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STUDY OF THERMAL MANAGEMENT FOR SPACE PLATFORM APPLICATIONS

UNMANNED MODULE THERMAL MANAGEMENT AND RADIATOR TECHNOLOGIES

by J. A. Oren

VOUGHT CORPORATION

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABS: Candidate techniques for thermal management of unmanned modules docked to a large 250 kW platform were evaluated. Both automatically deployed and space constructed radiator systems were studied to identify characteristics and potential problems. Radiator coating requirements and current state-of-the-art were identified. An assessment of the technology needs was made and advancements were recommended.

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16. Abstract

An evaluation was made of candidate techniques for thermal management of unmanned modules docked to a large 250 kW platform. The most promising concepts were identified. Evaluations were made for both automatically deployed and space constructed radiator systems to identify characteristics and potential problems. Radiator coating requirements and current state-of-the-art were identified. An assessment of the technology needs was made and advancements were recommended.

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FOREWORD

The studies presented herein represent the efforts and contributions made by a number of Vought personnel in addition to the author. These include:

Dennis Stalmach	-	Unmanned Module Thermal Management Studies
Ken Dougan	-	Space Constructable Radiator Deployment Studies
Jim Hicks	-	Dynamic Analysis of Automatically Deployed Radiators
Mike Fleming	-	Radiator Coatings Studies

The author is grateful for the support of these and other personnel at Vought and for the helpful direction of Mr. Sol Gorland, NASA Project Manager during the study.

STUDY OF THERMAL MANAGEMENT FOR SPACE
PLATFORM APPLICATIONS

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1.0 SUMMARY

This report documents studies that were performed by the Vought Corporation under Modification 1 to Contract NAS3-22270 for the NASA Lewis Research Center during the period of 1 November 1980 through 31 March 1981. The objectives of the study were: (1) Identification of the options in thermal control for unmanned modules docked to the 250 kW space platform and determining those most promising; (2) Study of deployment for automatically deployed and space constructed radiators, to identify potential problems and characteristics; (3) Examination of radiator coating needs for long life large space platforms and identify some of the options available; and (4) Assessment of advancements needed to achieve technology readiness in the unmanned modules, radiator deployment and radiator coatings areas.

A schedule of the total effort for contract NAS3-22270 is shown in Figure 1. The study consisted of two separate efforts. The original contract effort was concerned with thermal management of large 250 kW space platforms. That effort consisted of Tasks I thru IV during the period of 16 November 1979 through 26 August 1980 and Task IV, Documentation, from 15 August to 10 December 1980. That original effort is documented in an interim report, Reference 1. The Modification 1 effort, discussed herein, consisted of Tasks I and V, Unmanned Module Definition and Thermal Management Requirements; Tasks II and VI, Thermal Management and Heat Rejection Concept Trade Studies for Unmanned Modules; Task VII, Radiator Deployment and Coating Studies; Task III, Technology Assessment; and Task IV, Documentation.

The Science and Applications Space Platform (SASP) second order configuration was selected as a representative unmanned module docked to the 250 kW space platform. Six promising concepts were identified for thermal control of the unmanned modules. These were:

- CONCEPT 1 : Decentralized, All Heat Pipe System
- CONCEPT 2 : Centralized Pump Driven Heat Pipe System Plugged Into Central Platform Cooling Loop
- CONCEPT 3 : Centralized Compressor Driven Heat Pipe System Plugged Into Central Platform Cooling Loop
- CONCEPT 4 : Decentralized Pumped Liquid System
- CONCEPT 5 : Centralized Pumped Liquid System Independent of Central Platform TMS (Radiators on Unmanned Module)
- CONCEPT 6 : Centralized Pumped Liquid System Plugged Into Central Platform

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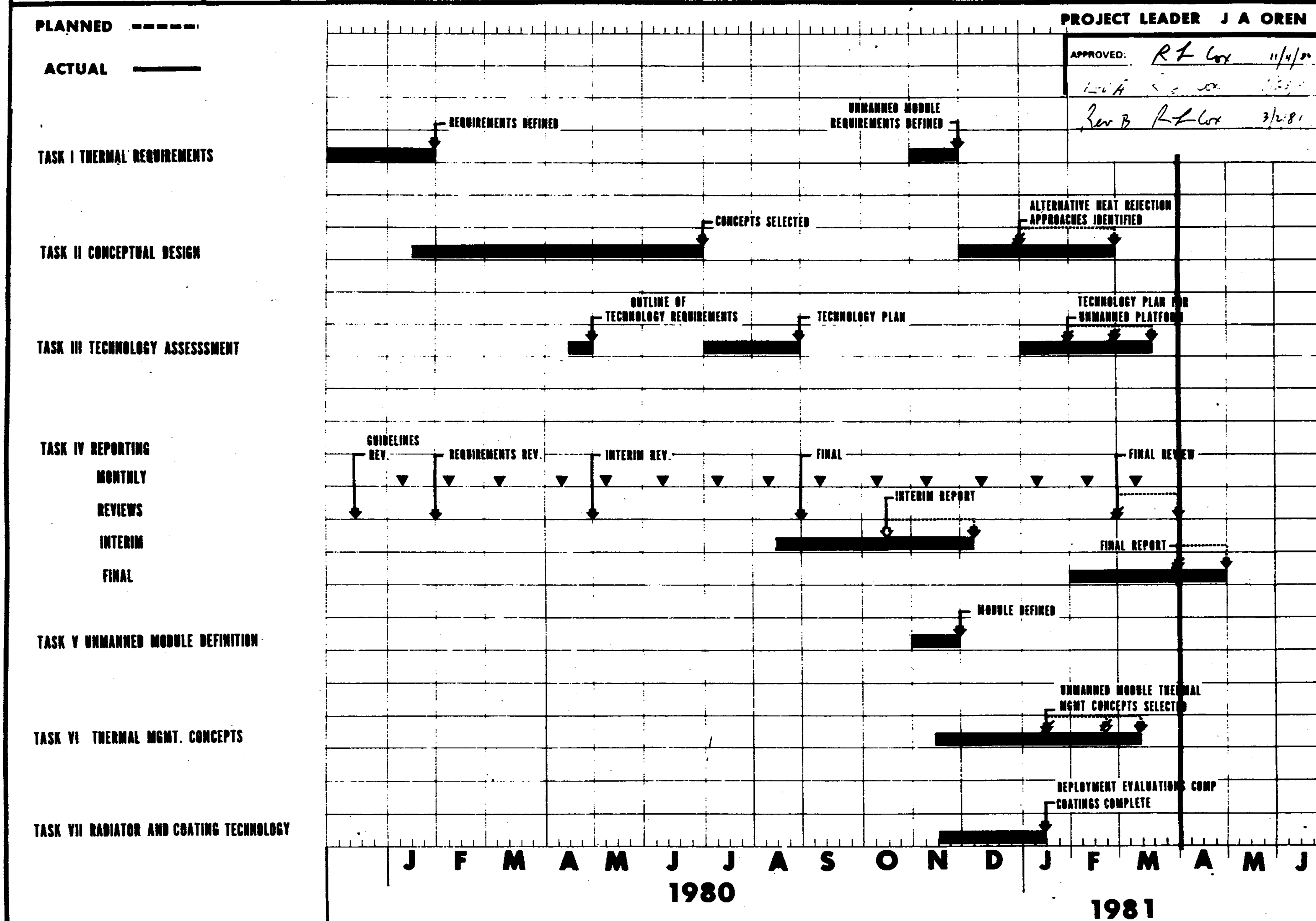


FIGURE 1

Component sizes, weights, performance, cost, and development requirements were determined for each concept.

Concept 2, the Centralized Pump Driven Heat Pipe System, was identified as the best overall approach. However, because of its undemonstrated technology it was selected as the high technology alternate. Concept 6, the Centralized Pumped Liquid System Connected to the 250 kW Central Loop, was selected as the best intermediate term (1985 to 1990) approach.

Dynamic and load analyses were performed for deployed radiator configurations typical of those evolved in the original contract effort. Dynamic analyses were conducted for on-orbit conditions to determine mode shapes and frequencies for the fully deployed configuration, and two partially deployed configurations. Displacements were determined in the stowed configuration for launch conditions to determine potential interference problems. Maneuvering loads were estimated for 0.01 g accelerations in two different directions. As a result of these analyses it was determined that the lowest modal frequency was approximately 0.1 Hz at a 60° half-angle partial deployment. Thus, the attitude control systems frequency bandwidth should be approximately an order-of-magnitude lower frequency, or less than 0.01 Hz. The loads analyses, for accelerations of 0.01 g in the plane of the panels and perpendicular to the plane of the panels, indicated no severely high attachment loads.

A study was conducted to determine the tools and procedures necessary for installation of the constructable radiator on-orbit and to estimate the orbital manhours required to assemble the radiator. The issues addressed in the study were the assembly sequence of the 250 kW space platform, the packaging of the 250 kW space platform and radiators in the Orbiter cargo bay, the radiator storage on orbit, the radiator installation, the equipment required for assembly and the time for installation. It was estimated that 5 Orbiter flights are necessary for delivery of the 250 kW space platform to orbit. Special equipment required for assembly of the constructable radiator include a space crane with a cherry picker; a grapple fixture capable of picking up a 1 inch diameter heat pipe; storage racks to contain the heat pipe radiators during transport, store them on-orbit and dispense them during installation; and various inspection tools and instrumentation. The time for on-orbit assembly, assuming preparation is complete and assuming two men working, was estimated to be 85 to 230 orbital manhours (42 to 115 hours with 2 men).

Thermal control coatings for radiator panels on large, long life space platforms were studied to establish the requirements, examine options for maintaining thermal control, review current technology, examine sources of contamination, and methods for cleaning and refurbishment.

A number of technology advancements needs were identified as a result of the technology assessment. These include fluid swivels, no leak quick-disconnects and contact heat exchangers for fluid loop systems; technologies needed for pump assisted heat pipes; coating technology; and space construction assembly technology.

The following conclusions were made in the study on Unmanned Module Thermal Management:

- o The Centralized Pump Augmented Heat Pipe approach is the best technical approach for thermal management of the Unmanned Module for the requirements studied. It is superior in almost every category. It is an unproven concept, however.
- o The Centralized Pumped Liquid which ties into the main 250 kW system is the best low risk concept.
- o The Decentralized All Heat Pipe System is not attractive. It is heavy, has low reliability, and high costs.
- o Ammonia is a superior working fluid for the two phase systems.
- o The Pumped Liquid Concepts are highly dependent upon the temperature requirements.

The following conclusions resulted from the radiator deployment studies:

- o No technology show stoppers appear to exist for automatic deployment of radiators using a scissors mechanism.
- o The assembly of the space constructable radiator for a 250 kW system appears possible in an Orbiter 7 day mission if the required tools and equipment are available and in place.
- o The radiator panels and equipment section for the Power Module of the 250 kW Space Platform can be packaged in the Orbiter cargo bay.

The radiator coatings studies resulted in the following conclusions:

- o The coating for the large space platform should be optically stable 10 year EOL $\alpha/\epsilon \leq 0.2/0.8$; should be non-porous, electrically conducting and non-sticking. No coating currently exists with these properties.

- o Methods for cleaning contaminants from coatings on-orbit are desirable but no good method currently exists.
- o The most promising refurbishment technique is the removal and replacement of tape coatings. Other such as applying new coating with brush or trowel appear less attractive.

As a result of the study it is recommended that development of augmented heat pipe thermal bus technologies be given high priority. This is based on the good payoff projected and because of the long lead time of technology development. Also, fluid swivels, quick disconnects and contact heat exchangers should be developed soon to support the nearer term pumped liquid loop. Coating development work should be stepped up in an effort to develop coatings which more nearly meet the desired characteristics. Methods of cleaning and refurbishment are needed. System level trade studies are recommended to determine the desirability of assembling the space constructable radiators on-orbit versus automatic deployment.

2.0 INTRODUCTION

The Study of Thermal Management for Space Platform applications, documented in Reference 1, examined thermal management techniques for large 250 kW systems. However, there were some important aspects of thermal management not addressed in that original study. Some of these important issues which were included in Modification 1 to the original contract included: (1) Thermal Management of Unmanned Modules; (2) Dynamic behavior of automatically deployed radiators; (3) Assembly needs and assembly effort for the 250 kW Space Constructable Radiator; and (4) Assessment of radiator coatings requirements, capabilities and refurbishment methods for large, long-life radiators.

The projected unmanned modules will require the maintaining of very narrow temperature ranges to support the projected payloads and instruments. This difference in requirement from the larger 250 kW platform justified an independent look to determine the best approaches and technology gaps for the unmanned module. Long life requirements for future platforms justify relooking at radiator coatings to identify options on how to achieve thermal control to end-of-life. The large size of the projected radiators causes concerns in the area of deployment and dynamics. These concerns and issues must be examined to determine the best approaches and to identify the technology advancements needed. Technology advancements must be initiated soon in order to achieve technology readiness in the 1987 to 1990 time period. The primary purpose of this study is the identification of approaches which best meet the future needs and determining the technology advancements required to support those approaches.

3.0 UNMANNED MODULE THERMAL MANAGEMENT

3.1 UNMANNED MODULE THERMAL MANAGEMENT REQUIREMENTS

This section presents the results of Task I and V of Modification 1 to Contract NAS3-22270. Recent and current studies on the Science and Applications Space Platform (SASP), the Advanced Science and Application Space Platform (ASASP), the 25 kW Power Module Evolution, and the Materials Experiment Carrier (MEC) were reviewed in order to define a representative unmanned module to be included on the 250 kW Space Platform. In addition, thermal control requirements including heat loads and temperature requirements for typical experiments for this unmanned module were defined.

During the initial phase of the contract, the primary emphasis was on thermal management of manned modules docked to the 250 kW Space Platform shown in Figure 2. One of the objectives of the follow-on is to provide more indepth design studies for unmanned module thermal control. In order to determine the effect of unmanned module thermal loads on the platform's centralized heat rejection system and to evaluate the potential of decentralized thermal control, an unmanned module representative of those planned for the 1990's must be defined. The purpose of Task V is to define such a module with the capability to accommodate a broad variety of unmanned payloads, including; earth viewers, magnetic field viewers, celestial and solar viewers, and other experiments such as materials processing. The purpose of Task I is to define the thermal control requirements of the unmanned module and its experiments. The requirements to be defined include instrument power, heat dissipation, and temperature constraints. A further objective of Task I is to establish a typical daily power profile for the unmanned module.

3.1.1 Unmanned Module Configuration (Task V)

The SASP second order configuration as defined in Reference 6 was selected as a representative unmanned module for the 1990 timeframe. The SASP is similar with respect to payload mission requirements, including simultaneous multiple-viewing directions, space for oversized payloads, and minimum view blockage. Figure 3 illustrates the basic Second Order Platform and the selected Extended Second Order Platform. A total of 9 payloads can be accommodated on the extended platform. The $\pm$ 180^{o} rotation provided by the rotary joints on each side arm allows independent pointing of these two arms. One arm can be dedicated to celestial viewing payloads while the other arm is dedicated to solar viewing payloads. Earth resources experiments requiring

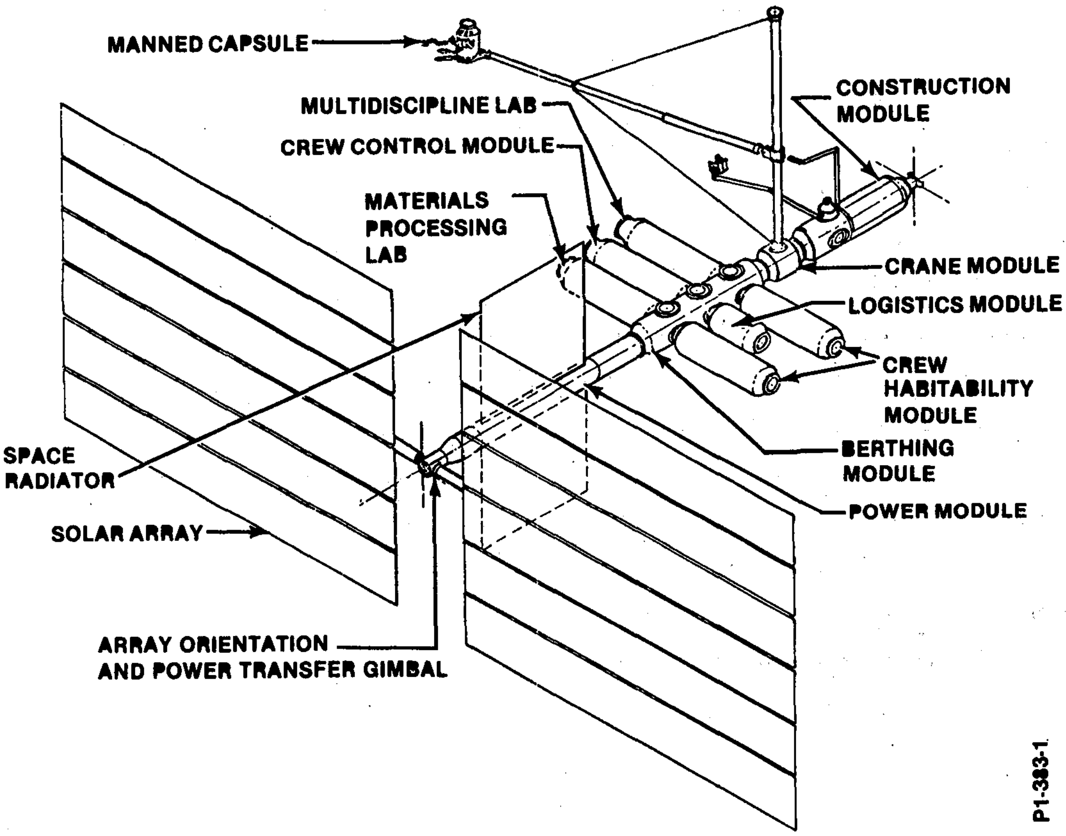


FIGURE 2 NASA BASELINE SPACE PLATFORM

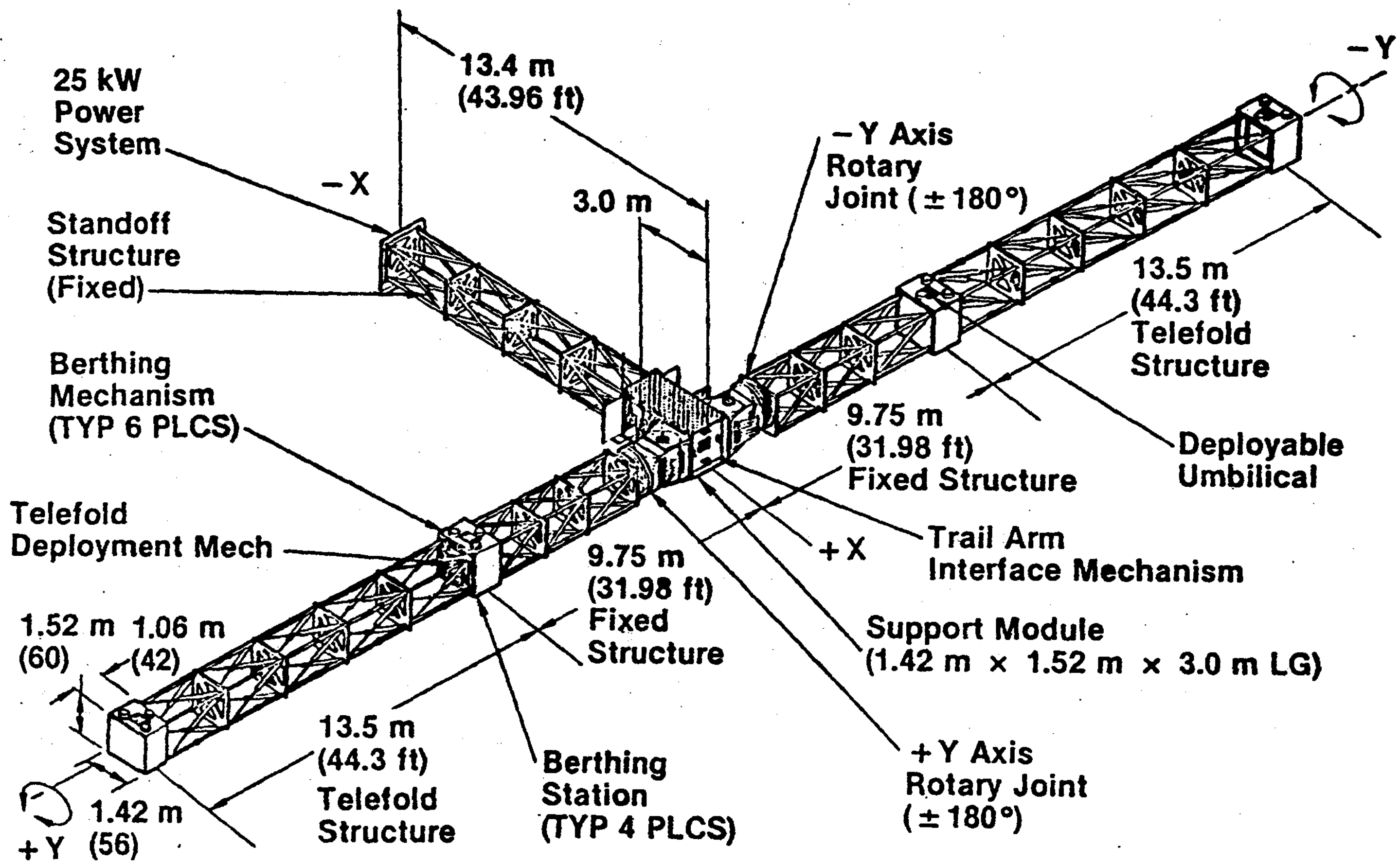


FIGURE 3 SELECTED UNMANNED MODULE : SASP CROSS-ARM CONFIGURATION

360° rotation can be accommodated on the trail arm extension. These pointing requirements result in the need for flex lines at the $\pm 180^{\circ}$ joints and a fluid swivel for the 360° rotating joint if a centralized thermal management system is employed.

Another potential concept for the unmanned module is the Advanced Science and Application Space Platform (ASASP) as defined in Reference 11. This advanced version of the SASP is proposed for 1990's readiness and is meant to accommodate payloads which require greater separation of scientific instruments for improved viewing and stabilization or payloads which are too large to fly on the SASP. Figure 4A gives the dimensions of the proposed ASASP configuration and Figure 4B shows the ASASP with a representative group of payloads.

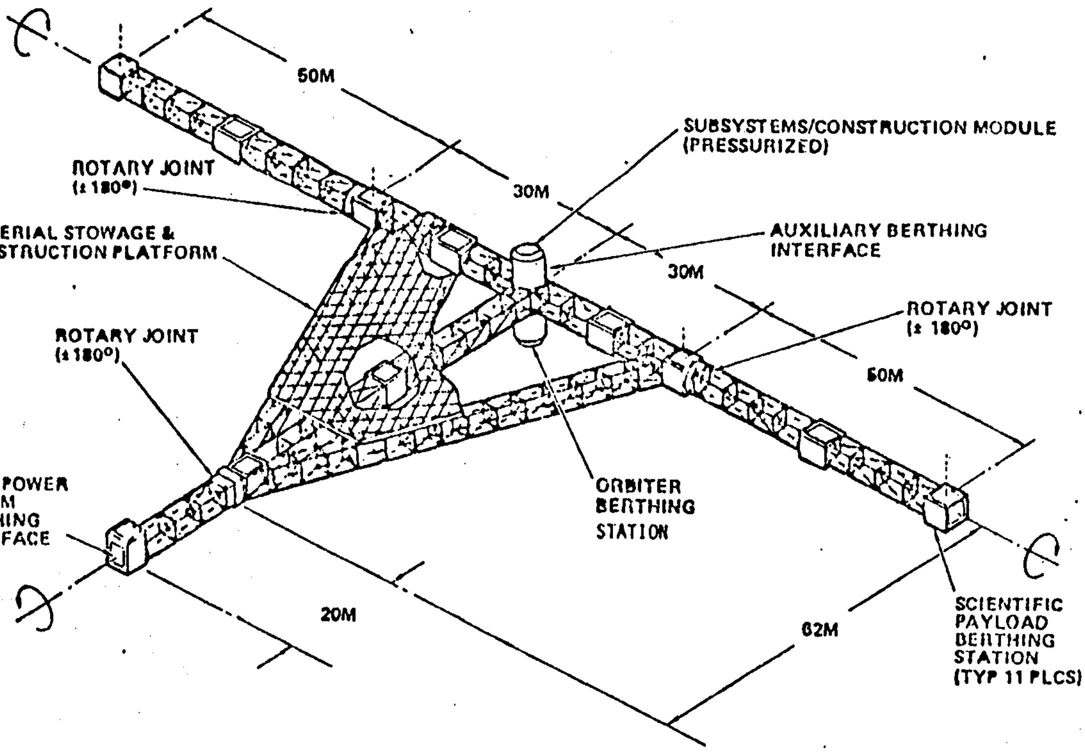
3.1.2 Unmanned Module Thermal Control Requirements

A wide variety of experiment types planned for unmanned flight were investigated in order to define the thermal requirements for the unmanned module. These included earth viewers, magnetic field viewers, celestial and solar viewers, and materials processing experiments. A representative grouping of payloads which are planned to fly on SASP is the B9 experiment set (Reference 4, previously designated A10 in Reference 7) shown in Figure 5. This experiment group is to be placed in a 400 km, 57° inclination orbit in late 1987. For purposes of defining the thermal control requirements of the unmanned module, we will assume these to be typical payloads.

Figure 6 provides a listing of the payloads included in the B9 group along with their peak power requirements. The power level for each instrument includes power for payload support equipment. The maximum power requirement for the B9 group, assuming all instruments are operating simultaneously, is 22.1 kW. For conservatism, it can be assumed that all of the electrical power must be rejected by the thermal management system as waste heat. Temperature constraints for these payloads are also given in Figure 6.

An operational timeline generated by TRW (Reference 4) for the B9 payload is presented in Figure 7. The resulting power profile for this operational timeline is presented in Figure 8. The average power requirement is 14.8 kW.

The four representative payloads for the ASASP that were illustrated in Figure 3B are the Large Ambient Deployable IR Telescope (IR TEL), the Astrometric Telescope (AST/TEL), the Particle Beam Injection Experiment (PBI),



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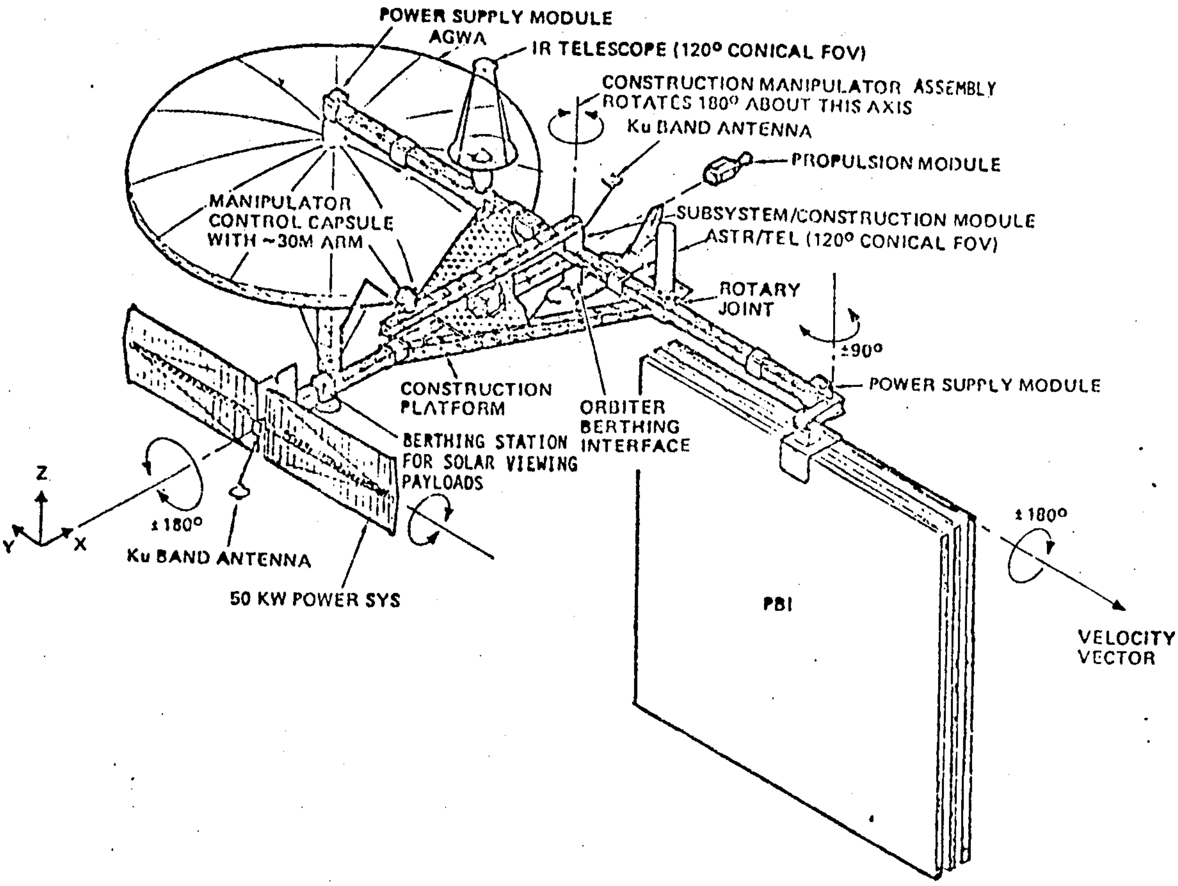


B.

FIGURE 4 ADVANCED SCIENCE AND APPLICATION SPACE PLATFORM

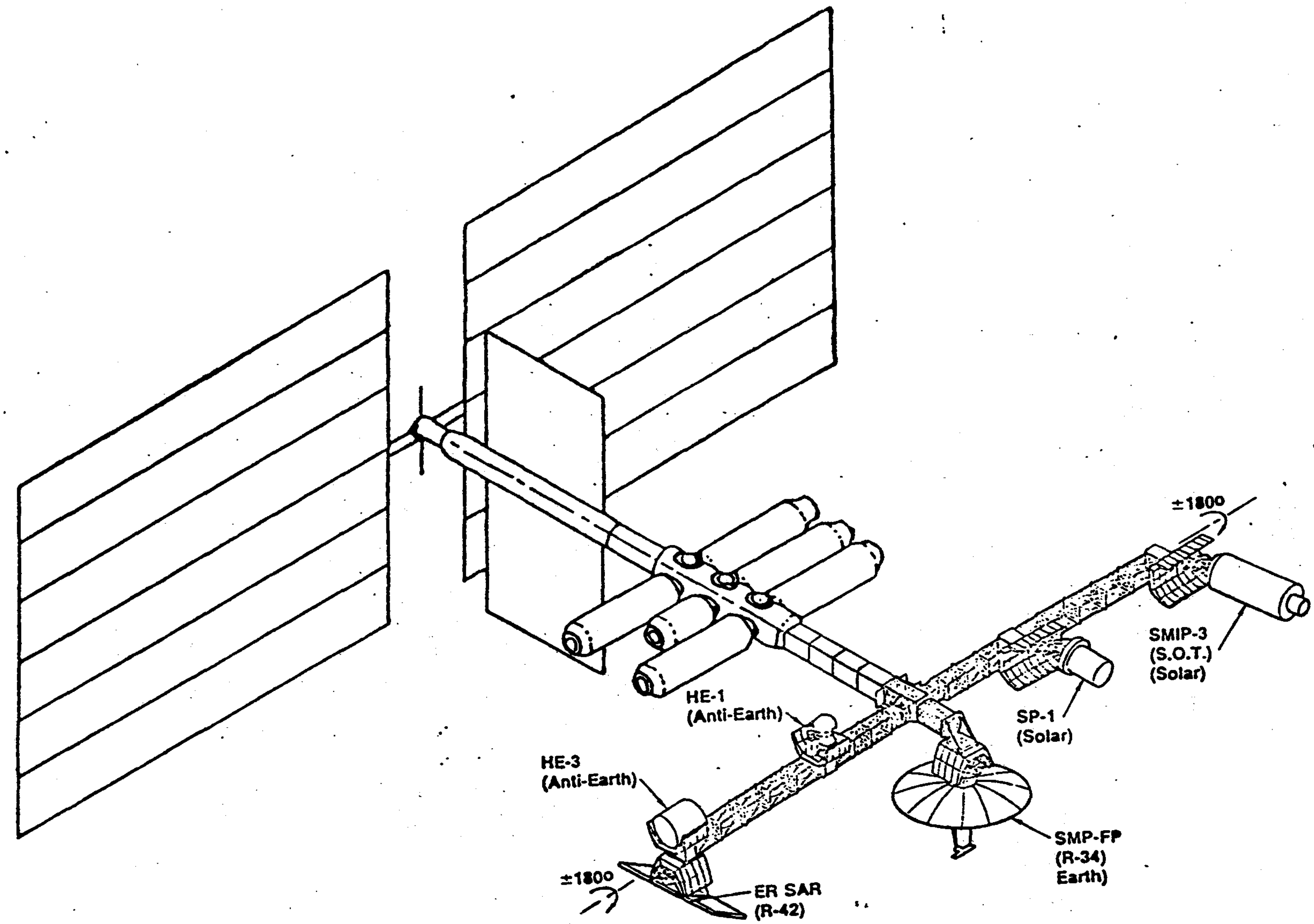


FIGURE 5 SASP WITH B9 EXPERIMENTS ON 250 kW PLATFORM

FIGURE 6
HEAT REJECTION REQUIREMENTS FOR B9 EXPERIMENT GROUPING

PAYLOAD	REQUIREMENT	POWER (kW)	TEMPERATURE LIMIT (°C)
EO-1 ENVIRONMENT OBSERVATORY	SOLAR[1]	1.55	15 to 25
HE-1 MEYER COSMIC RAY	ANTI-EARTH	1.39	15 ± 25
HE-3 COSMIC RAY INSTRUMENT	ANTI-EARTH	1.36	15 ± 25
ER-SAR EARTH RESOURCES SAR	EARTH	3.16	
SMR-FP SOIL MOISTURE RAD	EARTH	1.66	10 to 50
SP-1 SOL PHYSICS PALLET	SOLAR	2.7	17 to 23
SMIP-3 SOL OPTICAL TSC	SOLAR	3.78	10 to 50
MP-2 SOLIDIF. EXPER. SYS.	NONE	5.86	10 to 40

[1] MOUNTED ON SOLAR ARRAY

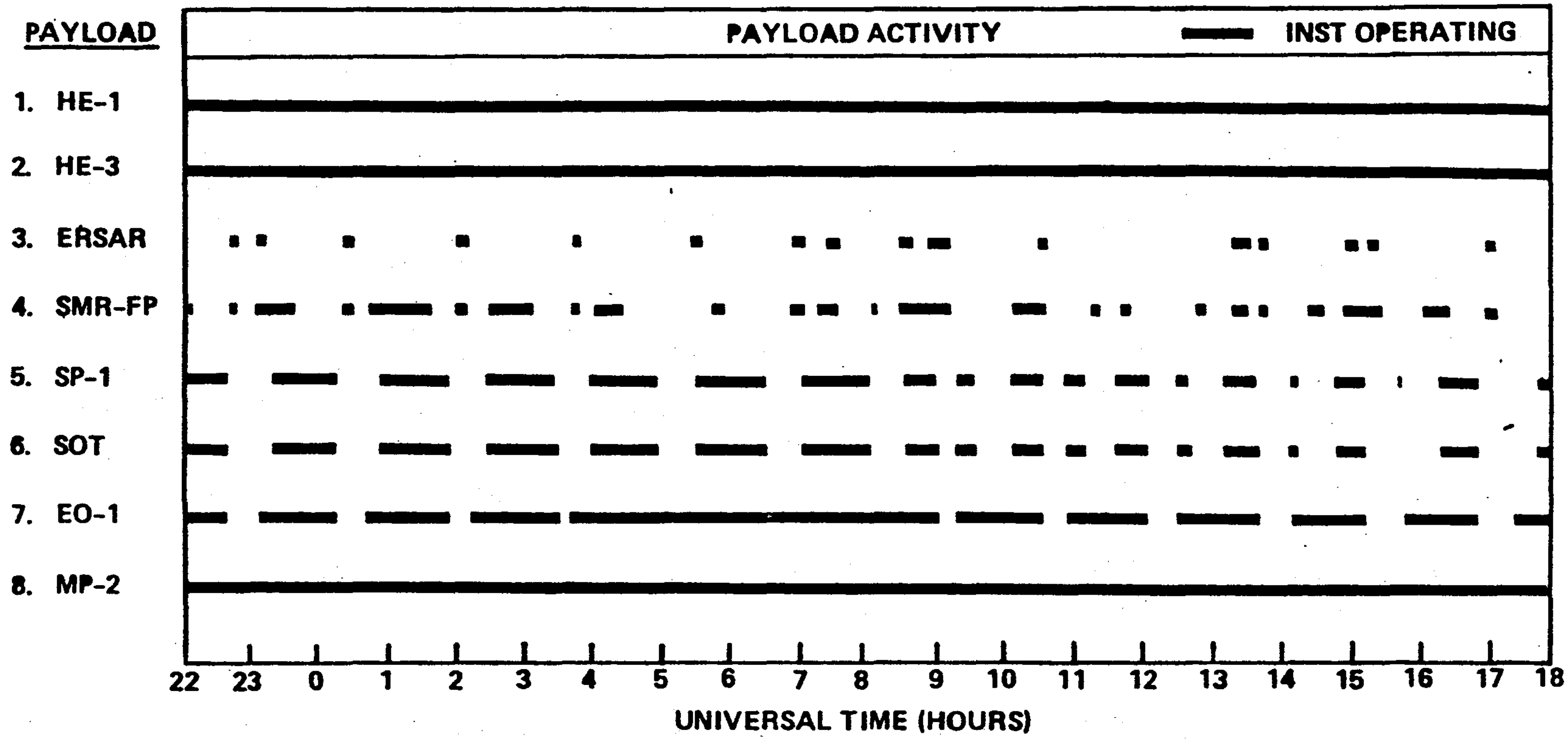


FIGURE 7

OPERATIONAL TIMELINE FOR SASP B9 PAYLOADS

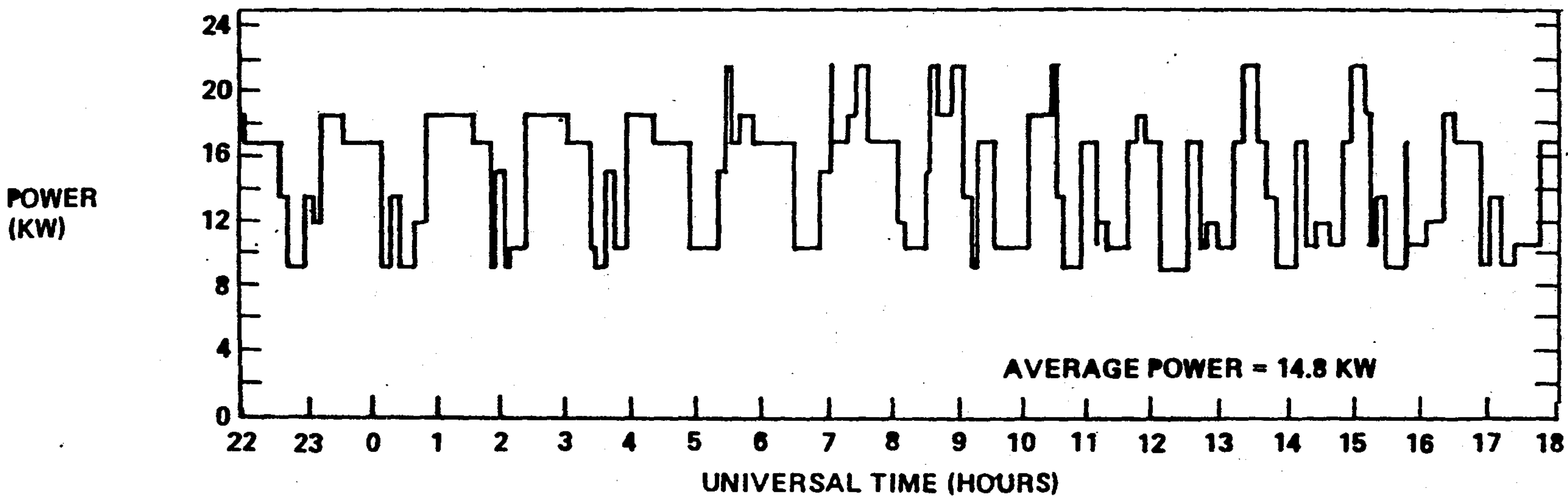


FIGURE 8
POWER PROFILE FOR SASP B9 PAYLOAD

and the Atmospheric Gravity Wave Antenna (AGWA). The required power levels of these payloads are presented in Figure 9. The PBI and AGWA require large amounts of peak power (400 kW and 250 kW respectively) for short periods of time. This maximum power requirement is met by batteries located at the payload. The estimated heat rejection required for these two experiments is 2 kW for the PBI and 16 kW for the AGWA. Additional information on the ASASP and its payloads may be found in Reference 6.

Additional payloads which may be unsuitable for SASP have been identified and are listed in Figure 10. The Public Services payload includes communications and navigation satellites or platforms that would be assembled and tested in low earth orbit before being transferred to a geosynchronous orbit. The assembly and testing of these payloads could be supported by the 250 kW Space Platform. Scaled-down test articles of a Satellite Power System (SPS) are also candidates for support during construction and testing. The first SPS Test Article (TA-1) would be used to resolve microwave transmission issues. Its microwave antenna would require up to 80 kW during testing. The estimated thermal heat load is 12.5 kW at 300^{o} to $400^{o}C$. The remaining three payloads are all related to materials processing. These payloads desire very low acceleration levels ($10^{-5}g$) which would require them to be located near the spacecraft center-of-gravity. Temperature requirements range from 0 C for bioprocessing to $150^{o}C$ for materials processing. Power levels range from 25 kW for MEC up to 200 kW for production modules.

The Second Order SASP has been identified as a representative unmanned module for the 1990 timeframe. A typical payload grouping for this module has also been identified. Power requirements, temperature requirements, and a power profile for this payload grouping have been determined. It appears that 25 kW of heat rejection will be adequate for the SASP or ASASP payload groupings considered. The 250 kW platform should also be designed to accommodate additional payloads such as the Public Services Platform, SPS Test Article, and Processing modules.

PAYLOADS		POWER REQUIRED (KILOWATTS)
IR TEL + IPS[1]		1.62
AST/TEL + IPS[1]		1.62
PBI[2]		
BATTERY CHARGING		1.58
DIAGNOSTIC PACKAGE		0.10
AGWA[3]		
BATTERY CHARGING		15.54
DIAGNOSTIC PACKAGE		0.10
PAYLOAD SUBSYSTEMS		
COMPUTER + 110	4 AT 0.55 KW EACH	2.20
SUPPORT ELECTRONICS	4 AT 0.22 KW EACH	.88
PAYLOAD TOTAL		23.64 KW

(1) ASSUMES DORNIER INSTRUMENT POINTING SYSTEM (IPS). POWER REQUIREMENT IS 0.62 KW.
(2) POWER PULSES OF 400 KW FOR 30 SECONDS ARE SUPPLIED BY BATTERIES AT PAYLOAD. FOLLOWING DISCHARGE, BATTERIES ARE CHARGED AT 1.58 KW FOR 180 MINUTES: DISCHARGE/CHARGE CYCLE THEN REPEATS FOLLOWED BY NO OPERATION FOR BALANCE OF WEEK.
(3) POWER PULSES OF 250 KW FOR 10 MINUTES ARE SUPPLIED BY BATTERIES AT PAYLOAD. FOLLOWING DISCHARGE, BATTERIES ARE CHARGED AT 15.54 KW FOR 230 MINUTES. DISCHARGE/CHARGE CYCLE REPEATS EVERY 2.67 ORBITS (6 ORBITS/DAY) FOR FOUR DAYS FOLLOWED BY NO OPERATION FOR BALANCE OF WEEK. TOTAL OF 24 OPERATIONS PER WEEK.

FIGURE 9 POWER REQUIREMENTS FOR ASASP

PAYLOAD	POWER/HEAT REJECTION (KW)	REFERENCE
PUBLIC SERVICES (COMMUNICATION/NAVIGATION) LEO ASSEMBLY AND TEST	3-30/2-15	8
SPS, TEST ARTICLE-1 TESTING	80/12.5	12
MATERIALS EXPERIMENT CARRIER (MEC)	25/25	10
MATERIALS EXPERIMENT CARRIER II (MEC)	40-50/40-50	10
MPS UNMANNED PRODUCTION	100-200/100-200	8

FIGURE 10 ADDITIONAL UNMANNED PAYLOADS

3.2 THERMAL CONTROL CONCEPTS FOR UNMANNED MODULES

Studies were conducted to identify promising concepts for thermal control of unmanned modules docked to the 250 kW space platform. The thermal control requirements for these modules are discussed in Section 3.1. Six promising concepts were evaluated which included heat pipe systems, pumped liquid systems, centralized systems, decentralized systems, radiators on the module and no radiators on the module. After the six promising concepts were identified, design analysis was performed on each to estimate component sizes and weights, system power requirements, deployed radiator area, system reliability, system costs and development costs. The systems were compared on the basis of these analyses.

3.2.1 Study Assumptions

The following assumptions were made for this study:

(1) The 250 kW thermal management system described in Reference 1 was assumed to be available to provide cooling to the unmanned module. However, cost and weight penalties of 876 Kg and $2.7 million were assessed the unmanned module system when it utilized these services for rejecting 25 kW of heat. These values were obtained by multiplying the per kW and weight of the 250 kW system by 25 kW.

(2) A power penalty of 165 kg/kW was assumed for the trades.

(3) Thermal loads and temperature constraints assumed for the study were as follows:

Item	Heat Load	Temperature Constraints oC
(a) Total Unmanned Module		
• Requirement #1	**25 kW**	20 ± 5
• Requirement #2	**20 kW**	15 to 40
	5 kW	20 ± 5
(b) Individual Ports		
• Requirement #1		
– Cross Arm Port	**10 kW**	20 ± 5
– Max Total Per Cross Arm	**10 kW**	20 ± 5
– Tail Arm	**5 kW**	20 ± 5
• Requirement #2		
– Cross Arm Port	**10 kW**	15 to 40
– Max Total Per Cross Arm	**10 kW**	15 to 40
– Tail Arm	**5 kW**	15 to 40
– 1 Port Anywhere on Module	**5 kW**	20 ± 5

Cost studies were conducted as a part of the concept trade studies using the RCA PRICE routine. Assumptions that were made for the cost were as follows:

(1) The assumed program schedule is:

- o Development Start : January 1988
- o Prototype Complete : January 1989
- o Development Complete : January 1990
- o Production Start : February 1991
- o Delivery : August 1992

(2) The year of economics is 1980 dollars.

(3) The year of technology is 1985.

(4) The total cost is prime contractor acquisition cost. No vehicle level tests, flight support or maintenance costs are included.

(5) PRICE routine complexity factors were based on historical cost data when available. Otherwise, component supplier costs estimates were used.

Figure 11 shows the engineering and manufacturing complexity factors which were derived for the various components for input to the PRICE routine. Also shown are the platform factor inputs. Typical values for the manufacturing and engineering complexity factors are shown in Figures 12 and 13. The platform factor of 2.5 was used which indicates manned space.

FIGURE 11

ASSUMPTIONS FOR COST ANALYSIS OF UNMANNED MODULE THERMAL CONTROL SYSTEM

- PRICE Routine Inputs

COMPONENT	ENGINEERING COMPLEXITY	MANUFACTURING COMPLEXITY	PLATFORM FACTOR
Radiator Panels	1.5	7.2	2.5*
Heat Pipes	1.172	6.5	2.5
Pump/Motor	.238	9.1	2.5
Accumulator	1.566	5.4	2.5
Temp Control Valve	.866	9.1	2.5
Temp Sensors	1.37	6.1	2.5
Heat Exchanger	0.865	9.1	2.5
Flex Hoses	1.633	5.2	2.5
Deployment Mechanism	1.361	6.1	2.5
Integration & Test	1.162	7.020	2.5

* Platform Factor of 2.5 is manned space

FIGURE 12

TYPICAL VALUES FOR MANUFACTURING

MANUFACTURING COMPLEXITY - A factor to describe the product producibility, usually an empirically derived factor. It is a function of the material type, finished density and fabrication methods.

TYPICAL VALUES

Equipments	Typical Examples	** WSCF	1.0 * Ground	1.4 Mobile	1.8 Airborne	2.0 Space	2.5 Manned Space
Antennas	Small, Spiral, Horn, Flush, Parabolic	4	4.75	5.39	5.64	6.55-7.04	6.92-7.44
	Scanning Radar 10-40' Wide	8	5.3	5.4	5.5	–	–
	Phased Arrays (Less Radiators)	6-8	5.9	6.2	6.4	7.0	7.2
Engines & Motors	Automobile - 100 to 400 H.P.	25-35	–	4.30	–	–	–
	Turbo-Jet (Prime Propulsion)	25-35	–	–	6.6-7.9	–	–
	Rocket Motors	14-15	–	–	6.1-6.5	6.4-7.3	7.2-8.2
	Electric Motors	75-100	4.47	5.08	5.3	5.4-6.3	5.4-6.3
Drive Assemblies	Machined Parts, Gears, etc.	7-10	5.11-5.24	5.5	5.8	–	–
	Mechanisms w/Stampings (Hi Prod)	12	3.33-3.73	–	–	–	–
Microwave Transmission	Waveguide, Isolators, Couplers,	11-20	5.4-5.6	5.4-5.6	5.5-5.7	5.5-5.9	5.5-5.9
	Stripline Circuitry	9	5.7	5.8	5.9	6.0	6.1
Optics	Good (Commercial)	70-90	5.1	5.4	6.3	6.7	7.3
	Excellent (Military)	70-90	5.4	5.8	7.3	7.8	8.0
	Highest (Add 0.1 per 10% Yield)	70-90	5.9	6.8	8.0	8.3	8.5
Ordnance Fuze	Automated Production	14-20	–	4.3-4.65	4.3-4.65	–	–
	Small Production-Min. Tooling	14-20	–	5.11-5.33	5.11-5.33	–	–
Servo	Mech Drive & Coupling Networks	65-75	5.63	5.63-5.7	5.7-6.26	5.7-6.86	5.7-6.86
Tools	Machine Tools	25-30	4.45-4.52	–	–	–	–
Printed CKT Cards (Boards Only)	Paper Phenolic	83	4.1-4.3	4.1-4.3	4.1-4.3	4.1-4.3	4.1-4.3
	Glass Expoxy, Double Sided	110	5.3	5.3	5.3	5.3	5.3
	(Add 0.2 for 3 Layers & 0.05 for Addn'l)						
	Add 0.1 for Plated-Thru Holes						
Cabling	Multiconductor w/MS Connectors	40	4.9	5.0	5.0	5.1	5.2
	Same w/ Hermetically Sealed Connectors	40	5.1	5.2	5.2	5.3	5.3
Battery	Lead Acid	68-125	4.47	4.49	4.61	4.8-5.4	4.9-5.6
	Nickel Cadmium	75	5.39	5.83	6.73	7.63	8.38
Gyro	Inertial Platform Type	79	6.01	6.56	6.8	6.9-8.1	7.0-9.4

*Platform Factors

**Mechanical Density, LB/FT^3

FIGURE 13

TYPICAL VALUES OF ENGINEERING COMPLEXITY

ENGINEERING COMPLEXITY - Used to scope development effort and to develop calendar time for first prototype.

TYPICAL VALUES

SCOPE OF DESIGN EFFORT	Extensive experience, with similar type designs. Many are experts in the field, top talent leading effort.	Normal experience, engineers previously completed similar type designs	Mixed experience, some are familiar with this type of design, others are new to job	Unfamiliar with design, many new to job
Simple modification to an existing design	.2	.3	.4	.5
Extensive modifications to an existing design	.6	.7	.8	.9
New design, within the established product line, continuation of existing state of art	.9	1.0	1.1	1.2
New design, different from established product line. Utilizes existing materials and/or electronic components	1.0	1.2	1.4	1.6
New design, different from established product line. Requires in-house development of new electronic components, or of new materials and processes	1.3	1.6	1.9	2.2
Same as above, except state of art being advanced or multiple design path required to search goals	1.9	2.3	2.7	3.1

3.2.2 Concept 1: Decentralized, All Heat Pipe System

The decentralized, all heat pipe radiator system has a separate radiator system for each docking location on the unmanned module arms. (Each location has two docking ports on opposite surfaces.) The system for one docking location, shown schematically in Figure 14, consists of four heat pipe radiator panels, 8 transport heat pipes and two payload heat exchangers. Five such systems are needed for the second order SASP; two for each cross arm/extension and one for the trail arm.

The four radiator panels are attached to the surrounding four faces of the platform so that they radiate from only one side (see Figure 15). The panels were assumed to be bonded honeycomb construction with 0.795 cm diameter panel heat pipes and 2.5 cm diameter transport pipes bonded internally. The panel heat pipe routing, shown in Figure 15, permits either of the transport heat pipes to communicate with the continuous panel heat pipes. All heat pipes are ammonia/aluminum.

The four radiator panels are thermally connected to two docking port contact heat exchangers by the eight 2.5 cm diameter transport heat pipes. Each panel will thermally serve each heat exchanger. The transport heat pipes are large, high capacity pipes with a heat transport of approximately 10 to 30 kW-m. The system contains 2 halves of contact heat exchangers which can be mated with the 2 halves from the payloads. The heat exchanger halves are flat-plate heat pipe exchangers with contact pressure being provided by pressurizing a diaphragm. No temperature control is provided by this system. This function is assumed to be provided by the payload side, thus providing more temperature flexibility.

The amount of heat rejection from available area for radiators at the cross arm ports, extension arm ports and trail arm ports is shown as a function of temperature in Figure 16. A range is shown which includes blockage effects. Also shown in Figure 16 are typical payload requirements for heat rejection and temperature. The heat rejection capability at 20°C is estimated as follows:

- Trail Arm : 5 kW
- Cross Arms : 4 kW each; 8 kW total
- Extension Arms : 7 kW each; 14 kW total

Total Heat Rejection : 27 kW

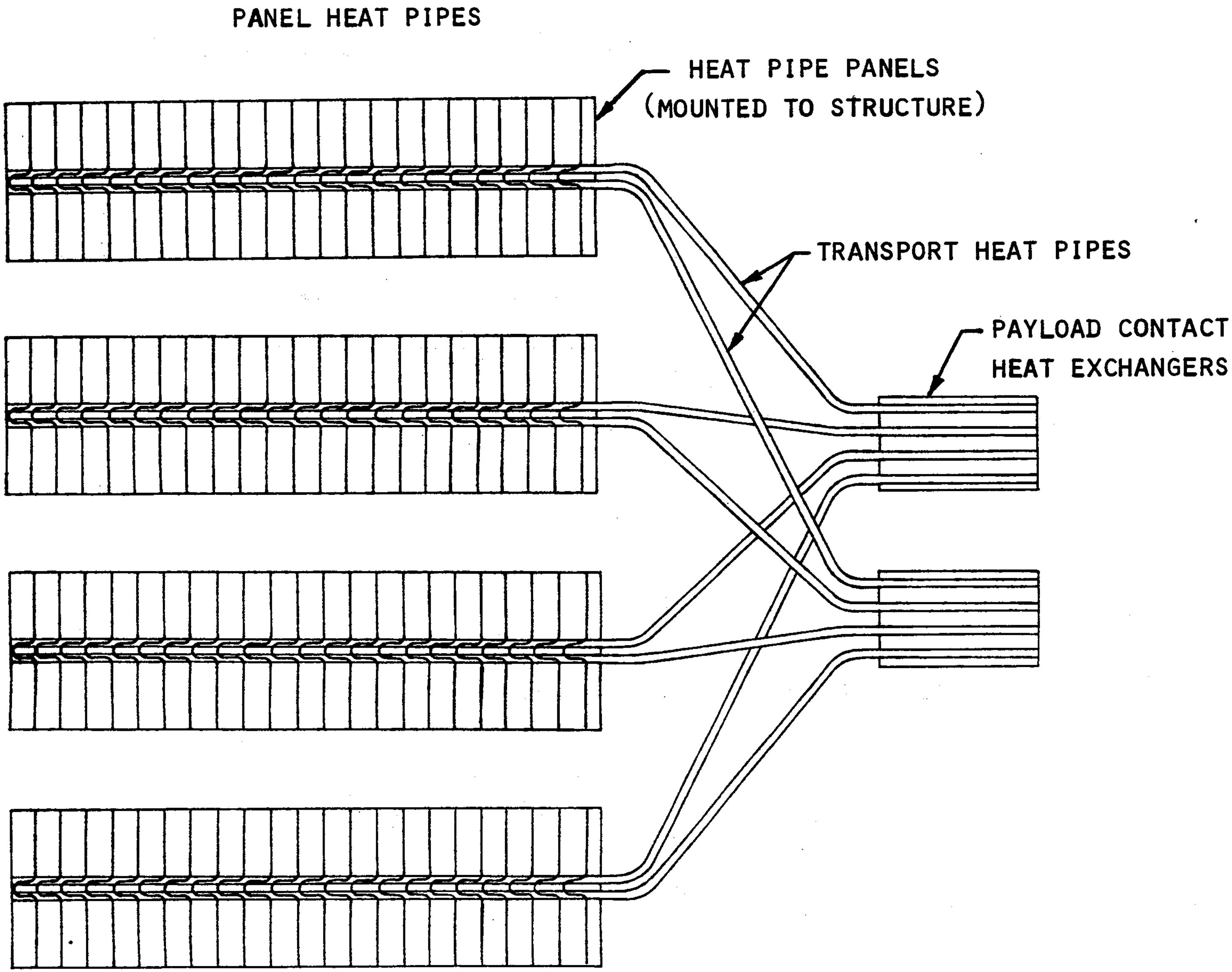


FIGURE 14
CONCEPT 1 - DECENTRALIZED, ALL HEAT PIPE SYSTEM

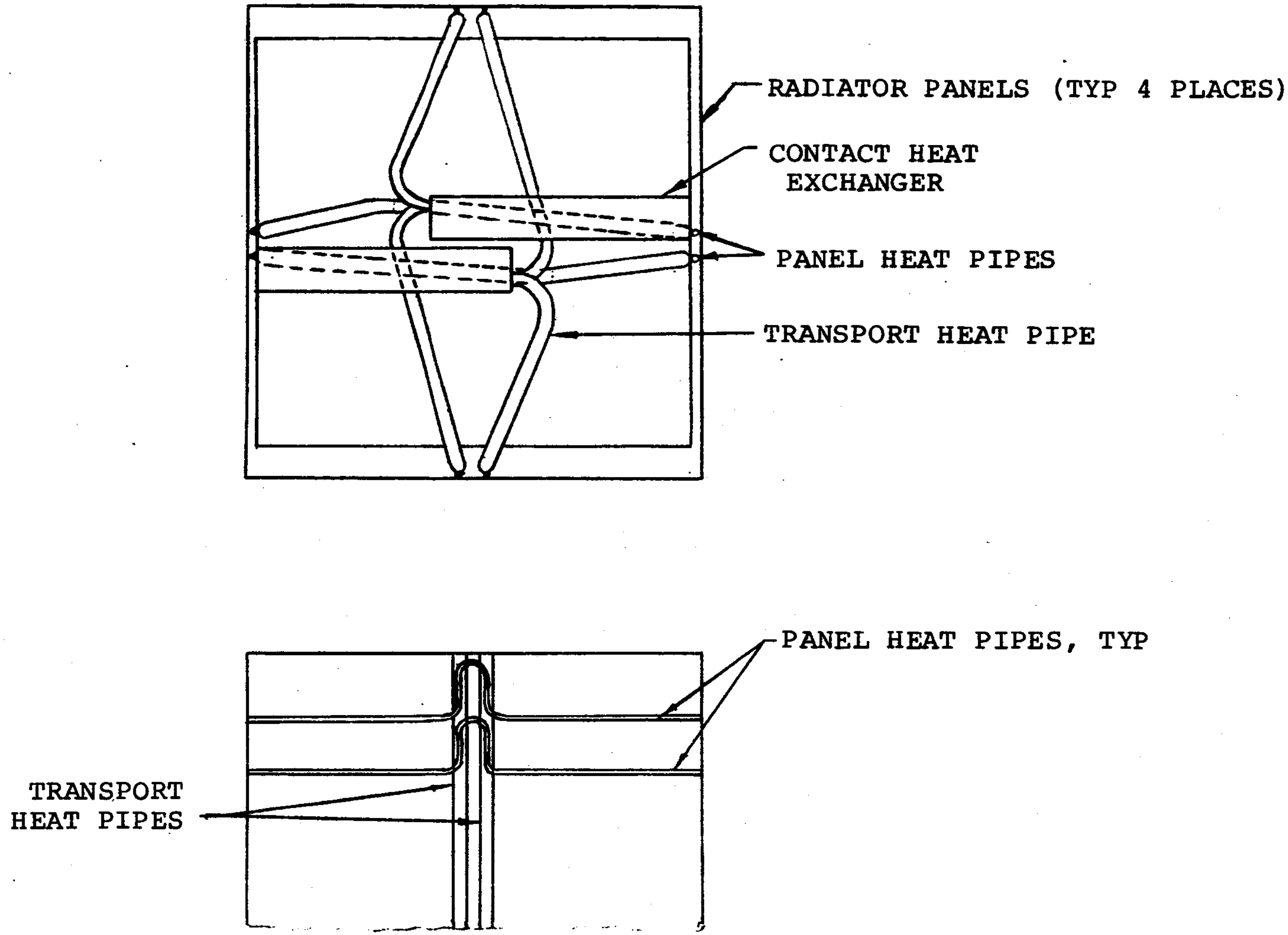
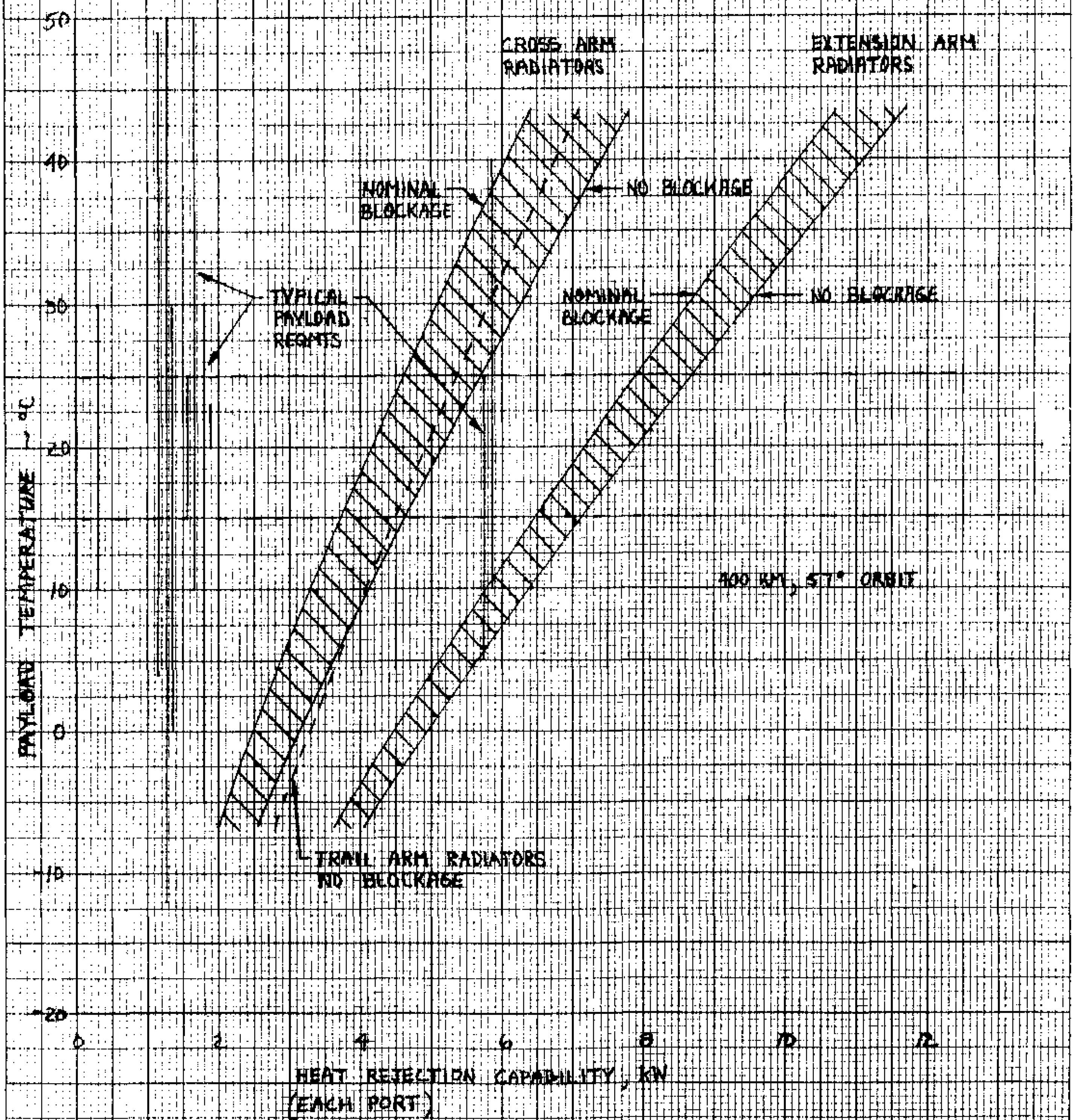


FIGURE 15 DECENTRALIZED ALL HEAT PIPE CONCEPT

VOUGHT

FIGURE 16

BODY MOUNTED HEAT PIPE RADIATOR
HEAT REJECTION CAPABILITIES



A summary of the physical characteristics of Concept 1 is provided in Figure 17. The total weight is estimated at 1683.5 kg. The cost estimate of $17.284 Million, shown in Figure 18, was estimated using the RCA PRICE routine.

FIGURE 17
CONCEPT 1 - DECENTRALIZED HEAT PIPE

COMPONENT	QTY	WEIGHT (KG) EA	WEIGHT (KG) TOT	DIMENSIONS	FAILURE RATE /MILLION HRS	COMMENTS
HIGH CAPACITY HEAT PIPE	16	5.62	90.0	2.5 cm OD x 2.1mm x 9.45m Long	Meteoroid = .003 Random = .50	QL = 12.85 kW-m @ 43°C
HIGH CAPACITY HEAT PIPE	16	9.07	145.1	2.5 cm OD x 2.1mm x 15.24m Long	Meteoroid = .005 Random = .50	QL = 28.70 kW-m @ 43°C
HIGH CAPACITY HEAT PIPE	8	4.72	37.8	2.54m OD x 2.1mm x 7.92m Long	Meteoroid = .002 Random = .50	QL = 10.72 kW-m @ 43°C
PANEL HEAT PIPES (AXIAL GROOVE)	856	.137	117.3	0.795cm OD x .762mm x 1.96m Long	Meteoroid = .110 Random = .25	QL = 965 w-cm @ 11°C
RADIATOR PANELS (EXCLUSIVE OF HEAT PIPES)	8	87.36	698.9	1.60mx12.50m	.1 - .2	0.787mm Facesheets
	8	46.54	372.3	1.60mx6.40m		
	4	35.35	141.4	1.60mx5.03m		
CONTACT HEAT EXCHANGERS	10	8.07	80.7	.305mx 1.219m x .102m	.40	
			1683.5			

FIGURE 18

CONCEPT 1 - DECENTRALIZED, ALL HEAT PIPE SYSTEM

COST IN THOUSANDS OF DOLLARS

COMPONENT	DEVELOPMENT	PRODUCTION	TOTAL
PANEL HEAT PIPES (AXIAL GROOVED)	10	344	354
HIGH CAPACITY HEAT PIPES	3051	2884	5935
RADIATOR PANELS	3771	1966	5737
CONTACT HEAT EXCHANGERS	1889	886	2775
INTEGRATION TEST	2214	265	2479
TOTAL	10,935	6345	17,280

3.2.3 Concept 2: Centralized Pump Driven Heat Pipe System

The centralized pump driven heat pipe system is shown schematically in Figure 19. The system consists of a closed loop containing a two phase working fluid which transfers its heat under near isothermal conditions in evaporators and condensers with a small liquid pump to circulate the fluid. The loop contains payload contact evaporative heat exchangers at each docking port, to interface with the payloads, and a condensing heat exchanger to interface with the 250 kW platform. Redundant loops are needed for reliability. Each loop contains a pump to circulate the fluid and an accumulator for make-up. A four-pass fluid swivel is located at each of three swivel joints to permit the two loops to cross the joint.

The circulating fluid is condensed in the water/ammonia condensing heat exchanger. The source of cooling is water from the 250 kW central heat transport loop at 4.4°C. The liquid ammonia leaving the heat exchanger enters the pump where the pressure is increased to facilitate circulation. The liquid ammonia proceeds through the liquid supply line, through the fluid swivels to the evaporative contact payload heat exchangers, where it is evaporated. The ammonia vapor then flows back to the condensing heat exchanger, closing the loop.

Sizing analyses were performed for the heat transport loop for a 25 kW total heat load and a maximum temperature drop of 5.6°C in the heat pipe from the condenser at 15.5°C to the evaporator at 21.1°C. (The cooling source for the condenser was assumed to be water entering at 4.4°C and exiting at 12.8°C.) The line sizes were determined to be 1.6 cm OD for the ammonia vapor return and 0.95 cm for the liquid supply. Shell and tube heat exchangers were assumed for the condenser with water in the shell and ammonia in the small tubes. The evaporator was assumed to be a high technology, currently undeveloped, contact heat exchanger.

Figure 20 shows a summary of the components in the system and physical descriptions of each. Total component plus power penalty weight was estimated to be 589 kg. When the 876 kg heat rejection penalty is added (a proration of the weight of the centralized 250 kW system, discussed in Section 3.2.1), the total weight comes to 1465 kg.

A cost study was made using the RCA PRICE routine. The results are summarized in Figure 21. Total system cost is estimated at $6.34 Million.

FIGURE 19 CONCEPT 2 - CENTRALIZED, PUMP DRIVEN HEAT PIPE SYSTEM
(PLUGS INTO CENTRAL PLATFORM)

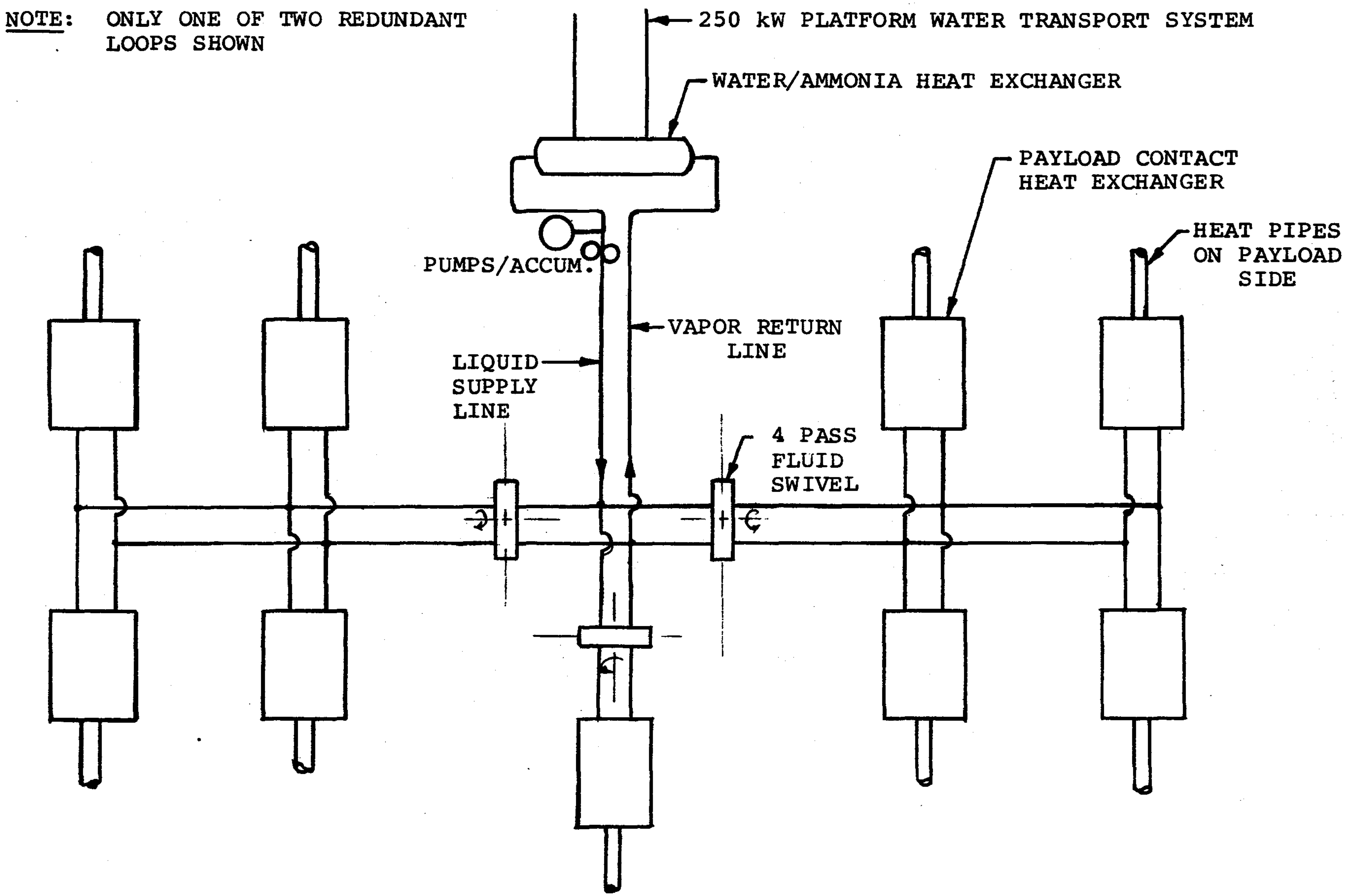


FIGURE 20
CONCEPT 2 - CENTRALIZED HEAT PIPE SYSTEM
(PLUGGED INTO 250 kW LOOP)

COMPONENT	QTY	WEIGHT (KG) EA	WEIGHT (KG) TOT	DIMENSIONS	FAILURE RATE /MILLION HRS EA	FAILURE RATE /MILLION HRS TOT	COMMENTS
1.59cm HEAT PIPE VAPOR TUBING WITH MICROMETEOROID PROTECTION	126m	.3 kg/m (.2 lb/ft)	38	2.5cm OD x 126m (1"OD x 414 ft)	0.1	0.1	
0.95cm ID HEAT PIPE LIQUID TUBING WITH MICROMETEOROID PROTECTION	126m	.15 kg/m	19	1.9cm OD x 126m (3/4"OD x 414 ft)	0.1	0.1	
WATER/AMMONIA SHELL AND TUBE HEAT EXCHANGER	2	30	60	10cm D x 1.5m (4" D x 5')	0.2	0.2	
LIQUID PUMP	4	2	8	7-1/2cm D x 10cm(3"D x 4")	2.9	.23	
10kW EVAPORATOR HEAT EXCHANGER	16	24	384	20cm D x 11 cm (8"D x 4-1/2')	0.4	3.2	
5 kW EVAPORATOR HEAT EXCHANGER	2	12	24	20cm D x 6 cm (8"D x 2-1/2')	0.4	0.4	
FLUID SWIVELS (4 PASS)	3	7	21	15cm D x 20cm (6" D x 8")	0.5	1.5	
INTEGRATION PUMPING POWER	-	9.2	9.2	-	-	-	
ACCUMULATOR	2	12.7	25.4	-	-	-	
			589				

FIGURE 21

CONCEPT 2 - CENTRALIZED, PUMP DRIVEN HEAT PIPE SYSTEM PLUGGED INTO CENTRAL PLATFORM TMS

COST IN THOUSANDS OF DOLLARS

COMPONENT	DEVELOPMENT	PRODUCTION	TOTAL
LIQUID TUBING	665	8	673
VAPOR TUBING	962	14	976
WATER/AMMONIA HEAT EXCHANGER	525	264	789
EVAPORATIVE HX - 5kW	278	20	298
EVAPORATIVE HX - 10kW	405	79	484
LIQUID PUMP	500	131	631
FLUID SWIVELS	2512	329	2841
INTEGRATION AND TEST	440	31	471
TOTAL	6287	876	7163

FIGURE 22 CONCEPT 3 - CENTRALIZED, COMPRESSOR DRIVEN HEAT PIPE SYSTEM
(PLUGS INTO CENTRAL PLATFORM)

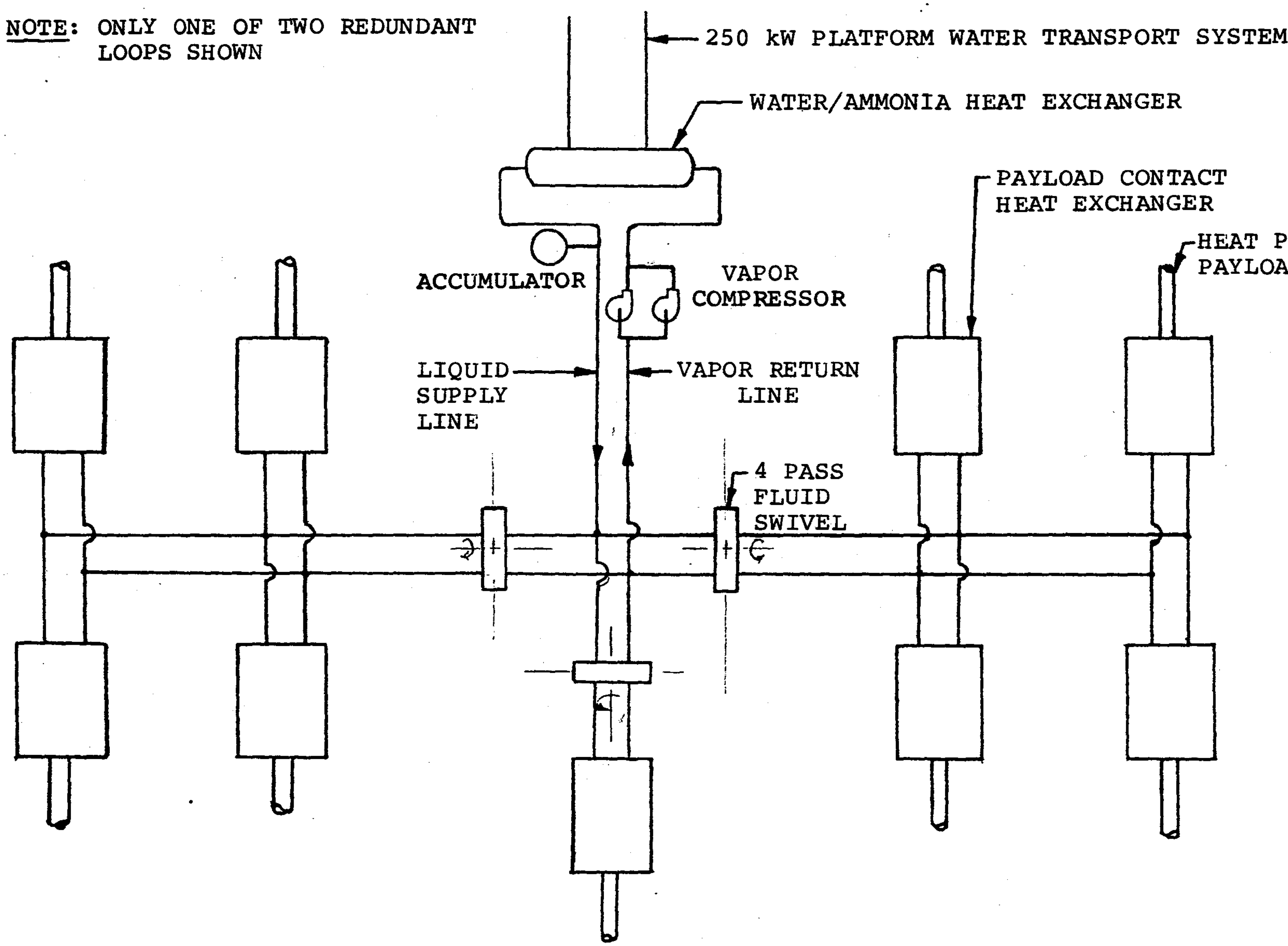


FIGURE 23 CONCEPT 3 - CENTRALIZED COMPRESSOR DRIVEN HEAT PIPE SYSTEM

(PLUGGED INTO 250 kW LOOP)

COMPONENT	QTY	WEIGHT (KG) EA	WEIGHT (KG) TOT	DIMENSIONS	FAILURE RATE /MILLION HRS EA	FAILURE RATE /MILLION HRS TOT	COMMENTS
1.59cm ID HEAT PIPE VAPOR TUBING WITH MICROMETEOROID PROTECTION	126m	.3 kg/m (.2 lb/ft)	38	2.5cm OD x 126m (1"OD x 414 ft)	0.1	0.1	
0.95cm ID HEAT PIPE LIQUID TUBING WITH MICROMETEOROID PROTECTION	126m	.15 kg/m (.1 lb/ft)	19	1.9cm OD x 126m (3/4"OD x 414 ft)	0.1	0.1	
WATER/AMMONIA SHELL AND TUBE HEAT EXCHANGER	2	13	26	10cm D x .64m (4"D x 2.1')	0.2	0.2	
COMPRESSOR	4	10	40	2780 cm^3	2.9	.23	
10kW EVAPORATOR HEAT EXCHANGER	16	24	384	20cm D x 11 cm (8"D x 4-1/2')	0.4	3.2	
5 kW EVAPORATOR HEAT EXCHANGER	2	12	24	20cm D x 6 cm (8"D x 2-1/2')	0.4	0.4	
FLUID SWIVELS (4 PASS)	3	7	21	15cm D x 20cm (6" D x 8")	0.5	1.5	
INTEGRATION PUMPING POWER	-	479	479	-	-	-	
ACCUMULATOR	2	12.7	25.4	-	-	-	
			1056				

3.2.4 Concept 3: Centralized Compressor Driven Heat Pipe System

A schematic of the centralized compressor driven heat pipe system is shown in Figure 22. It is basically the same as the pump driven heat pipe discussed in the previous section, except that the fluid is circulated by a compressor or blower located in the vapor return instead of by a pump located in the liquid line.

The system is a closed fluid loop in which a two phased working fluid is circulated via the compressor in the vapor line. The fluid (ammonia) transfers its heat under near isothermal conditions in the condenser and evaporator. Vapor enters the compressor at 742 kPa pressure and is compressed slightly to 903 kPa before it enters the condenser. The higher pressure (and correspondingly higher condensing temperature) permits the condenser to be considerably smaller and lighter for this concept than for the pump driven heat pipe. However, all the plumbing, evaporative heat exchangers, etc. are identical. The power to drive the compressor driven heat pipe is 2910 watts (compared to 56 watts for the pump driven heat pipe).

Figure 23 summarizes the physical characteristics of the compressor driven heat pipe. The total system weight including 479 kg equivalent of pumping power is 1056 kg. When the 876 kg heat of central heat rejection loop penalty is added, the total system weight becomes 1932 kg.

The results of a cost study for Concept 3 are shown in Figure 24. Total cost is estimated at $6.89 Million. The cost and physical characteristics were used in the concept comparison and evaluation studies described in Section 3.3

FIGURE 24
CONCEPT 3 - CENTRALIZED, COMPRESSOR DRIVEN HEAT PIPE SYSTEM
PLUGGED INTO CENTRAL PLATFORM TMS

COST IN THOUSANDS OF DOLLARS

COMPONENT	DEVELOPMENT	PRODUCTION	TOTAL
LIQUID TUBING	665	8	673
VAPOR TUBING	962	14	976
WATER/AMMONIA HEAT EXCHANGER	250	10	260
EVAPORATIVE HX - 5kW	278	10	288
EVAPORATIVE HX - 10kW	405	79	484
COMPRESSOR	274	511	785
FLUID SWIVELS	2512	329	2841
INTEGRATION AND TEST	539	45	584
TOTAL	5885	1006	6891

3.2.5 Concept 4: Decentralized Pumped Liquid System

The decentralized pumped liquid concept, shown schematically in Figure 25, consists of three independent pumped loops each with an associated set of radiators. For each loop shown there exists another equivalent redundant loop which shares the radiator for reliability. The three loops provide heat rejection for payloads (1) on the left cross arm and extension arms, (2) the trail arm and (3) the cross arm and extension arms. Each system consists of; four radiator panels covering the four exterior surfaces of the unmanned module, pumps and accumulator to circulate and store the fluid, two quick disconnects at each payload docking port (supply and return), and the interconnecting fluid lines and fittings.

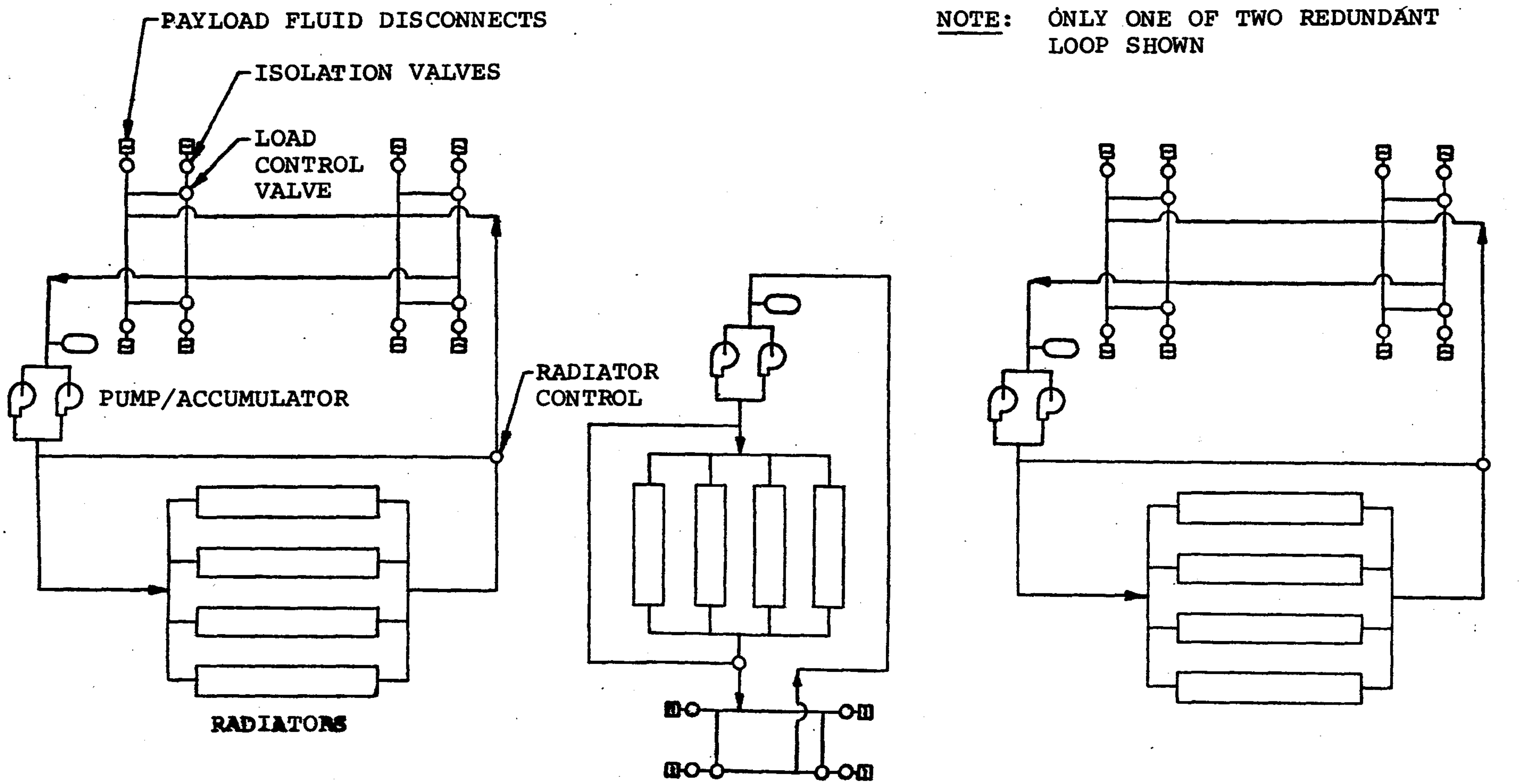
Each of the two cross arm/extension arm systems were sized and optimized for 10 kW maximum heat rejection. Lines were sized to provide up to 10 kW heat rejection at any of the individual ports. Quick disconnects provide the interface with the payloads. An isolation valve provides a backup for each quick disconnect. The trail arm system was sized for 5 kW maximum heat rejection with 5 kW allowed at either of the two ports. Control is provided at each payload docking port with a temperature controlled bypass valve that provides the proper fluid return temperature from the payload. Control is also provided for the radiator system with a temperature sensing bypass valve.

One advantage of the decentralized pumped loop approach is lack of a need for fluid swivels since no fluid crosses the rotary joints. Also, structure mounted radiator system requires no deployed area minimizing payload view blockage and inertial effects during rotation of the platform arms.

Concept 4 was sized and optimized for two sets of requirements: (1) the entire 25 kW heat load at $20 \pm 5^{\circ}C$ and (2) 5 kW at $20 \pm 5^{\circ}C$ and 20 kW at 15 to $40^{\circ}C$. The physical characteristics of the systems sized for the two sets of requirements are described in Figures 26 and 27. Weights were estimated to be 1662 kg for the first set of requirements and 1427 kg for the second set. The tighter temperature requirement (the first requirement) results in higher weight due primarily to higher flowrates which result in higher pumping power.

Results of the cost analysis are shown in Figure 28 with a projected system cost of $14.25 Million.

FIGURE 25
CONCEPT 4 - DECENTRALIZED PUMPED LIQUID SYSTEM



a) CROSS ARM & EXTENSION SYSTEM   b) TRAIL ARM SYSTEM   c) CROSS ARM & EXTENSION SYSTEM

FIGURE 26
CONCEPT 4 - DECENTRALIZED PUMPED FLUID

VOUGHT

25kW HEAT LOAD AT 20 ± 5°C

COMPONENT	QTY	WEIGHT (KG) EA	WEIGHT (KG) TOT	DIMENSIONS	FAILURE RATE /MILLION HRS	COMMENTS
1.905cm OD x .406mm Stainless Steel Tube	265m		50.6		Random = .05	
RADIATOR PANELS (DRY)	8	97.7	781.6	1.60m x 13.1m x .019m	Meteoroid = .289(Tot) Struct. Integ. = .1 - .2	10 kW arm
RADIATOR PANELS (DRY)	4	36.55	146.2	1.60m x 5.18m x .0127m	Meteoroid = .289(Tot) Struct. Integ. = .1 - .2	5 kW arm
ACCUMULATORS	4 2	3.22 1.59	12.9 3.2	7700cm^3 Fld Vol 3850cm^3 Fld Vol	.00085-.00389*	10 kW 5 kW
PUMPS	12	3.45	41.4		.0439 - .4082*	3413 kg/hr, ΔP = 372 Kpa
TEMPERATURE CONTROL VALVES	26	1.22	31.7		.275 - .282*	
ISOLATION VALVES	40	.68	27.2		.10	
QUICK DISCONNECT	40	.68	27.2		.15	
MICROPROCESSOR	6	2.04	12.2			
POWER PENALTY	1.93kW	164.2	316.9			
REFRIGERANT 21			211.4			
*SWITCH SYSTEM RELIABILITY = .99 TO .995			1662.5			

FIGURE 27 CONCEPT 4 - DECENTRALIZED PUMPED FLUID

5kW AT 20 ± 5°C; 20kW AT 15 TO 40°C

COMPONENT	QTY	WEIGHT (KG) EA	WEIGHT (KG) TOT	DIMENSIONS	FAILURE RATE /MILLION HRS	COMMENTS
1.905cm OD x .406mm Stainless Steel Tube	265m		50.6		Random = .05	
RADIATOR PANELS (DRY)	8	82.9	703.2	1.60m x 11.9m x .019m	Meteoroid = .289(Tot) Struct. Integ. = .1 - .2	10 kW arm
RADIATOR PANELS (DRY)	4	36.55	146.2	1.60m x 5.18m x .0127m	Meteoroid = .289(Tot) Struct. Integ. = .1 - .2	5 kW arm
ACCUMULATORS	4 2	2.81 1.59	11.2 3.2	6770cm^3 Fld Vol 3850cm^3 Fld Vol	.00085-.00389*	10 kW 5 kW
PUMPS	12	3.45	41.4		.0439 - .4082*	2408 kg/hr, ΔP = 372 Kpa
TEMPERATURE CONTROL VALVES	26	1.22	31.7		.275 - .282*	
ISOLATION VALVES	40	.68	27.2		.10	
QUICK DISCONNECT	40	.68	27.2		.15	
MICROPROCESSOR	6	2.04	12.2			
POWER PENALTY	1.11kW	164.2	182.3			
REFRIGERANT 21			190.5			
			1426.9			

*SWITCH SYSTEM RELIABILITY = 0.99 TO 0.995

FIGURE 28 CONCEPT 4 - DECENTRALIZED PUMPED LIQUID SYSTEM

COST IN THOUSANDS OF DOLLARS

COMPONENT	DEVELOPMENT	PRODUCTION	TOTAL
RADIATOR PANELS	4786	1346	6132
PUMPS	107	498	605
ACCUMULATORS	607	10	617
EXPERIMENT FLOW VALVES	75	310	385
RADIATOR FLOW CONTROL VALVES	75	120	195
TEMPERATURE SENSORS	20	14	34
MICROPROCESSOR	2064	539	2603
ISOLATION VALVES	80	547	627
LINES AND FITTINGS	782	14	796
QUICK DISCONNECTS	600	336	936
INTEGRATION AND TEST	1204	116	1320
TOTAL	10400	3850	14250

3.2.6 Concept 5: Pumped Liquid System Centralized on The Platform

Concept 5 is a centralized self contained pumped liquid loop and radiator system which rejects the entire 25 kW of heat load from the unmanned module. Figure 29 shows a schematic of the system. Only one of the two redundant fluid loops are shown for clarity. The system consists of a liquid loop with redundant pumps to circulate the liquid (Freon 21), a radiator subsystem deployed from the module surface, three four pass fluid swivels (for supply and return of each redundant loop), and 20 fluid quick disconnects for the 10 docking ports for each loop (40 total quick-disconnects for both loops), an isolation valve at each quick disconnect as a backup, control valves at each of the 10 docking ports and a control valve for radiator heat load control.

The fluid from the radiator subsystem (controlled to about $4^{\circ}C$) is circulated to the 10 heat sources (payloads) at flowrates regulated by the heat load control valves. The coordination of the individual heat load control valves would likely require a microprocessor controller. The flow is routed in parallel to each payload so that the $4^{\circ}C$ fluid is uniformly available to the payloads.

A sizing and optimization analysis was performed for the system components. The radiator subsystem was optimized using a specialized computer routine. This computer routine determines the optimum panel shape (length and width), flow routing on the panel, the spacing, tube diameter, tube thickness for micrometeoroid protection, and total weight. Assumptions for the radiator analysis included 25 kW heat load, a 10 year life, a meteoroid probability of no penetration for an individual loop of 0.95, pump efficiency of 0.3, an emissivity of 0.76, and honeycomb aluminum panel construction with facesheet thicknesses of 0.028 cm. An equivalent radiation sink temperature of $-40^{\circ}C$ was assumed. Two cases were analyzed: (1) radiator inlet temperature = $25^{\circ}C$, radiator outlet temperature = $15^{\circ}C$, and (2) radiator inlet temperature = $34^{\circ}C$, radiator outlet temperature = $15^{\circ}C$. The lines were also sized and the weights of other components were estimated. Figures 30 and 31 give summaries of the physical characteristics of the final systems. The total weight was estimated at 1866 kg for $T_{in}/T_{out} = 25^{\circ}C/15^{\circ}C$ and 1245 kg for $T_{in}/T_{out} = 34^{\circ}C/15^{\circ}C$. The system weight is demonstrated to be very sensitive to fluid temperature constraints especially as the inlet and outlet temperatures difference decreases.

The results of a cost analysis on the system is shown in Figure 32. The estimated total system cost is $21.6 Million.

FIGURE 29 CONCEPT 5 - CENTRALIZED PUMPED LIQUID SYSTEM

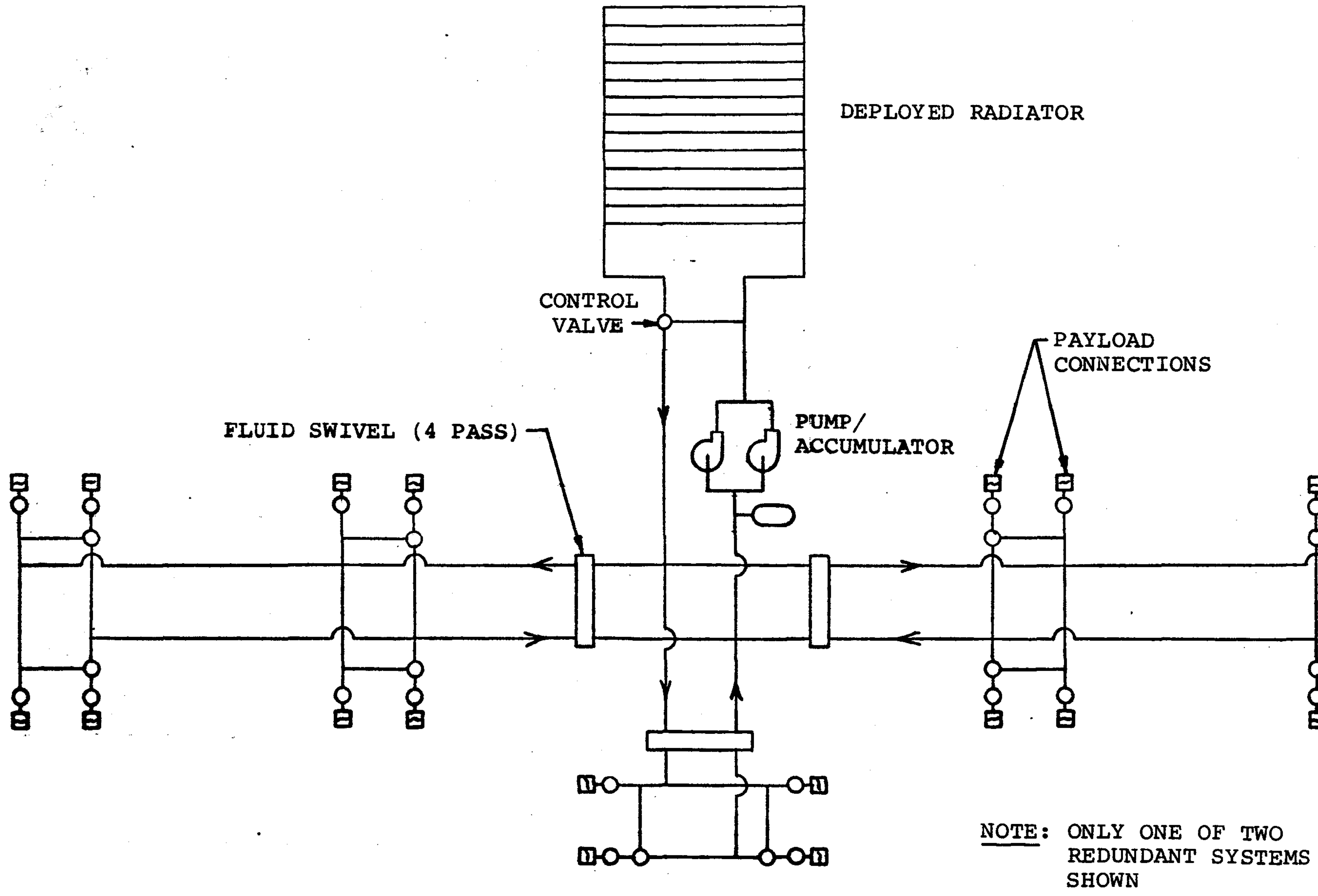


FIGURE 30 CONCEPT 5 - CENTRALIZED PUMPED FLUID - SASP RADIATORS

25 kW HEAT LOAD AT 20 + 5°C

COMPONENT	QTY	WEIGHT (KG) EA	TOT	DIMENSIONS	FAILURE RATE /MILLION HRS	COMMENTS
3.18cm ID, 0.686mm Wall Stainless Steel Tubing Bumper Protected	53.6m		70.6		Meteoroid = .289 Random = .05	Tube meteoroid bumper consists of 0.51mm stainless steel with 1.27cm spacing
2.67cm ID, 0.686mm Wall Stainless Steel Tubing No Bumper Protection	12.2m		5.8			
2.67cm ID, 0.686mm Wall Stainless Steel Tubing Bumper Protected	85.3 m		99.2			
1.91cm ID, 0.686mm Wall Stainless Steel Tube Bumper Protected	114.6 m		115.8			
RADIATOR PANELS (DRY)	6	82.63	495.8	1.52 x 8.53 x .0188	Meteoroid = .289(Tot) Struct. Integ. = .05 - .10	η = .895 (s = 15cm)
ACCUMULATOR (DRY)	2	14.1	28.2	34000 cm^3 Fluid Volume	.00085-.00389*	
PUMPS	4	4.63	18.5		.0439-.4082*	8532 kg/hr, ΔP = 578 Kpa; Power = 3.32 kW
TEMP CONTROL VALVES - ELECTRICAL	22	1.54	33.9		.275 - .282*	
ISOLATION VALVES	36	.68	24.5		.10	
QUICK DISCONNECT	36	.68	24.5		.15	
FLUID SWIVELS (4 PASS)	3	9.07	27.2		.50	
MICROPROCESSER	2	2.04	4.1			
POWER PENALTY	3.32 kW	164.2	545.1			
R-21			372.7			
			1865.9			

*REDUNDANT COMPONENT

FIGURE 31 CONCEPT 5 - CENTRALIZED PUMPED FLUID - SASP RADIATORS

5kW AT 20 ± 5°C; 20kW AT 15 TO 40°C

COMPONENT	QTY	WEIGHT (KG)		DIMENSIONS	FAILURE RATE /MILLION HRS	COMMENTS
		EA	TOT			
2.41cm ID, 0.533mm Wall Stainless Steel Tubing Bumper Protected	53.6m		53.3		Meteoroid = .289 Random = .05	Tube meteoroid bumper consists of 0.51mm stainless steel with 1.27cm spacing
1.78cm ID, 0.533mm Wall Stainless Steel Tubing No Bumper Protection	12.2m		3.0			
1.78cm ID, 0.533mm Wall Stainless Steel Tubing Bumper Protected	200m		164.9			
RADIATOR PANELS (DRY)	6	66.83	401.0	1.52 x 7.32 x .0167	Meteoroid = .289(Tot) Struct. Integ. = .05 - .10	
ACCUMULATOR (DRY)	2	7.1	14.2	17080 cm^3 Fluid Volume	.00085-.00389*	
PUMPS	4	3.76	15.0		.0439-.4082*	4472 kg/hr, ΔP = 593 Kpa; Power = 1.78 kW
TEMP CONTROL VALVES - ELECTRICAL	22	1.54	33.9		.275 - .282*	
ISOLATION VALVES	36	.68	24.5		.10	
QUICK DISCONNECT	36	.68	24.5		.15	
FLUID SWIVELS (4 PASS)	3	9.07	27.2		.50	
MICROPROCESSER	2	2.04	4.1			
POWER PENALTY	1.78kW	164.2	292.1			
R-21			186.9			
			1244.6			

*REDUNDANT COMPONENT

FIGURE 32

CONCEPT 5 - CENTRALIZED PUMPED LIQUID SYSTEM INDEPENDENT OF CENTRAL PLATFORM TMS (RADIATORS ON UNMANNED PLATFORM)

COST IN THOUSANDS OF DOLLARS

COMPONENT	DEVELOPMENT	PRODUCTION	TOTAL
RADIATORS	3816	732	4548
PUMPS	138	265	403
ACCUMULATORS	798	14	812
EXPERIMENT FLOW VALVES	75	310	385
RADIATOR FLOW CONTROL VALVES	75	55	130
TEMPERATURE SENSORS	20	15	35
MICROPROCESSER	2064	471	2535
ISOLATION VALVES	80	547	627
LINES AND FITTINGS	3657	65	3722
FLUID SWIVELS	2467	322	2789
QUICK DISCONNECTS	600	309	909
DEPLOYMENT MECHANISM	2919	113	3032
FLEX HOSES	206	8	214
INTEGRATION AND TEST	1308	124	1432
TOTAL	18223	3350	21573

3.2.7 Concept 6: Centralized Pumped Liquid System Utilizing Central Platform Heat Rejection

Concept 6 utilizes a pumped fluid loop to collect the unmanned module waste heat and transfer it into the 250 kW platform thermal management system for rejection. Figure 33 shows a schematic of one of the two redundant loops. Each loop consists of redundant pumps, an accumulator, 3 four pass fluid swivels, plumbing to route the fluid, quick disconnects for connecting to the central 250 kW loop heat exchanger, quick disconnects for payload interface with an isolation valve to back up each and a control valve for each payload interface.

The system was sized for the two sets of temperature requirements; 1) 25 kW at 20 $\pm$ 5°C, and 2) 5 kW at 20 $\pm$ 5°C plus 20 kW at 15 to 40°C. The physical characteristics for the two conditions are presented in Figures 35 and 36. The calculated system weights for the two conditions were 1216 kg and 769 kg respectively.

The results of the cost analysis is shown in Figure 36. The total system cost is projected to be $13 Million.

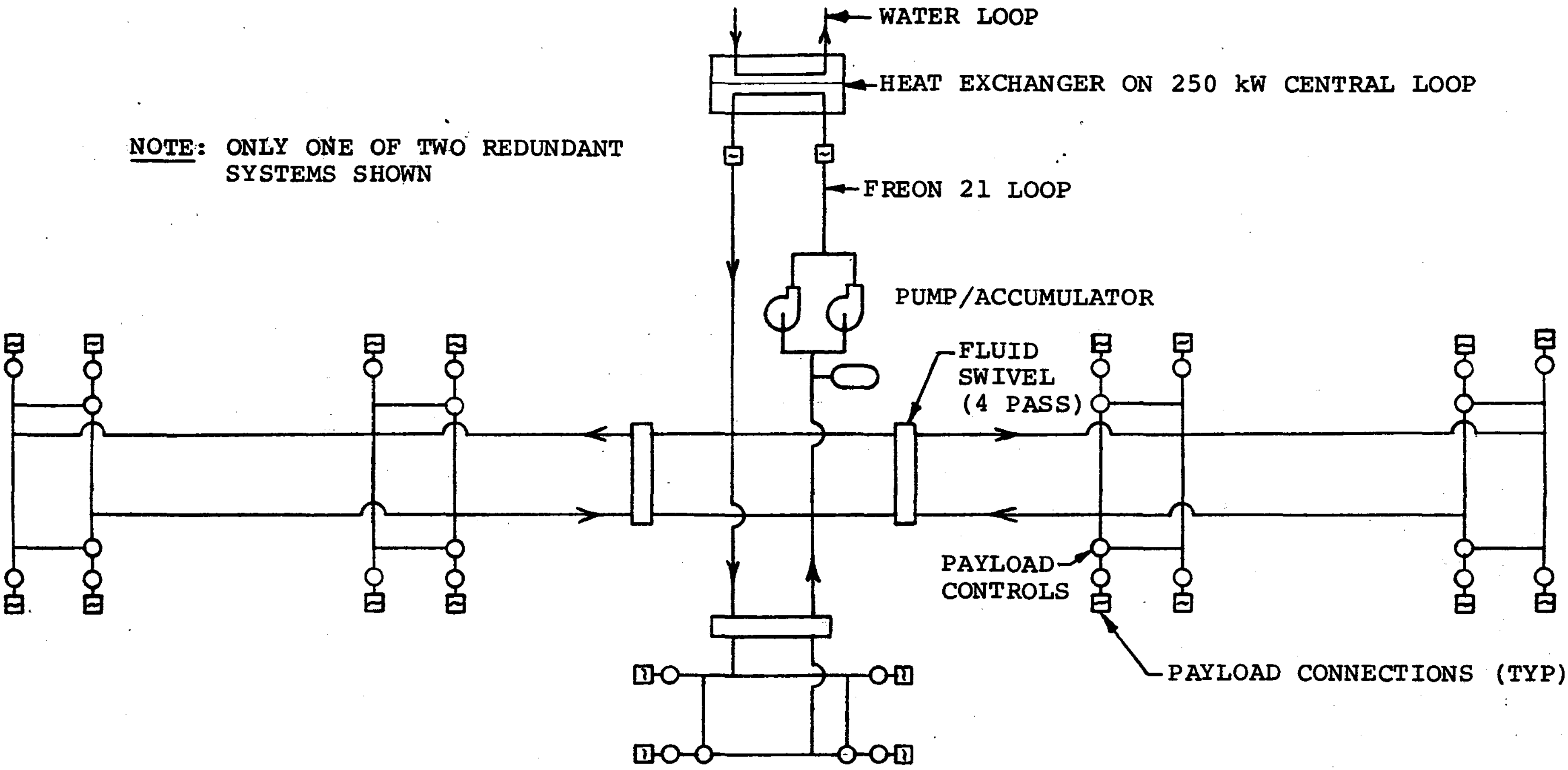


FIGURE 33

CONCEPT 6 - CENTRALIZED LIQUID SYSTEM TIED TO LARGE PLATFORM THERMAL MANAGEMENT SYSTEM

FIGURE 34 CONCEPT 6 - CENTRALIZED PUMPED FLUID - PLUG IN

25kW HEAT LOAD AT 20 ± 5°C

COMPONENT	QTY	WEIGHT (KG)		VOLUME m^3, EA	FAILURE RATE /MILLION HRS	COMMENTS
		EA	TOT			
3.18cm ID, 0.686mm Wall Stainless Steel Tubing Bumper Protected	53.6m		70.6		Meteoroid = .289 Random = .05	Tube meteoroid bumper consists of 0.51mm stainless steel with 1.27cm spacing
2.67cm ID, 0.686mm Wall Stainless Steel Tubing No Bumper Protection	12.2m		5.8			
2.67cm ID, 0.686mm Wall Stainless Steel Tubing Bumper Protected	85.3m		99.2			
1.91cm ID, 0.686mm Wall Stainless Steel Tube Bumper Protected	114.6 m		115.8			
ACCUMULATOR (DRY)	2	9.07	18.1	21800 cm^3 Fluid Volume	.00085-.00389*	
PUMPS	4	4.63	18.5		.0439-.4082*	8532 kg/hr, ΔP = 565 Kpa; Power = 3.24 kW
TEMP CONTROL VALVES - ELECTRICAL	20	1.54	30.8		.275 - .282*	
ISOLATION VALVES	40	.68	27.2		.10	
QUICK DISCONNECT	40	.68	27.2		.15	
FLUID SWIVELS (4 PASS)	3	9.07	27.2		.50	
MICROPROCESSER	2	2.04	4.1			Controls Valves
POWER PENALTY	3.24 kW	164.2	532.0			3.24 kW @ 164.2 kg/kW
R-21			239.4			
			1215.9			

*REDUNDANT COMPONENT

FIGURE 35 CONCEPT 6 - CENTRALIZED PUMPED FLUID - PLUG IN

5kW AT 20 ± 5°C; 20kW AT 15 TO 40°C

COMPONENT	QTY	WEIGHT (KG) EA	WEIGHT (KG) TOT	VOLUME m³, EA	FAILURE RATE /MILLION HRS	COMMENTS
2.41cm ID, 0.533mm Wall Stainless Steel Tubing Bumper Protected	53.6m		53.3		Meteoroid = .289 Random = .05	Tube meteoroid bumper consists of 0.51mm stainless steel with 1.27cm spacing
1.78cm ID, 0.533mm Wall Stainless Steel Tubing No Bumper Protection	12.2m		3.0			
1.78cm ID, 0.533mm Wall Stainless Steel Tubing Bumper Protected	200m		164.9			
ACCUMULATOR (DRY)	2	4.8	9.6	11500 cm³ Fluid Volume	.00085-.00389*	
PUMPS	4	3.76	15.0		.0439-.4082*	4472 kg/hr, ΔP = 565 Kpa; Power = 1.70 kW
TEMP CONTROL VALVES - ELECTRICAL	20	1.54	30.8		.275 - .282*	
ISOLATION VALVES	40	.68	27.2		.10	
QUICK DISCONNECT	40	.68	27.2		.15	
FLUID SWIVELS (4 PASS)	3	9.07	27.2		.50	
MICROPROCESSER	2	2.04	4.1			Controls Valves
POWER PENALTY	1.70kW	164.2	280			1.70 kW @ 164.2 kg/kW
R-21			127			
			769.3			

*REDUNDANT COMPONENT

FIGURE 36
CONCEPT 6 - CENTRALIZED PUMPED LIQUID SYSTEM
PLUGGED INTO CENTRAL PLATFORM

COST IN THOUSANDS OF DOLLARS

COMPONENT	DEVELOPMENT	PRODUCTION	TOTAL
PUMPS	138	265	403
ACCUMULATORS	798	14	812
EXPERIMENT FLOW VALVES	75	310	385
TEMPERATURE SENSORS	20	14	34
MICROPROCESSER	2064	471	2535
ISOLATION VALVES	80	547	627
LINES AND FITTINGS	3657	65	3722
FLUID SWIVELS	2467	322	2789
QUICK DISCONNECTS	600	309	909
INTEGRATION AND TEST	701	78	779
TOTAL	10600	2395	12995

3.3 CONCEPT COMPARISON AND SELECTION

The six concepts for thermal control of unmanned modules were evaluated and compared based on the results of the trade studies discussed above. The trade matrix shown in Figure 37 was the basis for this comparison. The matrix contains three major categories; Performance, Potential for Benefit, and Development Considerations.

Performance - The concepts are compared under two sets of temperature requirements in the performance category: (1) all 25 kW at 20 $\pm$ 5 C and (2) 15 kW at 15 to 40°C and 10 kW at 20 $\pm$ 5°C. For the weight criteria, Concept No. 2 is generally superior at 589 kg or 1465 kg if the central system penalties are added. The central system weight penalties are discounted, however, since that system will be there to support a number of different modules over the life of the 250 kW platform. Concept No. 6 is second with 769 kg of weight for the less stringent temperature requirement and 1216 kg for the tighter 20° $\pm$ 5°C requirement. (The less stringent requirement is considered most realistic). The remaining concepts are 3, 4, 5, and 1 in order of increasing weight using 20 kW requirement. For the power criteria, and the less stringent requirement, the decentralized heat pipe is best with no power required, followed closely by Concept No. 2 with 56 watts. The power for the remaining concepts ranges from 1.11 kW for Concept 4 to 2.91 kW for Concept 3. Concepts 1 and 4 have no deployed radiator area. The deployed area for the others is about the same but locations are different. Concept No. 5 is the only one with deployed area on the unmanned module. The deployed area for Concepts 2, 3, and 6 is prorated area using the specific area from the centralized 250 kW system study. The best reliability is provided by Concepts 2 and 3. Concept No. 4 is second best with Concepts 5 and 6 tied for fourth. Concept No. 1 has by far the poorest reliability at 35%.

Based on the above considerations, the following rankings are given in the "Performance" category (best concept first): 2,6,3,4,5,1

Potential For Benefit - The costs for the concepts are included under this category. Cost for the centralized approaches are shown with and without the prorated $2.7 Million penalty for use of the 250 kW system. Again, the $2.7 Million penalty is considered excessive since several payloads would use the services over its lifetime. The lowest cost approaches are Concept No. 2, the Pumped Heat Pipe, and Concept 3, the Compressor Assisted Heat Pipe. The second lowest actual cost is concept No. 6, the centralized

FIGURE 37 CONCEPT COMPARISON

RANKING CATEGORY	CONCEPT					
	#1-DECENT HEAT PIPE	#2-PUMPED HEAT PIPE	#3-COMPR HEAT PIPE	#4-DECENT PUMPD LIQ	#5-CENT PUMPD LIQ	#6-CENT LIQ PLUG IN
PERFORMANCE						
WEIGHT, KG: REQMT #1[1]	1684	589/1465[3]	1056/1932[3]	1663	2055	1216/2092[3]
: REQMT #2[2]	1684	589/1465	1056/1932	1427	1434	769/1645
POWER, kW : REQMT #1[1]	0	.056	2.91	1.93	3.32	3.24
: REQMT #2[2]	0	.056	2.91	1.11	1.78	1.70
DEPLOYED AREA, m^2	0	85	85	0	78	85
RELIABILITY (10 YEARS)	.35 (.77 PER SUBSYS)	.84	.84	.73 (.88 PER SUBSYS)	.62	.64
POTENTIAL FOR BENEFIT						
COST, $M	17.3	6.3/9.0[3]	6.3/9.0[3]	14.2	21.6	13.0/15.7[3]
GROWTH & RECONFIG	POOR	GOOD	GOOD	FAIR	GOOD	GOOD
AUTONOMOUS OPERATION	YES	NO	NO	YES	YES	NO
DEVELOPMENT CONSIDERATIONS						
COST, $M	10.9	5.7	5.9	10.4	18.2	10.6
LEAD TIME	5 YRS	7 YRS	7 YRS	3 YR	4 YRS	4 YRS
POTENTIAL FOR SUCCESS	FAIR	FAIR	FAIR	EXCEL	GOOD	GOOD
TECHNOLOGY ASSESSMENT	UNPROV FEAS	UNPROV FEAS	UNPROV FEAS	DEV	DEV[4]	DEV[4]

[1] 25 kW HEAT LOAD AT 20 ± 5°C

[2] 20 kW HEAT LOAD AT 15 to 40 °C; 5 kW AT 20 ± 5°C

[3] WITH PENALTIES OF 876 kg OR $2.7 MILLION COST ASSESSED FOR CENTRAL SYSTEM

[4] FLUID SWIVEL YET TO BE DEVELOPED; FEASIBILITY PROVEN, HOWEVER

liquid system plugged into the 250 kW loop at $13 Million. Concept 4 is third with $14.2 Million with 1 and 5 being last. Concepts 2, 3, 5 and 6 get a "good" rating in the growth and reconfiguration category, and Concept 4 gets a "fair" rating. Concepts 1, 4, and 5 provide autonomous operation while the other concepts do not.

Based on the above discussion the following rankings are given in the "Potential for Benefit" category (beginning with highest ranking): 2,3(tie),6,4,5,1

<u>Development Considerations</u> - This category includes development cost, lead time between development start and first production unit, potential for success and technology status. Concept 4 is considered superior in this category due to its advance status. No new technology is required and potential for success is excellent. Concept 2 is rated second since it is a highly developed concept with good potential for success. Only one technology advancement is needed: the four pass fluid swivel. Feasibility has been proven for the fluid swivel in tests, however. Concept 5 is a close third. Concepts 1, 2 and 3 rank lowest in this category.

Based upon this evaluation, the concepts are ranked as follows for this category: 4,6,5,1,2,3(tie)

<u>Overall Rankings</u> - Based upon the above concept evaluations, Concept 2, the pump assisted central heat pipe is superior in all categories except the development status. It has the lowest "on platform" weight of 589 kg, the lowest projected cost (after technology development) and the lowest power requirement. Concept 6, the central liquid loop is second best in all categories. It has a low "on platform" weight of 770 kg, developed technology and low cost. Concept 6 is selected as the best low risk approach for the intermediate term (1985 to 1990). Concept 2 is selected as the high technology alternate which if developed offers promise of significant benefit.

4.0 RADIATOR DEPLOYMENT STUDIES

4.1 DYNAMIC AND LOADS ANALYSIS OF DEPLOYED RADIATORS

This section presents the results of a dynamic analysis for a scissor radiator representative of the 250 kW system defined in Reference 1. The objective of the study was to determine vibration frequencies and maneuvering loads for on-orbit operation. To prevent undesirable dynamic interaction between the attitude control system and the flexible radiator structure, minimum radiator frequencies should be at least ten times the control system bandwidth. For the Shuttle Orbiter, the limit of the control system bandwidth has been estimated at 0.01 Hz providing a minimum allowable frequency of 0.1 Hz for the radiator modal frequency.

Mode shapes, frequencies, and loads were calculated for fully extended and half extended configurations and for one other intermediate position. The results indicate that the frequency criterion is met or exceeded for all configurations examined. Loads were computed for 0.01 g acceleration in the radiator plane and in a direction normal to the radiator plane. Reactions at the transition section base pivots and for the lower linkage attach points are presented.

4.1.1 Discussion of Analysis

The radiator configuration evaluated here consists of nine hinged panels which are actuated by means of a scissors linkage (Figure 38). Individual panels are 1.83 m wide by 4.45 m long. The finite element model used assumed that adjacent panels are joined by four equally-spaced hinges. Basic panel construction is 1.65 cm thick aluminum honeycomb with 0.280 mm bonded aluminum facesheets. Each panel has 26 flow tubes running lengthwise, and manifolds on the ends of the panels add to the flexural stiffness. In the analysis, these manifolds were modeled as 8.9 cm wide by 4.45 cm deep box sections with 0.635 mm wall thickness. Graphite/Epoxy actuator arms with a 5 cm wide by 2.92 cm deep rectangular cross section are hinged to the panels. Assumed arm elastic modulus was 1.38×10^8 kPa. The transition sections between the base and the lower panel and actuator arms were modeled as plates equivalent to 5 cm thick honeycomb with 0.280 mm thick aluminum facesheets. Rotational accelerations which can be 0.01 deg/sec^2 provide a negligible acceleration.

4.1.2 Results of Analysis

Reactions at the base pivots to a 0.01 g acceleration in the direction normal to the plane of the deployed radiator are presented in Figure

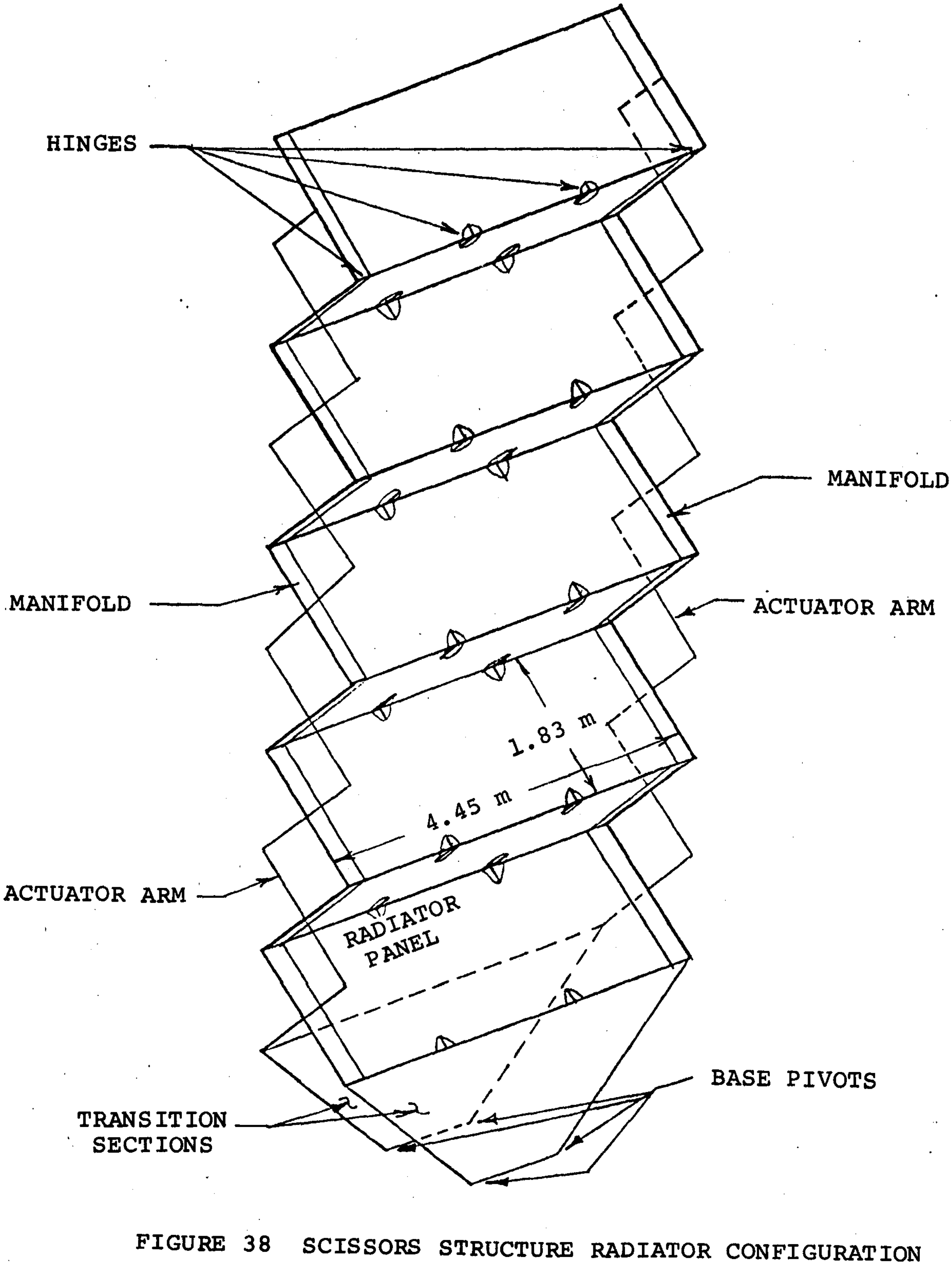


FIGURE 38 SCISSORS STRUCTURE RADIATOR CONFIGURATION

39. Figure 40 presents loads on the lower linkage arm at the connections with the transition section and the first radiator panel. Results are given for the fully deployed (15° half-angle) and the half-deployed (60° half-angle) configurations. Figures 41 and 42 give analogous results for in-plane acceleration.

Vibration mode shapes and frequencies for the deployed configuration are shown in Figure 43, for a 45° half-angle position in Figure 44, and for the half-deployed configuration in Figure 45. The fundamental mode for the deployed configuration is bending out-of-plane with a frequency of 0.117 Hz. For the intermediate position, the fundamental mode is in-plane bending at a frequency of 0.108 Hz, and for the half-deployed position, the fundamental is an extensional mode at 0.104 Hz. Hence, the first mode frequency exceeds the 0.1 Hz criterion in all cases examined and it is concluded that the baseline design is adequately stiff.

FIGURE 39 BASE ATTACHMENT LOADS FOR A_Y = 0.01 g

LOCATION		F_X (N)	F_Y (N)	F_Z (N)	M_X (N-M)	M_Y (N-M)	M_Z (N-M)
15° HALF ANGLE DEPLOYMENT	1	- 7.1	-16.5	507	-12.0	0.03	- 0.07
	2	8.5	-17.8	525	-12.0	-0.16	+ 0.07
	3	- 54.3	-26.7	-507	-12.8	2.2	7.0
	4	52.9	-28.0	-525	-12.8	-2.1	- 7.0
60° HALF ANGLE DEPLOYMENT	1	-103.6	-16.9	79.6	46.7	4.3	.96
	2	103.6	-16.9	79.6	46.7	-4.3	- .96
	3	- 752	-20.0	-79.6	46.7	31.3	- 7.1
	4	752	-20.0	-79.6	46.7	-31.3	7.1

FIGURE 40 ACTUATOR ARM ATTACHMENT LOADS FOR A_Y = 0.01 g

LOCATION		F_X (N)	F_Y (N)	F_Z (N)	M_X (N-M)	M_Y (N-M)	M_Z (N-M)
15° HALF ANGLE DEPLOYMENT	5	148	-448	-118.3	0	- 3.25	- 61.1
	6	-161	498	236.6	0	5.92	- 69.1
60° HALF ANGLE DEPLOYMENT	5	- 61	-52.9	- 61	0	- 2.7	68.8
	6	60	72.5	123	0	0.41	- 12.8

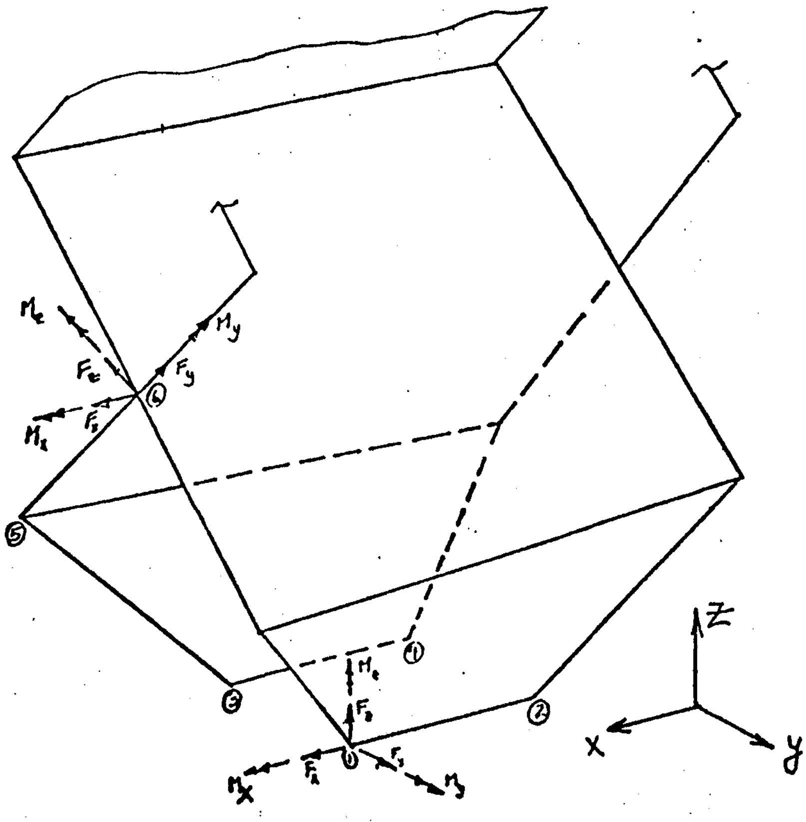


FIGURE 41 BASE ATTACHMENT LOADS FOR A_X = 0.01 g

LOCATION		F_X (N)	F_Y (N)	F_Z (N)	M_X (N-M)	M_Y (N-M)	M_Z (N-M)
15° HALF ANGLE DEPLOYMENT	1	-56.5	-151.7	738	26.0	2.0	-11.5
	2	-63.6	151.7	-738	-26.0	2.1	-11.5
	3	32.5	79.2	213	-13.7	- 0.43	7.2
	4	23.5	- 79.2	-213	13.7	- 0.19	7.2
60° HALF ANGLE DEPLOYMENT	1	-60.0	- 23.6	247	59.2	-17.2	-14.8
	2	-63.6	23.6	-247	-59.2	-17.2	-14.8
	3	27.1	- 34.2	153	-25.5	-10.2	7.1
	4	21.3	34.2	-153	25.5	-10.2	7.1

FIGURE 42 ACTUATOR ARM ATTACHMENT LOADS FOR A_X = 0.01 g

LOCATION		F_X (N)	F_Y (N)	F_Z (N)	M_X (N-M)	M_Y (N-M)	M_Z (N-M)
15° HALF ANGLE DEPLOYMENT	5	28.9	40.92	- 9.8	0	-12.5	- 7.6
	6	-28.0	- 15.1	19.6	0	7.6	1.1
60° HALF ANGLE DEPLOYMENT	5	27.6	21.8	15.1	0	-28.9	-32
	6	-15.1	9.8	-30.2	0	4.5	10.7

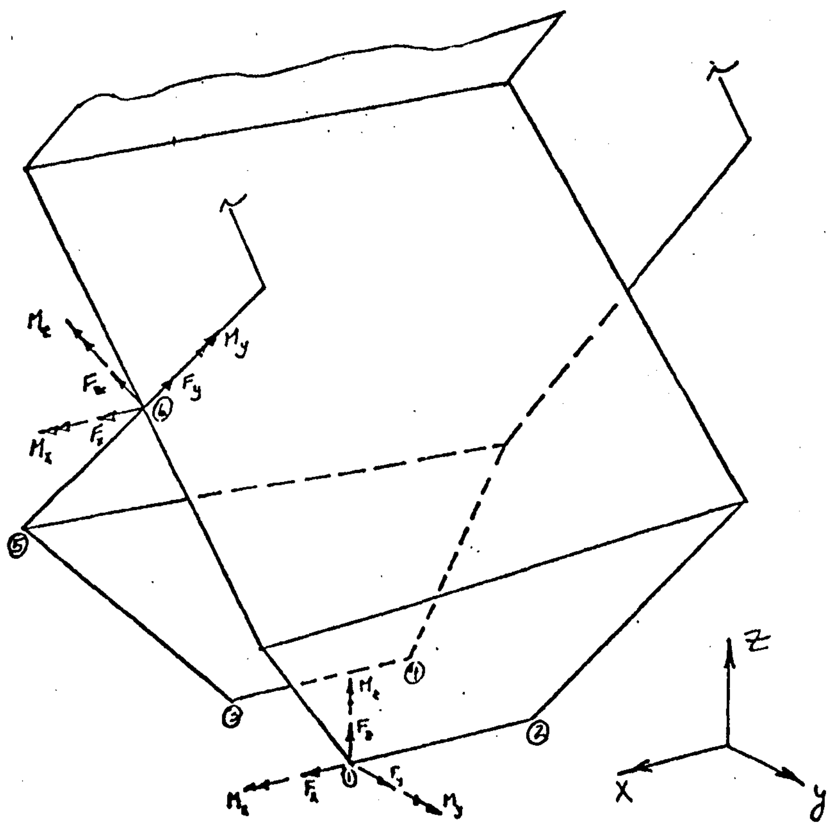
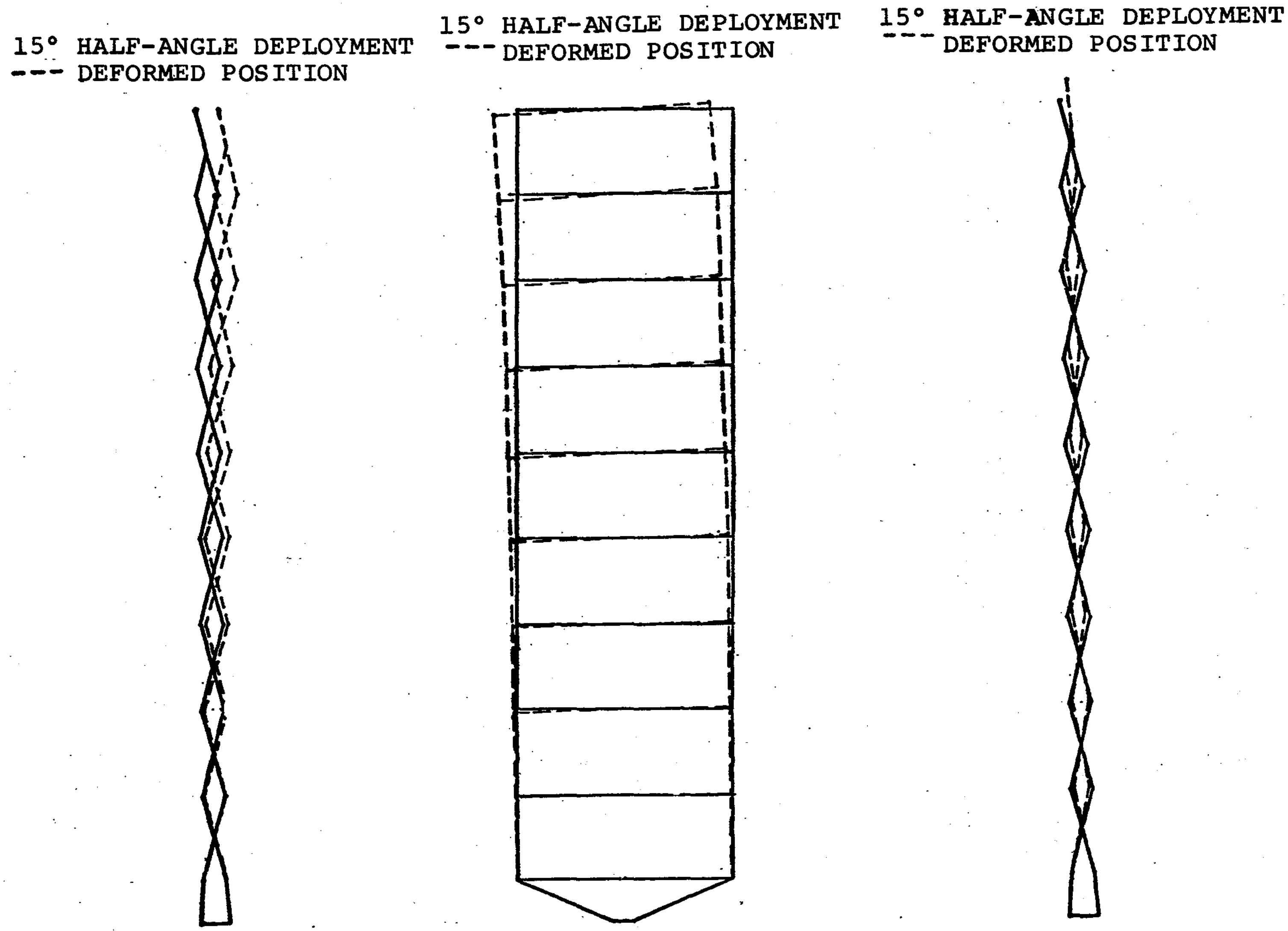


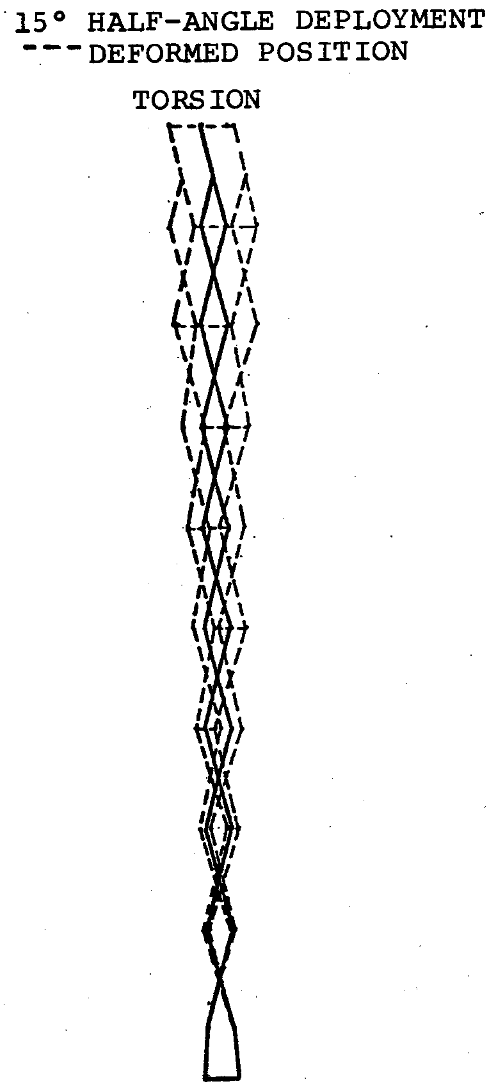
FIGURE 43
FREQUENCY AND MODE SHAPE ANALYSIS FOR 15° DEPLOYMENT



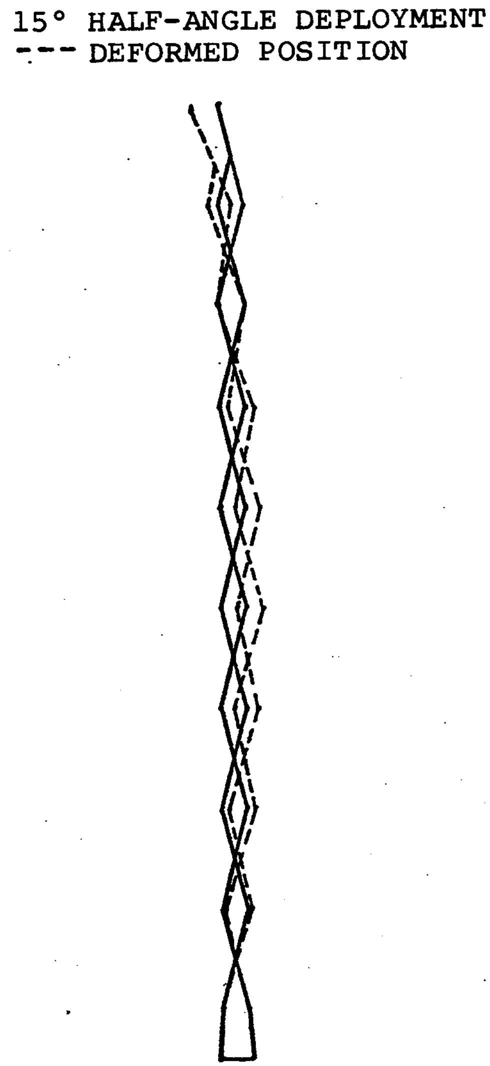
a) MODE 1, FREQUENCY = 0.117 Hz b) MODE 2, FREQUENCY = 0.231 Hz c) MODE 3, FREQUENCY = 0.341 Hz

FIGURE 43

FREQUENCY AND MODE SHAPE ANALYSIS FOR 15° DEPLOYMENT (CONT'D)

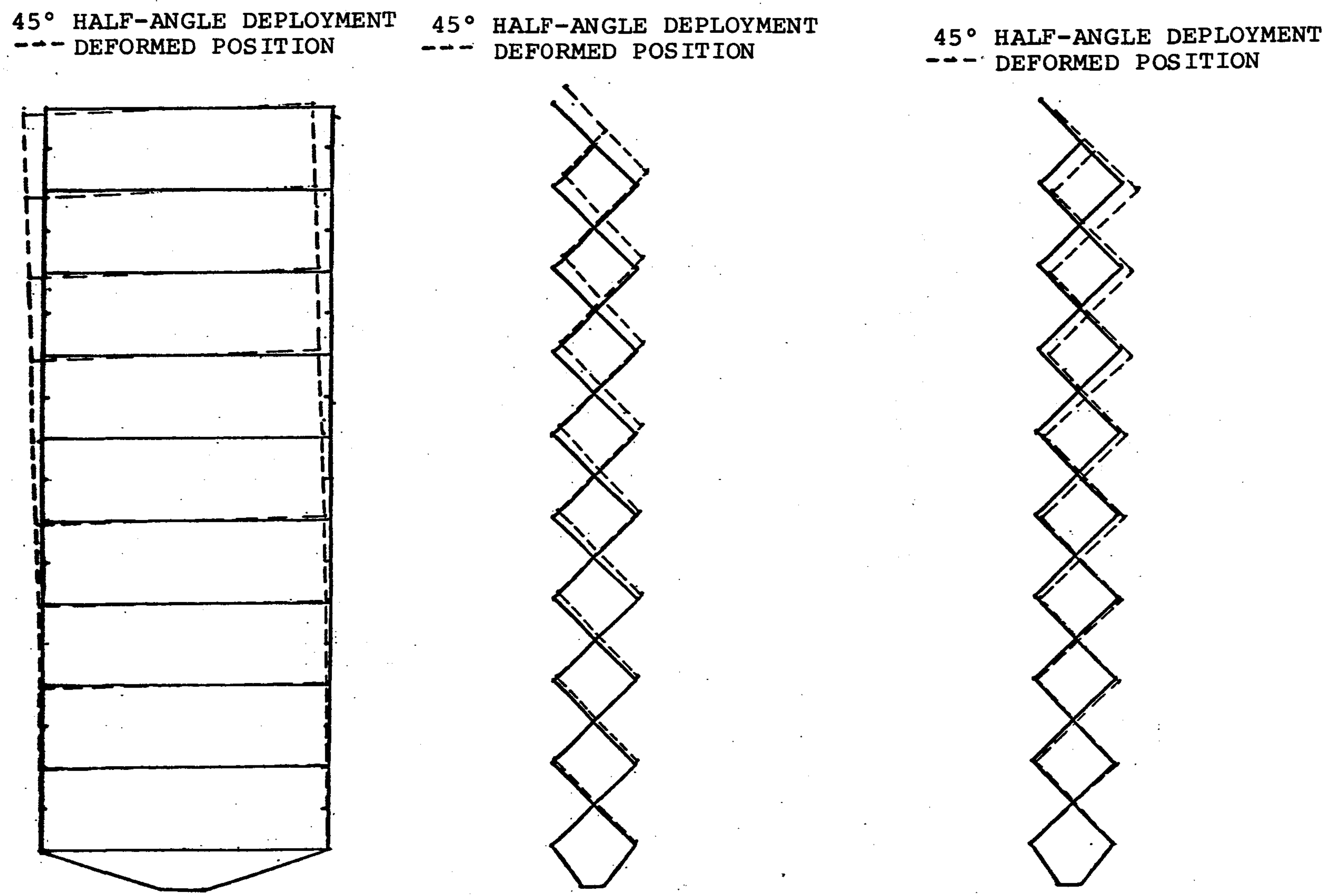


d) MODE 4, FREQUENCY = 0.566 Hz



e) MODE 5, FREQUENCY = 0.756 Hz

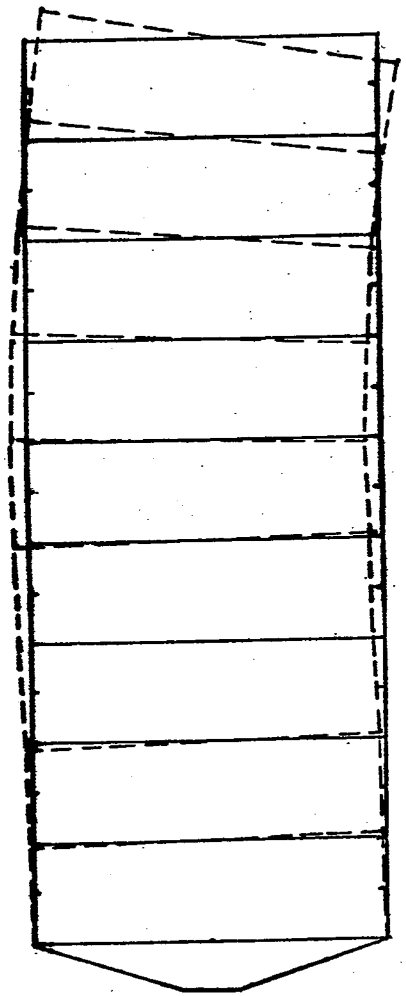
FIGURE 44
FREQUENCY AND MODE SHAPE ANALYSIS FOR 45° HALF ANGLE DEPLOYMENT



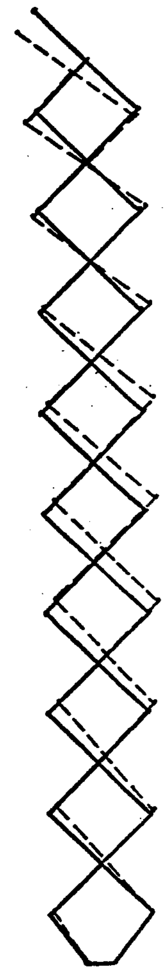
a) MODE 1, FREQUENCY = 0.108 Hz b) MODE 2, FREQUENCY = 0.120 Hz c) MODE 3, FREQUENCY = 0.160 Hz

FIGURE 44

FREQUENCY AND MODE SHAPE ANALYSIS FOR 45° HALF ANGLE DEPLOYMENT (CONT'D)

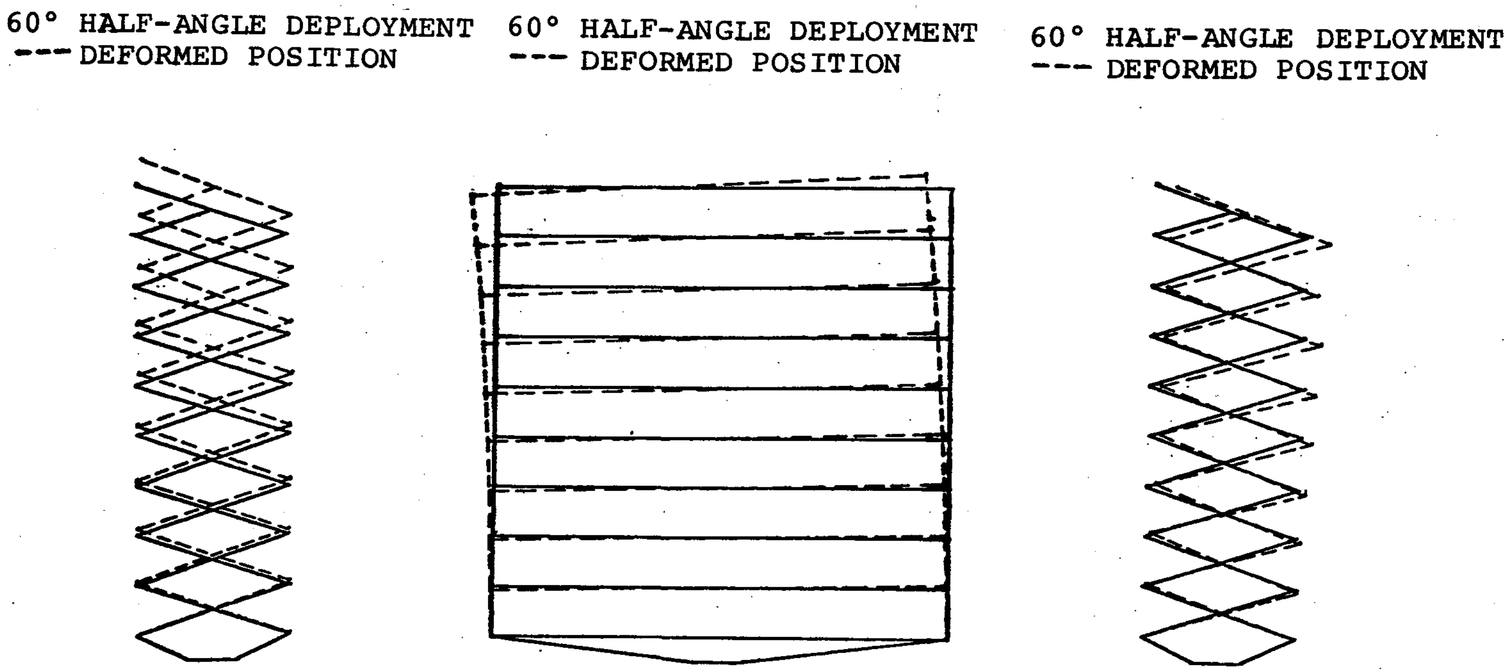


d) MODE 4, FREQUENCY = 0.726 Hz



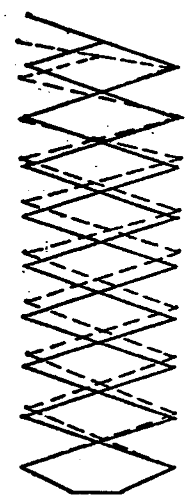
e) MODE 5, FREQUENCY = 0.794 Hz

FIGURE 45
FREQUENCY AND MODE SHAPE ANALYSIS FOR 60° HALF ANGLE DEPLOYMENT

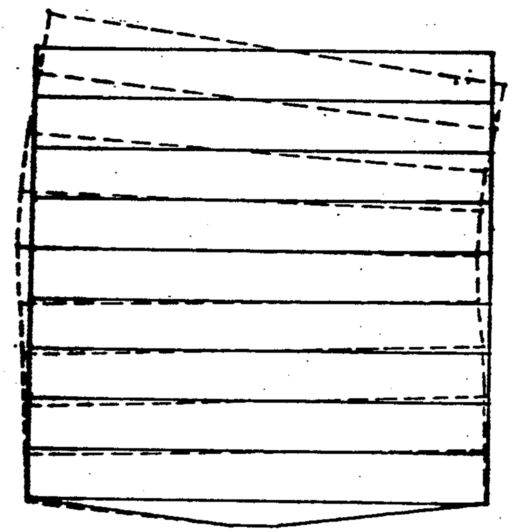


a) MODE 1, FREQUENCY = 0.104 HZ b) MODE 2, FREQUENCY = 0.120 Hz c) MODE 3, FREQUENCY = 0.205 Hz

FIGURE 45
FREQUENCY AND MODE SHAPE ANALYSIS FOR 60° HALF ANGLE DEPLOYMENT (CONT'D)



d) MODE 4, FREQUENCY = 0.695 Hz



e) MODE 5, FREQUENCY = 0.709 Hz

4.2 INSTALLATION OF CONSTRUCTABLE RADIATORS FOR 250 kW POWER PLATFORM

4.2.1 Assembly Sequence on Space Platform

In order to determine the assembly sequence, one must first determine the availability of the hardware at the construction site. To determine this, the load carrying capability of the Orbiter for the missions planned must be investigated. The Space Station Systems Analysis studies have identified beneficial uses for Low Earth Orbit (LEO) space platforms in a range of inclinations from 28.5° to 55°, and in a range of circular orbit altitudes from 370 to 650 km (200-350 NM), as well as later applications in Polar Earth Orbit (PEO) and Geostationary Equatorial Orbit (GEO). As can be seen from Figure 46, in order to obtain circular orbits of 400 km to 650 km the Orbiter must carry one OMS kit. Figure 47, taken from Reference 12, shows the various payload configurations for the Orbiter depending upon mission requirements for an OMS kit, a docking module, and EVA. For the space construction sequence used herein a payload envelope length of 15.46 M was used for the first delivery of the core module to the construction site and thereafter only a length of 13.41 M or 11.68 M can be used depending upon the planned use of EVA. The sequence of deliveries to the construction site are as follows:

Refer to Figure 48 for pictorial description.

1) Core Module - The core module is first delivered to the construction site and left unmanned in orbit.

2) Crane and Base Section of Power Module - In order to efficiently commence with construction of the space platform it is necessary to first install the crane on the core module. After the crane is installed it can be used to mate the base section of the Power Module to the core. Since the overall power module length is estimated to be 50.6 m long, it is necessary to deliver the base section of the Power Module on this second flight if the number of flights are to be minimized.

3) Power Module With Heat Pipes - The remaining four sections of the Power Module with the radiator heat pipes are delivered at this time. The heat pipes are externally mounted to the 13.4 m section of Power Module. The Power Module sections are installed on the space platform during this sequence, however the heat pipes remain in their transportation rack attached to the 13.4 m section of the Power Module. The heat pipes are not installed at this time because they would obstruct access to

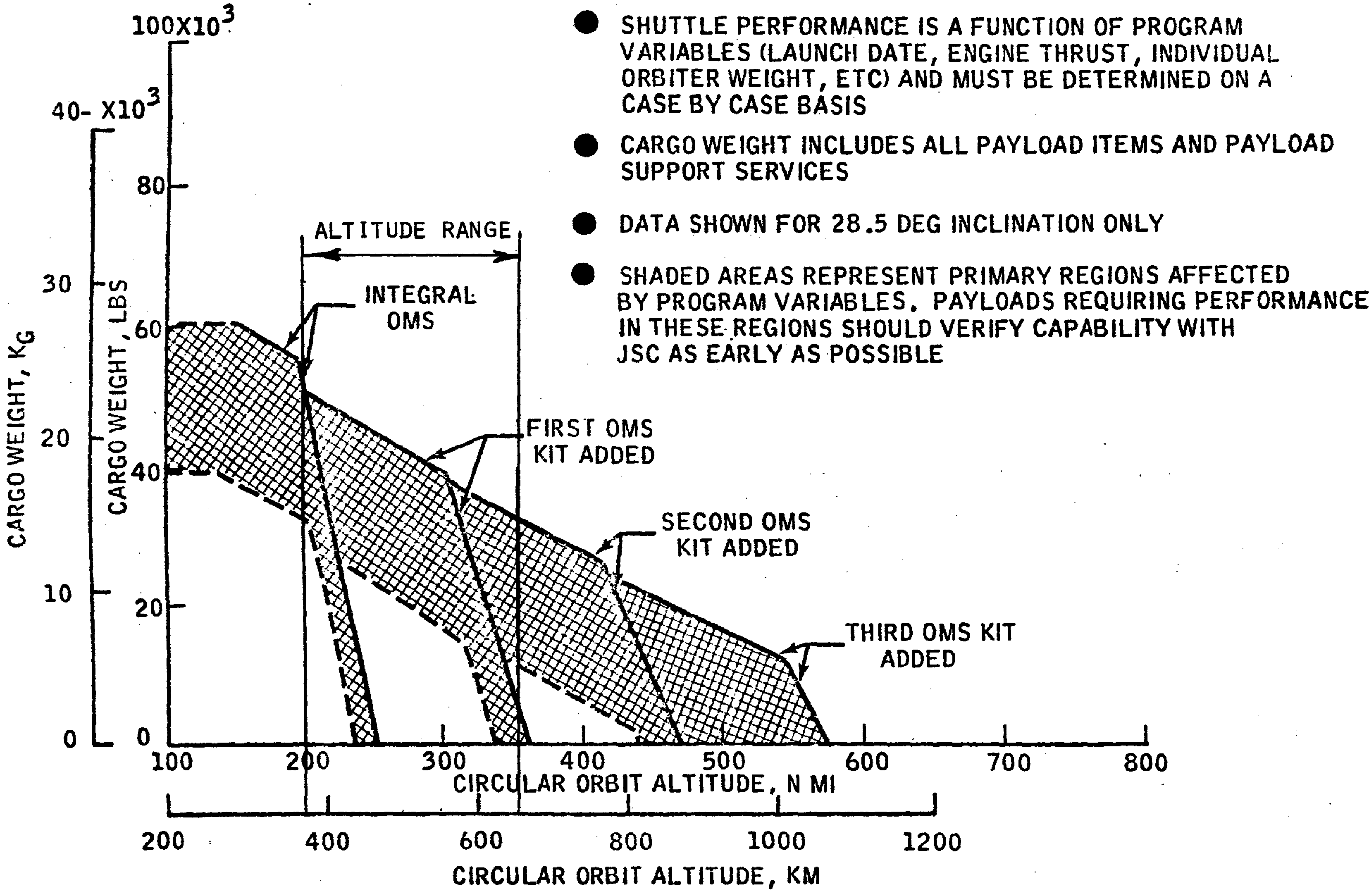


FIGURE 46
NEAR TERM CARGO WEIGHT VERSUS CIRCULAR ORBITAL ALTITUDE - KSC LAUNCH, DELIVERY ONLY

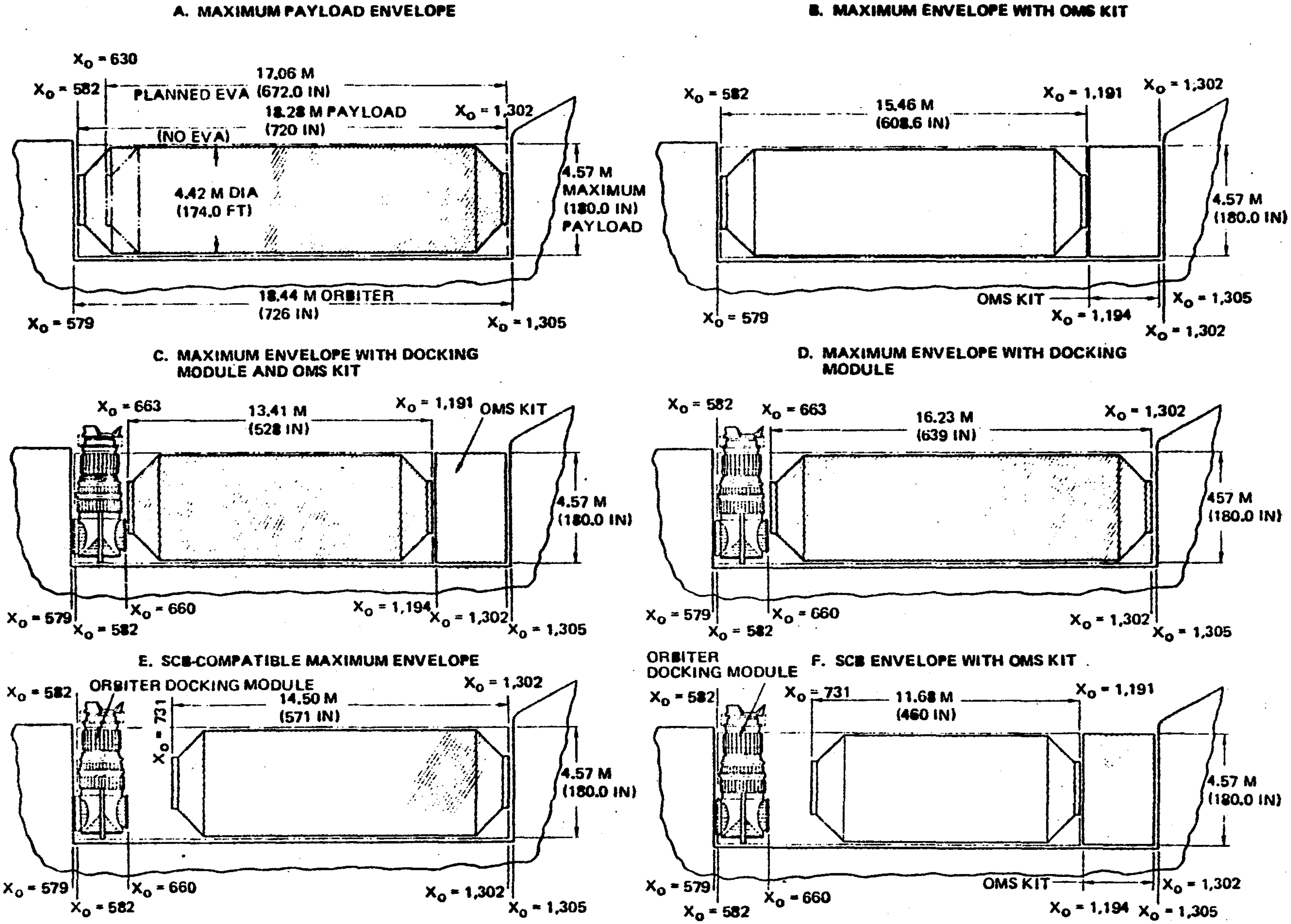
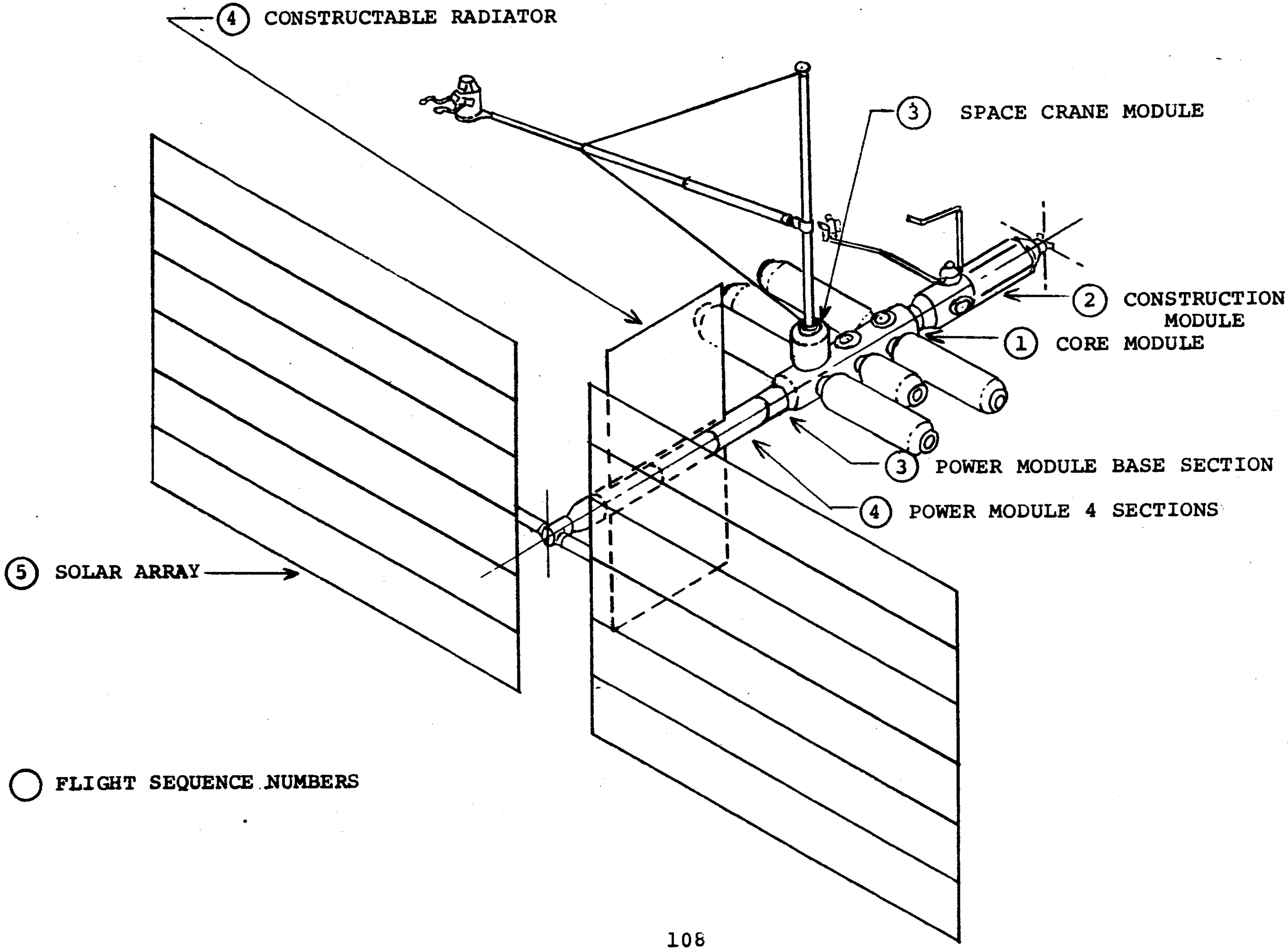


FIGURE 47 PAYLOAD ENVELOPE CONFIGURATIONS

(TAKEN FROM REFERENCE 12)

FIGURE 48 SPACE PLATFORM

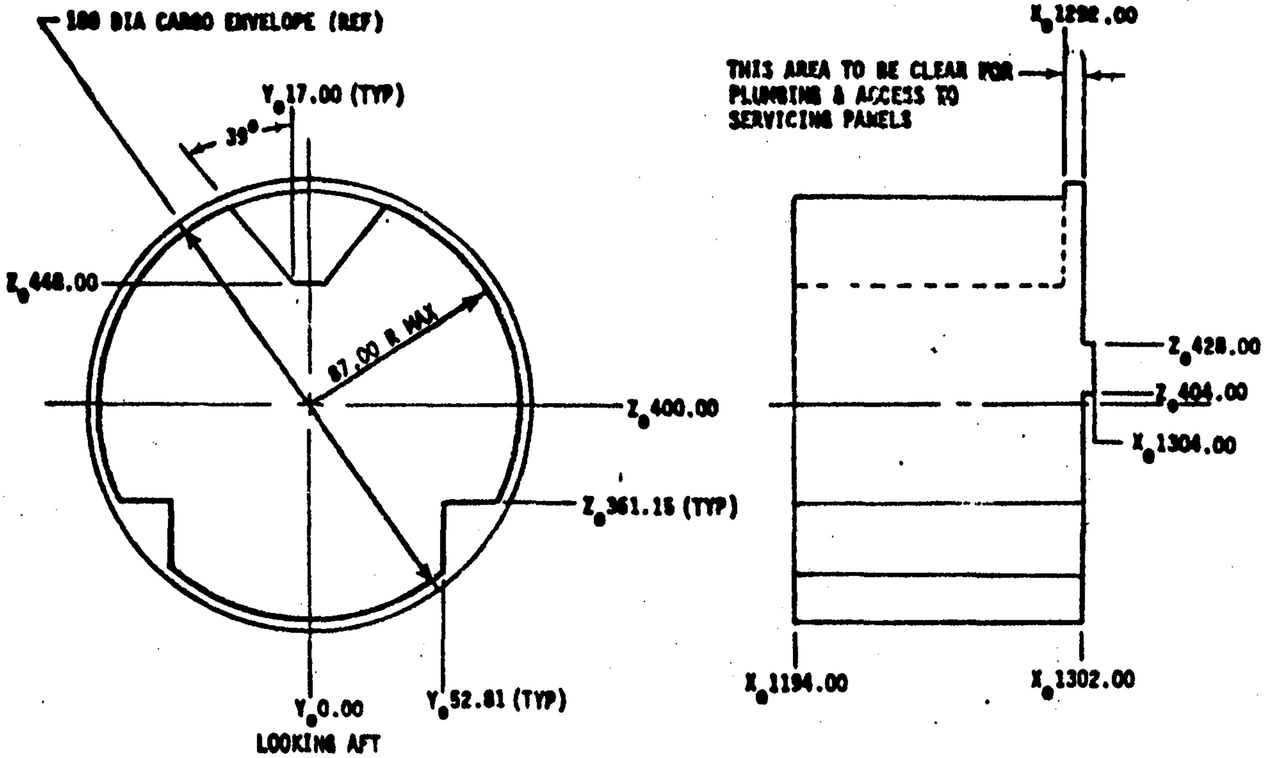


the far end of the Power Module during installation and deployment of the solar array which cannot be delivered until the next Shuttle arrives.

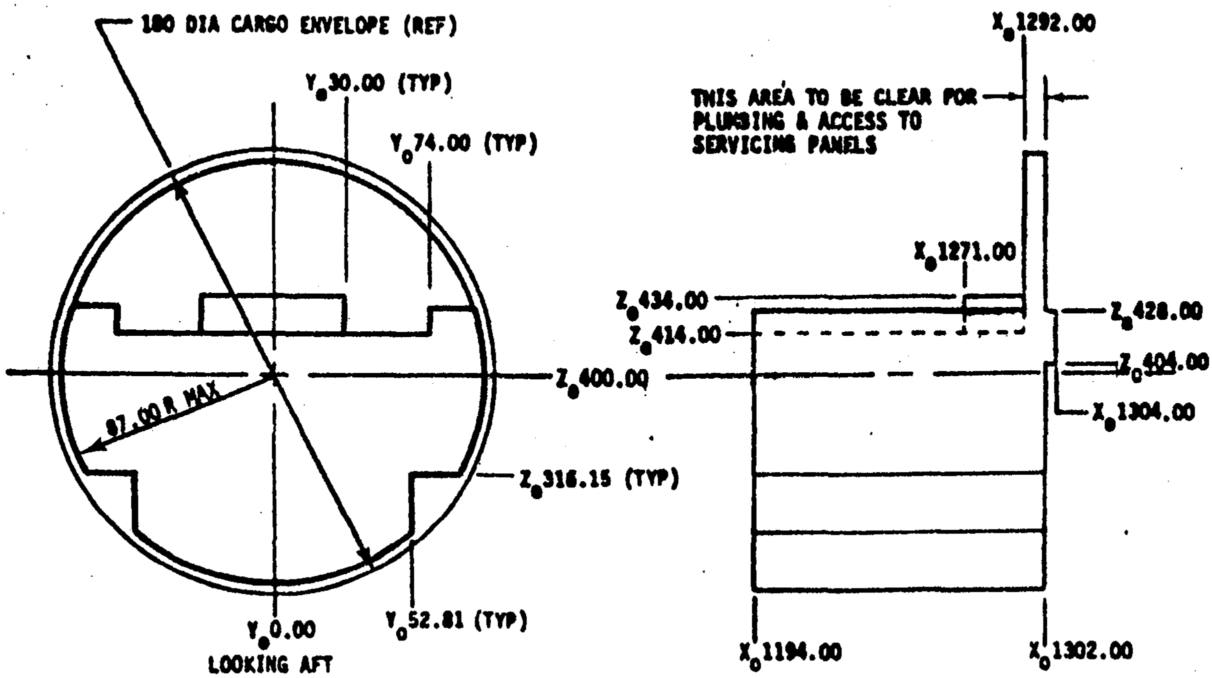
4) Solar Array - After the solar array is delivered and installed, the heat pipe constructable radiators are installed in the Power Module. This completes the installation sequence for the constructable radiators. The crew modules and other modules for operation of the space platform may now be installed as required.

4.2.2 Packaging for Delivery In The Orbiter

Packaging studies were performed to determine a configuration which would get both the Power Module and the heat pipe radiators into the Orbiter cargo compartment at the same time. The first effort was to determine the length of the Power Module. The radiators require a Power Module length of 48.7 m. In addition, one end of the Power Module requires a docking mechanism for connection to the core module, and the far end requires the solar array orientation and power transfer gimbal. A total length of 50.8 m was estimated for the Power Module. Using an Orbiter cargo bay configuration F envelope with OMS kit, Figure 47, a packaging configuration was established. Using the 500 feet per second (152 m/sec) OMS kit configuration, Figure 49, a packaging configuration of one 13.4 m length and three 11.0 m length power module sections was established. This provides for the 50.8 m Power Module considering that the 4.27 m base section is shipped on a separate previous flight. This packaging configuration is shown on Figure 50. This configuration allows a 1.72 sq. m cross sectional area for heat pipe radiator storage on the 13.4 m Power Module section. Using the storage configuration shown on Figure 51, only 1.13 sq. m are required for the 432 heat pipes. The excess cross section is sufficient to provide space for a mounting retaining structure to store the heat pipes on the Power Module until they can be erected in place after the solar array is installed. Details of the heat pipe mounting racks are given in Section 3.0. This packaging configuration allows for a Power Module diameter of 1.88 m which is sufficient for the internal heat pipe radiator heat exchangers and a 0.91 x 1.27 m crawl may be suitable for an EVA astronaut. Further studies are required to determine the exact structural and systems volume requirements for the Power Module cross section.



1500 FPS KIT ENVELOPE



500 & 1000 FPS KIT ENVELOPE

FIGURE 49 OMS KIT LIMIT ENVELOPES

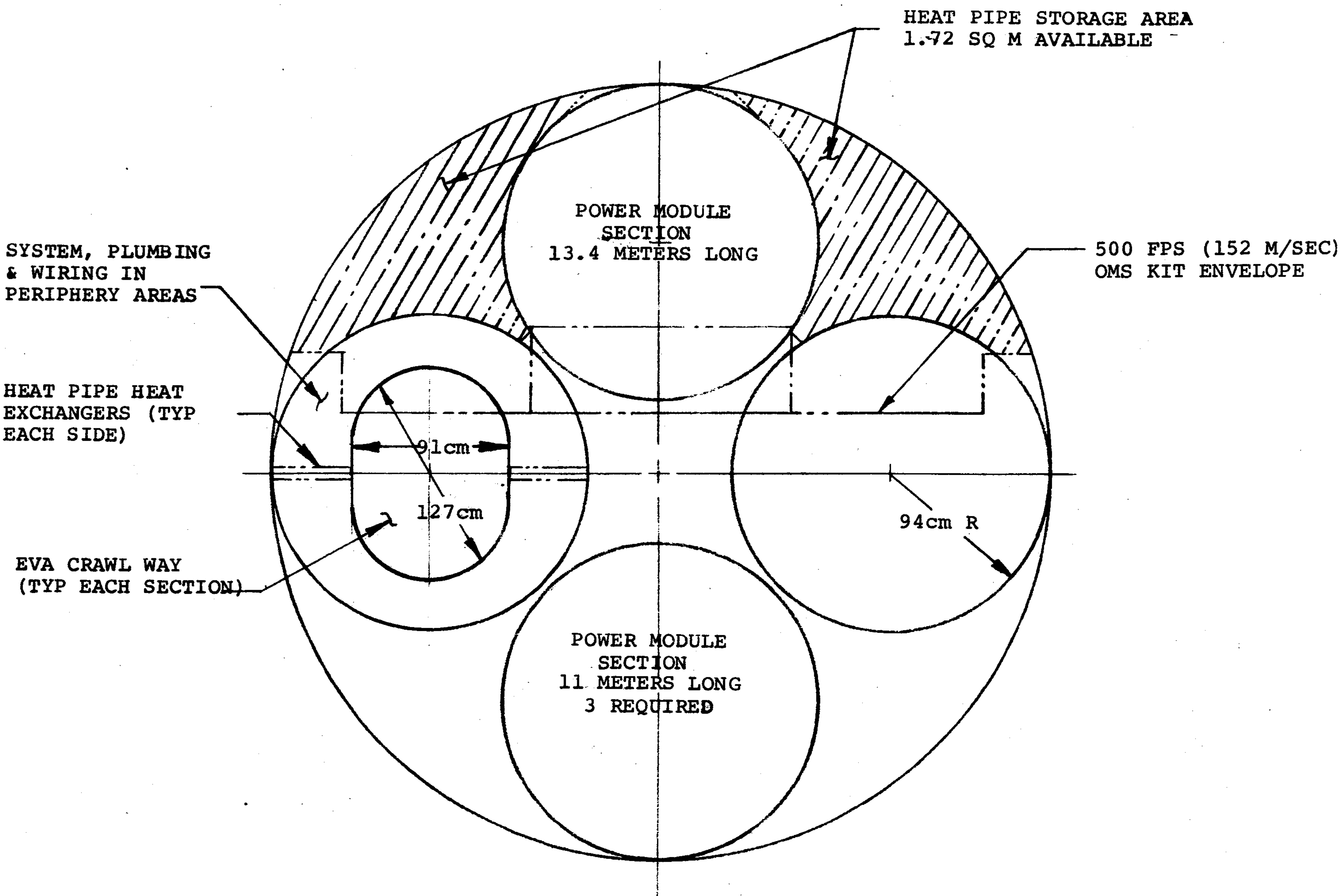
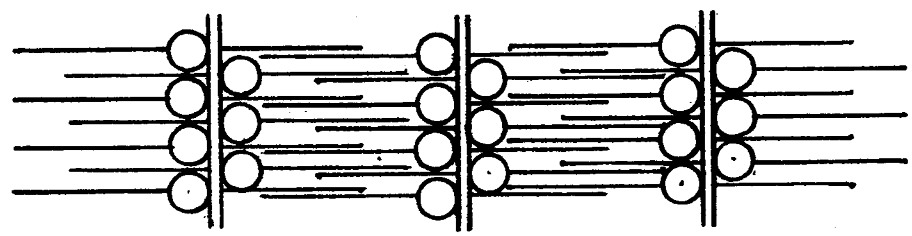


FIGURE 50 POWER MODULE & HEAT PIPE PACKAGING IN ORBITER CARGO BAY



432 HEAT PIPES WITH .64 cm DIVIDER BETWEEN ROWS AS SHOWN. CROSS SECTION AREA REQUIRED = 1.13 SQ. M

FIGURE 51
HEAT PIPE STORAGE CONFIGURATION

4.2.3 Radiator Storage on Unmanned Space Platform

The basic scenario used in this study included shipping the heat pipe radiators on the same flight as the Power Module. However, the assembly sequence requires that the Power Module be assembled from the core module outward. It is then most advantageous to install the solar array at the end of the Power Module before accessibility is obstructed by installation of the heat pipe radiators. For this assembly sequence the heat pipe radiators are stored on the sides of the 13.4 m Power Module section while the solar array is being installed as shown in Figure 52. For more information on the heat pipe storage racks see section 4.2.5.

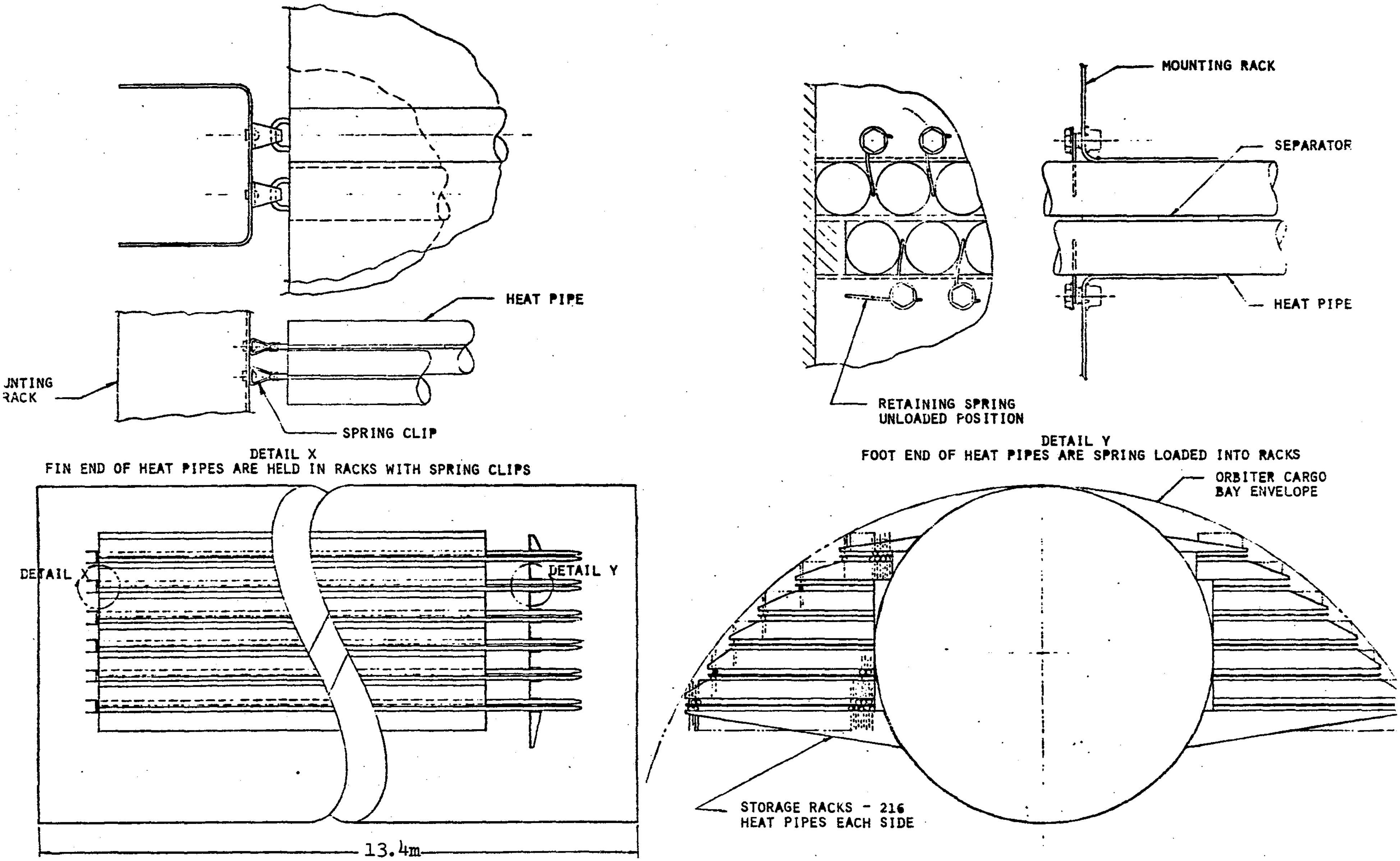
4.2.4 Installation on Power Module

Installation of the heat pipe radiators is made by use of the space crane and cherry picker. The heat pipes are picked up at the installation end, rotated and withdrawn from the storage rack mounted on the side of the Power Module. The heat pipe is then moved and rotated by the crane to the installation mounting hole where it is inserted, see Figure 53. Each heat pipe is clamped in place by its heat exchanger when it is properly in place. The heat pipe installation sequence is started at the far end. The pipes are installed one at a time working toward the core module until all pipes are installed on one side. The sequence is then repeated on the opposite side of the Power Module and from the opposite storage rack. The heat pipes will automatically key into position when installed in the heat exchangers. TV camera viewing will be required to align the heat pipes during insertion into the heat exchangers. A micro-switch or similar device at the end of each heat pipe will indicate when the heat pipe is in the correctly installed position.

4.2.5 Equipment Requirements for Assembly In-Orbit

Space Crane with Cherry Picker - A turret crane, the space crane, and EVA were studied for installation of the heat pipe radiator panels. Due to the length of the Power Module the turret crane was ruled out since its reach of 35m was insufficient. Installation of 432 panels on the outside of the Power Module is not considered practical as a scheduled EVA task. The best solution appears to be a space crane with a cherry picker. From an overview of the space platform it is apparent that the optimum location for a space crane is in the center of the platform which would require the shortest reach and also meet the requirements of other modules which require alignment and assembly of structural elements and installation of subsystem components

FIGURE 52 HEAT PIPE STORAGE RACKS MOUNTED ON SIDES OF 13.4 M POWER MODULE SECTION



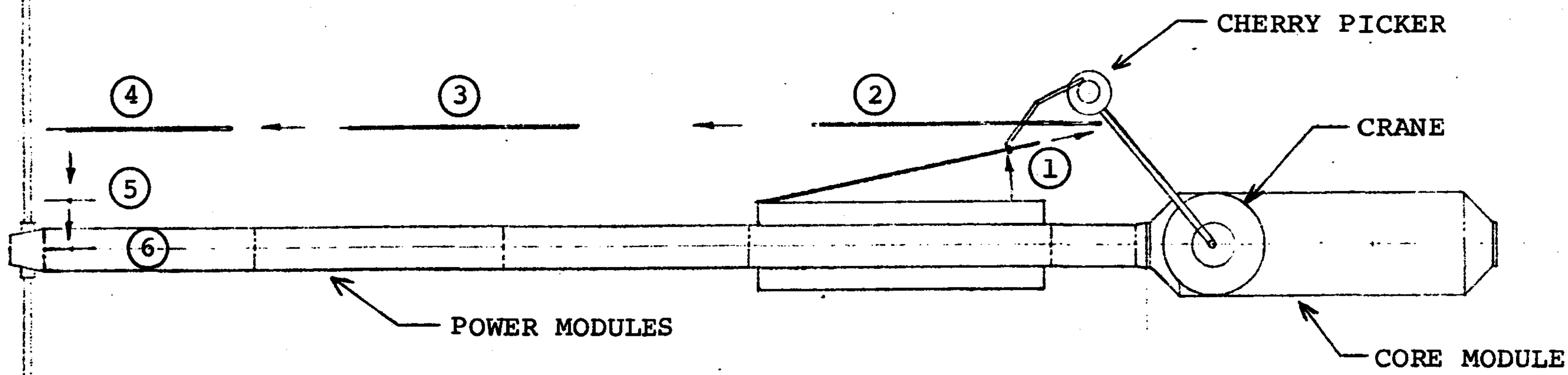
1. HEAT PIPE IS GRASPED IMMEDIATELY BELOW FIN & ROTATED OUTWARD FROM STORAGE RACK WITH TOP END REMAINING ATTACHED TO RACK. IT IS THEN PULLED AXIALLY FROM RACK.

2. HEAT PIPE IS NOW FREE FROM RACK

3. & 4. HEAT PIPE IS TRANSLATED TOWARD FAR END OF POWER MODULE WHILE BEING ROTATED 90° TOWARD INSERTION ORIENTATION.

5. HEAT PIPE IS NOW IN VERTICAL POSITION.

6. HEAT PIPE IS PLACED OVER INSTALLATION POINT AND THEN MOVED DOWN INTO THE MOUNTING HOLE.



- PLAN VIEW -

FIGURE 53

HEAT PIPE INSTALLATION SEQUENCE

and cabling. If the crane were mounted on the core module docking hatch nearest the Power Module it would require a reach of 20 feet through 185 feet to install the heat pipe radiators. Assuming that the crane is located as discussed, crane requirements for installation of heat pipe radiators would be as follows:

1) A reach of 6 to 56 meters.
2) A single arm is required to manipulate and position heat pipes up to 12.3 m in length x 23 cm wide x 2.5 cm thick weighing up to 16 kg.
3) The arm must be capable of orienting and positioning the end effector grapple point within 0.5 cm true position of the heat pipe installation and pick up points.
4) With the crane grapple fixture attached to the heat pipe it shall not impose a shear force greater than TBD newtons on the heat pipe while installed in the storage rack on heat exchanger. See Figure 54.

Grapple Fixture - A grapple fixture capable of picking up the 2.5 cm diameter heat pipe without damage is required, see Figure 55. The heat pipe will withstand a circumferential load of TBD lbs., a shear force of TBD lbs., and a bending moment of TBD lb/in.

Storage Rack - As previously discussed in Section 3.0, a storage rack is required to (1) contain the heat pipes during transportation, (2) store the heat pipes on the space platform prior to installation, and (3) act as a dispersor for the heat pipes during unloading/installation operations. A description of the storage rack is shown in Figure 52.

Installation Inspection Tools - Two inspection tools are used to determine when the heat pipes are correctly installed; a pressure transducer and a micro-switch. In addition a keyway is used to provide proper orientation of the heat pipe fins during installation. Figure 56 is a pictorial description of the installation inspection tools. These operations are as follows:

1) An alignment stripe will be marked on the heat pipe and at the heat pipe insertion hole to guide the installation of the heat pipe.
2) As the heat pipe nears the fully installed depth, the keys on the pipe will engage the keyway holes and rotate the pipe into the exact rotational orientation. When the heat pipe reaches

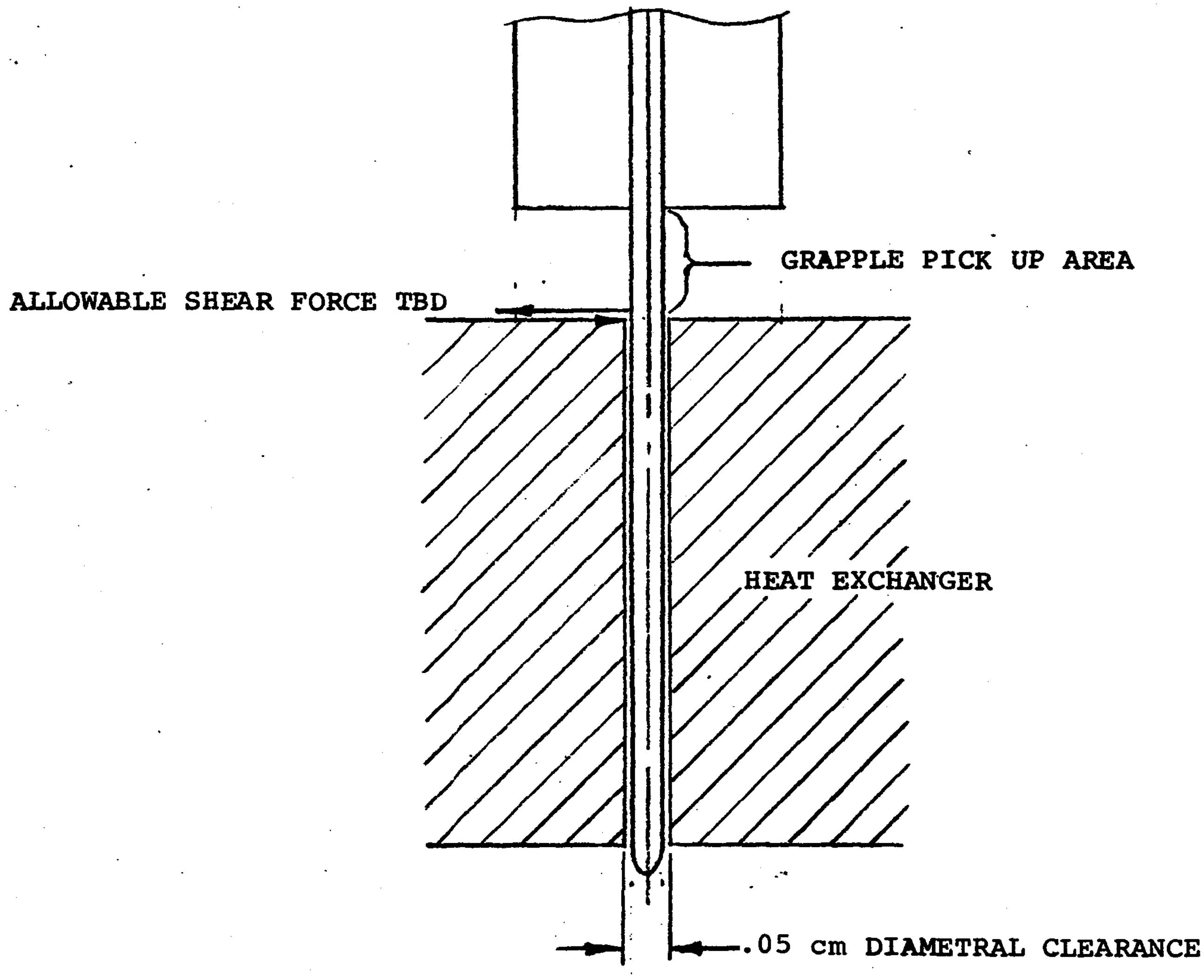


FIGURE 54
INSTALLATION LOAD

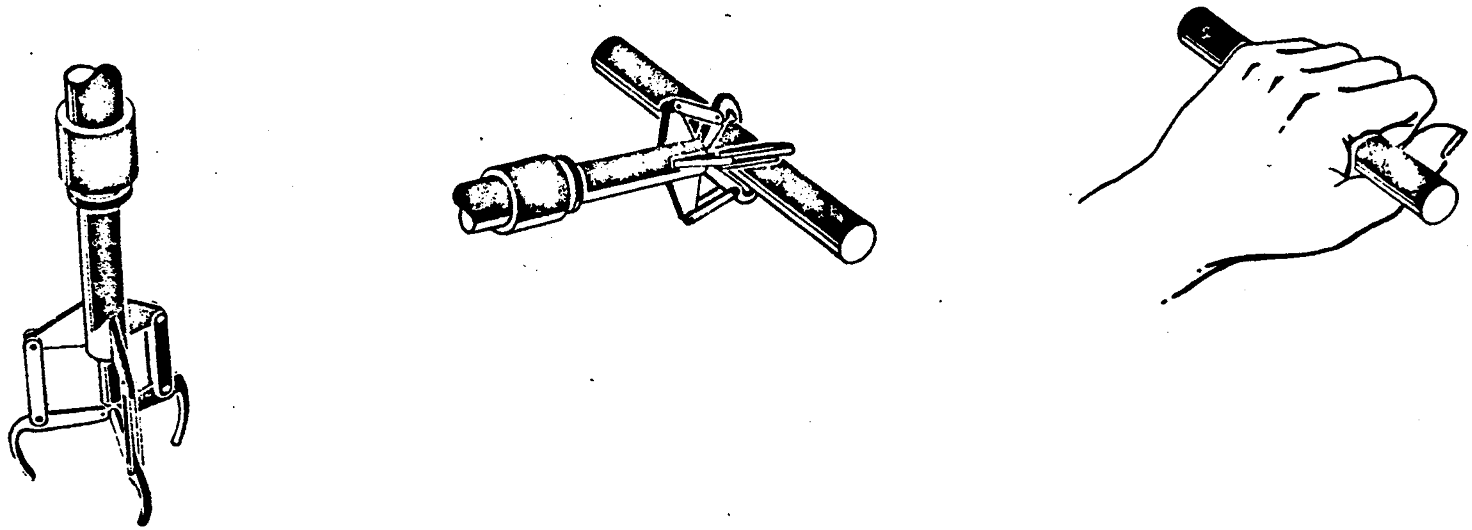


FIGURE 55
GRAPPLE FIXTURE - CLAW END EFFECTOR

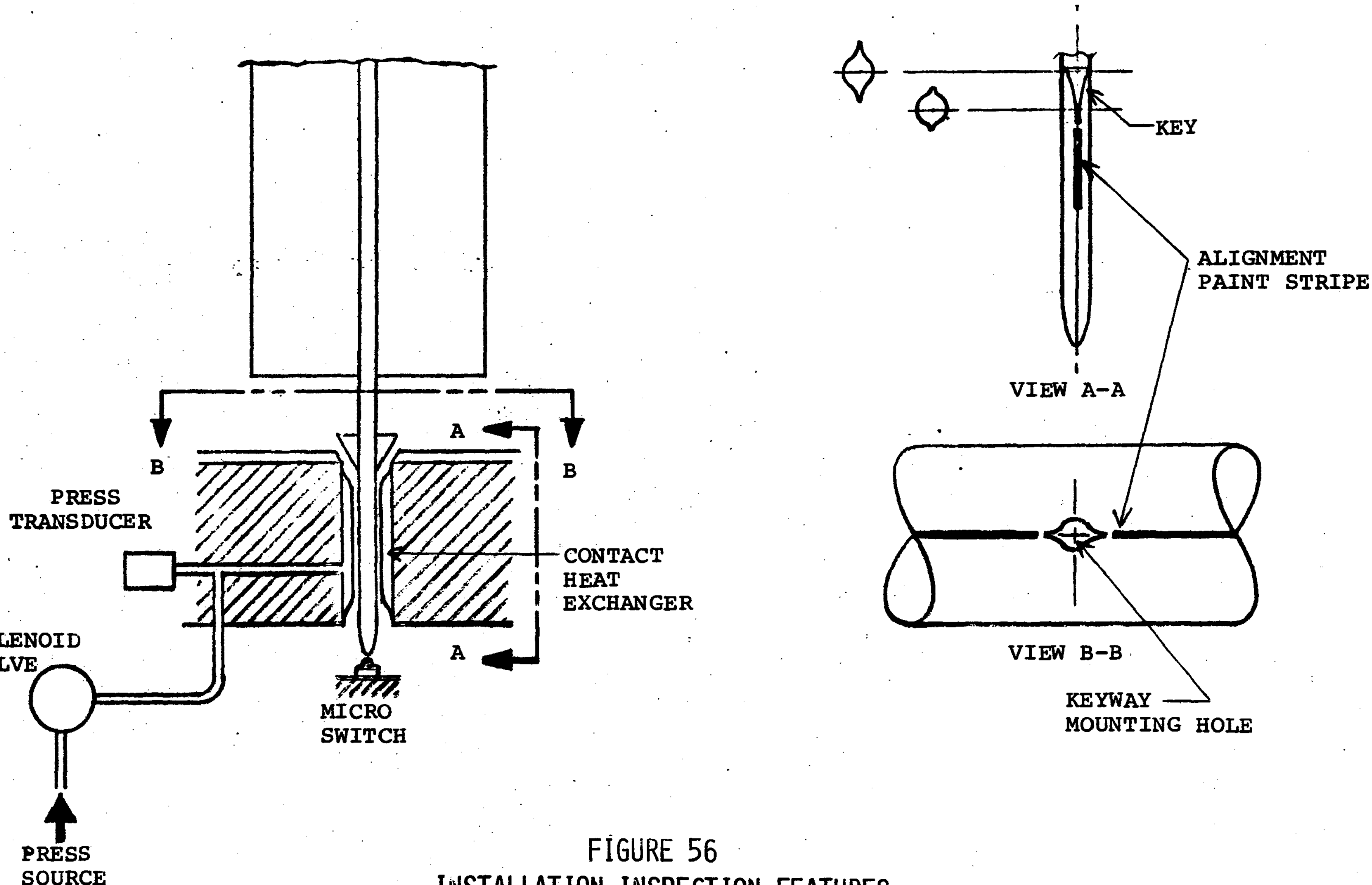


FIGURE 56
INSTALLATION INSPECTION FEATURES

the fully installed depth, it will engage the micro-switch which provides an indication in the control center. Until the heat pipe is rotated to the correct orientation it will not install to the full depth.

3) The contact heat exchanger is now pressurized to grasp the heat pipe and hold it in position. A pressure transducer is used to provide an indication in the control center when sufficient holding pressure is applied to the pipe.

4.2.6 Time Study

A time study was conducted for installation and installation inspection of the 432 heat pipes. The installation requires 2 men, one crane operator, and one technician in the control center to operate the controls for pressurizing the contact heat exchangers and monitoring the installation inspection system indicators. This time study includes only that time required for heat pipe removal from the storage racks, installation, and inspection of the 432 heat pipes. It does not include astronaut, crane, and grapple fixture preparation time to start the sequence of heat pipe installations. It does not include the time between shifts for the astronauts to prepare for this task.

To perform this task requires in the range of 84 to 230 manhours, or 42 to 115 hours for two men. Equating this to 4 hour shifts, it would take 10.5 to 28.8 shifts. Assuming 4 shifts per day, this would be 2.7 to 7.2 days.

5.0 RADIATOR COATINGS STUDIES

5.1 RADIATOR THERMAL COATING REQUIREMENTS FOR 250 kW SPACE PLATFORM

Ideally, the radiator coating would withstand mission environments and/or be capable of refurbishment on-orbit. The following are desirable physical properties to meet platform requirements.

1) Stable optical properties which solar absorptivity degrades 50% or less over 10 year life due to irradiation. Little change in emissivity.
2) Non-porous surface to minimize area for deposition of contamination.
3) Surface which is not conducive to sticking, absorbing or adsorbing contaminants and does not electrostatically attract particles.
4) Coating able to withstand wide thermal cycles.
5) Low outgassing characteristics.

There is currently no coating which has all these desirable properties. Current coating developments have been in the area of Teflon with vapor deposited metal and special white pigments such as Zinc Orthotitanate and zinc and aluminum oxide mixtures. The metal/Teflon coatings have been shown to significantly degrade on-orbit due to contamination and/or solar irradiance. The pigment coatings have shown some promise but cannot be cleaned, and there is no evidence that their susceptibility to contamination is any less than other coatings.

The smoothness and non-stick characteristics of Teflon would seem to make it an excellent candidate for a contamination resistant coating, however, degradation of solar absorptivity appears significant due to rocket engine exhaust products and other contamination (References 14 and 15).

5.2 REVIEW OF EXISTING RADIATOR COATINGS

A review was conducted of currently available radiator coatings. A list of the coatings and assessment of their key properties are shown in Figure 57. The most promising coatings are the silver Teflon and Zinc Orthotitanate (ZOT). The Teflon surface has the advantage of being easier to clean but the ZOT coating has higher emissivity with stable properties. The choice for a radiator coating will depend on many factors. One of these is expected solar exposure. If the radiators are orientable to avoid incident solar flux then solar absorptivity is not as important as emissivity.

FIGURE 57 RADIATOR COATING

COATING	SOLAR ABSORPTANCE	NORMAL EMITTANCE	MAXIMUM USE TEMP	THERMAL VACUUM STABILIZE	INSTALLATION PROCESS - APPEARANCE	HANDLEABILITY-DURABILITY	EASE OF CLEANING	REFURB METHOD	COST MATERIAL/ INSTAL.	PRIOR USE	SPEC	APPROX. WEIGHT
S13G-LO	0.22 spec 0.17 typ $\Delta\alpha \doteq .07$ @ 1500 ESH (S13G, OSO-III)	0.84 spec 0.89 typ	300°F	< 0.1% VCM < 1.0% TML	Spray Paint	Fair-Chips easily 0.010 inches thick	Fair Solvent Wipe	Brush	\$400/20 ft^2 high labor 45 min pot life-very short	Orbiter Hardware Numerous Satellite	Yes Vought	0.2 gm/in^2 Heavy
Silver Teflon Embossed	0.08 $\Delta\alpha \doteq 0.01$ to 0.03 @ 8000 ESH	0.80	250°F or 300°F if use 350° cure	< 0.1% VCM < 1.0% TML after bake	Hand layup autoclave cure-silver	Scratches easily; degrades in solar radiation after scratching	Fair Solvent Wipe	Hand layup-laborious	\$1400/33 ft^2 high labor	Orbiter Rads-P/L Bay door liner, Numerous Satellite	Yes Vought	0.215 gm/in^2 Heavy
Chromate Conversion Aluminum (Alodine)	0.05-0.15 $\Delta\alpha/\varepsilon$ = 0.09 @ 1800 ESH	0.35-0.50	350°F	Excellent	Brush or Dip-Mottled Streaky appearance-tan	Good-Can be scratched	Excellent Solvent Wipe	Brush	nil Matl. low labor	Orbiter Rads, Door Side FCA base plate, Pegasus	Yes MIL	-0-
Clear Anodize Aluminum	0.15 $\Delta\alpha$ = 0.1 - 0.2 @ 700 ESH	0.75	350°F	Excellent	Tank electro-process-modified sulphuric acid	Excellent	Excellent Solvent Wipe	Tank Strip & Tank Electro process	nil Matl. Moderate Labor	None - Requires Lab work & Space Prep.	None AFML Lab.	-0-
A-276	0.22 $\Delta\alpha$ = 0.15 after 1000 hrs solar radiation	0.8	200°F	< 0.1% VCM < 1.0% TML after bake	Spray Paint White, polyurethane Binder	Excellent	Excellent Solvent Wipe	Brush or Spray Touch Up	\$100/400Ft^2 Moderate Labor	Orbiter Hardware	Yes Rockwell	0.02 gm/in^2
Koropon	0.38 $\Delta\alpha$ Unknown	0.8	350°F	< 0.1% VCM < 1.0% TML after bake	Spray Paint Green Epoxy Binder	Excellent After Solar Radiation, Resists R-21	Excellent Solvent Wipe	Brush Touch Up	\$70/400 ft^2 Moderate Labor	Orbiter Hardware	Yes Rockwell	0.01 gm/in^2

FIGURE 57 RADIATOR COATING (CONT)

COATING	SOLAR ABSORPTANCE	NORMAL EMITTANCE	MAXIMUM USE TEMP	THERMAL VACUUM STABILIZE	INSTALLATION PROCESS - APPEARANCE	HANDLEABILITY-DURABILITY	EASE OF CLEANING	REFURB METHOD	COST MATERIAL/ INSTAL.	PRIOR USE	SPEC	APPROX. WEIGHT
NS43C Inorganic Yellow Coating-Static Charge Relief (Goddard)	0.20 $\Delta\alpha$ = 0–0.02 @ 1000 ESH	0.92	300°F	Excellent After Bake	Spray Paint Yellow/White $ZnO + Al_2O_3$ Silicate Binder	Fair, expect ground $\Delta\alpha$	Fair - Deionized Water	Unknown	Unknown-lab quantities only at present high labor	ISEE	No, Hand Made At Goddard or G.E.	60 gm/ft^2 Heavy
Zinc Ortho-titanate (Zn_2TiO_4) (Marshall)	0.14 $\Delta\alpha$ = 0.01 after 5000 hrs, low orbit, 0.10 inches thick	0.88	+600°F	Excellent	Spray Paint White Potassium silicate binder	Poor, expect ground $\Delta\alpha$	Not Cleanable	Strip & Re-Spray No Brushing	Hand Made Pigment by IITRI High Labor	AF Sat. by Aerospace α = 0.17 α = 0.24 after 1 yr GEO orbit	Same as Z-93 for Process, None for Pigment	Twice that of Z-93, heavy
MS-74 (Goddard)	α/ε = 0.19 = 0.23 $\Delta\alpha/\varepsilon$ = 0.01 OSO-H @ 8000 ESH		+500°F	Excellent	Spray Paint White, $ZnO + Al_2O_3 + TiO_2$; Potassium silicate	Fair, expect ground $\Delta\alpha$, 3 yr shelf life	Unknown-Wrap in Poly Bag to Protect, light Sanding to Clean	Brush Touch Up	Hand Made Pigment by NASA Goddard High Labor	OSO-H, IMP-H, ATS-b, Apollo experi.	No, Tech Memo 78086 gives M& P details	0.036 lb/ft^2
Z-93	0.17 $\Delta\alpha$ = 0 @ 2500 ESH	0.9	+600°F	Excellent	Spray Paint Zinc Oxide, Potassium Silicate	Poor, $\Delta\alpha$ = 0.05 on ground	Not Cleanable	Brush Touch Up	Hand Made Pigment by IITRI High Labor	Numerous Apollo Radiator	Yes	Approx. 0.04 lb/ft^2

Expected mission operations and radiator configuration as well as operational considerations are important to the selection of the best coating.

5.3 CONTAMINATION OF RADIATOR COATINGS

A study of degradation of thermal control surfaces of satellites has indicated contamination of these surfaces is a large contributor (Reference 14). On a very large vehicle such as a Multi-Hundred Kilowatt Space Platform sources of contamination would be prolific. Sources of contamination effecting TCS coatings which have been identified generically include:

- Material Offgassing
- Material Outgassing
- Rocket Engine Combustion Products
- Particulates
- Leakage and Pressurized Compartments
- Effluents from Experiments
- Orbiter Visits

The net amount of mass deposited on the thermal control surfaces was modeled in Reference (15) as:

Net Mass Depositing = (Mass Adsorption - Mass Desorption)

or

$$D = (F(I-J)\ S(I-J)\quad t) - (5.83 \times 10^{2}\ P_v (M/T)^{1/2}\quad t)$$

where:

D = Deposition in g/cm^2

$F(I-J)$ = Flux on surface 1 from source J

$S(I-J)$ = Sticking coefficient (unity or zero)

T = Temperature ^{o}K of surface I

t = Time interval $F(I-J)$ and T are constant

= Desorption coefficient

P_v = Vapor pressure at temperature of surface I

M = Molecular weight

Consideration of this model and the sources of the potential contamination are discussed below including possible methods of reducing and avoiding contamination from the identified sources.

5.3.1 Material Offgassing

Offgassing is the relative high mass loss characteristic of many non-metallic materials upon initial vacuum exposure. Offgassing is related to the volatiles which are either adsorbed or absorbed by the material and/or carried in the preparation of a material. After some period of time the mass loss will decrease to a long term steady state value (outgassing). The nature and amount of offgassing is, of course, a function of the material and previous history. Avoidance of offgassing contamination (by reduction of the mass flux (F(I-J)) of thermal control coatings can be accomplished by careful materials selection of spacecraft non-metallics which are low in offgassing. Vacuum exposure prior to spacecraft installation can also reduce the amount of offgassing.

Configurational and operational techniques can also be used to reduce offgassing contamination. These would essentially reduce the area of the thermal control surface which is in the line of sight of the offgassing material and thus reduce F(I-J) in the above equation through reduction of the "view factor". Location of thermal control surfaces out of the line of sight of known offgassing materials could be accomplished to the greatest extent possible. If the thermal control surface is on a deployable structure such as deployable radiators complete deployment could be delayed during the initial offgassing period.

5.3.2 Material Outgassing

Outgassing is the non-metallic characteristic of continuous mass loss over a long period of time resulting from the material bulk characteristics. The majority of deposition observed on Skylab was the result of outgassing of non-metallic materials (Reference 15). Criterion have been established (Reference 16) and lists of approved materials generated (Reference 17) to insure use of low outgassing materials on past and current spacecraft such as the Skylab and Shuttle Orbiter. It is expected, however, that outgassing will be a major contamination source on Orbiter as it was on Skylab.

To avoid this source to the greatest extent possible on a large multidiscipline spacecraft such as a Large Space Platform, strict guidelines on exposed non-metallic materials are required. Some outgassing, however, will always be present since such items as solar panels and multilayer insulation will continuously outgas. In addition, some element of outgassing from the thermal control coating itself can return to the surface or be deposited on other thermal control surfaces.

Reduction in the "view factor" to outgassing materials by locating thermal control surfaces out of the "line of sight" of the outgassing surfaces as much as possible. Operating at higher temperatures would have some benefit however, the above equation indicates this effect would be marginal on a non-porus coating which would reduce the surface area for deposition. Reference 14 data indicated more rapid solar absorptance degradation for porus cloth coatings than for silver Teflon. A non-porous coating would also be easier to effectively clean for refurbishment.

5.3.3 Rocket Engine Combustion Products

Rocket engine operation associated with the stability, orbital maneuvers, periodic reboost, resupply and other possible platform uses will result in a significant contamination source. Upon accumulation, this material causes a significant increase in solar absorptivity. Figure 58, taken from Reference 15, shows a plot of solar absorptivity vs deposition of bipropellant engine exhausts for two coatings. Thermal control surfaces which are in the exhaust plume are more directly affected, however some back flow of exhaust products can contribute to overall contamination. A long duration mission such as is the case for a large platform would make radiators especially susceptible to a long term accumulation of exhaust products.

Configurational and operational technique would appear the only methods which could potentially reduce the impact of this contamination. Thrusters for attitude control and/or radiators should be located to prohibit exhaust plume impingement on the radiator surfaces. When a large engine is to be fired such as for reboost or servicing the radiators could be retracted into a stowed position to prevent contamination. Shielding of the radiator surfaces from exhaust products could also be considered for an unavoidable continuous source.

5.3.4 Particulate Matter

Particulate matter can be transported to orbit on spacecraft surfaces or generated on-orbit as a consequence of material wear, micrometeoroid impact, or embrittlement and flaking of protective materials when exposed to space radiation and thermal cycling. Particles could be deposited on radiator surfaces electrostatically and thereby affect the coating properties. Methods to prevent particulate contamination mostly center on prevention. A model of particulate sources has not been attempted previously. Strict cleanliness requirements for the spacecraft and experiments, encapsulating moving joints and use of materials which do not tend to produce particulation under mission conditions would be effective methods of reducing contamination by particles.

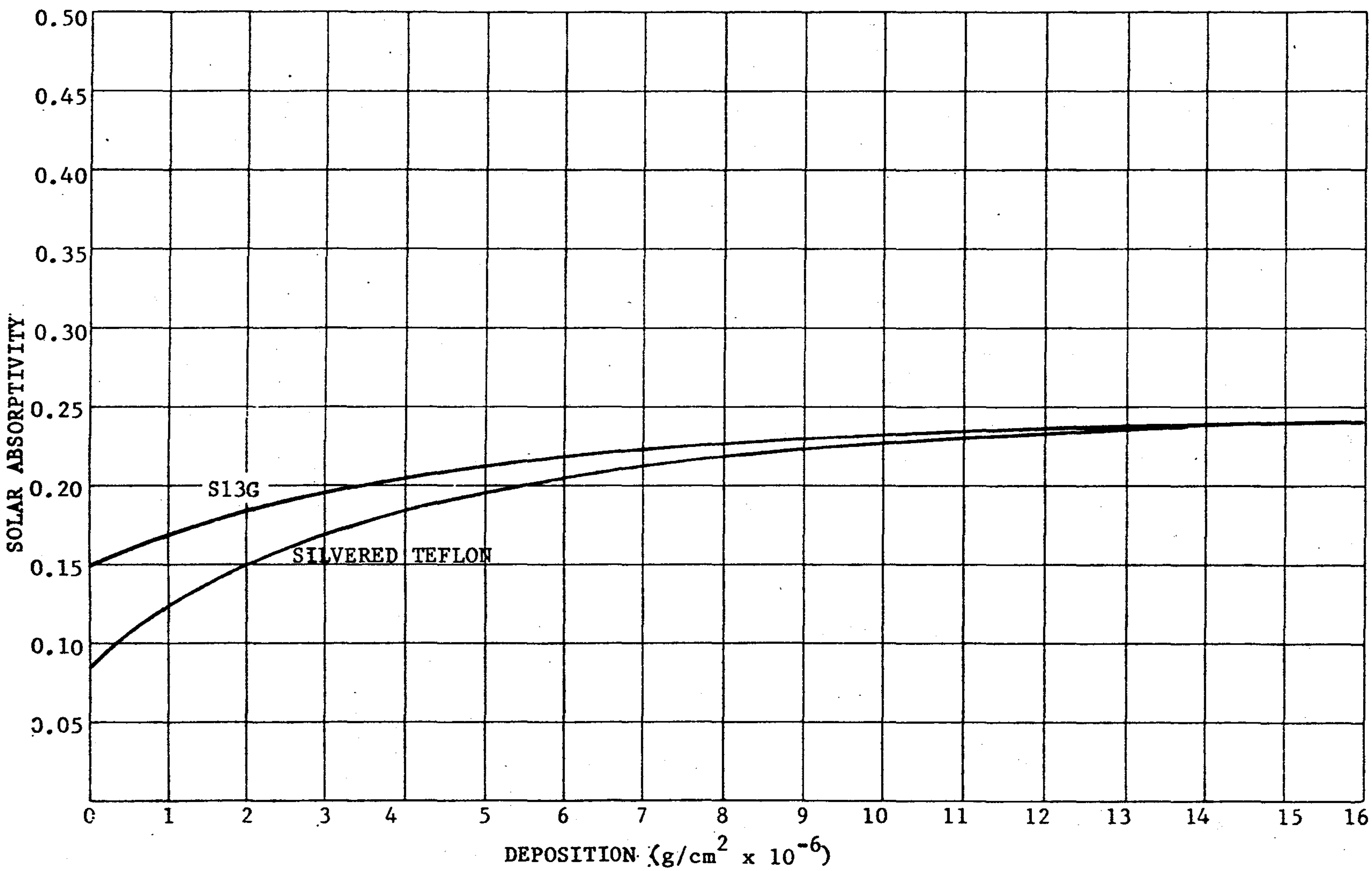


Figure 58 Absorptivity as a Function of Deposition for Bipropellent Engine Exhausts

5.3.5 Leakage from Pressurized Compartments

Leakage from habitated modules will likely continuously emerge from structural seams, hatches, microscopic cracks and seals around support hardware such as instrumentation feedthroughs. Leakages have historically been significant being 1.7 kg/day from the Skylab and are expected to be about 3.2 kg/day from the Orbiter. More would be expected from the platform due to the larger pressurized volume.

Leakage contaminants from these compartments will consist primarily of: 1) normal atmospheric gases, 2) internal materials and black box outgassing products, 3) astronaut byproducts, 4) frictional erosion creating particles from materials subject to abrasion, and 5) evaporation from liquid sources.

The normal cabin atmosphere leakage will likely not condense on radiator surfaces since these gases have desorption rates that exceed impingement rates of these gases. The second source of leakage products is from outgassed materials in the crew compartment interior. Total contribution from this source to the contaminant environment should be negligible. The third source, astronaut by products, are elements and compounds such as CO_2 emitted orally and dermally plus flatus and some fecal and urine products which escape their containers and should also present no problems. The fourth source, frictional erosion particles, will in the majority of cases be too large to pass through microscopic leakage orifices and will be removed from the cabin atmosphere through the Environmental Control Life Support System (ECLSS) debris filters. The last source identified is vapor evaporated from liquid sources. Much of this moisture will likely be collected by ECLSS condensate systems along with various condensibles and water soluble products in the atmosphere.

This source of contamination should not affect the thermal control coatings significantly.

5.3.6 Effluents From Experiments and Solar Array

The addition of the unmanned module which may support a number of different types of payloads and experiments provides an additional potential source of contaminants. The amount and type of contaminant is highly dependent on the type of experiment. Figure 59 illustrates the amount and type of effluents which are expected from currently planned Spacelab experiments. Most of these effluents are non-condensible gases and would not

TECHNOLOGY AREA	ELEMENT	COLUMN DENSITY (MOLECULES/CM^2)	PERCENTAGE TIME* OPERATED	
• PLASMA PHYSICS	A	3.7×10^{14}	13	
PLASMA	N_2	2.0×10^{18}	13	
	H_2	1.3×10^{16}	49	
• ATMOSPHERIC PHYSICS	N_2	3.4×10^{14}	28	
• HI ENERGY PHYSICS	X_e	5.4×10^{11}	100	
	H_e	1.1×10^{13}	100	
	CO_2	5.4×10^{11}	100	
	X_e	1.4×10^{13}	~1	
	CH_4	3.7×10^{12}	~1	
• IR ASTRONOMY	H_e	1.6×10^{13}	100	
• TECHNOLOGY	H_e	2.6×10^{13}	100	
• FLUID AND AEROSOL DYNAMICS	N_2	4.6×10^{14}	TBD	
	O_2	1.1×10^{14}	TBD	30
	H_e	1.1×10^{17}	TBD	

*NOMINAL LIMIT - OSS PAYLOADS - $\leq 10^{12}$ MOL./CM^2

FIGURE 59

CONTAMINATION EFFLUENTS – SPACELAB EXPERIMENTS (SL 1, 2, 3) affect radiator surfaces. Other expected experiments such as materials processing, however, may have effluents which could affect radiator optical properties. Since materials experiments are potentially so diverse it is impossible to identify these substances at this time. Placement of these types of payloads as much out of the radiator line of sight as possible would minimize effect of any damaging contamination.

The solar array itself is a source of contamination which could be potentially significant because of its large area. Figure 60 shows the physical factors involved in solar array contamination and the results of analysis of the contamination from the solar panels. The effect of this contamination on radiator surfaces is unknown and further study will be required to obtain long term degradation data. It would be very difficult to configurationally prevent coating contamination from this source due to the large size of the solar array. Solar panel design to reduce the amount of harmful contamination would seem to be the most effective method of prevention of coating degradation.

5.3.7 Orbiter Visits

The Orbiter vehicle is a source of all the contaminants listed previously. The most damaging of these to radiator properties is likely to be rocket engine exhaust products. Some firing of RCS and VCS engines will be necessary to approach and dock with a platform. Location of the radiators should be considered in Orbiter maneuvers in the vicinity of the Platform. If possible, the radiators could be protected or retracted during Orbiter visits to protect the surfaces or if the radiators have orientation capability they could be placed in the most favorable position to avoid contamination from the Orbiter during these mission phases.

5.3.8 Contamination Minimization

Contamination can be minimized by certain design, materials, processes and operational approaches. Figure 61 lists the contamination sources that were discussed earlier along with some contamination to a minimum. The matrix indicates which approach applies for each of the contamination sources.

The design approaches which can minimize the contamination include location of thermal control surfaces, and moving joint encapsulation. The materials and processes methods include material selection for low outgassing, offgassing and particulate matter, prelaunch vacuum exposure, selection of a

- **OUTGASSING**
  - ADHESIVE ON SOLAR CELL COVERS – DC93-500
  - ADHESIVE BETWEEN KAPTON SHEETS – HIGH-TEMPERATURE POLYESTER
  - ADHESIVE ON FIBERGLASS CLOTH – TFE TEFLON HINGE STRIPS BONDED TO KAPTON PANELS – HIGH-TEMPERATURE POLYESTER
  - SOLAR ARRAY VERTICAL AND HORIZONTAL PADDING – RTV 511 OR 577 SILICONE
  - LUBRICANTS ON ARRAY GIMBAL AND DEPLOYMENT CANISTERS
  - S GLASS/POLYIMIDE LONGERONS AND BATTENS

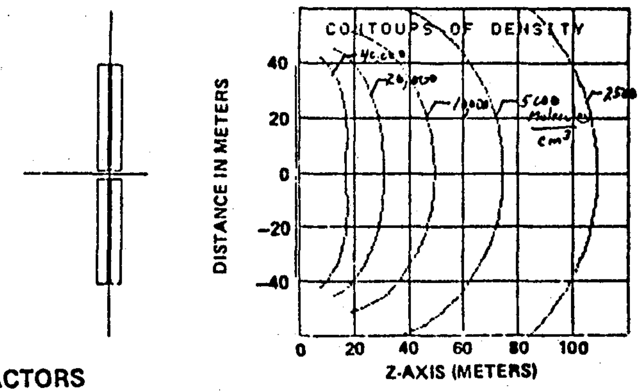
- **PARTICULATES**
  - DRY LUBE USED ON SOLAR ARRAY TENSIONING SYSTEM (DRUMS, REELS, SHAFTS)
  - FIBERGLASS CLOTH – S GLASS EPOXY HINGE PINS
  - DACRON BRAIDED CORD/PANEL EYELETS
  - MATERIAL WEAR DURING EXTENTION – RETRACTION OF COILED MAST (ALUMINUM DEPLOYMENT NUT, ALUMINUM ROLLER LUGS, ROTATABLE NUT, ROLLER GUIDE, DRIVE MOTOR, STEEL BEARINGS IN ALUMINUM TURNTABLE, S.S. KAYDON BEARINGS, AND VESPEL PINION GEARS)
  - THERMAL COATINGS ON LONGERONS/BATTENS
  - MICROMETEOROID IMPACT ON SOLAR CELL COVERS, LONGERONS, ETC.

BASED ON LMSC-D492693, MID-TERM REPORT, 18 JANUARY 1977

☐ = Acceptable Material Test Results

Potential Contamination Sources PM Array

SOLAR PANEL GEOMETRY AND CLOUD SHAPE



PHYSICAL FACTORS
- AREA – FLAT – 5.9×10^6 cm^2
- RATE – 10^{10} MOLECULES/(cm^2 SECOND)
- COLLISION X SECTION – 7.3×10^{-16} cm^2 ATOMIC OXYGEN VERSUS WATER
- AMBIENT DENSITY – 40:1 RANGE $1.6 \times 10^{+7}$ TO 6.6×10^8 MOLECULES/cm^3
- COSINE OUTGASSING PATTERN
- MEAN FREE PATH = f (DENSITY AND CROSS SECTION)

COMPUTATION METHOD
- 0.1 PERCENT CALCULATIONS FOR 1.0 PERCENT ACCURACY
- COORDINATE SYSTEM – PANEL CENTERED
- VARY PANEL ZONE AREA FOR REQUIRED ACCURACY

RESULTS

CONFIGURATION	AMBIENT (MOLECULES/cm^3)	Z-AXIS COLUMN DENSITY (MOLECULES/cm^2)
LOW AMBIENT –	1.6×10^7	1.601×10^8
MID AMBIENT –	7.6×10^7	1.595×10^8
HIGH AMBIENT	6.6×10^8	1.565×10^8
ARBITRARY AMBIENT	6.6×10^9	1.319×10^8
ARBITRARY CROSS SECTION X 10, 6.6×10^8/cm^3		1.319×10^8

Column Density - Analysis

FIGURE 60 CONTAMINATION FROM POWER SYSTEM

FIGURE 61 RADIATOR COATING STUDIES

CONTAMINATION SOURCES AND POSSIBLE METHODS OF MINIMIZING IMPACT ON THERMAL CONTROL SURFACES

	METHODS OF IMPACT MINIMIZATION									
	MATERIAL SELECTION	PRELAUNCH VACUUM EXPOSURE	LOCATION OF THERMAL CONTROL SURFACE	RADIATOR RETRACTION	DELAYED DEPLOYMENT	COATING SELECTION	MANEUVERING CONSTRAINTS	SHIELDING	CLEANLINESS	MOVING JOINT ENCAPSULATION
OFFGASSING	X	X	X	X	X	X				
OUTGASSING	X	X	X			X		X		
ENGINE PRODUCTS			X	X		X	X	X		
PARTICULATES	X								X	X
LEAKAGE FROM PRESSURIZED COMPARTMENTS	IMPACT ON TCS SURFACES PROBABLY NOT SIGNIFICANT									
EXPERIMENT EFFLUENTS			X					X	X	
ORBITER VISITS			X	X			X	X		
EVA	X						X		X	

coating not susceptible to contamination, and cleanliness procedures during manufacture and assembly. Operational methods of contamination reduction include radiator retraction during Orbiter docking, delayed deployment until after the Orbiter has left and maneuvering constraints to minimize use of maneuvering engines.

5.4 ON-ORBIT CLEANING AND REFURBISHMENT OF RADIATOR COATINGS

5.4.1 Cleaning

Techniques to clean the Orbiter panels on the ground have been developed. These techniques use a solvent consisting of a 50/50 mixture of Trichloroethane and methyl alcohol. Use of this technique on orbit would require a pressurized area in which to clean the panels. A low vapor pressure solvent could perhaps be developed for vacuum cleaning, however, none has currently been identified. Some additional contamination would be generated in the cleaning process which might interface with experiments and sensors. Rubbing of the Teflon surface with a dry, lint free cloth would be of doubtful benefit since it has not proved effective on the ground. The same problems exist for cleaning of painted surfaces in vacuum, however, some are cleanable in pressurized areas. Some coatings such as Zinc Orthotitanate and Z93 are reported to not be cleanable due to their porosity. The contaminant tends to permeate the entire coating thickness and the coating tends to soak up solvent. A coating could possibly be developed which is not so porous and could be cleaned by abrasion such as sanding. This would create additional particulate contamination on orbit which would have to be accommodated. This type of cleaning, however, would lend itself well to on-orbit activity.

The conclusion from an investigation of on-orbit cleaning is that no currently available coating is easily cleaned on-orbit. The metal/Teflon and some other coatings could be cleaned in a pressurized container where a solvent could be used. An on-orbit cleanable coating will require a development effort of both the coating and the cleaning method and equipment.

5.4.2 On-Orbit Coating Refurbishment

There are currently three general types of coatings, tape coatings such as silver Teflon and aluminum Teflon applied with an adhesive, paints which are sprayed or brushed on and metal treatments such as alodine and anodize. Refurbishment of the alodine or anodize coatings on-orbit would be prohibitive and spraying coating on-orbit would require zero-g experimentation to prove feasibility. A paint or trowol on type of coating would be feasible with a low vapor pressure viscous binder such as a silicone base. The exact properties of such a refurbished coating would have to experimentally be determined in a development program. The other possibility for on-orbit refurbishment is the metal tapes such as silver Teflon. The silver Teflon coating on the panels can be easily removed. New tape with a room temperature core adhesive can then be installed on the radiator surfaces. Performing this task EVA would probably require some special equipment and tools since manual dexterity would be limited. The coating would be limited to temperatures below 93°C due to the adhesive.

5.5 CONCLUSIONS/RECOMMENDATIONS FROM COATINGS STUDIES

This study of contamination of radiator coatings on a Large Space Platform revealed a potentially significant problem. There are many sources of contamination on such a spacecraft. A requirement for maximum allowable contamination due to radiator degradation has not been set on other spacecraft and due to the nature of the impact (gradually reduced radiator performance) probably will not be set for a platform. Contamination limits for various experiments have been established for Spacelab experiments. It is possible, however, these limits could be met and contamination still pose a problem to radiator performance. Shorter mission life and intermittent operation of experiments eliminate the concern for long term contamination deposition which must be dealt with for permanent radiators. It is recommended that a contamination model of the platform be made to study both short and long term radiator surface effects.

The crux of the radiator contamination problem is assurance of radiator performance for the life of the spacecraft. Figure 62 presents a list of options to meet this objective. A trade study including considerations of cost, launch weight, configurational and operational restrictions and available materials is required to determine the optimum approach. A contamination model would be an important element of such a trade study.

FIGURE 62 OPTIONS FOR RADIATOR PERFORMANCE ASSURANCE

1. OVERSIZE RADIATORS FOR END OF LIFE PROPERTIES

2. USE DECENTRALIZED RADIATORS WITH SHORTER MISSION LIFE FOR EXPERIMENT HEAT REJECTION

3. DEVELOP MAXIMUM CONTAMINATION REQUIREMENTS FOR PRESERVATON OF RADIATOR COATING PROPERTIES AND TAKE MATERIALS CONTROL AND OPERATIONAL ACTION TO MEET REQUIREMENTS

4. MAKE RADIATORS RETRACTABLE AND/OR ORIENTABLE TO AVOID CONTAMINATION TO GREATEST EXTENT POSSIBLE

5. LOCATE RADIATORS AT MINIMUM CONTAMINATION LOCATION

6. RESTRICT RENDEZVOUS VEHICLE APPROACH PATHS TO AVOID EXHAUST PLUME IMPINGEMENT

7. USE NON POROUS COATINGS LESS SUSCEPTIBLE TO CONTAMINATION DEPOSITION

8. DEVELOP ON ORBIT CLEANING OR REFURBISHMENT TECHNIQUES FOR COATING

6.0 TECHNOLOGY ASSESSMENT

The results of the unmanned platform thermal management studies and coatings studies were reviewed to determine the technology advancements required to support the future large space platform missions. The technology development areas were divided into pumped liquid systems, technology for two phase operation in zero g and radiator and coatings technologies. These are discussed separately below.

PUMPED LIQUID SYSTEM

The technology development needs identified for pumped liquid system are tabulated below along with the reasons:

Technology Item	Reason Needed
o 360° rotation, no leak, long life 4 pass fluid swivel	o Permits the use of centralized fluid systems with redundancy
o Lightweight, low cost, no leak high reliability quick disconnects	o Permits payloads to tie directly into the fluid system. This or contact heat exchangers required for all systems
o Fluid-to-fluid and fluid-to-heat pipe contact heat exchangers	o Permits a simplified and improved reliability interface of liquid loops with the payloads

TWO PHASED FLUID OPERATION IN ZERO G

The technology advancements needed to take advantage of the advantages of the augmented heat pipes and space refrigeration systems are tabulated below:

Technology Item	Reason Needed
o Two phase fluid management & heat transfer under zero gravity (Condensing and evaporating)	o Experimental and design data lacking for zero g two phase flow

o Pumps for saturated ammonia liquid	o Pump needed for pump augmented heat pipe
o Zero-g condensing heat exchanger technology	o Proven design approaches needed for zero-g operation
o Fluid swivels and/or thermal slip rings	o Permits central system operation
o Systems integration and controls	o System and control problems associated with augmented heat pipes must be well understood

RADIATOR AND THERMAL COATING TECHNOLOGY

Technology advancements are needed in a number of areas to provide the long life radiator systems that will be needed for future space platforms. These are listed below:

Technology Advancement Item	Reason Needed
o Develop an optically stable 10 year life coating with EOL 0.2 and 0.8 which is electrically conducting, and non-porous, non-sticking (contamination resistant)	o Reduce maintenance costs and improve system effectiveness.
o Develop on-orbit cleaning methods for radiator thermal coatings	o Reduce orbital replacement of radiators due to contamination

o Develop radiator thermal coating refurbishment and repair methods	o Reduce orbital replacement of radiators due to coating degradation
o Develop methods, procedures and tools for orbital assembly of the space constructable radiator	o Permits the on-orbit assembly of the space constructable radiator

7.0 CONCLUSIONS

Based on the studies discussed herein, the following conclusions have been made. The conclusions for each study are decribed separately below:

THERMAL MANAGEMENT OF UNMANNED MODULES

(1) The centralized pump augmented heat pipe approach is the best technical approach for thermal management of the unmanned module for the requirements studied. It is superior in almost every category. It is an unproven concept, however.

(2) The centralized pumped liquid which ties into the main 250 kW platform thermal management system is the best low risk concept.

(3) The decentralized all heat pipe system is not attractive. It is heavy, has low reliability, and high costs.

(4) Ammonia is a superior working fluid for the two phase systems.

(5) The pumped liquid concepts are highly dependent upon the temperature requirements.

RADIATOR DEPLOYMENT

(1) No technology show stoppers appear to exist for automatic deployment of radiators using a scissors mechanism.

(2) The assembly of the space constructable radiator for a 250 kW system appears possible in an Orbiter 7 day mission if the required tools and equipment are available and in place.

(3) The radiator panels and equipment section for the power module of the 250 kW space platform can be packaged in the Orbiter cargo bay.

RADIATOR COATINGS

(1) The coating for the large space platform should be optically stable 10 year EOL $\alpha/\varepsilon \leq 2/0.8$; should be non-porous, electrically conducting and non-sticking. No coating currently exists with the properties.

(2) Methods for cleaning contaminants from coatings on orbit are desirable but no good method currently exists.

(3) The most promising refurbishment technique is the removal and replacement of tape coatings. Other such as applying new coating with brush on trowol appear less attractive.

TECHNOLOGY ADVANCEMENTS

Advancements are needed in a number of technology areas to support the future long life space platform thermal management system.

In the area of liquid systems developments are needed for fluid swivels and/or thermal slip rings; efficient, no leak quick disconnects and contact heat exchangers. In the area of advanced augmented heat pipes, advancements are needed in zero-g two phase fluid management, components, system integration and controls. Radiator technology development include development of optically stable contamination resistant 10 year life coating with end-of-life coating $\alpha/\epsilon \leq 0.2/0.8$. Also on-orbit coating cleaning and refurbishment technique are needed. Methods, procedures and tools are needed for orbital assembly of the space constructable radiator.

8.0 RECOMMENDATIONS

This study has addressed a number of thermal management areas for future large, long life space platforms which are expected to be launched in the early 1990's. Based on the study, recommendations can be made regarding future courses of action to be taken over the next decade to ensure technology readiness when the need arises. These recommendations are not intended to repeat those made in Reference 1, Section 7.0 but to supplement them. These recommendations are summarized below:

UNMANNED MODULE THERMAL MANAGEMENT

The thrust in technology development that offers the greatest promise of significant payoff is in the area of the pump augmented heat pipe thermal bus. Because of the payoff projected in this area, it is recommended that technology development required to support that system be given a high priority in the coming few years. It is estimated that it will take a minimum of five to seven years to provide technology readiness in this area with the proper commitment.

A second technology area should be pursued in parallel with the two phased thermal bus is that of the pumped loop. These technology areas which are primarily those to support articulating joints and interfaces excpected on the future platforms, are needed to permit centralized systems and other design options which otherwise would not be available.

LONG LIFE RADIATORS

Analytical contamination studies should be made to assess the types and magnitude of contamination to be expected for the long life large space platform missions. The studies should be coupled with material studies which determine the effects that the projected contamination will have on the thermal optical properties degradation and to synthesize or identify coatings which will meet the requirements identified in this study in the contamination environment. Methods of cleaning and refurbishment should be considered as a part of this materials study.

System level trade studies should be conducted to determine the best method for deploying large rdiators in space. These studies determine the desirability of assembling the space constructable radiators on-orbit as opposed to automatically deployed radiators.

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