a Rotating Joint in a Communication Satellite - J T Sachs		The primary objective of this study was to investigate the various methods for transferring electrical power through a rotating joint in a spinning communications satellite having one or more earth oriented antennas					O			
LL 2-21	Lockheed Communications Satellite - Solar Array Subsystem		This document contains a description of a deployable solar array for a communications satellite Mechanical and power transfer trade-off studies are presented								
LL 2-22	Lockheed Solar Array Tracking System		Over the past 10 years Lockheed has developed and tested five solar array tracking systems, four of which have operated successfully on a number of satellite vehicles Included in these five designs are both continuous tracking and reset types, one and two axis trackers, and solar arrays from 8 sq ft to 80 sq ft (per drive assembly) Because of security restrictions, the tracking systems described in this report will be referred to as Type I, II III, Zombie and No 5	O		O	O				
LL 2-23	Solar Array Tracking System for the Lockheed Communication Satellite		Describes different ways by which sun-tracking of solar panels and power transfer can be accomplished Describes novel variable reluctance stepper motor	O		O	O	O			

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	LOCKHEED MISSILES & SPACE CO. (Cont)										
LL 2-24	Solid Film Lubricants in a Vacuum Environment - Bohn A Wolterberbear		This is a search covering, especially, solid lubricants for use in vacuu				O				
LL 2-25	Surface Physics Considerations of Space Collector Systems - J P Dallns		Entered on matrix Mostly lubrication and wear				O				
LL 2-26	Program 461 Reliability Materials Research and Application Evaluation of Bearing Materials and Lubricants for Space Environment	4/63	This is an early report of vacuum tests on various lubricants in motor ball bearings running at 8000 rpm Final report is Lockheed MRI 503 02 -			O	O				
LL 2-27	Space Materials Handbook - Second and Third Editions and Supplements - Rittenhouse, Et al	7/68	An extensive compilation of spacecraft materials, experience in space applications, recommended materials selection, materials properties effects of space environment on materials, and various other space-related information on lubricants, metals, insulation, adhesives, structural plastics, optical materials, sealants, electronic materials, and thermal control materials	●	●	●	●	●			●
LL 2-28	Program 461 Reliability Materials Research and Application Behavior of Slip Rings in a Space Environment, Final Report		The report covers vacuum tests on slip ring assemblies from four manufacturers These were assemblies designed for signal currents, not power-level currents. The report concluded that significant reduction in signal noise could be obtained by providing silver-MoS_2 brushes or low-vapor-pressure lube oil to the assembly					O			
LL 2-29	Qualification Test of Solar Array Flex Harness Type II - R. L Beard		Some flex cable information								O
LL 2-30	Qualification Test of Solar Array Flex Harness Type II - R L Beard, Et Al		-8 amp conductors 330° flexure failed humidity because of requirements								O

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	LOCKHEED MISSILES & SPACE CO. (Cont)										
LL 2-31	Report on Accelerated Life Test of Type II Solar Array Orientation System - H Chaney, Et Al		Report describes tracking tests made on solar array drive systems using a solar simulator in thermal vacuum chamber 2660 complete orbits were simulated Drive tested was a resettable drive system	O		O	O	O			
LL 2-32	Servo Drive Assembly - W W Bridges	4/69	This document is a spec, but perhaps, the hardware called out under components Paragraph 3 2, is developed Further request of LMSC required								
	MARTIN CO.										
ML 1-1	Dynamic Analysis and Preliminary Design for Satellite Guidance Subsystem		A self-contained guidance and control system for a hypothetical, unmanned one year mission in space is presented. system operation is based on the use of altitude measurements to define the in-plane orbit parameters and preselected star occultation time measurements to define the orbit plane orientation parameters. Over-all system operation is presented and system errors are evaluated, using an IBM 7090 computer program A detailed description of each of the subsystems is given and the reliability of these systems is predicted for the one-year mission, using component failure rate data It is shown that the system could be instrumented using state-of-the-art hardware A preliminary missions analysis indicates that the system would have considerable utility in manned satellite missions requiring exit from orbit and rendezvous with earth-based target points								

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	M.I.T MASSACHUSETTS INSTITUTE OF TECHNOLOGY										
MIT 2-1	Three Axis Attitude Control of a Synchronous Communications Satellite - John U Bousch, Et Al	70	Les-7 will be a synchronous communications satellite with automatic station-keeping and three axis attitude control capabilities On the earth oriented face of the satellite body will be a 30-inch diameter X-band (8 GHz) lens antenna A 500 watt solar plant consisting of two flat panels, each about 5 ft square, will be deployed on shafts from the north and south faces of the satellite body and oriented toward the sun so that, relative to the panels, the body will rotate once per orbit	●		●	●	●			
MIT 2-2	A Non-Sliding Rotary Electrical Connector - W P Fleming	4/70	This paper describes a new type of rotary electrical contact which virtually eliminate conventional wear problems because it has no sliding surfaces Through the use of a seldom used principle of motion intimate physical contact between rotating and stationary bodies is achieved through large apparent contact areas with no sliding			●		●			
MIT 2-3	Rotary Transformer Design - E Landsman		A high power rotary transformer (1kW) was considered as a replacement for slip rings in a future satellite A study was done to determine the best electrical design taking into account mechanical limitations while maximizing efficiency						●		

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	MIDWEST RESEARCH INSTITUTE A.F MATERIAL LABORATORY										
MM 3-1	Friction and Wear Behavior of Solid Films - Paul J Bryant, Et Al	2/66	A new friction and wear system is described The coefficient of friction and the wear rate of a single crystal or a compressed pellet sample may be measured in the same atmosphere as cleavage energy or stress-relaxation experiments are being conducted This combined ability in one system gives a true basis for actual frictional tests The simultaneous experiments may be performed in ultra-high vacuum, or reported for the friction and wear of graphite in two forms: pyrolytic graphite, and compressed graphite lamellae Data are compared for both sample forms in six environments: air vacuum, oxygen water methanol and carbon tetrachloride The effect of each environment was more pronounced on crystalline graphite samples than on pellet samples The most notable difference is the low wear rate which has been measured for pyrolytic samples in ultra-high vacuum This absence of "dusting wear" accompanied by a moderate coefficient of friction for unannealed pyrolytic graphite is very interesting in regard to many possible applications				●				
MM 3-2	Solid Lubricant Handbook for use in the Space Industry - Campbell, Et Al		This is an excellent reference work listing solid lubricants and their specifications Tables show results of performance tests and suggested uses for each solid lube An extremely useful source of information				●				
MM 3-3	Liquid Lubricant Handbook for use in the Space Industry - Campbell, Et Al		This book is an excellent reference work listing grease and oil specifications and tables of detailed grease and oil properties, both chemical and physical An extremely useful source of information on liquid lubricants				●				

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	NATIONAL RESEARCH LABORATORIES										
NX 1-1	Electrical Noise Level Measurements of NRC Mercury Slip Rings rotating at 12,000 RPM and a Surface Rubbing Speed of 70 Ft/Sec - H T Hammell, Et Al	4/61	Electrical noise level tests on NRC mercury slip rings were carried out to determine their suitability for use with strain gauges at 12,000 rpm The noise level was found to be small when compared with a reference signal of 20 microvolts RMS					●			
	NAVY SPACE SYSTEMS ACTIVITY										
NX 2-1	Space Electrical Power Systems for the Mid-1970's - Richard V Silverman	9/69	An evaluation of candidate electrical power systems capable of providing up to 6.5 KW for an earth orbiting mission is presented in this report Three power systems could be ready for a Mid-1970 launch if proper funding were provided for development programs They are: a solar cell/battery system; a reactor/thermoelectric system; and a reactor/organic rankine system The preferred system for the proposed mission is the reactor/thermoelectric system, based on its inherent simplicity, lower weight, lower unit costs, and high degree of technology readiness relative to the competing systems								
	NORTH AMERICAN AVIATION SPACE & INFORMATION DIV										
NX [illegible]	Dry Film Lubricant Evaluation with Various Anodic Coatings	6/64	Results of Alpha LFW-1 Tests in room atmos are given for two different bonded solid lubes applied to 2024 aluminum alloy test pieces treated with following anodic coatings: a) Sulfuric acid, b) Chromic acid, and c) Hard-coat Wear life for lubeco #905 was best on sulfuric acid anodize poorest on hard-coat Electro film #2306 was better on hard-coat and sulfuric acid than on chromic acid anodize Lubeco #905 on sulfuric acid anodize was best combination of all				○				

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	POLYSCIENTIFICS DIV. LITTON INDUSTRIES										
PP 1-1	Poly-Scientifics Role in Space - E W Glossbrenner		A thorough review of brush/slip-ring/ lubricant developments for space use over the past decade 78 references to papers and reports Current Poly-Sci practices for brush/ slip-ring/lubricant are presented and problems yet to be solved are summarized					●			
	RESEARCH & DEVELOPMENT MAGAZINE										
RR 1-1	Improved Silicones - Joel S Rummins	3/70	Paper discusses low volatility silicone polymers of high viscosity - fluids are too viscous and have too high a power point (-40°) for most space applications such as ODAPT				○				
	ROCKETDYNE										
RL 2-1	High Vacuum Lubricant Test - J McCain	12/64	Testing has been completed on the transport dynamics vacuum lubricant tester and is continuing on the high load, high vacuum lubricant tester to determine adverse effects on lubricants under load in vacuum Fabroid is used on the J-2 gimbal seat, and RA0112-006 type I dry film lubricant is used on the side panels retainers and shaft The objectives of this program were, (1) to demonstrate that fabroid and the dry film lubricant would not be adversely affected by gimbal requirements of vacuum exposure at temperatures down to -200 F and (2), to screen other promising candidate materials in an attempt to provide a better lubricant for the gimbal				○				

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	ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF TECH										
RS 3-1	Large Solar Array Development in U K - E C Treble	1/69	Aspects of large solar array technology are reviewed with particular reference to the development of an experimental 560 W deployable array, which has some novel features The array consists of very thin silicon solar cells mounted on Kapton polyimide film It is stowed by folding the Kapton concertina fashion into rectangular compartments and deployment is initiated by duplicated pyrotechnic actuators and takes about two minutes to complete The estimated all-up weight of the 78 sq ft array including stowage compartments, cushioning and deployment mechanism is 25 2 lb, giving a power-weight ratio of 22 3 W/lb at 55C The main problem areas are discussed in some detail, with an indication of the progress made to date								
RS 3-2	An Investigation into the Cause of Lack of Contact Between Synchro Slip-Rings and Brushes - L G Atkinson, Et Al		This note describes test made on a number of synchros in an attempt to discover the cause of lack of contact between synchro slip-rings and brushes after storage It is concluded that the failures were due to the presence of a silver chloride film on the surface of silver platinum rings, formed after the rings had been in contact with carbon tetrachloride during a cleaning process					○			

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	SPERRY GYROSCOPE										
SS 1-1	Evaluation of Slip-Ring Capsules	1/64	There were no failures of any samples either initially or following the environmental tests in dielectric strength or insulation resistance The insulation resistance of all samples was greater than 2 million megohms with the exception of sample C which had lower though still satisfactory insulation resistances between adjacent circuits All circuits of all samples were continuous throughout the environmental tests However, the D sample developed a one ohm contact resistance variation in the redblack circuit following the high temperature test, and remained throughout all further testing It is suspected that the high temperature caused a deformation in one of the brushes or holders resulting in a lack of contactly pressure causing the high contact resistance The noise level of all samples was below the noise level of the test circuits (12 5 microvolts) initially				●			
	SWISS LABORATORY FOR HOROLOGICAL RESEARCH										
SS 2-1	Comparative Friction and Wear Behavior of New Materials Usable in Ultra High Vacuum H E Hintermann and H Gass		Paper gives results of vacuum tests on ball bearing and sliding tests of several materials Good bearing life was obtained with bearings made with following materials Races Steel coated with Tic Balls Sintered alumina Cages: Silver/Indalon Alloy				○				
	T P W SYSTEMS										
[illegible] 1-1	Effects of Energy Dissipation in the Bearing Assemblies of Dual-Spin Spacecraft		Describes effects of bearing flexibility on spin-stabilized spacecraft attitude			○					
[illegible] 1-2	Equipment Specification Solar Array Drive Subsystem for Nimbus E Spacecraft	4/69	This specification establishes the requirements for performance design, fabrication tests and quality assurance provisions for the Nimbus Solar Array Drive Assembly	●	○	●	●	●			

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	SYSTEMS (CONT)										
TT 1-3	Final Report for Nimbus Solar Array Subsystem		Summarizes details of Solar Array Sub-system design motors, bearings, gears and power transfer devices	●	●	●	●	●			
TT 1-4	Document No 12644-6001-R7-00 Title Classified		Unclassified Abstract - A set of boundry layer friction data was generated for comparison with an identical set of orbital friction data The test materials ran profiles, and experiment elements were identical to those used in previous AFRPL In-Space Friction Tests (AFRPL-RE-69-207) Comparison of the results from these two tests shows excellent agreement between the orbital and the Molecular Sink results				O				
	USAF/GE U.S. AIR FORCE & GENERAL ELECTRIC CO.										
V 1-1	Friction and Wear of Solid Materials - A J Haltner, Et Al	4/69	The friction of thin films of electroplate silver on 521000 steel in ultra-high vacuum has been shown to be lower at all loads if the film has been subjected to a high normal force loading The friction of molybdenite sliding in the presence of oxygen increases when the system is pressurized with nitrogen, but pressurization with nitrogen decreases friction when sliding occurs in the presence of ammonia				O				
VV 1-2	Friction and Wear of Solid Materials Sliding in Ultrahigh Vacuum and Controlled, Gaseous Environments - Arthur J Haltner	4/68	Improvements have been made in the ultra-high vacuum friction and wear apparatus (UHVFW) previously developed A new normal force feedthrough has been constructed and installed which permits continuous variation of the normal force to in excess of 9 KG Cleanliness of the foreline pumping system has been improved with the installation of sorption pumps to replace the mercury diffusion pump previously used A redesign of the gas inlet system has made it possible for the first time to control the gaseous enviornment inside the chamber of the ultrahigh vacuum friction apparatus				O				

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	USAF MATERIALS LABORATORY										
VV 2-1	Aerospace Greases - Lubrication Demands and The State-Of-The-Art - John B. Christian	9/68	An excellent summary of grease information Includes discussions and lists of thickeners, base fluids, and promising compounded greases for space applications A good source of candidate greases for ODAPT				●				
VV 2-2	Air Force Materials Laboratory Solid Film Lubrication Research - B D McConnell	4/64	The report outlines the general range of bearing lubrication requirements of present aerospace vehicles as well as briefly describes the range of requirements anticipated for future Air Force weapon systems Some of the Air Force Materials Laboratory sponsored programs designed to meet these requirements are discussed in detail This report covers only those concerned with solid film lubrication and contains discussion of both development-type programs and related basic or fundamental-type programs Program objectives approaches to the problems, data obtained to date and future work are discussed for each program.			O	O				
VV 2-3	Lubrication Techniques for use in Vacuum - R J Benzing	4/68	This is a review paper giving results of vacuum tests and actual space applications as obtained from work carried out and reported by others Sources used were the "Space Materials Handbook"; AD-612 158; AD-484 607; and others				O				

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[illegible]	[illegible] Candidate High Temperature Lubricants for Advanced Aerospace Systems - Roland E [illegible]	8/64	Ten new candidate fluids of various classes were investigated for high temperature lubricant application The basic physical, chemical and anti-wear characteristics of the new materials were determined by oxidation corrosion fourball wear and other standard test methods For comparison similar data were obtained for a mil-[illegible]-29368 trimethylolpropane (TMP) ester base stock a polyphenylether (5P-4E) base fluid and a super-refined mineral oil formulation A cyclic phosphonitrile [illegible] M-trifluoromethylphenoxy tri- and tetraphosphonitriles (+10 F pour point), has demonstrated outstanding oxidative and antiwear properties compared with 5P-4E The oxidative stability of 2-phenoxy-3-(5-nonyl) pyrazine and 1-N-heptyl-6-N-nonyl-pyrazine was much improved when formulated with phenyl alpha-naphthylamine and bis(P-phenoxyphenyl) diphenylether				●				
	USAF MATERIALS LABORATORY (Cont)										
[illegible]	Fundamental Mechanisms of Lubrication in Space Environment - Part I and Part II - [illegible] Brown, Et Al	5/65	Sliding and rolling friction experiments were performed both in air and in vacuum (pressure generally in the range of 10 to the minus 9th power to 0 000006 torr) In conjunction with the rolling friction experiments in vacuum a partial pressure analyzer was used to obtain spectra of gases evolved during rotation Initial friction and wear experiments were conducted for both the lubricated and unlubricated state of various substrates materials utilizing a spherically tipped (1/8 in radius) in oscillating on a flat surface at the rate of 10 oscillations per minute Materials investigated include copper 52100 steel, porous bronze, and niresist cast iron as substrate metals Stearic acid epoxy-MoS_2 self lubricating composite dioctylphthalate two low vapor pressure greases and a graphite-MoS_2-sodium silicate film were the lubricants Partial pressure analyzer results showed that among the various specimens analyzed, evolved gases differed considerable both in quantity and in composition Gas evolution was greatest for unlubricated specimens and for specimens in which lubrication had failed The grease lubricated specimens evolved much less gas than did the graphite-MoS_2-sodium silicate lubricated specimens				●				

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	USAF MATERIALS LABORATORY (Cont)										
VV 2-6	Greases Based on Perfluoro Polymeric Fluids - A new Class of Greases for Aerospace Use - Christain, Et Al	4/66	Report shows that perfluoro polymeric fluids (not otherwise identified - they could be fluorinated polyethers such as is used in Krytox) thickened with fluorinated ethylene-propylene copolymer (FEP) or with ammeline exhibit good ball bearing lubrication in air and at 10^{-7} - 10^{-9} torr				●				
	USAF - WRIGHT AIR DEVELOPMENT DIVISION										
VV 3-1	Molecular Approach to Dry Film Lubrication in a Vacuum Space Environment - R M Van Vliet	7/60	An early review report of lubrication literature related to space vacuum				O				
	UNIVERSITY OF COLORADO										
VV 4-1	Development, Fabrication, Assembly and Testing of Biaxial Pointing Control and Associated Telemetering Systems - Vernon L Stone	11/67	The development of the solar biaxial and lunar biaxial pointing controls was begun in 1947 The contract being reported upon is the sixth in the series for the Air Force Cambridge Research Laboratories; these units are also being used by the Naval Research Laboratory and the National Aeronautics and Space Administration This project involves the work being done on both lunar and solar biaxial pointing controls								
VV 4-2	Provide Payload for Aerobee Refurbish and Test a Lunar Pointing Control and Telemetry System - V L Stone, Et Al		This work covered the mathematical analysis of the servo electronic system used in both the solar and lunar model III biaxial pointing controls developed by the University of Colorado The LaPlace transform was used in the mathematical study As of the date of this report the study is incomplete due to the difficulties of evaluating certain physical constants However, further work is being done and should prove the value of the mathematical study which has been done								

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	VIRGINIA POLYTECHNIC INSTITUTE & POLY-SCIENTIFIC DIVISION OF LITTON INDUSTRIES										
VV 1-1	Sliding Electrical Contacts in Vacuum and Space	9/69	Proceedings from Seminar					●			
	WESTINGHOUSE RESEARCH LABORATORIES										
WW 1-1	Analytical and Experimental Study of Adapting Bearings for use in an Ultra-high Vacuum Environment Phase I, Screening of Wear and Friction Characteristics of Plastics Dry Powders, Composites, and Alloys P H Bowen	2/62	This report includes: analytical and experimental study of adapting bearings for use in an ultra-high vacuum environment Phase II Outgassing determination of plastics, dry powders, and composites, By P H Bowen Analytical and experimental study of adapting bearings for use in an ultra-high vacuum environment Phase III Evaluation of dry powder lubricants and self-lubricating materials in ultra-high vacuum bearing tests, by P H Bowen An investigation was made of the lubrication of gears and bearings in vacuum environments by using dry powders as a lubricant, and dry self-lubricating materials in the bearing retainer The wear and friction characteristics of various dry powders and dry self-lubricating materials were evaluated The materials included reinforced thermosetting plastics, dry lubricant filled and unfilled thermoplastics and dry lubricant filled sintered alloys			○	○				
WW 1-2	Analytical and Experimental Study of Adapting Bearings for use in an Ultra-High Vacuum Environment Phase IV Screening of Dry Lubricants for use in Highly Loaded Low-Speed Bearings and Gears - P H Bowen	8/62	Report covers evaluation in air, N_2, and vacuum of a large number of composites Screening tests helped to find optimum compositions The generally best composite consisted of Ag or Cu plus Teflon plus WSe_2 Another utilized an experimental thermoplastic which is more resistant to gamma radiation than Teflon An idler gear of self-lubricating composite successfully lubricated a pair of loaded metal gears			○	○				

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	WESTINGHOUSE RESEARCH LABORATORIES (Cont)										
WW 1-3	Lubricant Study in Ultra-High Vacuum and in Various Gas Environments - Bowen, Et Al	3/66	Report gives comparative test results in vacuum and in gases (CO_2, O_2, and H_2O) of three lubricants for rolling contact bearings and sliding friction On an overall basis the best lube was a bonded coating of sodium silicate binder plus 40 percent tungsten diselenide			○	○	○			
WW 1-4	Lubrication of Bearings and Gears for Aerospace Facilities - Paul H. Bowen	4/65	This report describes the analysical and experimental study of adapting lubrication techniques developed to satisfy the friction requirements associated with the vehicle handling system of the Mark I aerospace environmental chamber This report is in two parts The first part covers adapting solid lubrication techniques for the rolling element bearings and wheel of the horizontal load assembly and functionally evaluating the solid lubricated horizontal load assembly in an ultra-high vacuum under loads producing hertz stresses in the bearings up to 500,000 psi The second part of the report covers adapting solid lubrication techniques for the gears of the rolling and pitch assembly and functionally evaluating these solid lubricated gears in a four square gear tester operated in an ultra-high vacuum under loads producing hertz stresses in the gear teeth up to 199,000 psi.		●	●	●				
WW 1-5	Lubrication of Bearings and Gears in Aerospace Environmental Facilities - Bowen	7/63	A wide ranging study directed at finding suitable dry lubricants for use in bearings and on gears used in handling equipment of the AEDC large space vacuum environmental test chamber		●	●	●				

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