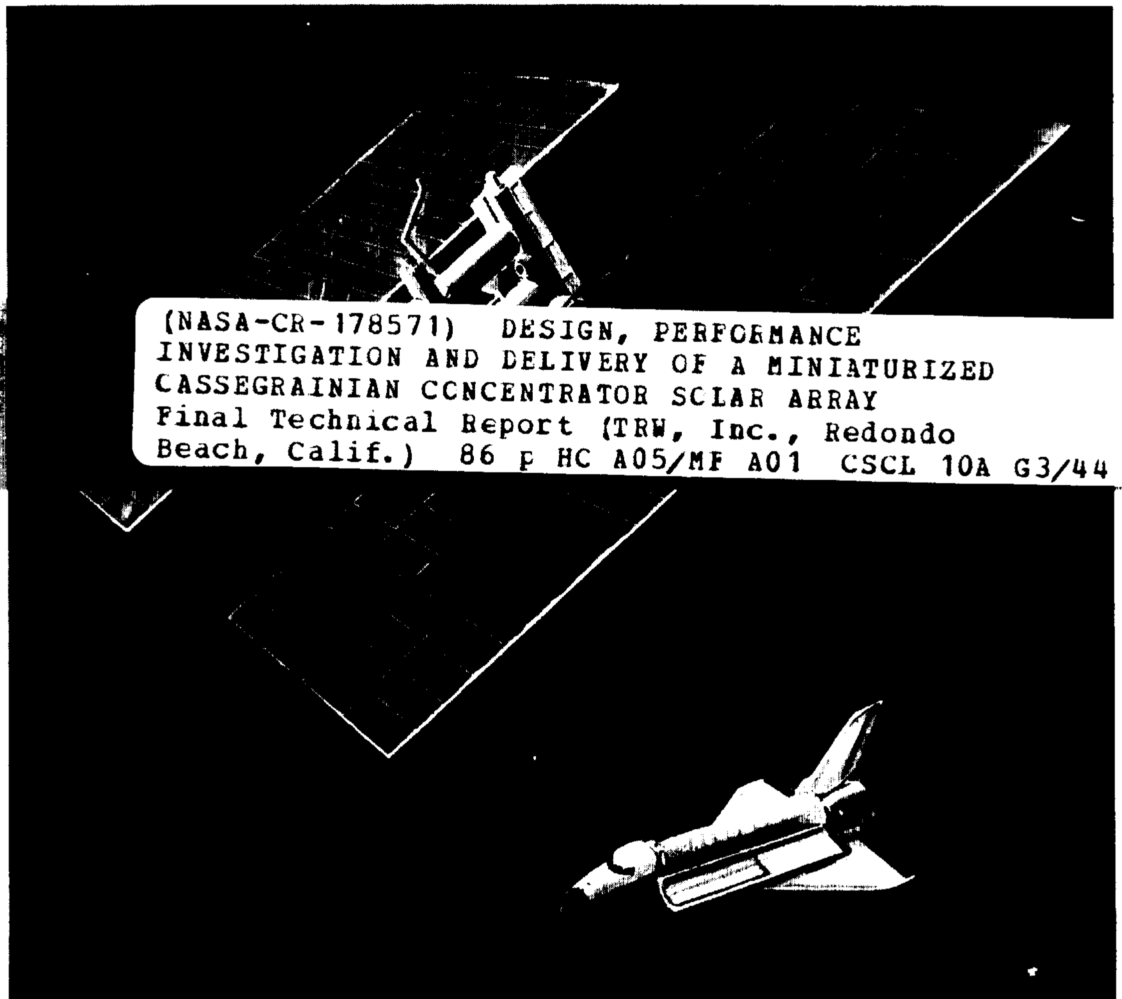
Design, Performance Investigation, and Delivery of a Miniaturized Cassegrainian Concentrator Solar Array



Engineering and Test Division
TRW Space & Technology Group
One Space Park
Redondo Beach, CA 90278

Final Technical Report
May 1985
Contract Number NAS8-35635
Document Number 42977-6002-UT-00

Prepared by
Robert E. Patterson

Work Performed for:
Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama 35812

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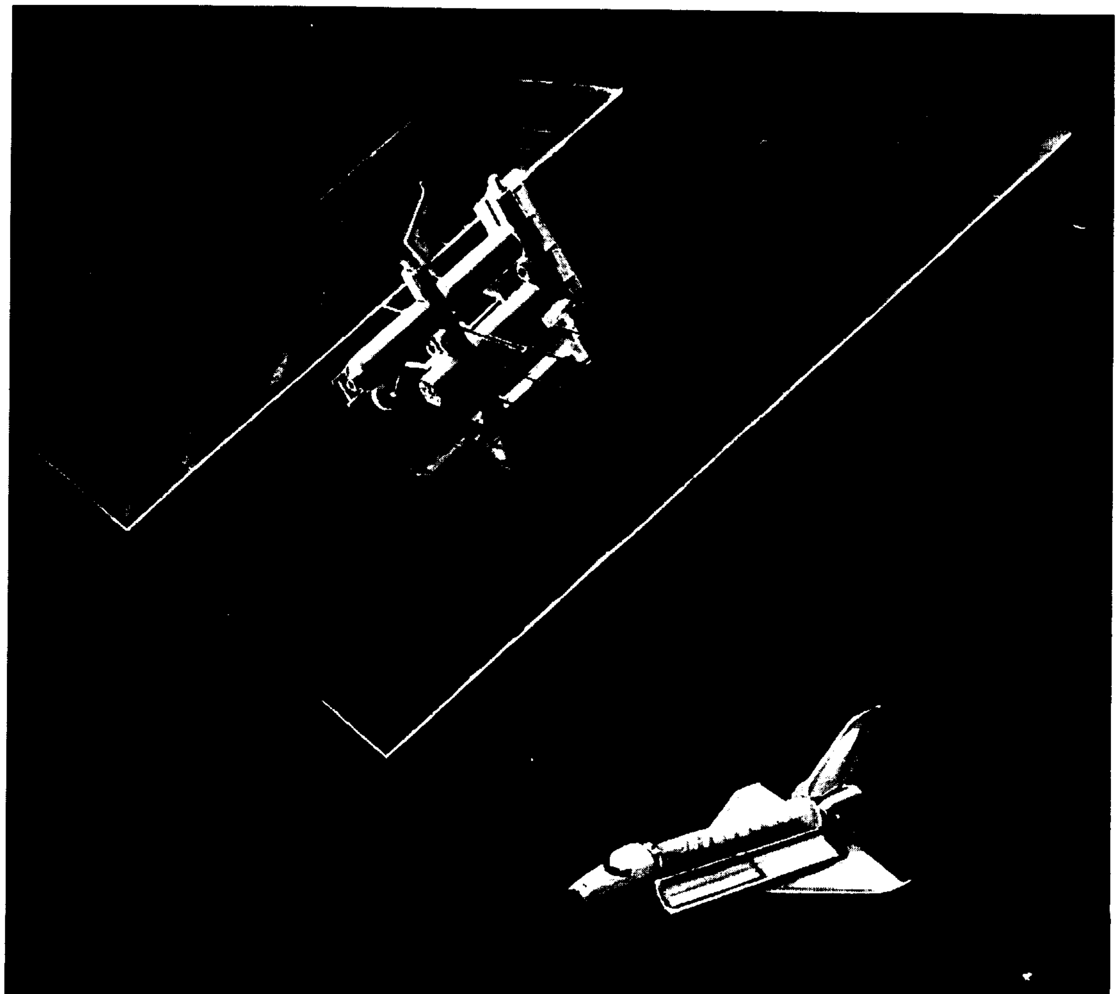

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Table of Contents

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FOREWORD

This report documents work performed by the TRW Space and Technology Group, Redondo Beach, California, for the NASA George C. Marshall Space Flight Center (NASA/MSFC), Huntsville, Alabama, under Contract NAS8-35635.

This final report is submitted in compliance with the contract statement of work and covers the entire contract period of performance from October 1983 through March 1985.

The study was managed for TRW by Robert E. Patterson of the Power Sources Engineering Department, Power and Electronics Hardware Laboratory, and for NASA/MSFC by Ralph Carruth of the Power Branch. Ted Edge of NASA/MSFC was responsible for reviewing the Final Report.

The very helpful participation in this study by many personnel of TRW and NASA/MSFC is gratefully acknowledged.

Cassegrainian Concentrator Solar Array Project Team

TRW

Ira Allard	Manufacturing Engineering
Peter Barrett	Dynamic Analysis
Saul Bashin	Product Design
Tyrone Eason	Subcontracts
Larry Gilman	Mechanical Design
Ralph Griebel	Electrical Assembly
Jerry Jacoby	Optical Design
Mark Kruer	Electrical Design
Joel Marks	Electrical Testing
George Mesch	Manufacturing
Robert Patterson	Project Manager
William Winters	Materials

Section 1. Introduction

INTRODUCTION

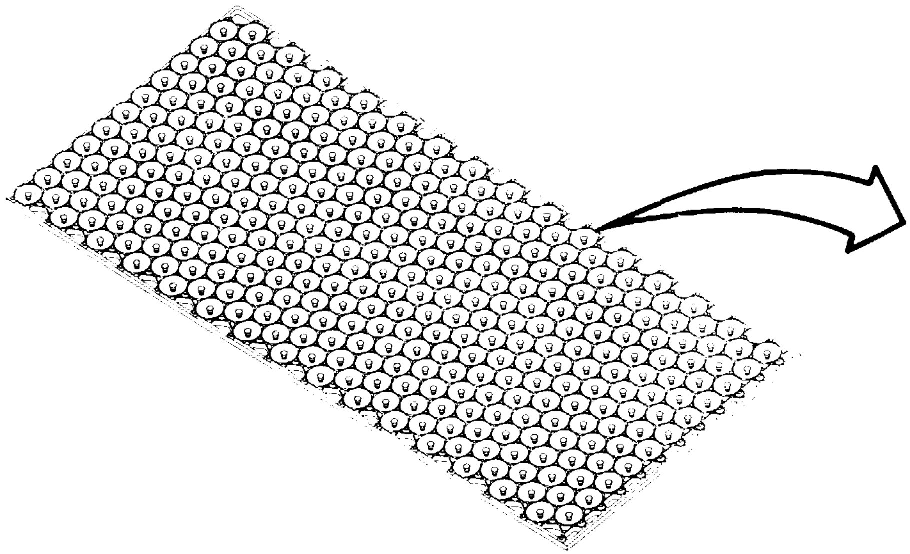
A miniaturized Cassegrainian concentrator (MCC) solar array concept is being developed with the objective of significantly reducing the recurring cost of multikilowatt solar arrays. The desired cost reduction is obtained as a result of using very small high efficiency solar cells in conjunction with low-cost optics.

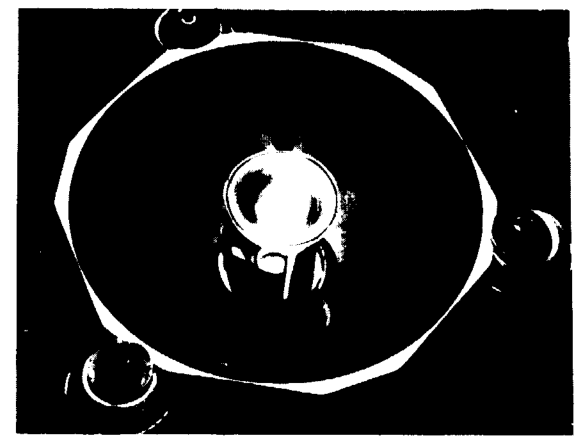
The MCC single element concept and panel concept are shown on the facing page. Incident solar radiation is reflected from a primary parabolic reflector to a secondary hyperbolic reflector and finally to a 4-millimeter diameter solar cell. A light catcher cone is used to improve off-axis performance. An element is approximately 13-millimeters thick which permits efficient launch stowage of the concentrator system panels without complex optical component deployments or retractions. The MCC elements are packed in bays within graphite epoxy frames and are electrically connected into appropriate series-parallel circuits.

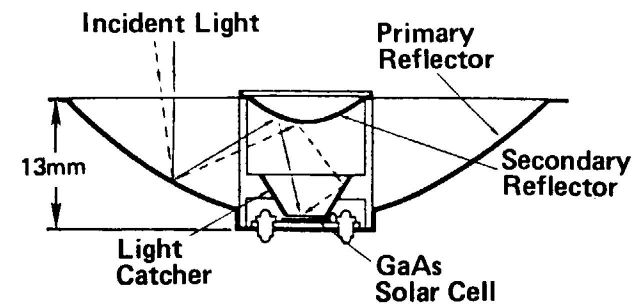
A MCC single element with a 21-cm^2 entrance aperture and a 20 percent efficient, 0.25-cm^2 gallium arsenide solar cell has the same power output as 30-cm^2 of 11-percent efficiency (at 68°C) silicon solar cells. The MCC concept provides the potential for a significant reduction in array cost due to a 99 percent reduction in required cell area and a 30 percent reduction in array area relative to a planar array of equivalent power. The approach also offers early opportunities for the application of advanced high efficiency cell types that may be more readily available as small-area devices in large quantities from production facilities otherwise limited by market size and capital investment factors.

The analysis and rationale on precursor studies that led to the miniaturized Cassegrainian concentrator approach have been described elsewhere in detail (1, 2, 3, 4). First generation feasibility hardware and a preliminary concept of a 100 kW MCC solar array system developed under the previous contract (NAS8-34131) are described in Reference 5. This report covers all work accomplished under Contract NAS8-35635, and includes (a) second generation element hardware development, (b) first generation support structure demonstration hardware development and (c) performance prediction updates.

Miniaturized Cassegrainian Concentrator Concept







Required cell area reduced by 99%

Permits cost-effective use of high-efficiency solar cells

Provides potential for significant reduction in array cost and area

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TRW Space &
Technology Group

Section 2.
Technical Summary

TECHNICAL SUMMARY OF PRECURSOR CONTRACT

Under the precursor NASA Contract NAS8-34131, a miniaturized Cassegrainian concentrator (MCC) module was designed, assembled, and tested. Results support technical feasibility. Thermal vacuum testing and analysis confirmed earlier predictions that miniaturization results in acceptable solar cell temperatures with passive thermal control for a concentrator element with an effective concentration ratio of 130. Electrical performance of the demonstration hardware was as predicted at normal solar incidence. A light catcher cone improved off-pointing performance, but its full predicted effectiveness was not achieved.

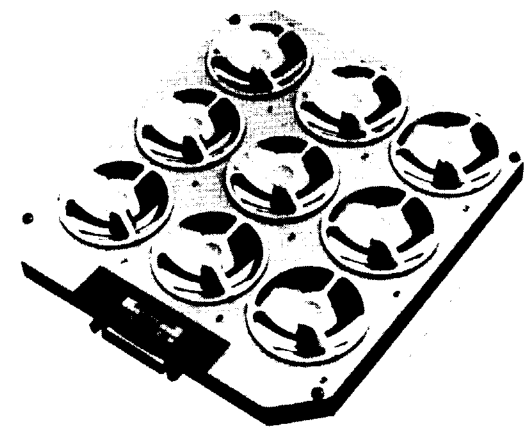
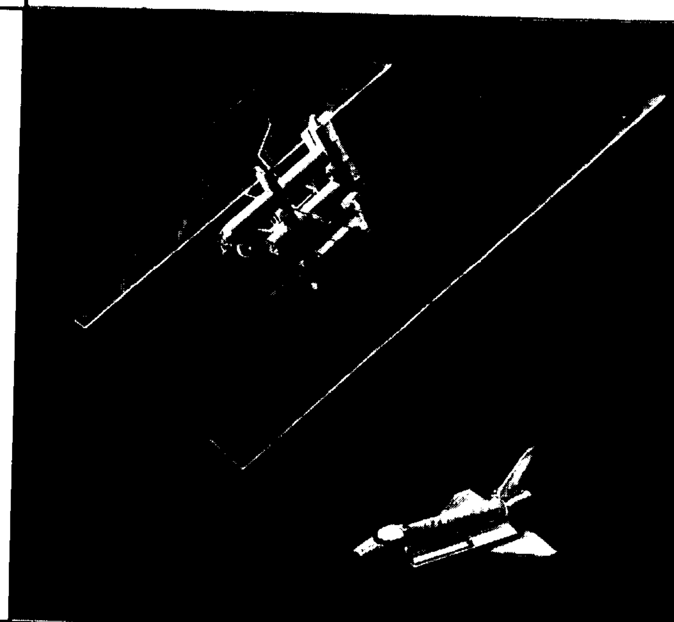
A number of element and module design trade studies were performed. A packing density study led to the selection of hexagonal close packing of untruncated elements as the baseline approach because it maximizes W/kg performance and minimizes element cost per unit power output. Electrical cell stack configuration, coverglass location, reflector material/configuration, and element radiator configuration studies were performed. These studies identified multiple acceptable approaches.

A MCC solar array system study was performed to assess the practicality of assembling the basic MCC element into a total array system capable of producing multihundred kilowatts of power for Space Platform/Space Station or other low earth orbit long lifetime missions. Preliminary mechanical and electrical subsystems were developed in order to determine first order performance characteristics. Results of the study support the feasibility of a 100-kilowatt MCC array system with beginning-of-life performance of 160 W/m^2 and 28 W/kg. It would occupy approximately 8 linear feet of Shuttle Cargo Bay in the fully stowed configuration.

The performance numbers are based on 20 percent efficient (at operating temperature) solar cells and 0.25-millimeter thick electroformed nickel optics. These performance numbers can be improved upon significantly with the development of higher efficiency solar cells and/or lighter weight optics. This effort (NASA 8-34131) is fully documented in Reference 5.

Technical Summary of Precursor Contract

TRW

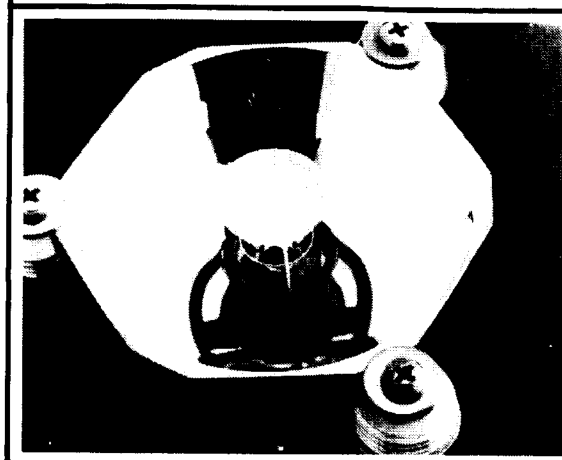
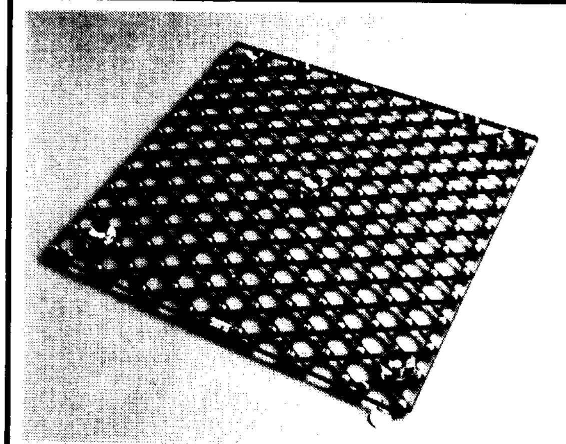
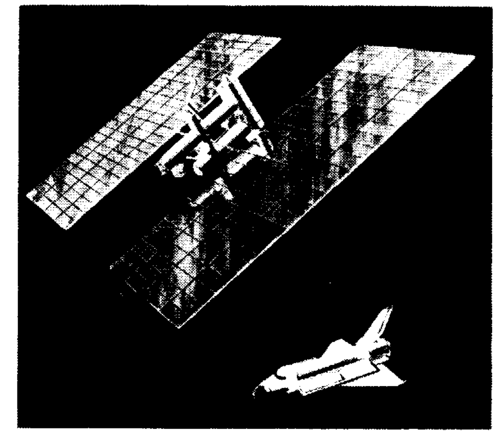
NINE-ELEMENT CASSEGRAINIAN CONCENTRATOR DEMONSTRATION MODULE		• TEST RESULTS SUPPORT TECHNICAL FEASIBILITY • 85°C CELL TEMPERATURE IN LOW EARTH ORBIT CONFIRMED BY THERMAL VACUUM TEST • CELL STACK ASSEMBLED USING CONVENTIONAL JOINING PROCESSES • OPTICAL ELEMENTS ALIGNED USING MECHANICAL INTERFERENCE FIT
100 KW BOL CASSEGRAINIAN CONCENTRATOR SOLAR ARRAY SYSTEM STUDY		• TWO WING DESIGN BASELINED BUT CONFIGURATIONS ARE NOT CONSTRAINED • FOLD-OUT RIGID PANELS WITH FOLDING BEAM SUPPORT (USED ON SKYLAB) • MODULAR CONCEPT (12.5 KW PER SUBWING MODULE) • ACCURATE ELEMENT POINTING (MAXIMUM RSS OF 1.1°) • 160 W/m^2 (CURRENT TECHNOLOGY) • 28 W/kg (CURRENT TECHNOLOGY) • POTENTIAL OF 60 W/kg WITH TECHNOLOGY DEVELOPMENT • ERECTABLE (EVA) ARRAY OPTIONAL

CONTRACT NAS8-35635 TECHNICAL RESULTS SUMMARY

The objectives of this contract were to (1) demonstrate element performance improvement (with respect to the nine element module tested under Contract NAS8-34131, Reference 5), (2) demonstrate one of the panel structural designs identified on Contract NAS8-34131 and (3) update solar array performance predictions based on the element and panel hardware demonstrations.

Second generation MCC element hardware was designed, fabricated and tested and had a significant performance improvement in on-axis optical efficiency over first generation hardware (70% versus 55%). Gallium arsenide solar cells were evaluated which were up to 18% efficient at AMO 100X at 28°C. A 26 inch by 56 inch graphite epoxy tri-hex grid element support structure was fabricated into 26 inch by 28 inch sections. Load deflection tests verified predicted panel stiffness. Five second generation MCC elements were installed in one of the 26 inch by 28 inch panel sections. This work demonstrates feasibility of producing a lightweight, stiff, MCC element support structure. Based on hardware performance results, MCC solar array system performance of 160 W/m^2 and 28 W/kg remains a reasonable design goal.

Contract NAS8-35635 Technical Results Summary

MCC Element	MCC Module	100-kW Array Predictions
		
• Optical efficiency improved from 55 to 70 percent • AMO 100X cell efficiencies of 17 to 18 percent at 28°C	• Graphite epoxy tri-hex grid fabricated by Fiber Science • Load deflection tests verified predicted stiffness	• 160 W/m^2 BOL • 28 W/kg BOL

Section 3.
MCC Element Design, Assembly and Test

- Objective and Approach
- Element Thermal Analysis
- Cell Stack and Mechanical Design
- Element Component Design and Fabrication
- Element Assembly
- Element Performance

MCC ELEMENT DEVELOPMENT OBJECTIVE AND APPROACH

The approach to accomplishing the objective of improving element optical efficiency from 55% to 79% is shown on the facing page.

MCC Element Development
Objective and Approach

TRW

Objective

- Develop a second generation MCC element with a design goal of 79% efficiency

Approach

- Improve optical surface reflectance by using silver coatings rather than aluminum coatings
- Reduce secondary support blockage
- Simplify element assembly

THERMAL ANALYSIS SUMMARY FOR A 200 NAUTICAL MILE 28.5° INCLINED ORBIT

Five different element configurations were analyzed to determine their effect on cell operating temperature. All analyses assumed a tri-hex grid element support structure (selected as the baseline approach for this contract as discussed in Section 4). The hex portion of this structure has an "opening" which is smaller than the element aperture. Thus, a separate radiator of an MCC element either needs to be smaller than the tri-hex grid opening, or it needs to be attached following element installation into the structure if it is larger than the tri-hex grid opening. Integral radiator designs do not have this constraint.

The 10-mil thick copper optics with integral radiator was selected as the baseline design because it has the lowest operating temperature of the five candidate configurations. This concept also is easier to assemble into panels than designs requiring installation of a separate radiator following element attachment to the panel.

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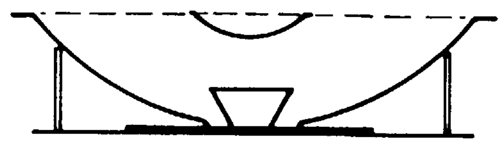
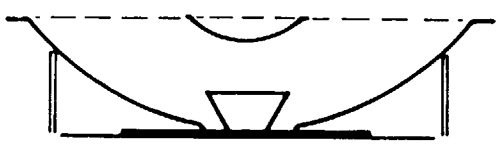
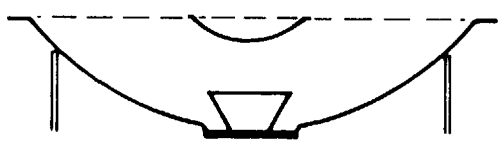
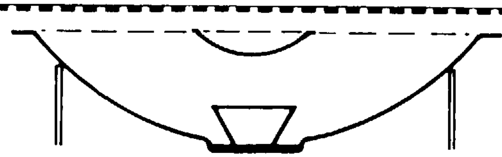
TRW Space & Technology Group

Thermal Analysis Summary for a 200 Nautical Mile 28.5° Inclined Orbit

TRW

CONFIGURATION	DESCRIPTION	CELL TEMPERATURE*
	• 10 MIL THICK NICKEL OPTICS • 10 MIL THICK ALUMINUM RADIATOR • RADIATOR AREA SAME AS ENTRANCE APERTURE • SECONDARY ATTACHMENT OF RADIATOR REQUIRED	86°C
	• 10 MIL THICK NICKEL OPTICS • 10 MIL THICK ALUMINUM RADIATOR • RADIATOR AREA SMALLER THAN ENTRANCE APERTURE TO ALLOW INSERTION THROUGH TRI-HEX GRID WHILE ATTACHED TO OPTICS	95°C
	• 10 MIL THICK NICKEL OPTICS • INTEGRAL RADIATOR	110°C
	• 10 MIL THICK COPPER OPTICS • INTEGRAL RADIATOR	85°C
	• 10 MIL THICK ALUMINUM OPTICS • INTEGRAL RADIATOR	92°C

BASELINE DESIGN

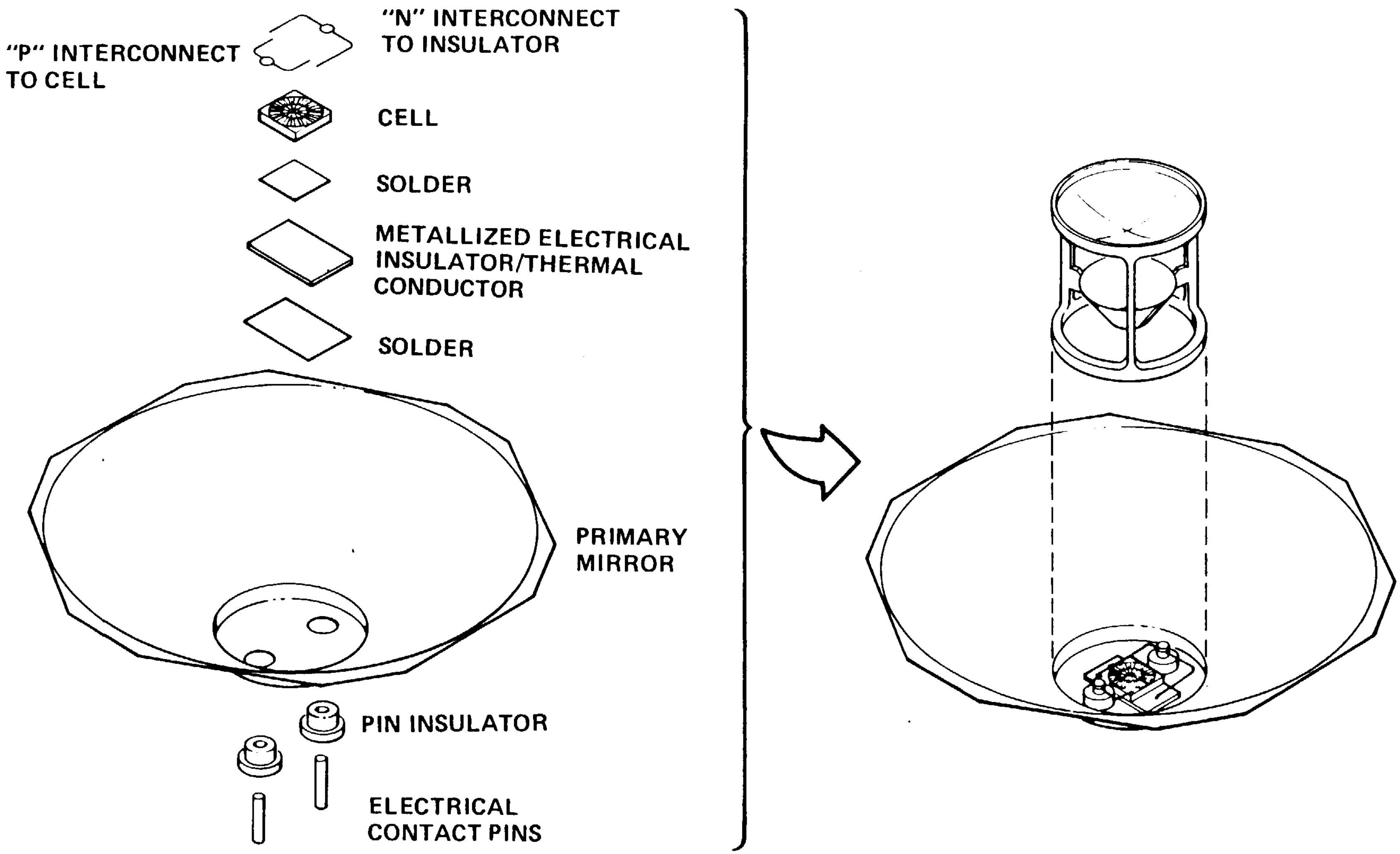
*NON-ECLIPSE ORBITAL AVERAGE

5-00689/20

CASSEGRAINIAN CONCENTRATOR ELEMENT ASSEMBLY

The basic design approach for the MCC element was to produce self aligning sub-assemblies. The "bird cage" secondary support structure was designed to locate the secondary reflector as well as the light catcher cone. Alignment along the optical axis is much improved over the "spider support structure" used for first generation hardware. The primary reflector and cell stack was designed for single operation assembly.

Cassegrainian Concentrator Element Assembly



MCC ELEMENT COMPONENT SUMMARY DATA

MCC element component data is summarized in the facing page table. The primary difference between second generation and first generation hardware is the switch from aluminum to silver optical surfaces to improve optical transmission (85% nominal reflectance for aluminum to 95% nominal reflectance for silver). Also, second generation hardware uses a BeO insulator to electrically isolate the cell stack from the primary reflector, whereas, first generation hardware had the cell back contact common to an integral radiator through a molybdenum heat spreader.

MCC Element Component Summary Data

COMPONENT	TRW REFERENCE DRAWING	BASE MATERIAL		FRONT COATINGS*/ CONTACTS		REAR COATINGS*/ CONTACTS	
		TYPE	THICKNESS (INCH)	TYPE	THICKNESS	TYPE	THICKNESS
PRIMARY REFLECTOR	SK 101-1R	Ni Cu Ni	0.001 0.008 0.001	INCONEL Ag SiO_x	250 Å 1400 Å 1388 Å	PAINT – –	0.002 – –
SECONDARY REFLECTOR	SK 102-1	Ni	0.010	INCONEL Ag SiO_x	250 Å 1400 Å 1388 Å	PAINT – –	0.002 – –
LIGHT CATCHER CONE	SK 103	Ni	0.010	INCONEL Ag SiO_x	250 Å 1400 Å 1388 Å	– – –	– – –
CONCENTRATOR SOLAR CELL	SK 104	GaAs	0.013	Au Zn Au Ag	3.5 μm	Au Ge Ni Au	3.5 μm
INSULATOR/ HEAT SINK	SK 200-1	BeO 0.018 INCH	0.018	MoMn Ni Au	0.0004 INCH 0.0001 INCH 0.0001 INCH	MoMn Ni Au	0.0004 INCH 0.0001 INCH 0.0001 INCH
SECONDARY SUPPORT (BIRDCAGE)	SK 113	STAINLESS STEEL (302) OR 6062 Al	– –	– –	– –	– –	– –

*IN ORDER OF APPLICATION

ELEMENT COMPONENT FABRICATION METHOD

Element component fabrication methods are identified and rated in the facing page table. Mirror fabrication method remains unchanged relative to first generation hardware. Second generation hardware uses gallium arsenide solar cells rather than silicon.

Element Component Fabrication Method

Component	Material	Fabrication Method	Quality
Parabolic mirror	Ni/Cu/Ni	Electroforming	Very good
• Coatings	Ag/SiO	Vacuum deposit	Good
Hyperbolic mirror	Ni	Electroforming	Very good
• Coatings	Ag/SiO	Vacuum deposit	Very good
Conic mirror	Ni	Electroforming	Good
• Coatings	Ag/SiO	Vacuum deposit	Fair
Birdcage	6062 Al or 302 SS	Machined blank	Very good
• Windows	NA	Laser, EDM	Poor, excellent
Cell	GaAs	Vapor phase epitaxy	Very good
• Metallization	Au/Zn/Ge/Ni/Ag*	Vacuum deposit	Good
• AR coating	(Proprietary)	Vacuum deposit	Good
Cell insulator	BeO	Isopress/sinter/dice	Excellent
• Metallization	MoMn/Ni/Au	Silkscreen/plate/plate	Excellent
Terminals	Brass	Standard machining	Very good
Terminal insulators	Polyimide	Standard machining	Good

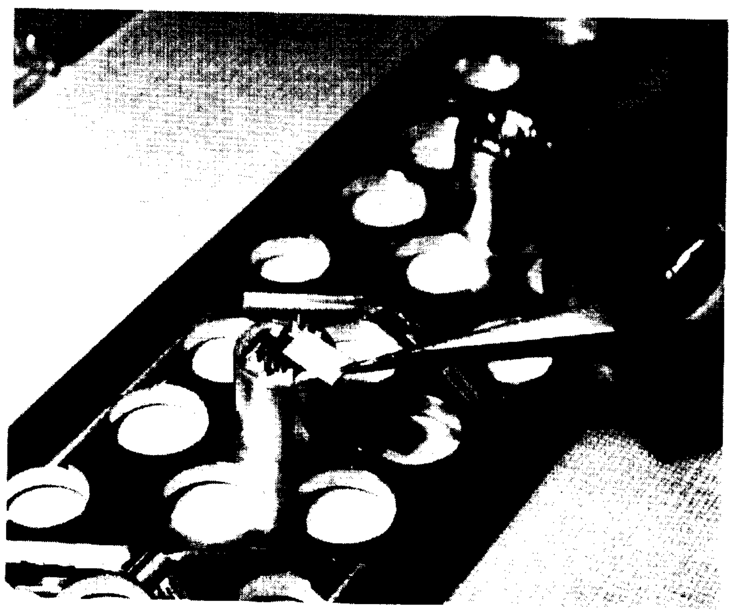
* Not in order

MCC ELEMENT CELL STACK ASSEMBLY TOOL

A five station assembly tool was produced which permits the simultaneous assembly of five cell stack subassemblies. The cell stack is manually stacked on a self aligning station as shown in Figure a. The primary reflector is then placed on top of the cell stack and secured to the tool with a spring clamp as shown in Figure b. The loaded five station assembly tool is heated in a vapor phase condensation reflow soldering unit. This enables all cell stack joining to be accomplished in one operation, and consequently, is well suited for low cost assembly.

MCC Element Cell Stack Assembly Tool

a) Cell stack only



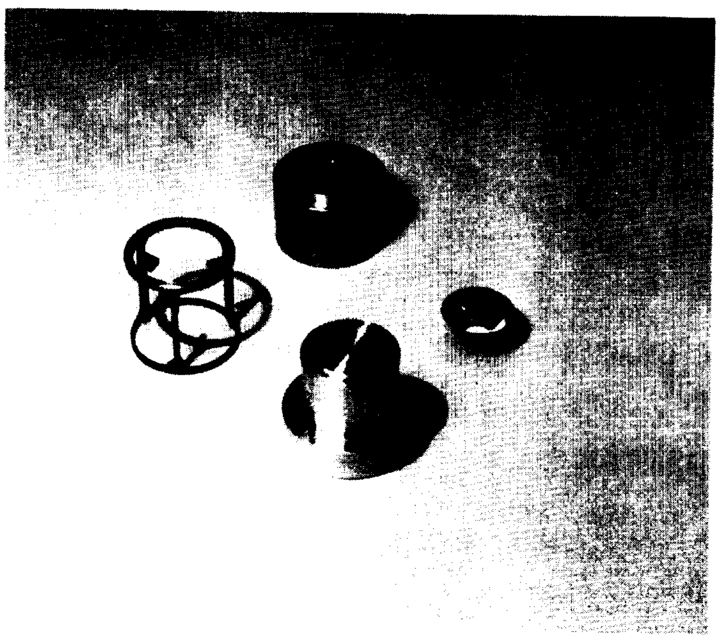
b) Cell stack with primary

MCC ELEMENT CONE-TO-BIRDCAGE ASSEMBLY

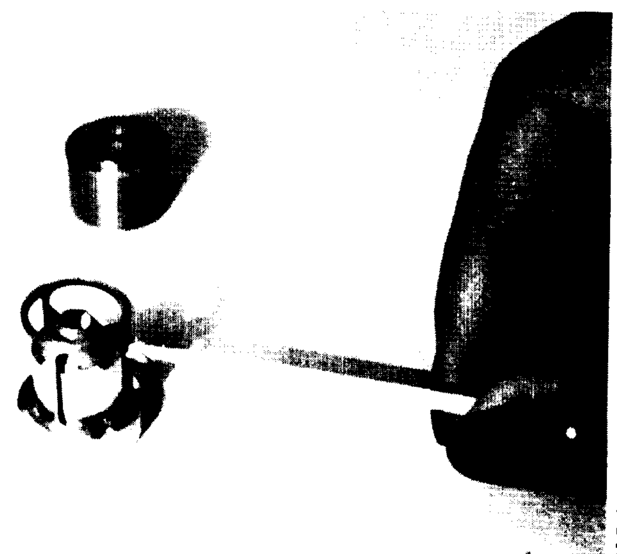
The cone is aligned and bonded with adhesive to the birdcage support structure using the tool shown on the facing page.

MCC Element Cone-to-Birdcage Assembly

a) Unassembled



b) Assembled in tool



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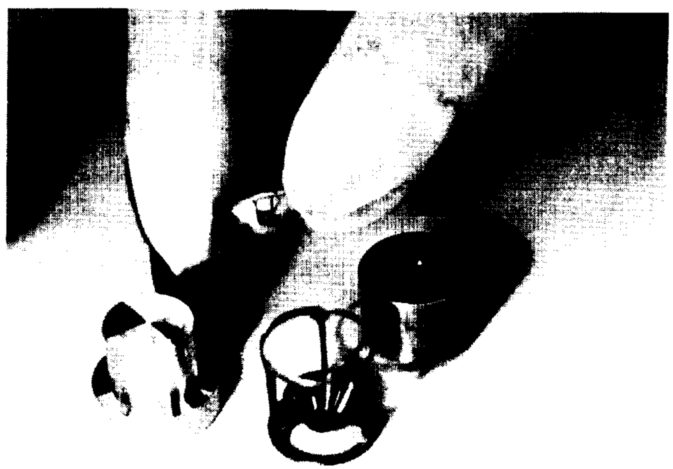
MCC ELEMENT SECONDARY-TO-BIRDCAGE ASSEMBLY

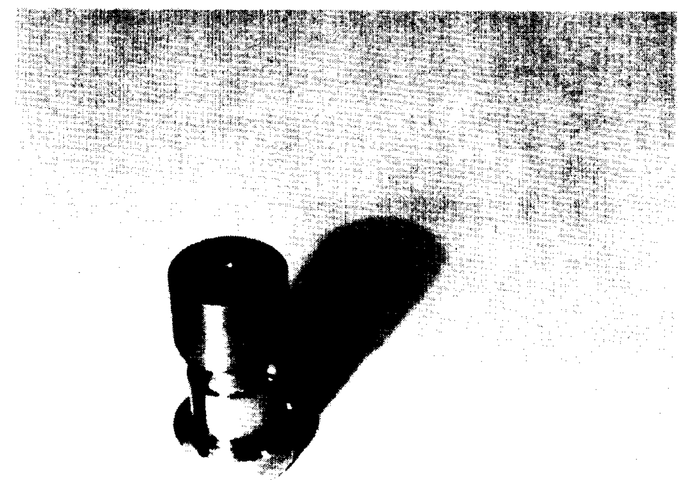
The secondary reflector is aligned and bonded with adhesive to the birdcage support structure using the tool shown on the facing page.

MCC Element Secondary-to-Birdcage Assembly

a) Unassembled



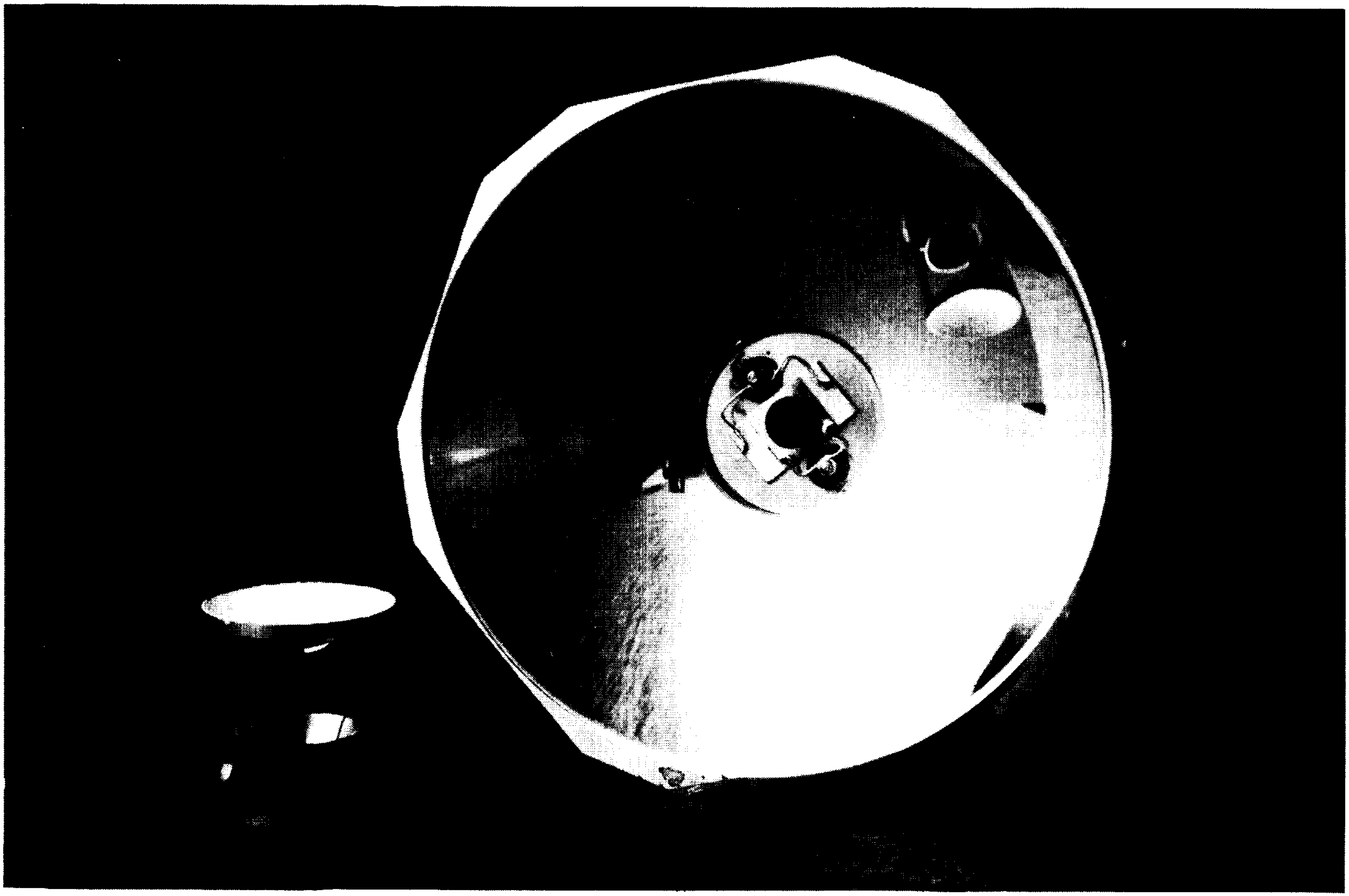
b) Assembled in tool



MCC ELEMENT WITH BIRDCAGE ASSEMBLY SHOWN SEPARATELY

The two major MCC element subassemblies are shown separately on the facing page. The birdcage support structure subassembly is self aligning with the primary reflector-cell stack subassembly. The two subassemblies are bonded together with adhesive.

MCC Element With Birdcage Assembly Shown Separately



MCC ELEMENT ASSEMBLY LOSSES
UNDER 1 SUN AMO ILLUMINATION

MCC element assembly losses are shown in the facing page table. Of great significance is the 12.8% average loss in maximum power. This number is significantly greater than that experienced for silicon planar arrays (1 to 2%) and for that experienced on the precursor concentrator contract (NAS8-34131) which used silicon concentrator cells. Current and voltage losses contribute approximately equal to the power loss. Cell stack losses are under investigation under the follow-on contract effort (NAS8-36159).

MCC Element Assembly Losses Under 1 Sun AMO Illumination

GaAs SOLAR CELL PERFORMANCE DEGRADED BY 11% DUE TO ELEMENT ASSEMBLY. INVESTIGATION IN PROGRESS TO REDUCE ASSEMBLY LOSSES TO 1 TO 2 PERCENT

PARAMETER	BEFORE ASSEMBLY		AFTER ASSEMBLY		PERCENT CHANGE**
	AVERAGE*	σ	AVERAGE*	σ	
OPEN CIRCUIT VOLTAGE	0.891 V	0.031 V	0.854 V	0.029 V	-4.1
SHORT CIRCUIT CURRENT	3.443 mA	0.181 mA	3.292 mA	0.104 mA	-4.4
VOLTAGE AT MAXIMUM POWER	0.761 V	0.034 V	0.713 V	0.029 V	-6.2
CURRENT AT MAXIMUM POWER	3.202 mA	0.161 mA	3.037 mA	0.087 mA	-5.2
MAXIMUM POWER	2.43 mW	0.144 mW	2.167 mW	0.138 mW	-11.0
FILL FACTOR	0.794	0.019	0.771	0.013	-2.9
EFFICIENCY	14.4%	0.9%	12.8%	0.8%	-11.0

*AVERAGE OF 9 ELEMENTS AT 1 SUN AND AT 28°C
**FOR PARAMETER AVERAGE

MCC ON-AXIS ELEMENT OPTICAL PERFORMANCE

The optical transmission design goal for this contract is 79%. Based on hardware measurements of reflectance and geometry (birdcage blockage, etc) the predicted transmission for second generation hardware is 77%. The measured optical transmission is 70% (average). Thus, actual transmission is approximately 10% lower than predicted transmission. Optical transmission improvement is discussed further in Section 5. Optical transmission improvement is under development on the follow-on contract effort (NAS8-36159).

On-Axis Element Optical Performance

MEASURED PERFORMANCE IS WITHIN 10 PERCENT OF PREDICTED PERFORMANCE. INVESTIGATION IS IN PROGRESS TO DETERMINE AND ELIMINATE OR REDUCE IMPACT OF CAUSE

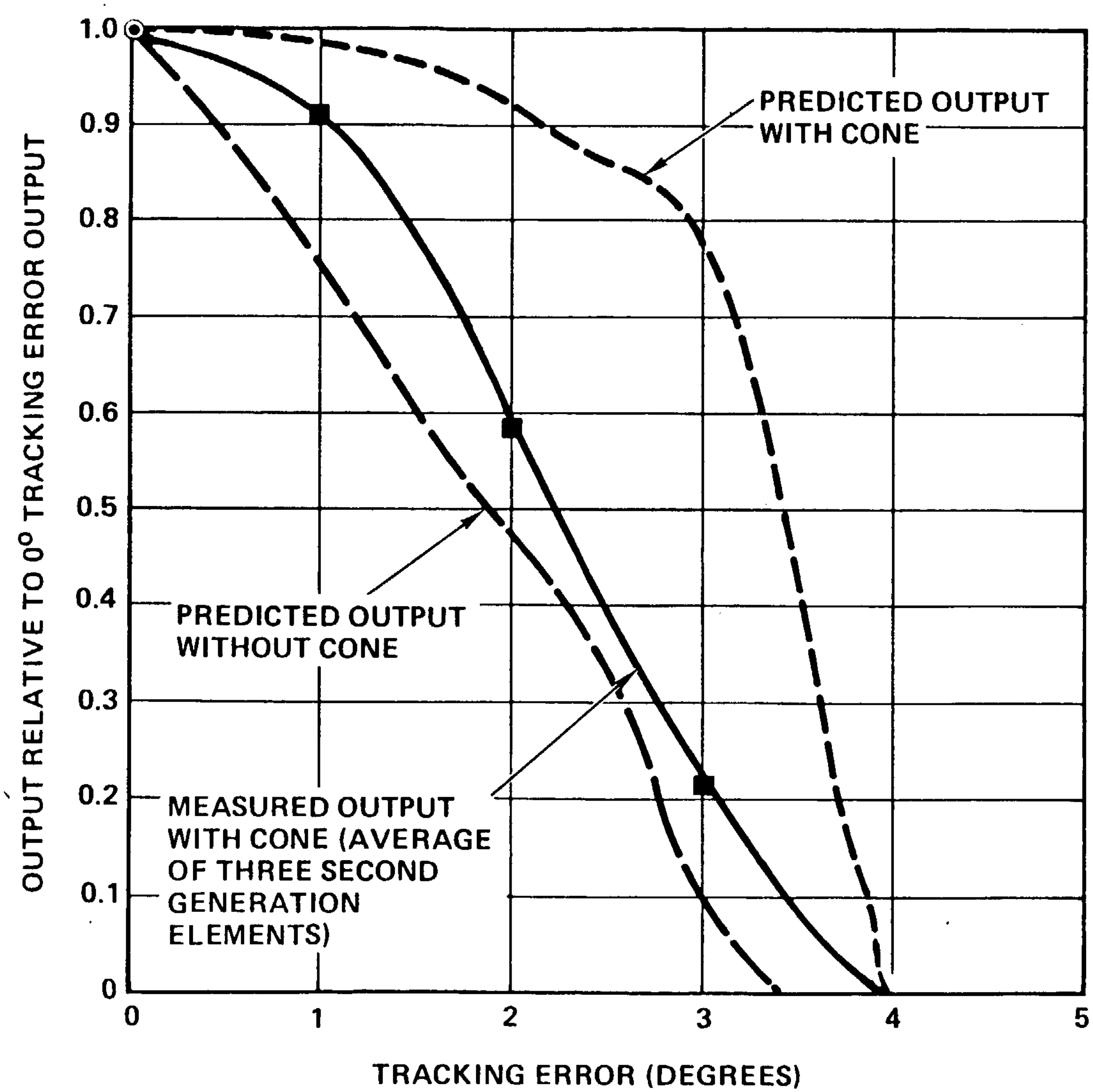
PARAMETER	MEASURED VALUE	CORRESPONDING TRANSMISSION FACTOR
PRIMARY REFLECTANCE	0.965	0.965
SECONDARY REFLECTANCE	0.922	0.922
SECONDARY BLOCKAGE (WITH FLANGE)	7.8 PERCENT	0.921
BIRDCAGE BLOCKAGE	6.1 PERCENT	0.939
PREDICTED ELEMENT OPTICAL TRANSMISSION*	N/A	0.77
MEASURED ELEMENT OPTICAL TRANSMISSION **	0.70	0.70

*PRODUCT OF 0.965, 0.922, 0.921 AND 0.939
**AVERAGE OF 8 ELEMENTS

PRELIMINARY OFF-POINTING TEST RESULTS

Single second generation elements were tested at TRW using a motorized solar tracker to determine off-axis performance. Results of this test are presented and show that although the cone improves off-axis performance over that predicted without a cone, the total predicted effectiveness of the cone has not been achieved. These results are similar to first generation hardware results, and are not surprising since second generation hardware design did not differ from first generation hardware design with respect to off-pointing performance. Off-pointing performance improvement is under investigation on the follow-on contract (NAS8-36159).

Preliminary Off-Pointing Test Results



- ADDITIONAL TESTING AND ANALYSIS ARE IN PROGRESS TO RECONCILE DIFFERENCES BETWEEN PREDICTED AND MEASURED PERFORMANCE
- THE FOLLOWING POTENTIAL CAUSES ARE UNDER INVESTIGATION:

  GAP BETWEEN CONE AND CELL

  LIGHT NOT COMPLETELY FOCUSSED ON CELL

  MISALIGNMENT OF ASSEMBLY PARTS

  DISTORTION OF MIRRORS

  FIGURE OF MIRRORS NOT CORRECT

  LIGHT SCATTERING

  GaAs CELL REFLECTANCE LOSSES

Section 4.
MCC Module Design, Fabrication, and Assembly

- Objective and Approach
- Baseline Structure Selection
- Tri-Hex Grid Specification and Fabrication
- Tri-Hex Grid Load Deflection Test
- Module with Elements Installed
- MCC Panel Weight Analysis

MODULE DEVELOPMENT OBJECTIVE AND APPROACH

The basic module development approach is summarized on the facing page. The tri-hex grid was selected as the baseline design. A specification was developed and an RFP was issued. Fiber Science was selected based on their lowest risk approach as discussed in this section.

Module Development Objective and Approach

Objective

- Demonstrate one of the panel structural designs from NAS8-34131

Approach

- Review concepts from NAS8-34131
- Select baseline design and develop preliminary specifications
- Review designs with vendors and finalize specification
- Prepare and issue RFP
- Review responses and select supplier
- Attach elements to structure

PANEL STRUCTURAL CONFIGURATION SUMMARY

The facing page presents a table summarizing the panel structural configurations developed under the previous contract (NAS8-34131, Reference 5). The filament wound tri-hex grid structure was selected as the baseline design based on excellent thermal stability, excellent strength to weight ratio, and low cost fabrication potential.

Panel Structural Configuration Summary

TRW

Construction	Grid/Material	Grid Manufacturing Process	Panel Off-Pointing Error*	Grid Material Cost	Grid Fab Cost
Frame/open grid	Hex/graphite	Formed strips/bonded	0.13°	Moderate	Moderate
Frame/open grid	Hex/kelvar	Formed strips/bonded	0.23°	Low	Moderate
Frame/Open grid	Tri-hex/plastic	Injection molded	Not analyzed	Lowest	Lowest
Integral frame/open grid	Tri-hex/graphite	Filament winding	0.03°	Moderate	Low
Integral frame/open grid	Tri-hex/kelvar	Filament winding	0.23°	Low	Low
Frame/sandwich**	Hex/aluminum	Formed strips/bonded	0.28°	Low	Moderate

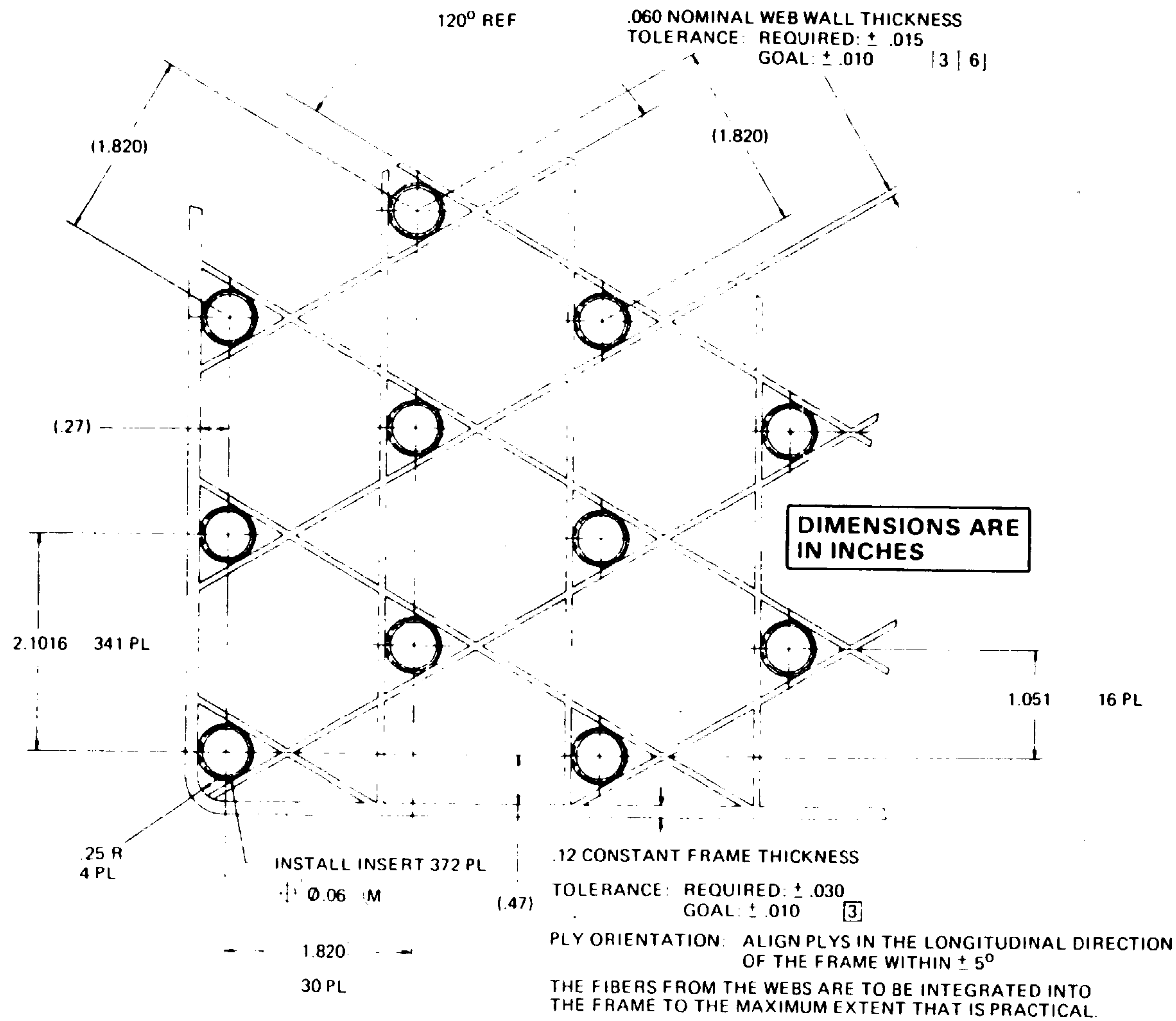
* Due to thermal distortion
** Multiple element design

Selected as baseline design based on excellent thermal stability, excellent strength to weight ratio, and low cost fabrication potential

SPECIFICATION

The specification shown on the following three facing pages was developed and used to procure the tri-hex grid panel. An RFP was issued to four companies for a best effort fixed price contract to produce the tri-hex grid panel per the specification.

Specification for 26 Inch by 56 Inch Tri-Hex Grid Panel Substrate with Inserts for Element Attachment



The facing page is the second page of the three page specification.

Specification for 26 Inch by 56 Inch Tri-Hex Grid Panel Substrate with Inserts for Element Attachment (Continued)

1. Material: graphite filament in a suitable resin matrix material

Requirements: $\boxed{3}$	**Goals:** $\boxed{3}$
40 percent minimum fiber volume	60 percent minimum fiber volume
CTE: 0° 35E10-6 in/in/°F max	CTE: 0° 00E10-6 in/in/°F max
90° 20E10-6 in/in/°F max	90° 12E10-6 in/in/°F max
Tension/compression modulus:	Tension/compression modulus:
0° 13.0 MSI min	0° 20.0 MSI min
90° 0.9 MSI min	90° 1.3 MSI min
Tension/compression ultimate strength:	Tension/compression ultimate strength:
0° 130 KSI min	0° 210 KSI min
90° 5 KSI min	90° 5 KSI min
Service temperature	Service temperature
215° F max	300° F max
-200° F min	-200° F min

The facing page is the third page of the three page specification.

Specification for 26 Inch by 56 Inch Tri-Hex Grid Panel Substrate with Inserts for Element Attachment (Continued)

2. Panel flatness:
   - Requirement: 0.020 in 10 inches
   - Goal: 0.005 in 10 inches $\boxed{3}$

$\boxed{3}$ The specifications given as "Requirements" need to be met for the demonstration panels. The specifications given as "Goals" represent a more efficient structure, and future production panels should meet or exceed these specifications where ever practical

4. Production panels will require a space qualified material system

5. The fibers are to be aligned in thelongitudinal direction of each web. The fibers shall not be interrupted at the web intersections but shall crossover alternately with a minimum of 20 crossovers

$\boxed{6}$ Minimum web wall thickness for future production panels might be as thin as 0.020

FIBER SCIENCE TRI-HEX GRID MOLD DEVELOPMENT

Fiber Science was selected based on their initial low risk approach. The geometry of the tri-hex grid is such that extraction of the part from the mold is very difficult. The original Fiber Science approach was to use a machined plaster mold which could be broken out after filament winding and curing to remove the mold from the finished part. Studies using subscale plaster molds showed two basic problems. The plaster material is brittle and the machining of the slots resulted in a very weak mold structure. The second problem was that resin migrated into the interfaces between the mold and the insert during fabrication making it difficult to remove the grid along with the inserts intact after curing.

A single piece aluminum mold was tried next. However, subscale tests showed that the mold/part differential thermal expansion set up high binding forces in the mold that made it virtually impossible to remove the part.

The third tooling was successful and consisted of an assemblable tool consisting of hexagonal and triangular shaped parts assembled on a baseplate. This configuration allowed the baseplate to be separated and then permit subsequent removal, individually, of the hexagonal and triangular shaped parts from the finished tri-hex grid.

Fiber Science Tri-Hex Grid Mold Development

Fiber Science selected based on lowest risk approach

Original approach was to use a non-reusable machined plaster mold

Plaster mold approach did not work due to mold brittleness

Machined aluminum mold also was investigated, however grid removal on subscale tests was difficult

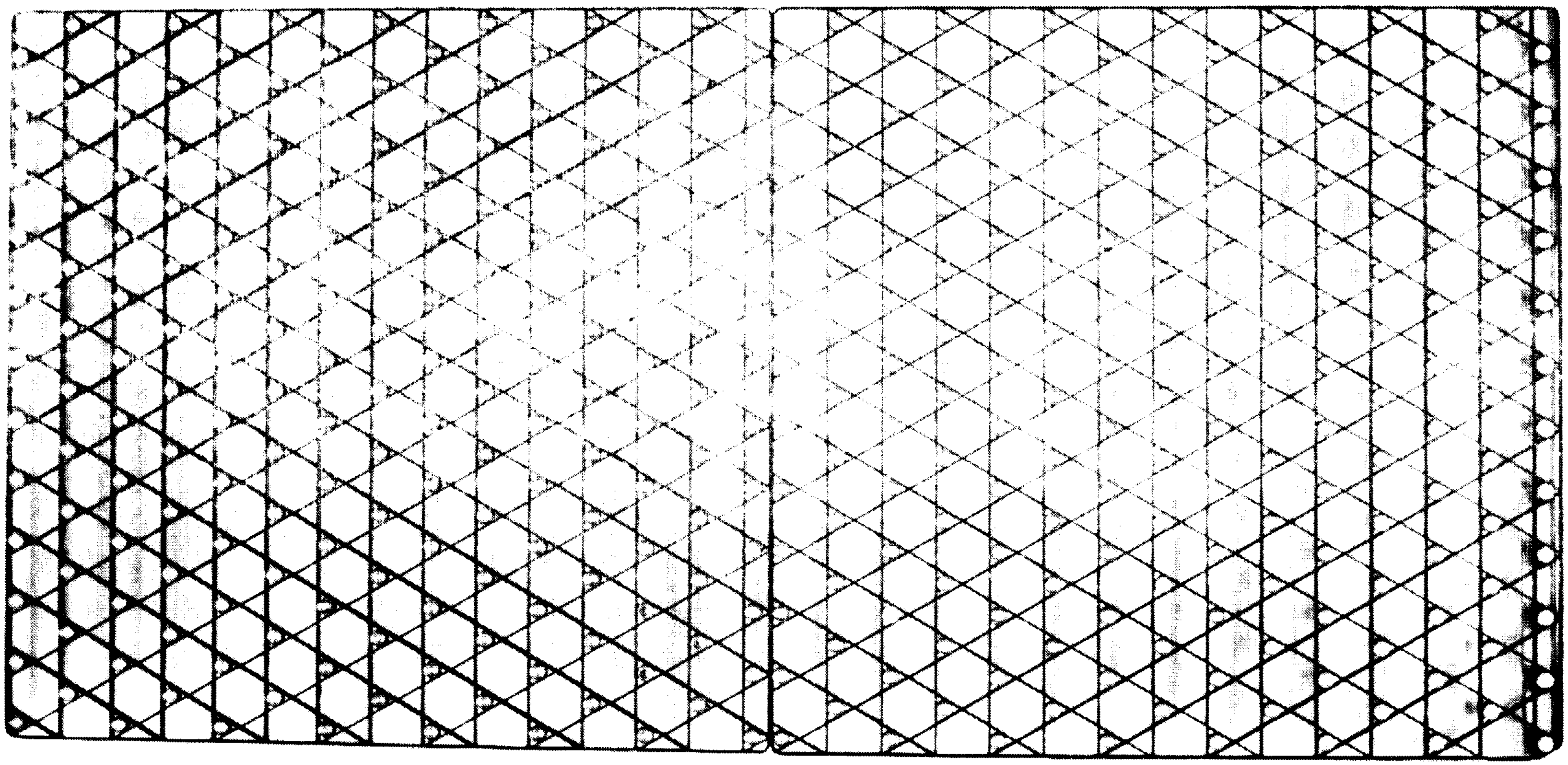
An aluminum "assembled" mold proved to be successful

26 BY 56 INCH TRI-HEX GRID SUBSTRATE
(Two Halves Bonded Together)

To minimize tooling cost and to demonstrate multiple use of the assemblable tool, the 26 by 56 inch panel substrate was fabricated by producing two 26 by 28 inch panels from the same tool and then bonding them together. A DEN 431/xu 205 epoxy resin system with a long pot life was used (debulked before use). A single T300-3k graphite roving was used. The theoretical packing of the fibers was not obtained because of the difficulty in squeezing out the excess resin at the cross-overs. Worst case fiber volume fraction is estimated to be between 20 and 30%. The layup in the mold was not compacted (compaction tooling complexity beyond the scope of the subcontract with Fiber Science). The mold was vacuum bagged and cured at 350°F. No resin was allowed to bleed off. The finished panel has a flatness of approximately ± 0.050 inch.

The work done by Fiber Science proves the feasibility of manufacturing the tri-hex grid. Further development is required to improve panel grid flatness, fiber volume fraction, and insert attachment.

26 by 56 Inch Tri-Hex Grid Substrate (Two Halves Bonded Together)



T300-3K graphite roving
DEN 431/xu 205 epoxy resin system
350°F cure

PANEL LOAD DEFLECTION TEST RESULTS

Static loading tests were performed on the developmental tri-hex grid substrates to measure stiffness and deflection characteristics and to correlate analytical computer models with the experimentally-derived mechanical characteristics. The figure shows a typical test set-up. The panels were supported with various edge conditions and uniformly loaded by application of thin rubber mats up to a maximum loading of 16 lb/ft^2, which represents about 16 g's based on expected STS acoustic/vibration launch/landing environments.

The calculated flexural modulus from the bending tests was about 10×10^6 psi. The deflections were consistent with the predicted results based on the actual graphite fiber volume ratio.

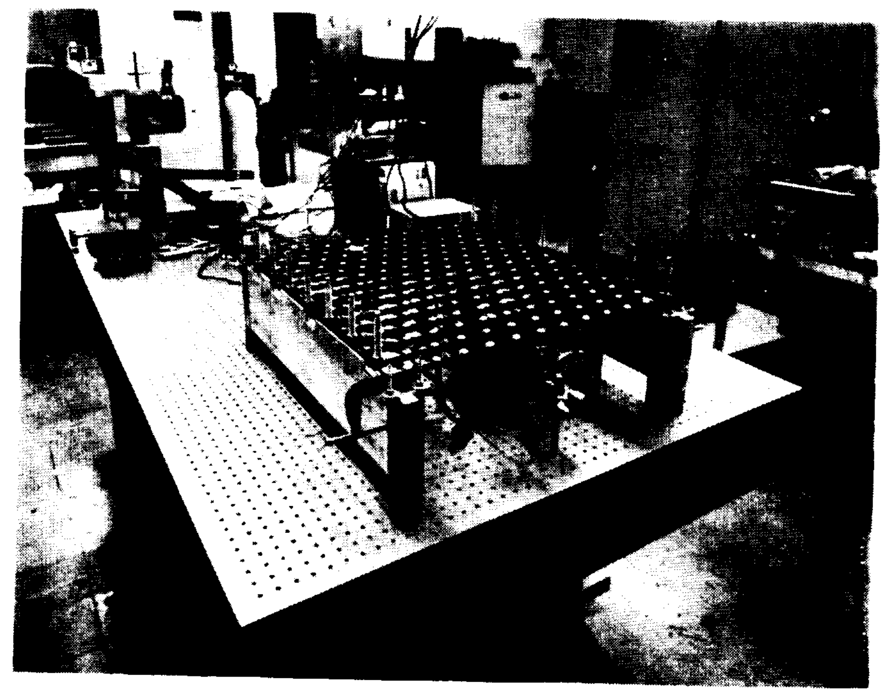
Panel Load Deflection Test Results

Load deflection tests performed on 26 x 28 in. panel

Deflections were consistent with predicted results (based on actual fiber volume ratio)

Flexural modulus of 10 x 10^6 psi achieved based on test results

Flexural modulus/density of graphite epoxy of 350 (msi/lb)(inch^3) achievable using IM6 graphite at 62% fiber volume (approximately 3.5 times more weight efficient than aluminum)



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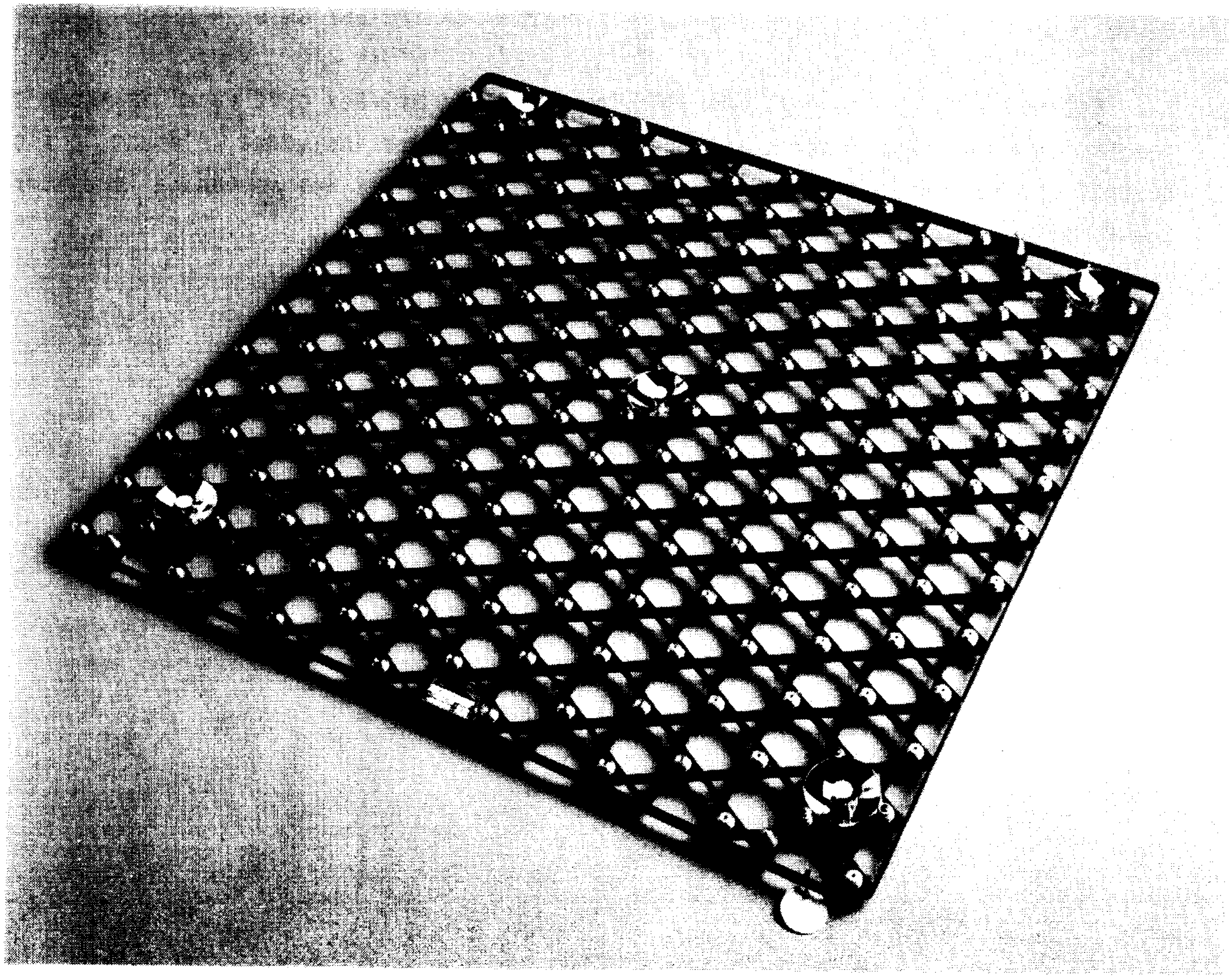
TRI-HEX GRID WITH ELEMENTS

A 26 inch by 28 inch tri-hex grid panel with five live elements attached is shown on the facing page. The five elements are individually electrically connected to a connector. Element attachment inserts have been installed so that the panel can be fully populated as elements become available.

Tri-Hex Grid With Elements



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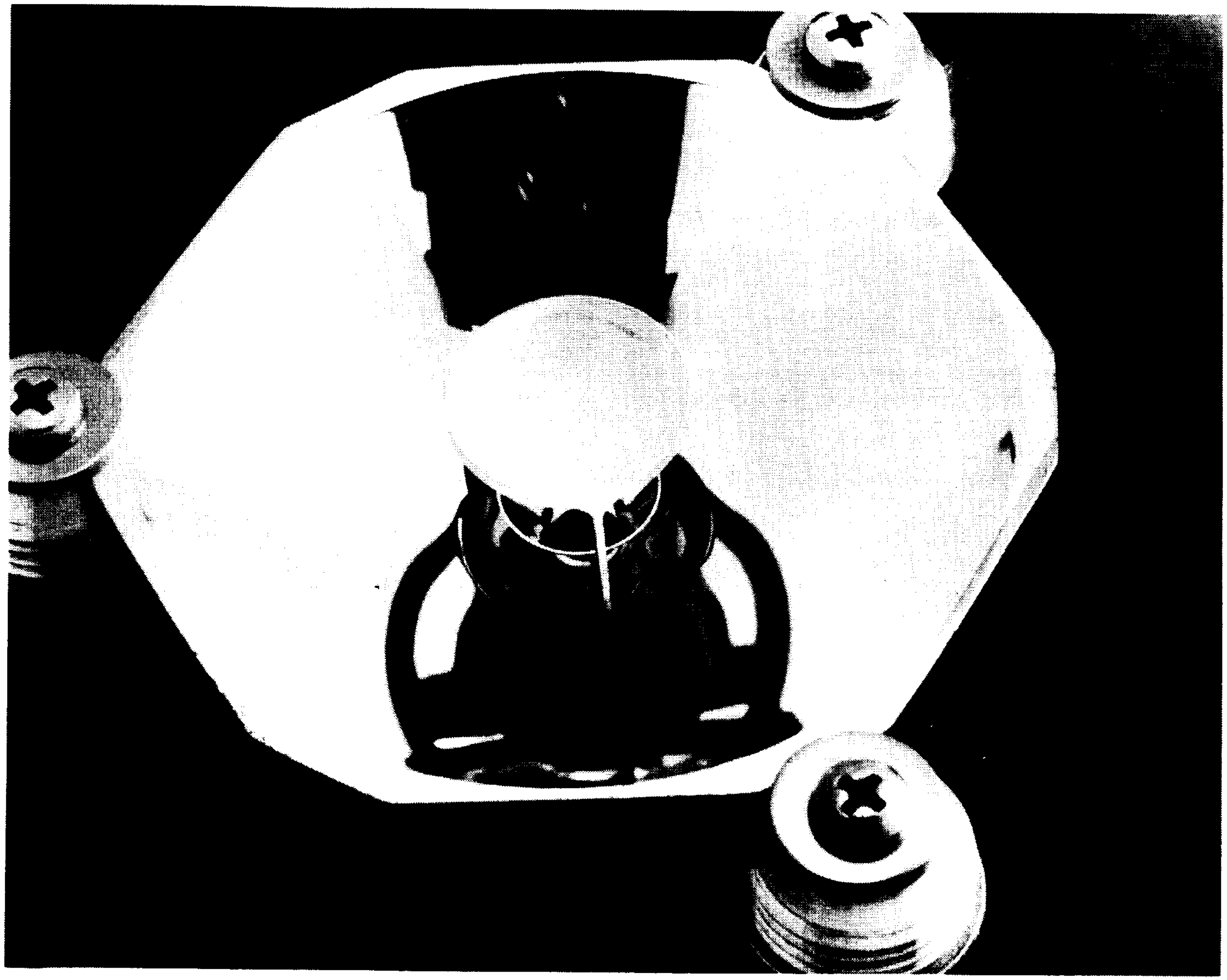
FRONT SIDE VIEW OF MCC ELEMENT IN TRI-HEX GRID

A front side close-up of one MCC element in the tri-hex grid panel is shown on the facing page. The inserts are designed to allow each individual element to float so that as the panel is thermal cycles, the structure does not mechanically distort the MCC element.

Front Side View of MCC Element in Tri-Hex Grid



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BACKSIDE VIEW OF MCC ELEMENT IN TRI-HEX GRID

A backside close-up view of a MCC element in the tri-hex grid panel is shown on the facing page. The rear side of the element is painted white to minimize element operating temperature in low earth orbit when earth albedo and IR impinge on the rear side (earth facing) of the panel.

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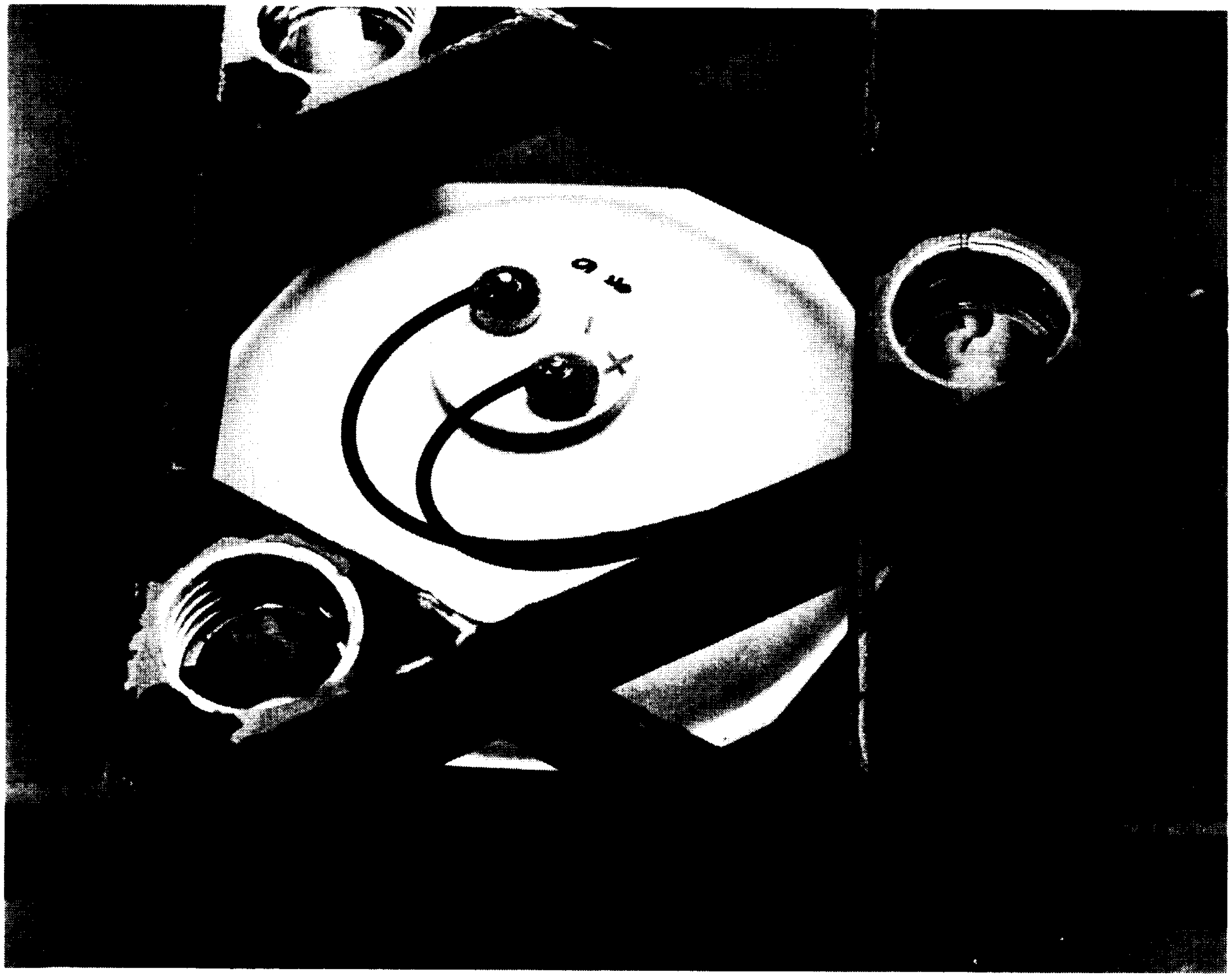
Backside View of MCC Element in Tri-Hex Grid



MCC PANEL WEIGHT ANALYSIS

A MCC panel weight analysis is presented on the facing page. The total mass for the as built panel is 1.286 kg. The projected mass for a fully populated quarter panel is 5.342 kg. Work under the previous contract indicated that a fully populated quarter panel with a mass of 4.159 kg corresponds to a 28 W/kg array system performance (beginning of life). Thus the first generation MCC panel hardware is approximately 30% heavier than a 28 W/kg flightweight design.

MCC Panel Weight Analysis

COMPONENT	ENGINEERING DEMONSTRATION MODULE						FLIGHTWEIGHT DESIGN*		
	AS BUILT ONE-EIGHTH SIZE PANEL WITH FIVE MCC ELEMENTS			PROJECTED WEIGHT FOR FULLY POPULATED QUARTER PANEL			WEIGHT FOR FULLY POPULATED QUARTER PANEL		
	UNIT MASS (g)	QUANTITY	TOTAL MASS (g)	UNIT MASS (g)	QUANTITY	TOTAL MASS (g)	UNIT MASS (g)	QUANTITY	TOTAL MASS (g)
TRI-HEX GRID PANEL AND FRAME	878	1	878	1509	1	1509	714	1	714
MCC ELEMENT (CELL STACK AND OPTICS)	9.6	5	48	9.6	330	3168	9.6	330***	3168
ELEMENT ATTACH-MENT HARDWARE	**	**	264	3.3	372	1224	0.5	372	186
PANEL WIRING AND CONNECTOR	52	1	52	91	1	91	91	1	91
DISPLAY HARDWARE	11	4	44	–	–	–	–	–	–
TOTAL PANEL MASS			1286			5342			4159****

*PANEL DESIGN CONSISTENT WITH 28 W/kg ARRAY SYSTEM PERFORMANCE (BEGINNING OF LIFE)

**180 FEMALE MOUNTS AT 1.3g EACH AND 15 MALE MOUNTS AT 2.0g EACH

***330 ELEMENTS PRODUCE 137W AT THE ARRAY SYSTEM LEVEL

****ARRAY STRUCTURE ADDS AN ADDITIONAL 19.5% IN MASS

5-00689/28

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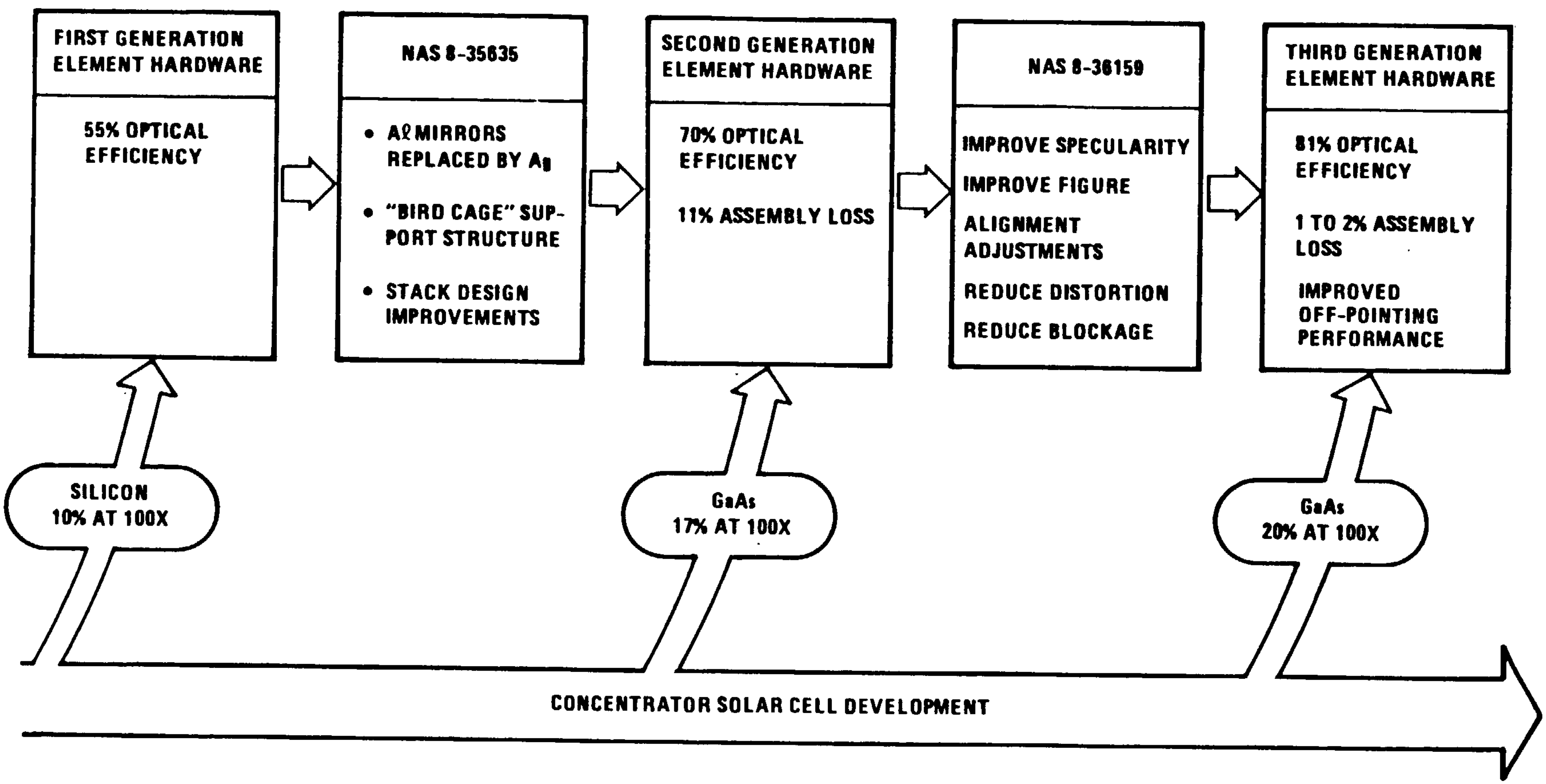
Section 5.
MCC Solar Array Performance Predictions

- MCC Element Performance Evolution
- Tri-Hex Grid Panel Evolution
- 100 kW MCC Solar Array System Performance

MCC ELEMENT EVOLUTION

In general, second generation hardware had improved performance over first generation hardware primarily due to improved mirror reflectance (silver versus aluminum) and reduced secondary reflector support blockage. Also, there was a significant improvement in cell efficiency with the switch from a 10% efficient silicon cell to an 18% (maximum) efficient gallium arsenide cell. It is anticipated that third generation hardware will experience even further performance improvements by improving reflector specularity and figure, making alignment adjustments, reducing distortion and blockage and using more efficient (20%) gallium arsenide concentrator solar cells.

MCC Element Evolution



TRI-HEX GRID PANEL EVOLUTION

First generation MCC panel hardware has a 20 to 30% fiber volume and aluminum inserts. Second generation hardware to be developed under contract NAS8-36159 will increase fiber volume and eliminate aluminum inserts to achieve a 28 W/kg (beginning of life) array system performance and to achieve thermally compatible inserts.

Tri-Hex Grid Panel Evolution

FIRST GENERATION TRI-HEX GRID

- 26W/KG (PANEL LEVEL)
- 20 TO 30% FIBER VOLUME
- ALUMINUM INSERTS

→

NAS 8-36159

INCREASE FIBER VOLUME

ELIMINATE ALUMINUM INSERTS

→

SECOND GENERATION TRI-HEX GRID

- 33W/KG (PANEL LEVEL)*
- 60% FIBER VOLUME
- THERMALLY COMPATIBLE INSERTS

*CORRESPONDS TO 28W/KG AT THE ARRAY SYSTEM LEVEL

BOL PERFORMANCE PREDICTION FOR A 235 NAUTICAL MILE ORBIT

The performance prediction for a 100 kilowatt solar array system concept is summarized and shows a beginning of life (BOL) performance of 160 W/m^2 and 28 W/kg. This analysis was developed under the previous contract NAS8-34131, Reference 5), and was reviewed under this contract. Based on performance results of hardware built under contract NAS8-35635, an optical transmission of 81%, a cell efficiency of 20% and a quarter panel mass of 4.259 kg remain reasonable and achievable design goals.

Array power is based on 250,368 elements at 0.417 W/element (including all degradation factors). Overall packing factor is 0.79.

BOL Performance Prediction for a 235 Nautical Mile Orbit

NOMINAL DESIGN FACTORS	
PARAMETER	VALUE
CELL EFFICIENCY	20% AT 85°C
OPTICAL EFFICIENCY	0.81
WIRING & DIODE DROP	0.97
CELL MISMATCH *	0.98
OFF-POINTING	0.98

* INCLUDES ASSEMBLY LOSS

NOMINAL PERFORMANCE	
PARAMETER	VALUE
ARRAY POWER	104 kW
ARRAY AREA	651 m^2
ARRAY MASS	3700 kg
AREAL POWER	160 W/m^2
SPECIFIC POWER	28 W/kg

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Section 6. Conclusions

CONCLUSIONS

The objectives of this contract were to: (1) demonstrate element performance improvement (with respect to the nine element module tested under contract NAS8-34131, Reference 5), (2) demonstrate one of the panel structural designs identified on contract NAS8-34131 and (3) update solar array performance predictions based on the element and panel hardware demonstrations.

Second generation MCC element hardware was designed, fabricated and tested and had a significant performance improvement in on-axis optical efficiency over first generation hardware (70% versus 55%). Gallium arsenide solar cells were evaluated which were up to 18% efficient at AMO 100X at 28°C. A 26 inch by 56 inch graphite epoxy tri-hex grid element support structure was fabricated in 26 inch by 28 inch sections. Load deflection tests verified predicted panel stiffness. Five second generation MCC elements were installed in one of the 26 inch by 28 inch panel sections. This work demonstrates feasibility of producing a lightweight, still, MCC element support structure. Based on hardware performance results, MCC solar array system performance of 160 W/m^2 and 28 W/kg remain a reasonable design goal.

Conclusions

Second generation MCC element test results demonstrate feasibility of optical transmission design goal of 81 percent (optical transmission of second generation hardware improved from 55 to 70 percent).

Module test results demonstrate feasibility of producing lightweight, stiff, graphite epoxy tri-hex grid MCC elements support structures.

Prior analysis, second generation MCC element test results, and tri-hex grid module test results support feasibility of a 100-kW MCC array system with BOL performance of 160 W/m^2 and 28 W/kg.

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Section 7.
Future Work

FOLLOW-ON CONTRACT PLANS

A follow-on contract (NAS8-36159) is currently in progress to continue development of the MCC solar array. Contract tasks are shown on the facing page. The overall objective is to further improve both on-axis and off-axis performance of the MCC element and to develop fully populated panel segment hardware capable of withstanding a Shuttle launch environment and performing five years life in a low earth orbit with minimum degradation.

Follow-On Contract Plans

Further develop optical components including both on-axis and off-axis optical performance and producibility. Select baseline material and manufacturing processes.

Develop a concentrator stack element design with a design goal of 5 years in low earth orbit.

Develop a lightweight element grid structure with thermally compatible element attachment inserts.

Design, fabricate, and test a fully populated 15 x 56 inch panel. Life testing (5 years in low earth orbit) to be performed at MSFC.

Design, fabricate, and test a fully populated 18 x 18 inch prototype panel.

Section 8.
References

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References

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3. H. Rauschenbach and R. Patterson, "Design Requirements for High Efficiency High Concentration Ratio Space Solar Cells," TRW Space and Technology Group, *Space Photovoltaic Research and Technology, 1980,* NASA Conference Publication 2169, October 1980

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5. R.E. Patterson, TRW Space and Technology Group, Redondo Beach, California 90278, "Study of Multi-Kilowatt Solar Arrays for Earth Orbit Applications," Final Report on Contract NAS8-34131 to NASA MSFC, Document Number 38172-6001-UE-00, 15 October 1983