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DEPLOYABLE/ERECTABLE TRADE STUDY FOR SPACE STATION TRUSS STRUCTURES

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FOREWORD

This technical memorandum documents the results of a study conducted at the Langley Research Center and compares the Space Station 9 foot single fold deployable truss, 15 foot erectable truss, and the 10 foot double fold tetrahedral truss. The study task was negotiated between the Langley Space Station Office and the Space Station Project Systems Synthesis Office of Level B at the Johnson Space Center. A cursory examination of the 15 foot PACTRUSS was also included. The study team consisted of personnel from Langley Research Center's Space Station Office, Structures and Dynamics Division, Flight Dynamics and Controls Division, Space Systems Division, and Facilities Engineering Division.

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INTRODUCTION

In this paper the results of a trade study on truss structures for Space Station are presented. Although this study has been conducted with the reference gravity gradient space station of reference 1 (hereafter referred to as the Reference Document) in mind, the results are generally applicable to other configurations.

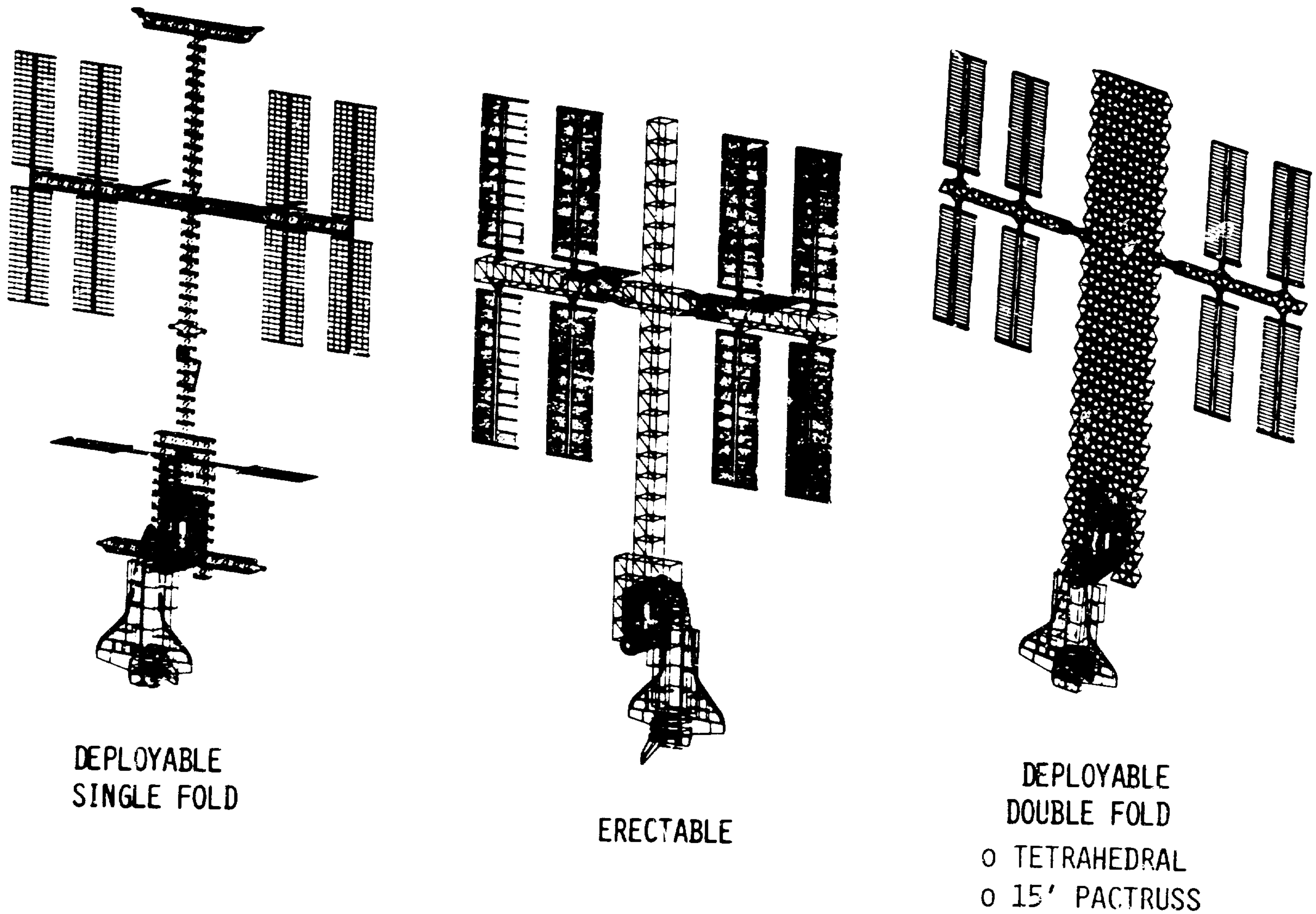
Four approaches for constructing the space station were considered in this paper and are shown in sketch A. Three of the trusses, the 9 foot single fold deployable, the 15 foot erectable and the 10 foot double fold tetrahedral truss are described in detail in reference 2 and the 15 foot PACTRUSS is described in Appendix A.

The primary rationale for considering a 9 foot single-fold deployable truss (9 foot is the largest uncollapsed cross-section that fits in the Shuttle cargo bay) is that of ease of initial on-orbit construction and preintegration of utility lines and subsystems. The primary rationale for considering the 15 foot erectable truss is that the truss bay size accommodates Shuttle size payloads and the growth of the initial station in any dimension is a simple extension of the initial construction process. The primary rationale for considering the double-fold 10 foot tetrahedral truss is that a relatively large amount of truss structure can be deployed from a single Shuttle flight to provide a large number of nodal attachments which represent a "pegboard" for attaching a wide variety of payloads. The 15 foot double-fold PACTRUSS was developed to incorporate the best features of the erectable truss and the deployable tetrahedral truss. That is, the 15 foot PACTRUSS accommodates Shuttle size payloads within each truss bay, yet the whole keel structure can be deployed from a single Shuttle flight.

The integration of subsystems on the 15 foot erectable truss, the 10 foot tetrahedral truss, and the 15 foot PACTRUSS is perceived to be simple on-orbit plug-in installation of highly preintegrated subsystem modules. These modules would be field connected by pre-checked out wiring harnesses and other utility lines which would be unspooled or unfolded and attached to the truss on-orbit. This utility line installation could occur from the MRMS as it traveled between subsystem locations. This "modularized" approach to subsystem integration has several desirable characteristics which could simplify the Station design process. First, by virtue of the fact that the subsystems are "plugged-in" on orbit, their interface with the truss is reduced to simple geometric and mechanical considerations. For example, once the truss size is selected, highly preintegrated power modules can be designed without concerns such as interfacing with the truss for launch integration. Second, downstream subsystem changes would not feed back and affect the initial truss design. These simple interfaces would have the effect of reducing the interdependence of work packages thus simplifying the SE&I process. Third, replacement of the highly preintegrated and modularized subsystems would be a reversal and repeat of the initial installation process, thus greatly simplifying maintenance or replacement operations.

To provide an understanding of the characteristics of the four trusses under consideration, several quantifiable features of the trusses are tabulated in Table 1. Many of these numbers are taken directly from reference 2. The

STRUCTURAL OPTIONS CONSIDERED



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Sketch A. - General Truss Concepts Considered In Trade Study deployed volume/bay is listed since it may be desirable to embed payloads or utilities in the truss to minimize interference with station operations and growth. A large interior volume would presumably be desirable for accepting more payloads, as well as providing adequate space for access and servicing. The minimum package volume on the other hand is the volume required in the cargo bay for launch of the structure only. The free-play keel distortion is the accumulated deflection that would occur in the station keel for the same assumed free-play in each joint. A cursory look at these comparisons indicates that the deeper 15 foot truss has numerous advantages at the cost of an initial increased on-orbit construction time.

To provide a basis for comparing these different construction approaches, a set of discriminators were established and are listed in Table 2. In subsequent sections each of the five discriminators are described and each truss is qualitatively evaluated with an adjective rating. For each discriminator a truss concept is given a satisfactory (S) unless it is perceived to possess either some advantage (A) or disadvantage (D). For any truss concept to be acceptable for construction of the Space Station, additional effort is required to remove any perceived disadvantage.

REFERENCES

1. "Space Station Reference Configuration Description." JSC 19989, August 1984.

2. Mikulas, Martin M., Jr., et. al.: Space Station Truss Structures and Construction Considerations. NASA TM 86338, January 1985.

Table 1. - COMPARISON OF CANDIDATE STRUCTURAL APPROACHES

	9' DEPLOYABLE (3 BAY KEEL)	15' ERECTABLE (3 BAY KEEL)	15' PACTRUSS (3 BAY KEEL)	10' TETRAHEDRAL (6 BAY KEEL)
DEPLOYED VOLUME/BAY	1	4.6	4.6	.24/.97
WEIGHT	1	.5	1	1.16
NUMBER OF STRUTS AND NODES	1	.5	.5	1.6
MINIMUM PACKAGE VOL.	1	.2	.3 - .6	.6
STIFFNESS	1	2.78	2.78	1.08
FREE-PLAY KEEL DISTORTION	1	.24	.24	1.7
COST	1	.3	?	?
CONSTRUCTION TIME	1	1.2 - 1.3	?	?

Table 2. - SPACE STATION TRUSS STRUCTURE DISCRIMINATORS

DISCRIMINATORS	
CUSTOMER ACCOMMODATIONS	GROWTH POTENTIAL
	PAYLOAD ACCOMMODATIONS
SUBSYSTEM INTEGRATION	1) POWER CABLES ETC.
	2) RCS THRUSTERS ETC.
	3) THERMAL & PROPELLANT LINES
	4) INSTALLATION & SERVICING
	5) ROTARY JOINT
	6) MRMS
	7) SE&I REQUIRED
CONSTRUCTION OPERATIONS	EVA HOURS
	NUMBER OF EVAS
COST	TRUSS { WEIGHT, PART COUNT D.D.&T., DEPLOYER
	CONSTRUCTION
TRUSS DESIGN CRITERIA	REDUNDANCY, REPAIRABILITY & MAINTAINABILITY
	PREDICTABILITY
	STIFFNESS

I. CUSTOMER ACCOMMODATIONS

The Space Station is planned to be placed in orbit in the early 1990s and is expected to provide a space operation base for the next 20 years or more. Due to this long life it is important that the truss structure be capable of evolutionary growth in all three dimensions, be capable of accommodating unanticipated alterations, and be capable of accommodating a wide variety of Shuttle compatible payloads with a minimum of interference to growth and station operations.

Growth Potential

To provide a truss with growth capability in all three dimensions it is necessary that the nodal cluster at the intersection of the struts be designed so that additional struts can be added on-orbit. Such a node is shown schematically in figure I-1 for an orthogonal truss. To permit complete 3-dimensional growth in addition to having cubic diagonal positions for payload attachments, it is necessary that each node possess 26 attachment positions. A photograph of such a node is shown in figure I-2 with two quick attachment erectable joints. Such nodes have been used for many years in the construction of ground structures and there is a large body of knowledge relative to their use. For applications in space, the node would be shipped to orbit with the necessary number of quick attachment erectable joints bolted in place to construct the structure. Extra joints could be attached initially or could be bolted on in orbit if needed for growth. Special receptacles for attaching payloads would be bolted to the cubic diagonal holes and are discussed in a subsequent section on payload accommodation. The impact of integrating such a node in the different truss concepts is shown in Table I-1. Although there is a possible interference problem on the 9 foot deployable with the deployment threads as shown in figure I-3, it is believed possible to integrate a 3-D node in any of the truss concepts. To make a better estimate of the impact and weight penalty on the deployable trusses, detailed designs of the joints must be made.

In addition to providing a capability for growing the truss in three dimensions, it would be desirable that attached payloads not interfere with future growth or station operations. These issues are discussed in the next section on payload accommodations.

Payload Accommodations

The most common types of payloads to be accommodated by the station are either small instruments or experiments, or large cargo bay sized payloads. It is likely that the smaller payloads will be integrated onto a standardized pallet in the Shuttle/Station mission system. For launch efficiency this pallet would likely be sized to make maximum use of the cargo bay volume (pallet size 10' - 14' in diameter). Most larger payloads (storage tanks, large instruments, spacecraft, etc.) are likely to be sized to maximize cargo bay volume efficiency.

Schematics of how such payloads would be accommodated by the different truss geometries are shown in figure I-4.

9 Foot Truss.- The upper sketch in figure I-4 depicts the cross-section of a 3 bay wide keel with payloads attached. The left hand payload is a 14' diameter pallet with several small experiments attached while the right hand payload is a large 14' diameter sphere or cylinder (the cylinder could be two or three bays long). As seen in the sketch, such payloads would prohibit lateral growth of the keel and also interfere with station operations of the MRMS.

15 Foot Erectable Truss or PACTRUSS.- The middle sketch in figure I-4 depicts the cross-section of a 3 bay wide keel with payloads attached. Because of the 15' size of the truss bays, the cargo bay compatible payloads can be embedded within the truss structure. This feature permits lateral growth of the keel if desired (indicated by the dashed lines) as well as minimizing interference with station operations on the MRMS. An additional potential advantage of this attachment scheme is that payloads could be placed near principal moment of inertia axes to minimize offset mass eccentricities.

For a number of reasons it may be deemed desirable to grow the station keel in the orbital plane, as shown in figure I-5. Such a growth would maintain "planar" symmetric payload placement which minimizes eccentric masses. It may also be found necessary to increase the bending stiffness of the keel or to provide increased payload space. Such growth would permit a large number of payloads to be clustered close to the station c.g. to minimize gravity gradient "g" effects. As seen in figure I-5, growth in the orbital plane is easily accomplished with the 15' truss and the MRMS could reach three bays without further capability. If it were desired to grow the keel in the orbital plane further than three bays, a plane change capability would have to be provided for the MRMS to operate on that surface.

10 Foot Tetrahedral Truss.- The lower sketch of figure I-4 depicts the cross-section of a 6 bay wide keel with payloads attached. As mentioned previously, the basic philosophy associated with the deployable double-fold tetrahedral truss is to take advantage of its high packaging efficiency and place a large amount of truss in orbit initially. In keeping with the "pegboard" philosophy of the tetrahedral truss the payloads are shown attached to the upper and lower truss nodes. Although more truss is initially provided, there is considerable interference with station operations and general 3-D growth is inhibited.

Payload Attachment and Protection Concepts.- As mentioned previously it is likely that small instruments and experiments will be integrated onto a standardized Shuttle/Station pallet. A potential growth version of a 15' truss station which would accommodate many such payloads is shown in figure I-6. In this version a large number of bays have been added to the lower portion of the keel to provide numerous payload attachment ports in the vicinity of the modules and close to the station c.g. This growth could occur in a gradual, evolutionary fashion using an erectable approach. The growth could take many forms and could include growth in the orbital plane as pointed out previously. Because of the high redundancy of such a truss, many selective struts can be omitted to accommodate a wide variety of payload sizes and shapes. A sketch of an octagonal pallet which would fit in the cargo bay is shown attached to a 15' truss structure in figure I-7. Attachment arms which would fold to fit in the cargo bay are shown in the upper right hand "blow-up" of a truss corner node. A payload attachment fixture is shown attached to the truss node in a cubic diagonal position, and the pallet arm with a simple protrusion connector is shown in position prior to insertion and lock up. Since the four longerons truss is redundant, the face diagonal can be removed for payload insertion without destroying the integrity of the truss. In a multiple bay keel or in an area where there are many bays as shown in the left hand insert, the high redundancy of the truss would permit the diagonal to be permanently omitted if desired. Such a subsurface attachment of the pallet permits complete unobstructed movement and operation of the MRMS over the truss surface yet still provides excellent access for servicing.

For some payloads it may be necessary to provide protection from propulsion plumes, radiation, micrometeoroids, or to provide thermal control. A concept for providing such shielding is shown in figure I-8. In this concept, deployable "curtains" would be added as needed to provide the protection necessary. A hatch would be provided for access and as can be seen in the figure, the 15' truss provides a large interior volume for servicing. An alternate, more highly preintegrated system is shown in figure I-9. In this concept, the octagonal pallet as shown in figure I-7 would have a collapsible protective covering attached which would be deployed on-orbit. A hatch is shown on top of the shield for access. Such a system could provide protection from plume contamination of the Shuttle during docking maneuvers and the hatch could be left open during other times.

The 15' truss could also accommodate a 14' pressurized volume such as the Spacelab as shown in figure I-10. Although the cylindrical volume shown is one bay long, longer payloads could be accommodated by removing more members from the redundant structure.

Customer Accommodation Summary

An evaluation of the customer accommodation discriminators is presented in Table I-2. The 9' single fold deployable truss was assessed to be deficient in growth potential due to interference provided by the cargo bay size payloads. Payload accommodations was assessed as satisfactory. The 15' erectable truss and the 15' PACTRUSS were perceived to have an advantage in both growth potential and payload accommodations because of the bay size compatibility with cargo bay size payloads. The tetrahedral truss could probably be grown in a satisfactory fashion and has an advantage in being able to accommodate a large number of payloads.

Table I-1. - [illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	WEIGHT PENALTY
DEPLOYABLE (5 BAY [illegible])	SMALL	POSSIBLE INTERFERENCE WITH DEPLOYMENT THREADS (SEE FIGURE I-2)	[illegible]	1.[illegible] LB	[illegible]72 LB
15' ERECTABLE (5 BAY [illegible])	NONE	NONE	[illegible]	1.[illegible] LB	555 LB
15' [illegible] (5 BAY [illegible])	SMALL	SMALL	[illegible]	1.[illegible] LB	555 LB
TETRAHEDRAL (5 BAY [illegible])	NONE	NONE	[illegible]	1.[illegible] LB	1015 LB

Table I-2. - DEPLOYABLE VS. ERECTABLE TRADE COMPARISON

		PREINTEGRATED SUBSYSTEMS	"MODULARIZED" SUBSYSTEMS		
DISCRIMINATORS		9' DEPLOYABLE	15' ERECTABLE	15' PACTRUSS	TETRAHEDRAL
CUSTOMR ACMDTNS	GROWTH POTENTIAL	D	A	A	S
	PAYLOAD ACCOMMODATIONS	S	A	A	A
SUBSYSTEM INTEGRATION	1) POWER CABLES ETC.				
	2) RCS THRUSTERS ETC.				
	3) THERMAL AND PROP. LINES				
	4) INSTALLATION & SERVICING				
	5) ROTARY JOINTS				
	6) MRMS				
	7) SE&I REQUIRED				
CONSTR. OPS.	EVA HOURS				
	NUMBER OF EVAs PER FLIGHT				
COST	TRUSS WEIGHT, PART COUNT D.D.&T., DEPLOYER				
	CONSTRUCTION				
TRUSS CRITERIA	REDUNDANCY, REPAIRABILITY AND MAINTAINABILITY				
	PREDICTABILITY				
	STIFFNESS				

A - ADVANTAGE, S - SATISFACTORY, D - DISADVANTAGE

3-DIMENSIONAL NODE PERMITS HIGHLY VERSATILE GROWTH

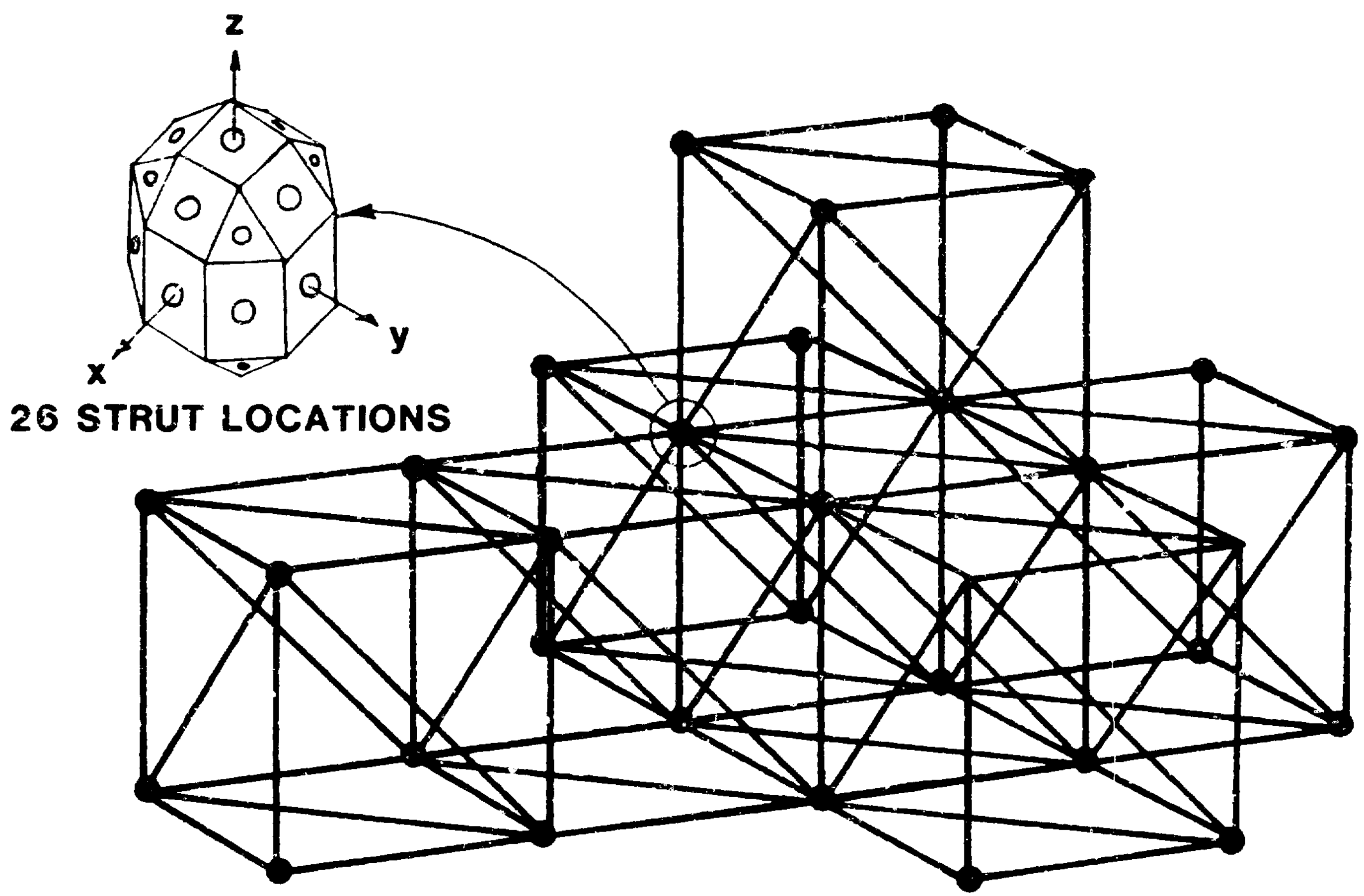

Figure I-1. - Schematic of truss structure showing growth capability offered by 3-D nodal cluster.

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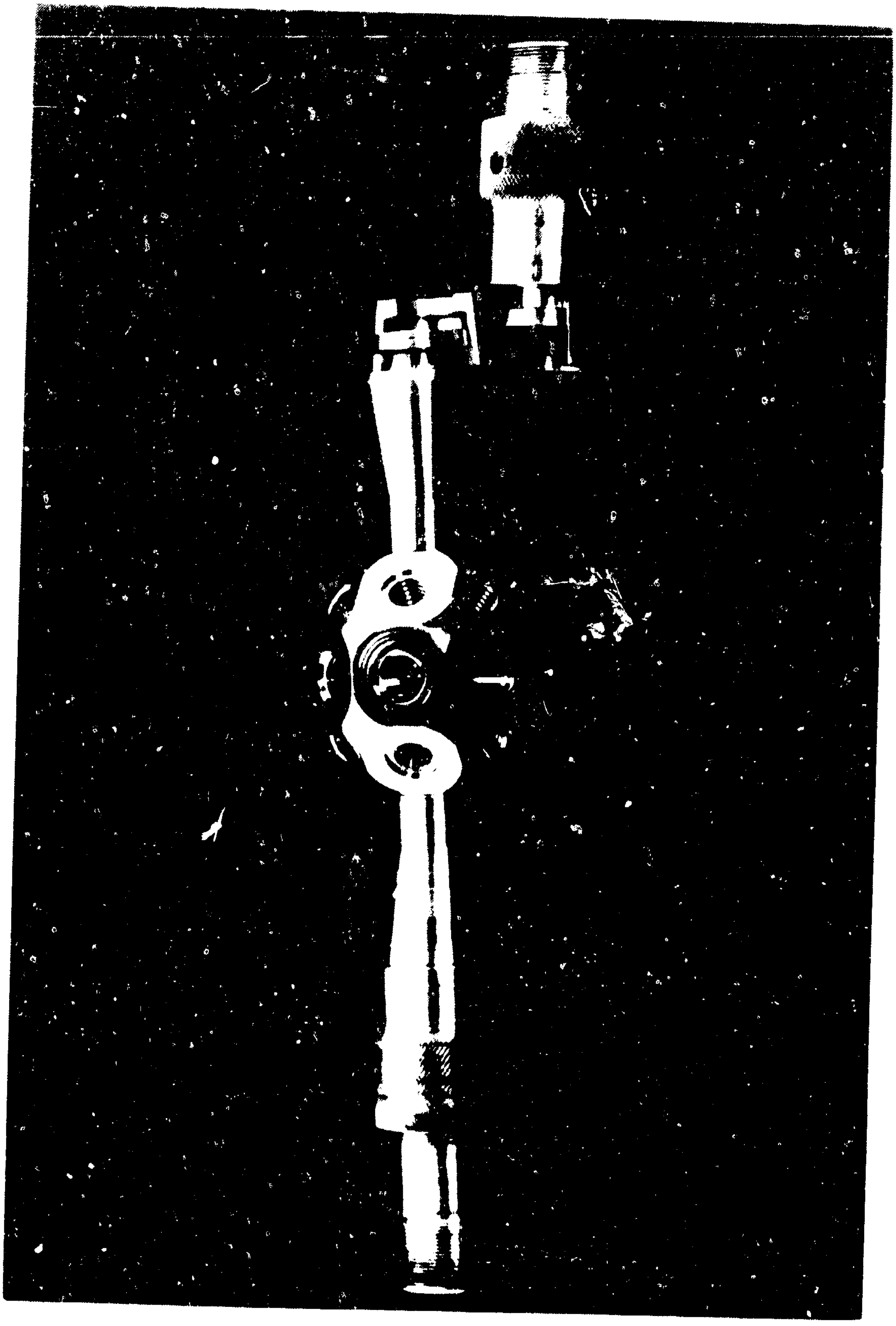


Figure I-2. - Photograph of 3-D node for an orthogonal truss.

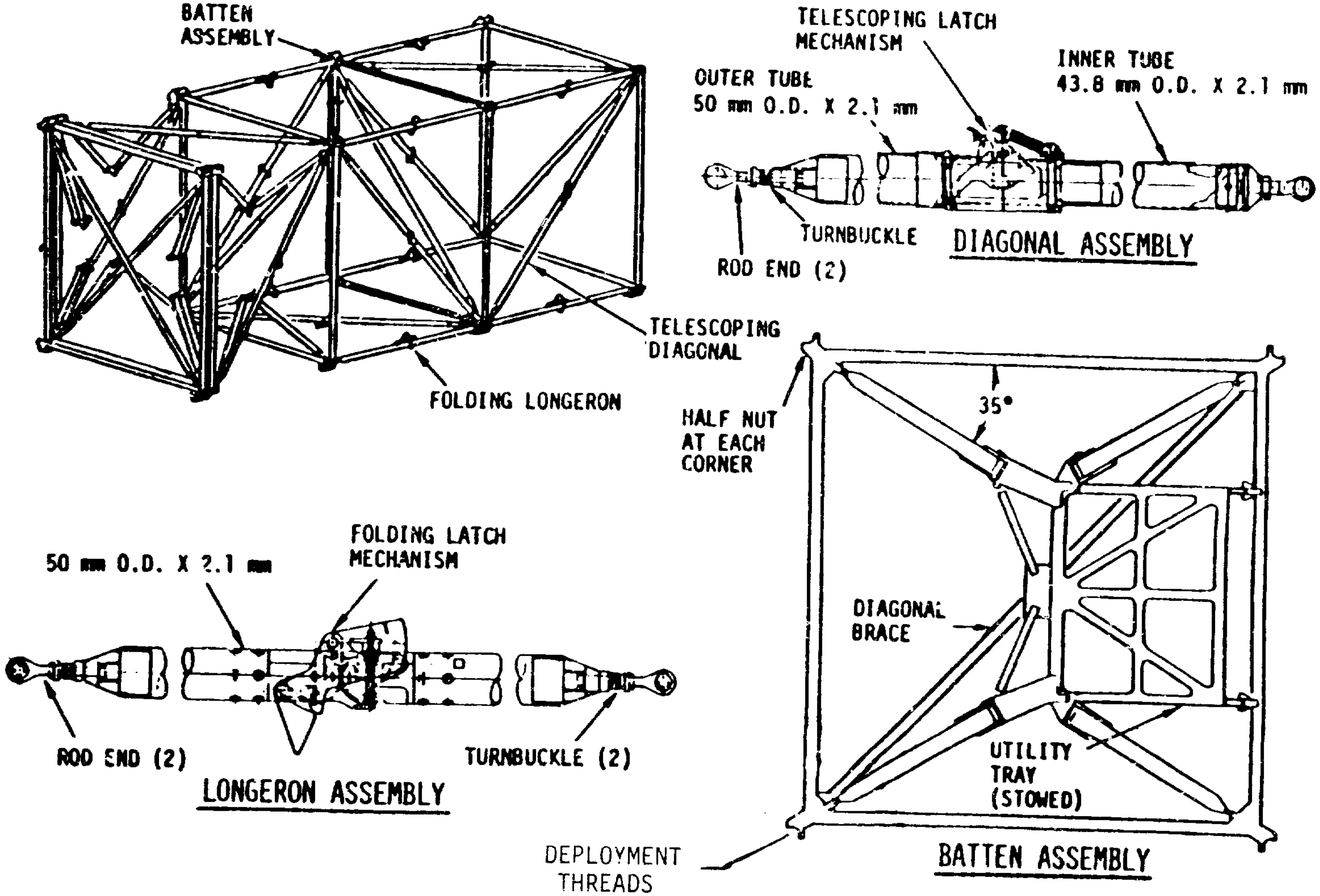


Figure I-3. - Schematic of 9 foot single fold deployable truss showing half-nut threads being considered for deployment

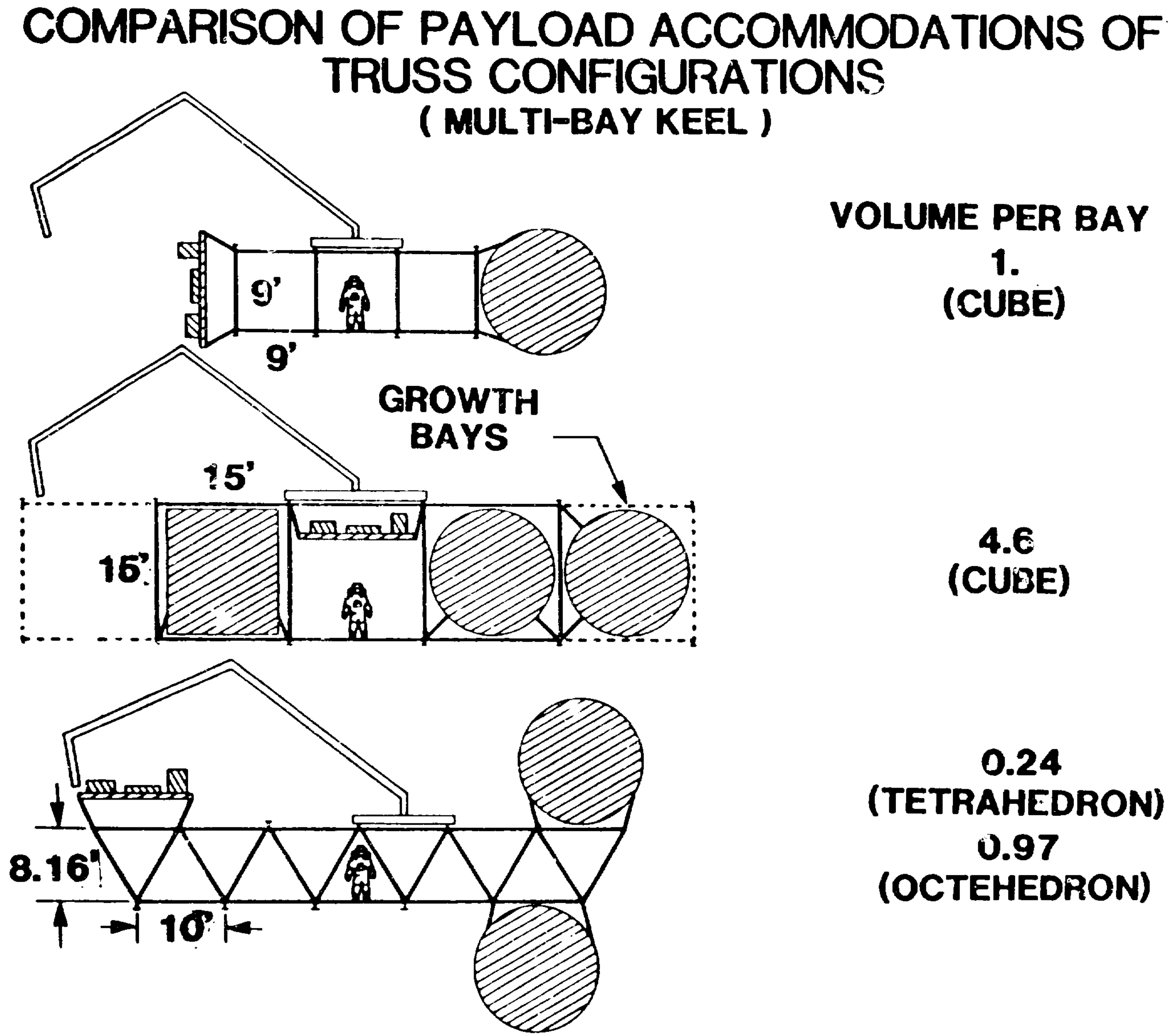


Figure I-4. - Schematic comparing payload attachment schemes for the different truss concepts.

3-D GROWTH CAPABILITY OF 15' TRUSS

- MAINTAIN "PLANAR" SYMMETRIC PAYLOAD ATTACHMENT POTENTIAL
- INCREASE STIFFNESS
- INCREASE PAYLOAD SPACE

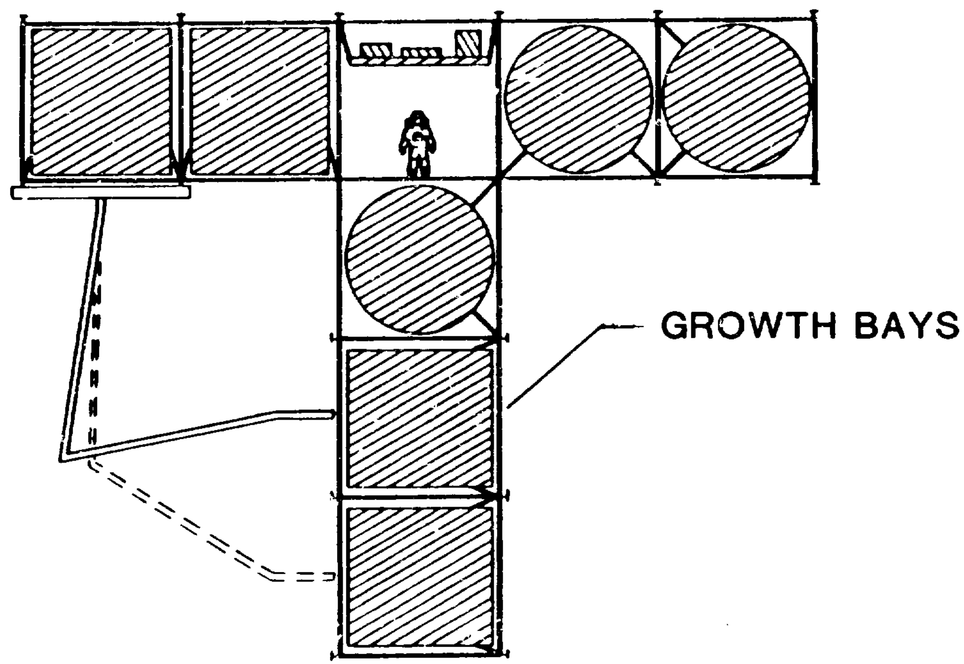
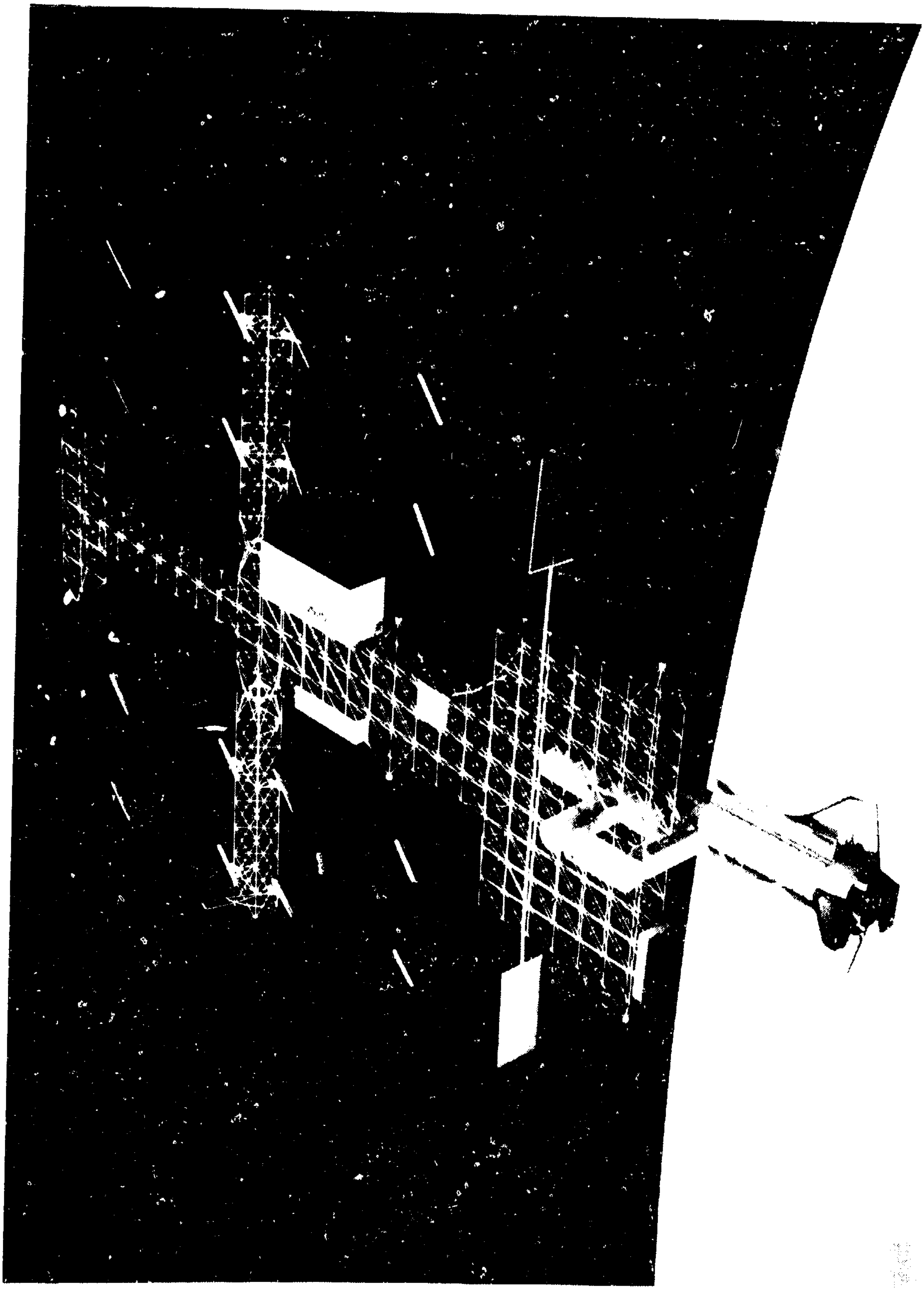
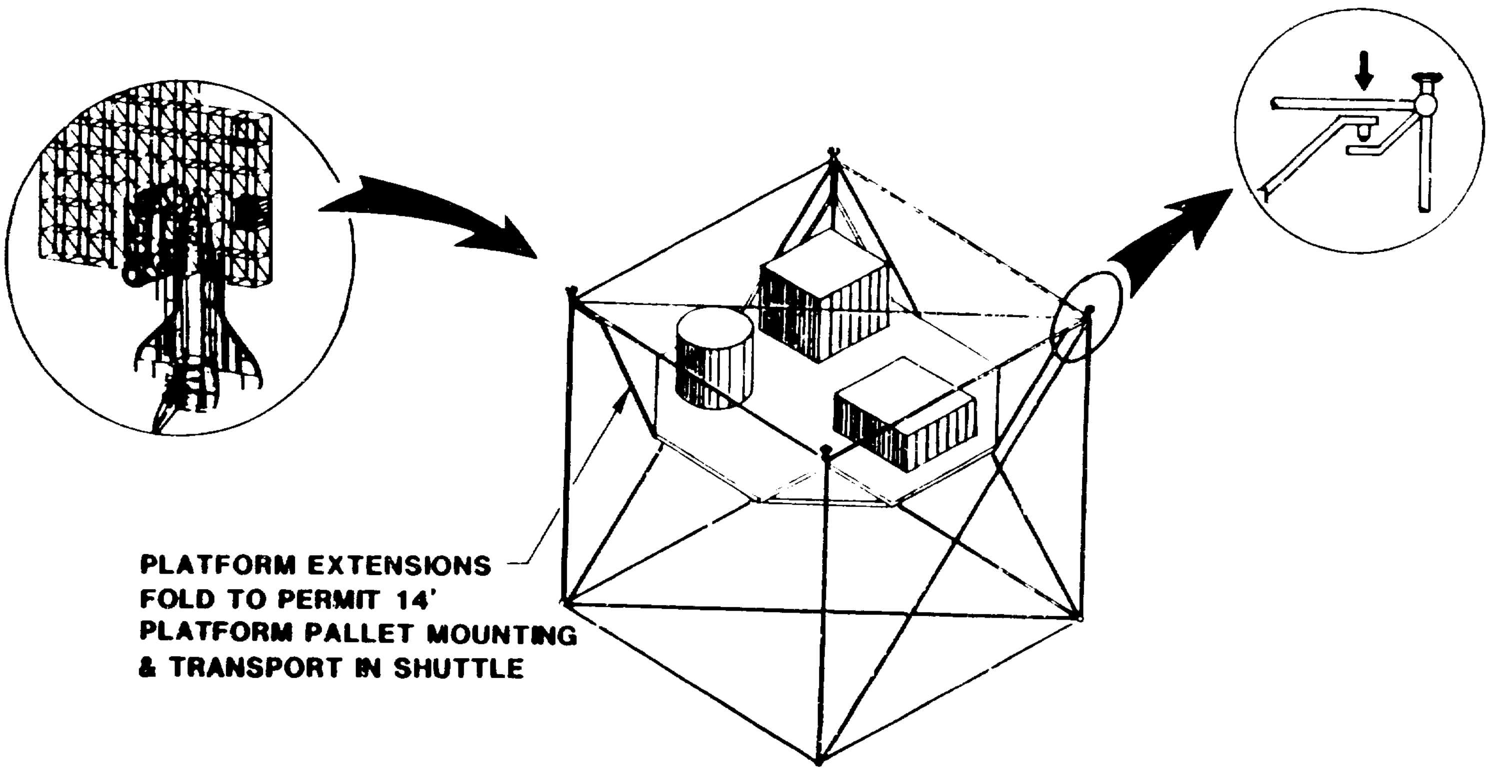


Figure I-5. - Schematic showing 3-D growth of keel in the orbital plane.



RECESSED EQUIPMENT/EXPERIMENT PLATFORM PERMITS MRMS PASSAGE



THESE SHUTTLE-COMPATIBLE PALLETS PROVIDE AN "LDEF-LIKE" SCENARIO FOR ACCOMMODATING A LARGE NUMBER OF FLIGHT EXPERIMENTS WITH MINIMAL INTERFERENCE TO SPACE STATION OPERATIONS

Figure I-7. - Schematic of a Shuttle/Station pallet with instruments or small experiments attached.

15′ STRUCTURE PROVIDES USEABLE INTERIOR VOLUME

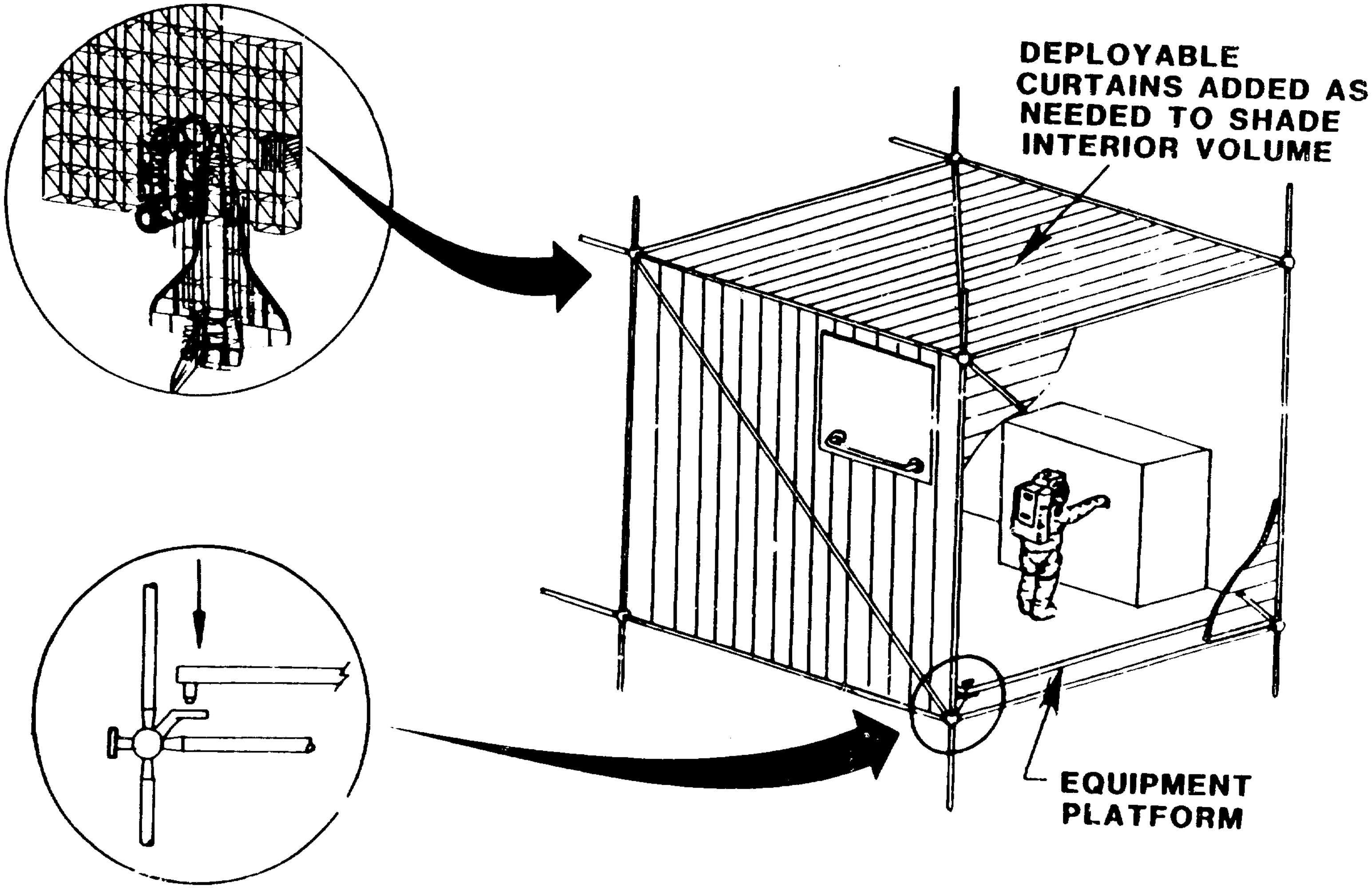


Figure I-8. - Schematic of environmental control deployable "curtain" added to a truss bay to provide a protected cubicle.

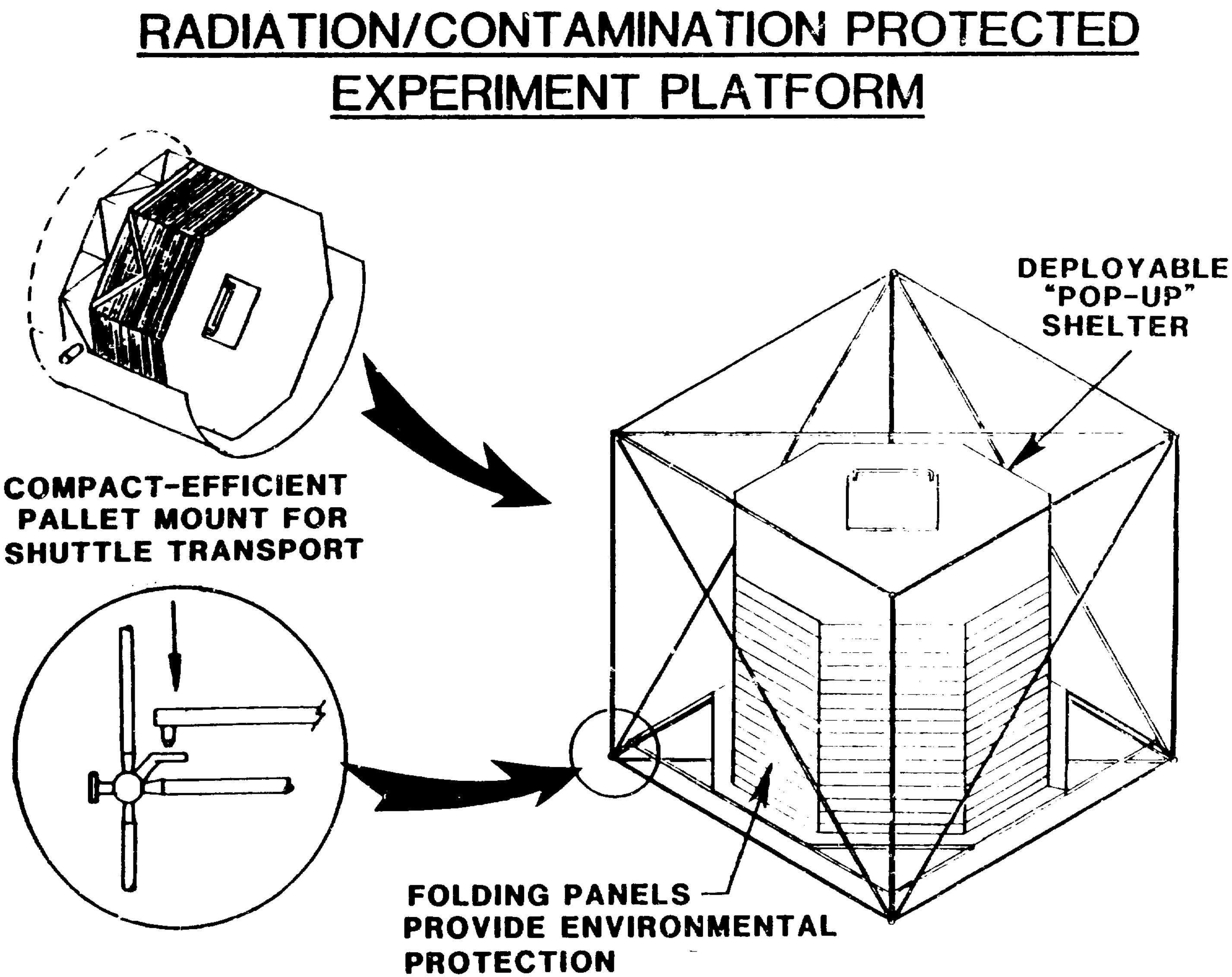


Figure I-9. - Schematic showing a deployable environmental shelter for protecting payloads.

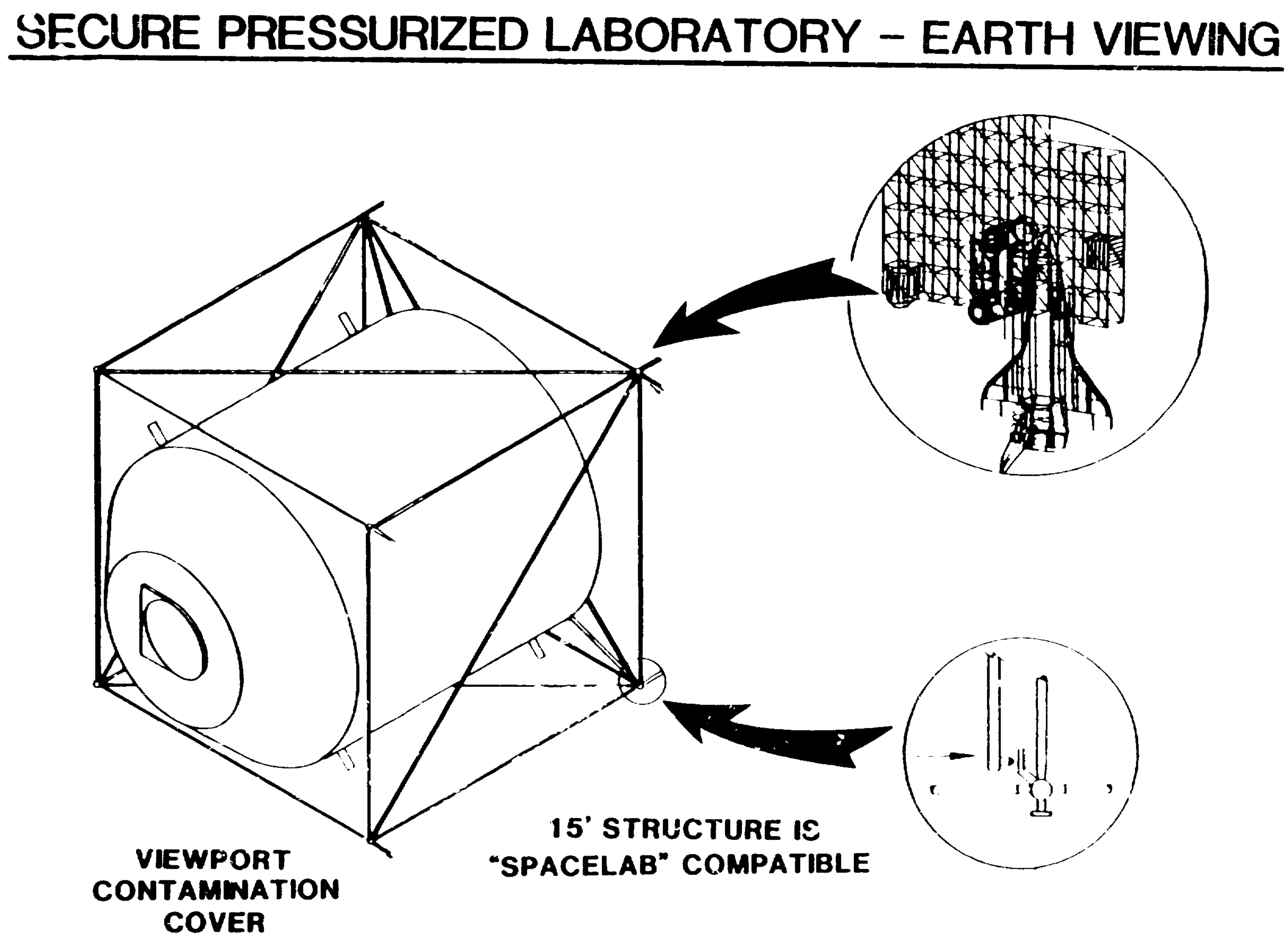


Figure I-10. - Schematic indicating how a cylindrical volume could be accommodated by the 15 foot truss.

II. SUBSYSTEM INTEGRATION

A major consideration in the choice of a truss configuration for the Space Station is the issue of preintegration of many subsystem elements with the truss during prelaunch build-up versus the integration on-orbit of these subsystem elements by extravehicular activity (EVA). The configurations of the subsystems and their interfaces to the truss were, therefore, reviewed in light of the following requirements and objectives:

- o Identify subsystem interfaces to the truss and subsystem-to-subsystem interfaces which are truss related.
- o Provide subsystem installation input to the construction scenario for the estimation of EVA hours to construct the station.
- o Identify discriminators and key drivers in truss/subsystem integration area.
- o Identify which subsystem elements can be preintegrated with the 9 foot deployable and which must be installed on orbit (see Table II-1).
- o Conduct trades of five major subsystem elements' interfaces to each of three truss configurations (see Tables II-2, II-3, II-4, II-5, and II-6).

Subsystem configurations are those discussed in references II-1, II-2, and II-3 with additional descriptions supplied informally.

The build-up scenario described in references II-1 and II-3 were those generally used in determining which subsystems are brought to orbit on which Shuttle flights. The Shuttle payload packaging shown in references II-1 and II-3 were also used to determine the feasibility of preintegration of the subsystem elements. Shuttle payload weight limits were not used in this study. Weight limit of 35,000 pounds will probably be violated on those Shuttle flights where modules weighing between 35,000 and 54,000 pounds as shown in Table 4.3.3.4-2 (page 180) of reference II-1 are brought to orbit.

Subsystem Discussion

A discussion of the review of each subsystem is contained in this section. Where subsystem information was lacking, assumptions were made and are documented below.

The method of installation of each subsystem element in each truss configuration was evaluated. The results are shown in Table II-1. Trade studies were then made for the attitude control assembly, keel mounted propulsion tank modules, rotary joint, regenerative fuel cell and power conditioner, and the mobile remote manipulator system (MRMS). The evaluation criteria include envelope/packaging, installation, alignment to the truss, access for servicing, and orbital replacement of units for each truss configuration considered.

Electrical Power Subsystem.- The electrical power subsystem is described in reference II-2. Each power cable is 0.4 inches x 2 inches and can handle 75 kw. To allow for the eventual distribution of 300 kw of power in the growth station, four cables will be installed on the IOC Station. It is assumed that the cable can be bent on a radius to thickness ratio of 10 to 1 which is a 4 inch bend radius. Preintegration of this cable with the 9 foot deployable truss is shown in figure II-1. The inboard folds must be supported temporarily during launch in order to prevent breaking the temporary string or velcro ties. Preintegration of the transverse boom rotary joint and the inboard regenerative fuel cell and power conditioner in a single 9 foot truss bay is shown in reference II-1. Later configuration information for these two subsystem elements shows that the power conditioners and rotary joint cannot be preintegrated into one 9 foot bay. The interference between them is shown in figure II-2. The inboard power conditioner must be installed by EVA/MRMS one bay outboard of the bay containing the rotary joint. There is currently no room in the Shuttle cargo bay packaging arrangement for these two power conditioners. Outboard power conditioners can be preintegrated into the 9 foot truss for the fourth Shuttle flight. Trades for the power conditioners are shown in Table II-2. Power transfer across the rotary joint is by the electrical power transfer unit or roll ring assembly (see figures II-2 and II-3) under development for the electrical power subsystem. Utility power controllers will likely be integrated into the subsystem elements for which they are providing power. Power management controller configuration has not been decided upon at this time. It is assumed that, if it is hardware, it can be preintegrated with the folded transverse boom truss. It is noted that there should be a quick disconnect arrangement between the power conditioner and the radiators so that either can be removed without too much disturbance of the other. It is assumed that photovoltaic (PV) blankets and beta joints can be preintegrated as shown in reference II-1.

Other assumptions regarding the electrical power subsystem are as follows:

- o All power cables throughout the Station will be foldable on a small enough bend radius to allow preintegration for the 9 foot deployable. This same configuration cable will be used for the 15 foot erectable truss.
- o The Data Management System (DMS) (fiber optics) is embedded in all elements of the electrical power subsystem.
- o Photovoltaic is the IOC power source.

Utilities integration required for the electrical power subsystem are as follows:

- o Installation of four regenerative fuel cells and power conditioners in the 9 foot or the 15 foot transverse boom truss cubes outboard of the transverse boom alpha joints.
- o Installation of power management controller and main bus switching unit.
- o Power cable installation on the truss and hookup throughout the power management and distribution (PMAD) system.

- DMS fiber optic connections for data monitoring and PMAD control.

- Power cable hookup from the solar blankets to the power conditioning and storage equipment.

- Installation of four radiators on the transverse boom.

Guidance Navigation and Control Subsystem (GN&C).- This subsystem consists of magnetic torquers (if used) and an attitude control assembly (ACA) containing six to eight control moment gyros (CMG), one inertial reference unit, one or two star trackers and computers. The ACA is the central cube for the 9 foot deployable truss and is preintegrated into the transverse boom. The ACA is installed in the central truss cube for the 15 foot erectable truss and on the outside of the tetrahedral truss. It can have some CMGs missing or unused until later in the build-up. Trades for the ACA-to-truss interfaces for the three truss configurations are shown in Table II-3.

Other assumptions regarding the GN&C subsystem are as follows:

- Although active cooling may be required for the CMGs, they must be designed for interim passive cooling since they must be operated prior to the installation of the active cooling system several flights later.

- Installation and hookup of the magnetic torquers is not covered since this subsystem element and its location are not defined.

- The ACA constitutes the 9 foot truss central bay thus assuring truss alignment. The ACA will be aligned to the 15 foot truss central bay on the ground. The truss members will be disassembled and reassembled on-orbit using the same members, therefore, assuring on-orbit alignment.

Utilities integration required for the GN&C subsystem are as follows:

- Mounting of ACA at the cross of the boom and keel; on the ground for the 9 foot deployable and on-orbit for the 15 foot erectable.

- Connections to the power subsystem (PMAD).

- Active thermal control system ammonia pipe hookup.

- Electrical line to magnetic torquers located on the keel or the transverse boom.

- IDMS fiber optic hookup for data and control function transfer.

Communications and Tracking Subsystem (C&T).- Antennas which are installed on the transverse boom during the first Shuttle flight are temporary. After the station is built-up they are supplanted by antennas on the upper boom and the lower part of the truss. These transverse boom mounted antennas either will be removed and stored or left in place as spares. For the second Shuttle flight the orbiter docks to the berthing ring on the transverse boom. The antennas shown in reference II-1 have a stand-off distance of 20 to 30 feet.

All of these antennas are close to the docking Shuttle and some may physically interfere with this vehicle.

Assumptions regarding this subsystem are as follows:

- o IF amplifiers, which are installed in the habitation/laboratory modules will be temporarily installed on the transverse boom until the appropriate modules are installed.
- o All antenna installations on the transverse boom made during the first Shuttle flight are temporary.
- o IOC antennas will not require on-orbit alignment to the Space Station reference axes.
- o Antennas cannot be preintegrated with the 9 foot deployable truss.

Utilities integration required for this subsystem are as follows:

- o Mounting of antennas, waveguides, and transmitters/receivers onto the truss and MRMS.
- o Connections from PMAD subsystem.
- o Coax from modules to transmitter/receiver boxes located near antennas (from IF amplifiers on the transverse boom during first build-up Shuttle flight).
- o DMS data lines and processors - fiber optics cables.
- o Communication BUS hookup to habitability module.

Information and Data Management Subsystem.- Assumptions regarding this subsystem are as follows:

- o All processors and other devices are parts of the other subsystems or installed in modules except when the Space Station is in the early build-up stage.
- o Before the habitation modules are installed, a DMS processor must be installed on the transverse boom to process controls and information data from the subsystem for operation and check-out.
- o An umbilical from this DMS processor, temporarily installed on the transverse boom to the Shuttle payload bay, is required for check-out and initialization of the interim Space Station.
- o Fiber optics cables can be preintegrated within the 9 foot deployable truss.

Utilities integration required for this subsystem are as follows:

- o Electrical power to DMS components.

- o Attachment of fiber optic cables to truss on the preintegrated 9 foot deployable and on the on-orbit integrated 15 foot erectable truss.

Propulsion Subsystem.- The propulsion subsystem is described in reference II-1. It is noted that there are 1600 feet of rigid, insulated propellant lines with heater blankets required for the IOC Space Station.

Trades for the keel mounted propellant tank assemblies are shown in Table II-4. Assumptions regarding this subsystem are as follows:

- o Satellite servicing propellant storage and distribution system is not considered.

- o All propellant tanks are brought to orbit filled with propellant.

- o Two three-tank modules are mounted within the lower bay of the keel. These two modules are preintegrated with the 9 foot deployable and are installed on-orbit for the 15 foot erectable.

- o Propellant tanks are covered with electric heater blankets and an insulation blanket.

- o All propellant lines are rigid, stainless steel tubing covered with electric heater blankets and insulation. They are brought to orbit empty.

- o Thruster clusters cannot be preintegrated with the 9 foot truss.

- o Control of the RCS engines and propellant management and monitoring of system performance, temperature, and health will be accomplished through the DMS fiber optic subsystem.

Utilities integration required for this subsystem are as follows:

- o Mounting of propellant tank modules in the keel and on the logistics module.

- o Mounting of RCS engines thruster clusters on the truss.

- o Installation of 1600 feet of rigid propellant pipe.

- o Electrical hook-up for power to solenoid valves, heater blankets, signal and data processors.

- o DMS fiber optic connections to the propulsion subsystem signal and data processor.

Thermal Control Subsystem (TCS) Active.- The subsystem described in reference II-1 uses two phase anhydrous ammonia to provide three cooling temperatures to the modules and to unspecified payloads. Six ammonia lines are, therefore, required between the lower radiators and the modules. It is assumed that six ammonia lines will be required running from the lower radiators to the top of the keel to provide active cooling for payloads. These cooling lines will be insulated rigid aluminum pipe.

It is not clear whether the lower radiator booms and manifolds can be preintegrated with the 9 foot truss so that the package can fit into the Shuttle cargo bay.

The power subsystem provides its own cooling and is not addressed in this subsystem section of the report. Assumptions regarding the thermal control subsystem are as follows:

- o Three ammonia liquid and three ammonia vapor lines will run the length of the keel for active cooling of certain elements of the Space Station.
- o Ammonia lines are insulated; rigid aluminum pipe and, therefore, cannot be preintegrated with either truss concept.
- o Pumps and accumulator are brought to orbit with a habitation or laboratory module. Therefore, the system cannot be used until the proper module is installed, the pumps hooked up, and the system is charged with ammonia.
- o Active heating aspect of thermal control subsystem is not included.

Utilities integration required for this subsystem are as follows:

- o Mounting of six ammonia lines the length of the keel, keel extensions, and to heat exchangers on all modules.
- o Mounting/deployment or radiator panels near the keel extensions (includes the lower alpha joint).
- o Electrical power to pumps, control devices and thermal control subsystem data processors.
- o Hookup of ammonia lines to cold plates, heat exchangers and pumps.
- o DMS fiber optic hookup to TCS signal and data processors.

Structures and Mechanisms.- A separate study of a rotary joint for the 9 foot truss is in progress. The bearing is 6 feet in diameter and 26 inches long and considered to be state-of-the-art. The bearing, preintegrated with the 9 foot truss bays, is shown in figure II-3. A feasible continuous bearing for the 15 foot bay truss may require extensive development. An alternative discrete bearing concept is shown in figure II-4. In all truss configurations electrical power will be transmitted across the rotary joint through a center mounted roll ring assembly which is under development by Lewis Research Center. Trades on the truss impacts on the rotary joint are contained in Table II-5.

A concept for the MRMS envisioned for Station build-up, transport of modules and other hardware, and station and payload servicing is that shown in figure II-5 and described in reference II-4. This MRMS is approximately the size of a truss bay for the 9 foot and 15 foot trusses and approximately 9 feet by 18 feet for the tetrahedral truss. It travels on guide pins mounted on the truss nodes and thus avoids the need for truss mounted rails. Trades for MRMS integration are shown in Table II-6.

Assumptions regarding the structures and mechanisms subsystem are as follows:

- Electrical power and DMS signals, either electrical or fiber optic, are the only utilities crossing the alpha joints on the upper boom.

- Ammonia liquid and vapor, DMS signals, and electrical power cross the lower alpha joint to the lower radiators.

- The truss diagonals for all preintegrated 9 foot truss bays are not spring loaded and can be easily removed for access to preintegrated subsystem elements.

- The EVA and environmental control and life support subsystem (ECLSS) utilities integration are considered to be included with the module utilities integration.

Utilities integration required for the structures and mechanisms subsystem are as follows:

- Rotary joint installation on the transverse boom.

- MRMS installation onto the truss.

- Mounting of modules to truss.

- Module-to-module and module-to-airlock attachment.

- Electrical power hookups to the modules.

- DMS fiber optic hookups to the modules.

- Coaxial cable hookup to module which feeds the C&T transmitters and receivers on the lower keel and upper boom.

- Installation of propellant tanks and propellant feed line to logistics module.

- Hookup of ammonia lines to module heat exchangers.

- Hookup of electrical power and DMS data lines to the upper alpha joints and electrical power, DMS data lines, and ammonia lines to the lower alpha joints.

- Preintegration or on-orbit installation of electrical power, electrical signal, coax, and fiber optic cable harnesses throughout the space station truss.

- MRMS battery charging station installation and hookup.

SUBSYSTEM INTEGRATION SUMMARY

The degree of subsystem preintegration with the 9 foot deployable truss shown in reference II-1 is not being realized as more subsystem description data becomes available. Subsystem integration summary trade comparison for the deployable versus erectable trusses is shown in Table II-7. A summary of the subsystem integration effects is as follows:

1. Power cable, coaxial and fiber optic cables, attitude control assembly (ACA), transverse boom mounted rotary joint, outboard regenerative fuel cell and power conditioners, and keel mounted propellant tanks can be preintegrated into the 9 foot deployable truss.

2. Reaction control system (RCS) thruster clusters, temporarily mounted transverse boom antennas, RF boxes, and data management subsystem (DMS) central processor cannot be preintegrated.

3. The inboard regenerative fuel cell and power conditioner cannot be preintegrated into the transverse boom.

4. Beta joints and deployable photovoltaic blankets can be preintegrated provided their packaged configuration is as shown in reference II-1.

5. Thermal control lines and propellant lines are rigid insulated tubing and cannot be preintegrated.

6. Fifteen foot erectable truss provides the most space and access for installation and servicing of all subsystem elements.

7. Rotary joint studies for the 9 foot truss are further along than for the 15 foot truss. Further definition of the rotary joint is necessary in order to assess its effect on subsystem integration.

8. The on-orbit integrated truss construction approach with modularized subsystem integration has potential for simplifying the systems engineering and integration process between subsystem elements and work packages.

REFERENCES

II-1 Space Station Reference Configuration Description, JSC 19989, August 1984.

II-2 Power System Reference Configuration, Lewis Research Center, February 27, 1985.

II-3 Mikulas, Martin M., Jr.; Croomes, S. D.; Schneider, W.; Bush, H. G.; Nagy, K.; Pelischek, T.; Lake, M. S.; and Wesselski, C.: Space Station Truss Structures and Construction Considerations. NASA TM 86338, January 1985.

II-4 Bush, Harold G.; Mikulas, Martin M., Jr.; Wallsom, Richard E.; and Jensen, J. Kermit: Conceptual Design of a Mobile Remote Manipulator System. NASA TM 86262, July 1984.

TABLE II-1.-METHOD OF INSTALLATION OF SUBSYSTEM ELEMENTS

SUBSYSTEM	ELEMENT	9 FOOT DEPLOYABLE	15 FOOT ERECTABLE	TETRAHEDRAL
ELECTRICAL POWER	PV BLANKETS	PREINTEGRATED	EVA/MRMS	EVA/MRMS
	BETA JOINTS	PREINTEGRATED		
	* RFC AND POWER CONDITIONING EQUIPMENT	PREINTEGRATED		
		EVA/SRMS		
	POWER MANAGEMENT CONTROLLER	?		
	MBSU/UPC	?		
	BOOM RADIATORS	EVA/SRMS		
	CABLES	PREINTEGRATED		
GN&C	* ATTITUDE CONTROL ASSEMBLY	PREINTEGRATED	EVA/RMS	EVA/RMS
	MAGNETIC TORQUERS	?	?	?
C&T	ANTENNAS	EVA	EVA	EVA
	R.F. BOXES	EVA		
	COAX	PREINTEGRATED		
	WAVE GUIDES	EVA		
	PROCESSORS	EVA		
DMS	FIBER OPTIC CABLES	PREINTEGRATED	EVA/MRMS	EVA/MRMS
	DISTRIBUTED PROCESSORS	PREINTEGRATED	EVA/MRMS	EVA/MRMS
	CENTRAL PROCESSORS	IN THE HAB. MOD	IN THE HAB. MOD	IN THE HAB. MOD
	TEMPORARY CENTRAL PROCESSOR ON TRANSVERSE BOOM	EVA/SRMS	EVA/SRMS	EVA/MRMS
PROPULSION	THRUSTER CLUSTERS	EVA/MRMS	EVA/MRMS	EVA/MRMS
	* KEEL TANKS	PREINTEGRATED	EVA/MRMS	EVA/MRMS
	LOG MODULE TANKS	PART OF LOG MODULE	PART OF LOG MODULE	PART OF LOG MODULE
	PROPELLANT PIPES	EVA/MRMS	EVA/MRMS	EVA/MRMS
STRUCTURE AND MECHANISMS	* ALPHA JOINT, TRANS. BOOM	PREINTEGRATED	EVA/MRMS	EVA/MRMS
	MODULE ATTACHMENTS	EVA/MRMS/SRMS	EVA/MRMS/SRMS	EVA/MRMS/SRMS
	* MRMS	EVA/SRMS	EVA/SRMS	EVA/SRMS
THERMAL CONTROL SYSTEM	RADIATOR BOOMS	?	EVA/MRMS	EVA/MRMS
	RADIATOR ALPHA JOINT	?		
	RADIATORS	EVA/MRMS		
	COOLANT LINES	EVA/MRMS		
	PUMP/ACCUMULATOR	PART OF HAB. MODULE	PART OF HAB. MODULE	PART OF HAB. MODULE
	HEAT EXCHANGERS	PART OF HAB. MODULE	PART OF HAB. MODULE	PART OF HAB. MODULE

* SEE ADDITIONAL SUBSYSTEM ELEMENTS TRADES

TABLE II-2.- TRUSS IMPACTS ON REGENERATIVE FUEL CELL AND POWER CONDITIONER OF ELECTRICAL SUBSYSTEM

Criteria	9 Foot Deployable	15 Foot Erectable	Tetrahedral
Envelope/ packaging	Will fit into truss bays outboard of rotary joint	Will fit readily into truss bays outboard of rotary joint	?
Installation	Inboard unit installed by EVA/SRMS or MRMS. Outboard units preintegrated into truss	Installed on-orbit by EVA/ SRMS or MRMS	Installed on-orbit by EVA/ SRMS or MRMS
Orbital replacement of units	Requires removal of spring-loaded telescoping truss diagonal	Units can be removed with or without removal of truss diagonal	Requirement for removal of truss members is unclear if unit inside truss

TABLE II-3.- TRUSS IMPACTS ON ATTITUDE CONTROL ASSEMBLY (ACA)*
OF THE GUIDANCE NAVIGATION AND CONTROL SUBSYSTEM

Interfaces to truss	9 Foot Deployable	15 Foot Erectable	Tetrahedral
Envelope/ packaging	ACA is the 9 foot central cube. Requires a very dense packaging design due to CMG size of 3-4 foot	To fit into the cargo bay ACA will be 9 foot by 9 foot times some larger length. ACA will fit into the 15 foot central cube and provides improved access over the 9 foot.	ACA will not fit inside truss but must be mounted to the outside
Installation	Installed during prelaunch build-up (preintegrated)	Installed on-orbit as truss is erected	Installed on-orbit after truss is deployed
Alignment to truss	Since ACA is the central cube and is rigid, alignment to truss is built-in and assured	Aligned to truss cube on the ground. Truss disassembled and ACA reinstalled to same, adjusted truss members on-orbit	Alignment method not known
Orbital replacement of units	Replacement of CMG, IRP, startracker, computer on-orbit most difficult due to dense pack and smaller cube face	Replacement easier than 9 foot due to open package and longer ACA length	Replacement easiest of the 3 since the ACA is mounted outside the truss

* Attitude control assembly (ACA) consisting of: 6-8 CMG, 1 inertial reference unit, startracker and computers.

TABLE II-4.- TRUSS IMPACTS ON KEEL MOUNTED TANK ASSEMBLIES* OF PROPULSION SUBSYSTEM

Interfaces to Truss	9 Foot Deployable	15 Foot Erectable	Tetrahedral
Envelope/packaging	Can be installed in truss cube in 3 tank modules. Requires some packaging design consideration since 3 tanks on the same C.L. exceed the 9 foot dimension	2-3 tank assemblies will fit into truss cube with room to spare	Individual tanks can be fitted into individual tetrahedrons. Requires most support structure and more distributed plumbing than 9 foot or the 15 foot. Tanks can also be located on truss face.
Installation	Installed during prelaunch build-up (preintegrated)	Installed on-orbit by EVA as truss is erected	Installed on-orbit by EVA after truss is deployed
Orbital replacement of tanks	3 tank module can be replaced. Temporary removal of 1 truss diagonal probably required.	3 tank module can be removed without removal of diagonal	Individual tank removal most difficult of the 3 unless tank modules installed outside of truss
Envelope for valves, nipples, pipes, sensors, etc.	Requires good 3D system design to fit it all in so that items can be removed on-orbit	Can be designed to be fairly open arrangement and easy to replace	If tanks outside there is adequate space. If tanks are inside, plumbing is distributed over large area

* Tank assembly consisting of six spherical, insulated, and electrically heated propellant tanks located on the keel.

TABLE II-5.-TRUSS IMPACTS ON THE TRANSVERSE BOOM ALPHA JOINT OF THE STRUCTURES AND MECHANISMS SUBSYSTEM

Criteria	9 Foot Deployable	15 Foot Erectable	Tetrahedral
Bearing Configuration Considered	Continuous ball bearings on 6' dia by 2' long drum	Will likely require annular ring, discrete contact bearing rotary joint concept	Same bearing as for the nine foot truss
Envelope/ packaging	6' dia x 2' bearing assembly and roll ring assembly installed in one 9' bay	Discrete contact bearing will probably require 2 bays for transition truss. Square bay built-up on 1 side for MRMS travel	Truss transition configuration is unknown
Installation	Installed with roll ring assembly and transition truss during prelaunch build-up (preintegration)	Bearing with roll ring assembly and transition truss installed on-orbit by EVA/SRMS or MRMS	Bearing with roll ring assembly and transition truss installed on-orbit by EVA/SRMS or MRMS
Bearing Design Status	Advanced development underway	Advanced development required	Same as for the nine foot truss

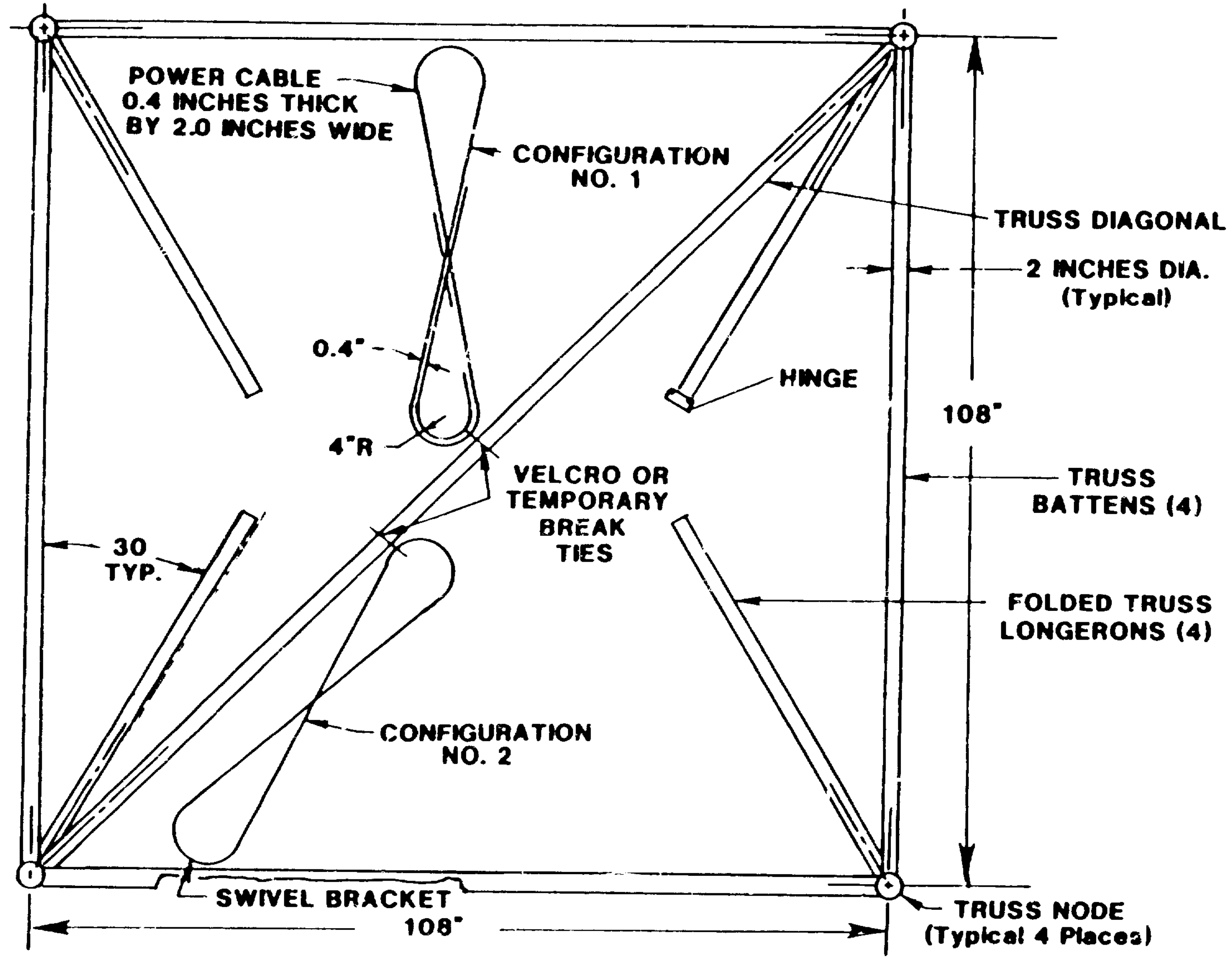
TABLE II-6.- TRUSS IMPACTS ON MOBILE REMOTE MANIPULATOR SYSTEM ELEMENT OF THE STRUCTURES AND MECHANISMS SUBSYSTEMS

Criteria	9 Foot Deployable	15 Foot Erectable	Tetrahedral
Size/cargo capacity	9' x 9', 81 ft^2 cargo bed; less room for batteries, control and drive mechanisms, and cargo than the 15' for the same amount of construction	15' x 15', 225 ft^2 cargo bed; more room for batteries, control and drive mechanisms and for cargo. Fewer trips needed for the same amount of construction than for the 9'	Approximately 9 feet by 18 feet
Cargo size	Modules and other elements the size of Shuttle cargo bay cross section will overhang platform in width and length	Modules and elements the size of Shuttle cargo bay cross section will overhang the platform in length only	Modules and elements the size of the Shuttle cargo bay will overhang the platform in width
Track considerations	Square bays allow guide pins to be placed on the same pitch in Y and Z directions for ease of travel in 2 directions	Square bays allow guide pins to be placed on the same pitch in Y and Z directions for ease of travel in 2 directions	Track pitch in Z direction twice that in Y direction. Creates a more complex arrangement for bi-directional travel
Shuttle packaging	Fits in the Shuttle cargo bay	Must be folded to fit in Shuttle cargo bay	9' width MRMS fits in Shuttle cargo bay

Table II-7. - DEPLOYABLE VS. ERECTABLE TRADE COMPARISON

		PREINTEGRATED SUBSYSTEMS	"MODULARIZED" SUBSYSTEMS		
DISCRIMINATORS		9' DEPLOYABLE	15' ERECTABLE	15' PACTRUSS	TETRAHEDRAL
CUSTOMR ACMDTNS	GROWTH POTENTIAL				
	PAYLOAD ACCOMMODATIONS				
SUBSYSTEM INTEGRATION	1) POWER CABLES ETC.	A	D	D	D
	2) RCS THRUSTERS ETC.	S	S	S	S
	3) THERMAL AND PROP. LINES	S	S	S	S
	4) INSTALLATION & SERVICING	S	A	A	A
	5) ROTARY JOINTS	A	D	D	D
	6) MRMS	S	S	S	S
	7) SE&I REQUIRED	D	A	A	A
CONSTR. OPS.	EVA HOURS				
	NUMBER OF EVAs PER FLIGHT				
COST	TRUSS WEIGHT, PART COUNT D.D.&T., DEPLOYER				
	CONSTRUCTION				
TRUSS CRITERIA	REDUNDANCY, REPAIRABILITY AND MAINTAINABILITY				
	PREDICTABILITY				
	STIFFNESS				

A - ADVANTAGE, S - SATISFACTORY, D - DISADVANTAGE



F.gure II-1.- Power Cable Installed in the Folded 9 Foot Truss

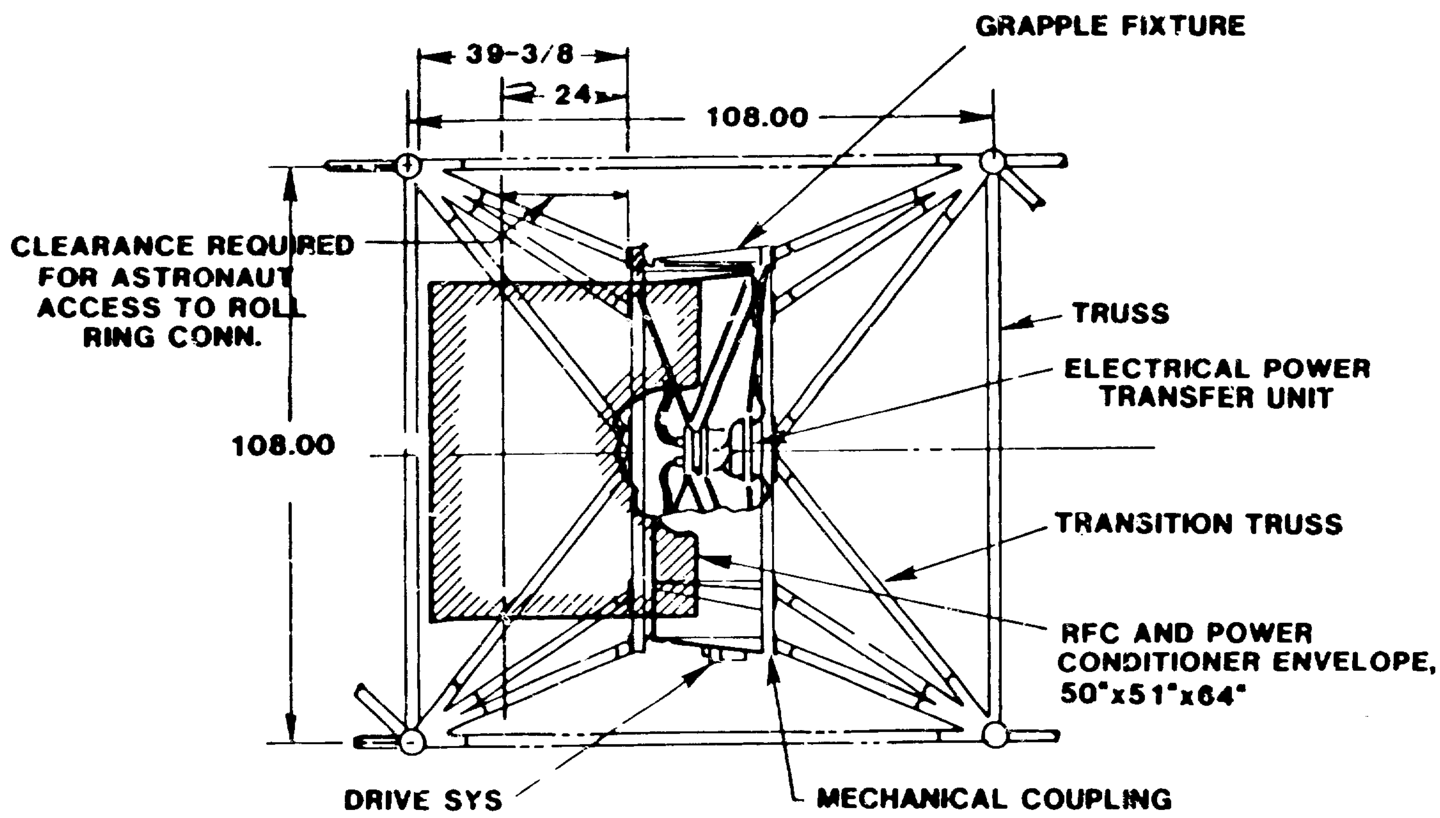


Figure II-2.- Rotary Joint and Power Conditioner Interference Resulting from Preintegration on the 9 Foot Truss

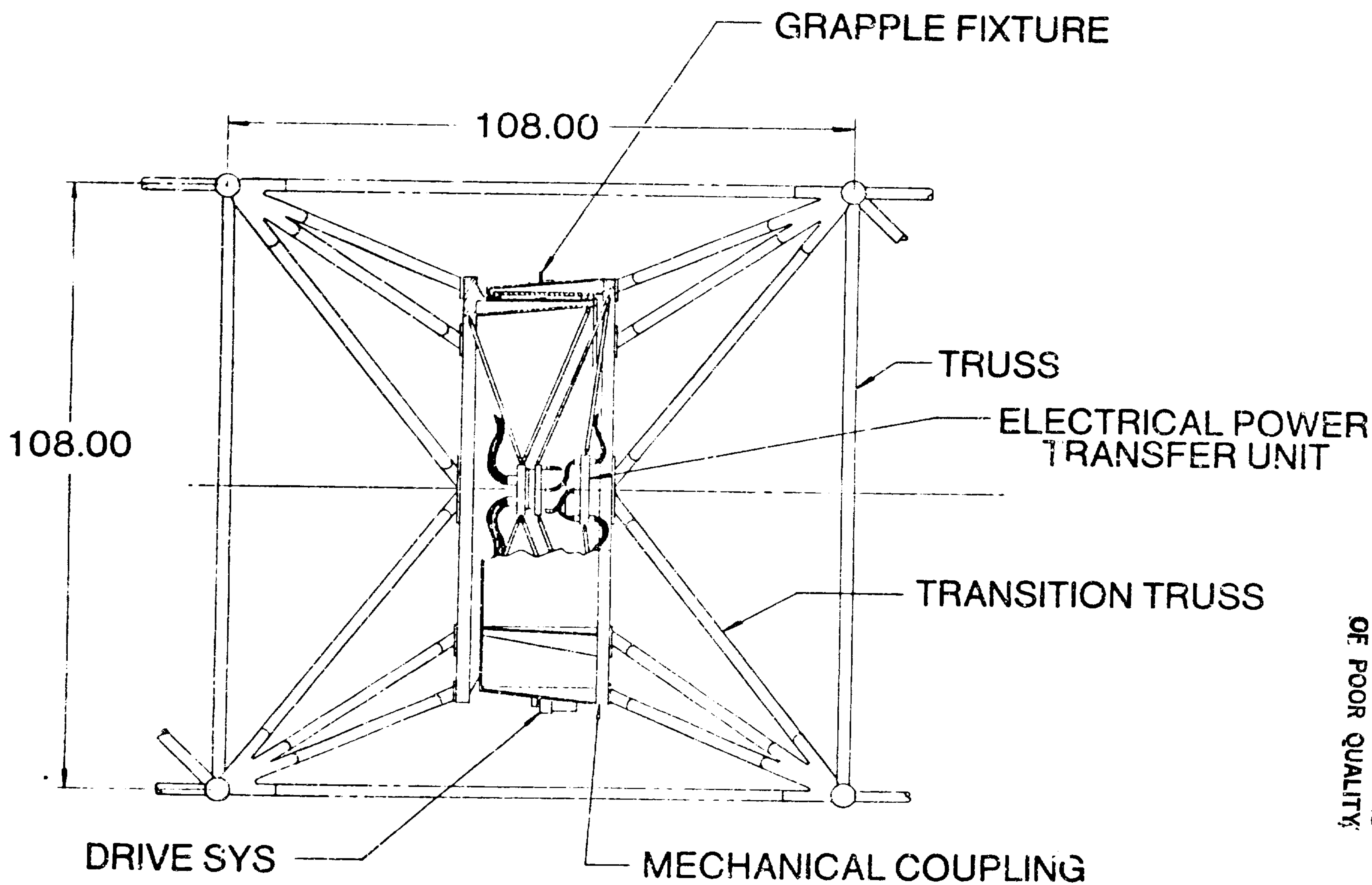


Figure II-3.- Solar Array Rotary Joint Concept and Truss Structure

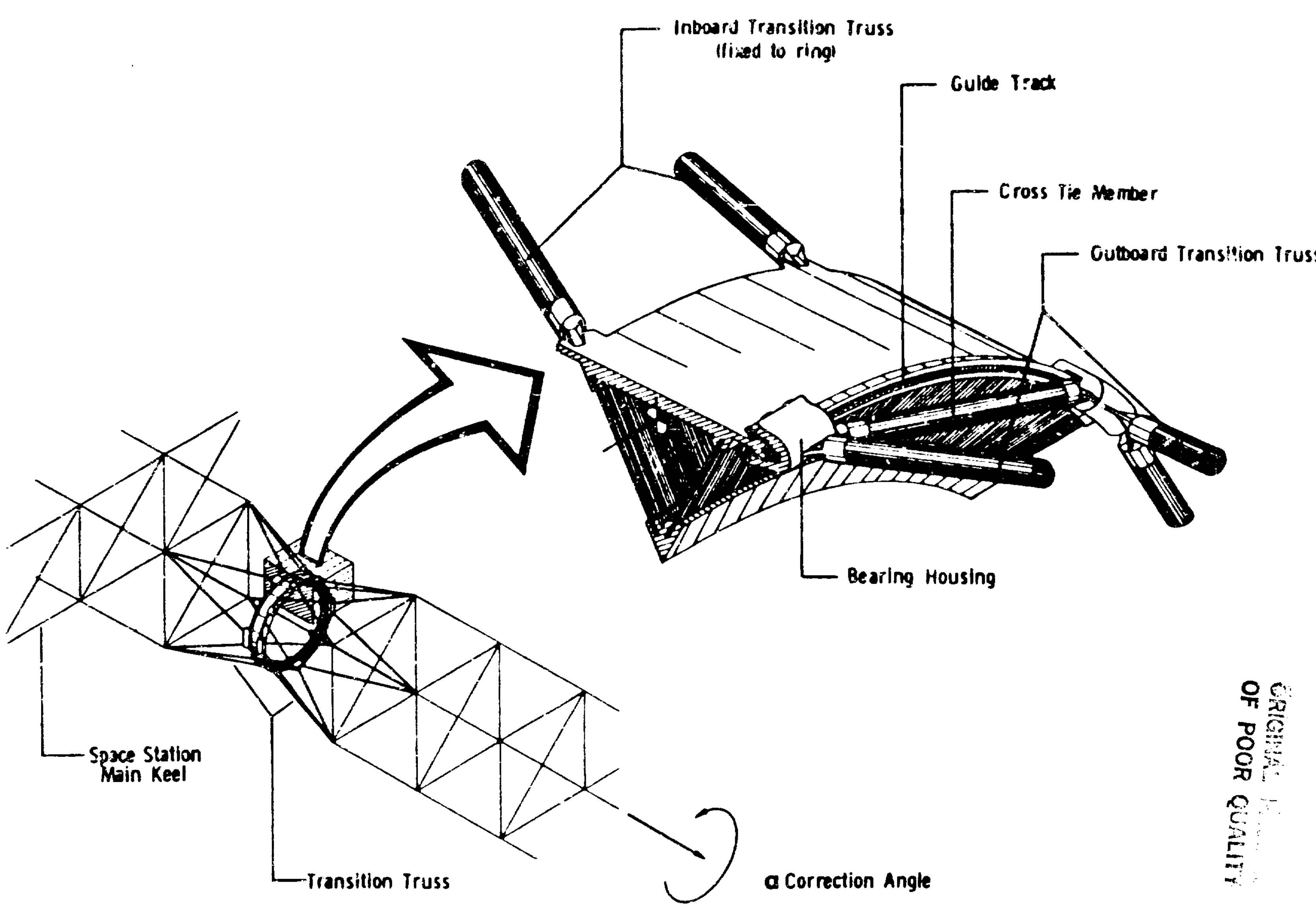


Figure II-4.- Alpha Rotary Joint Concept with Discrete Bearings

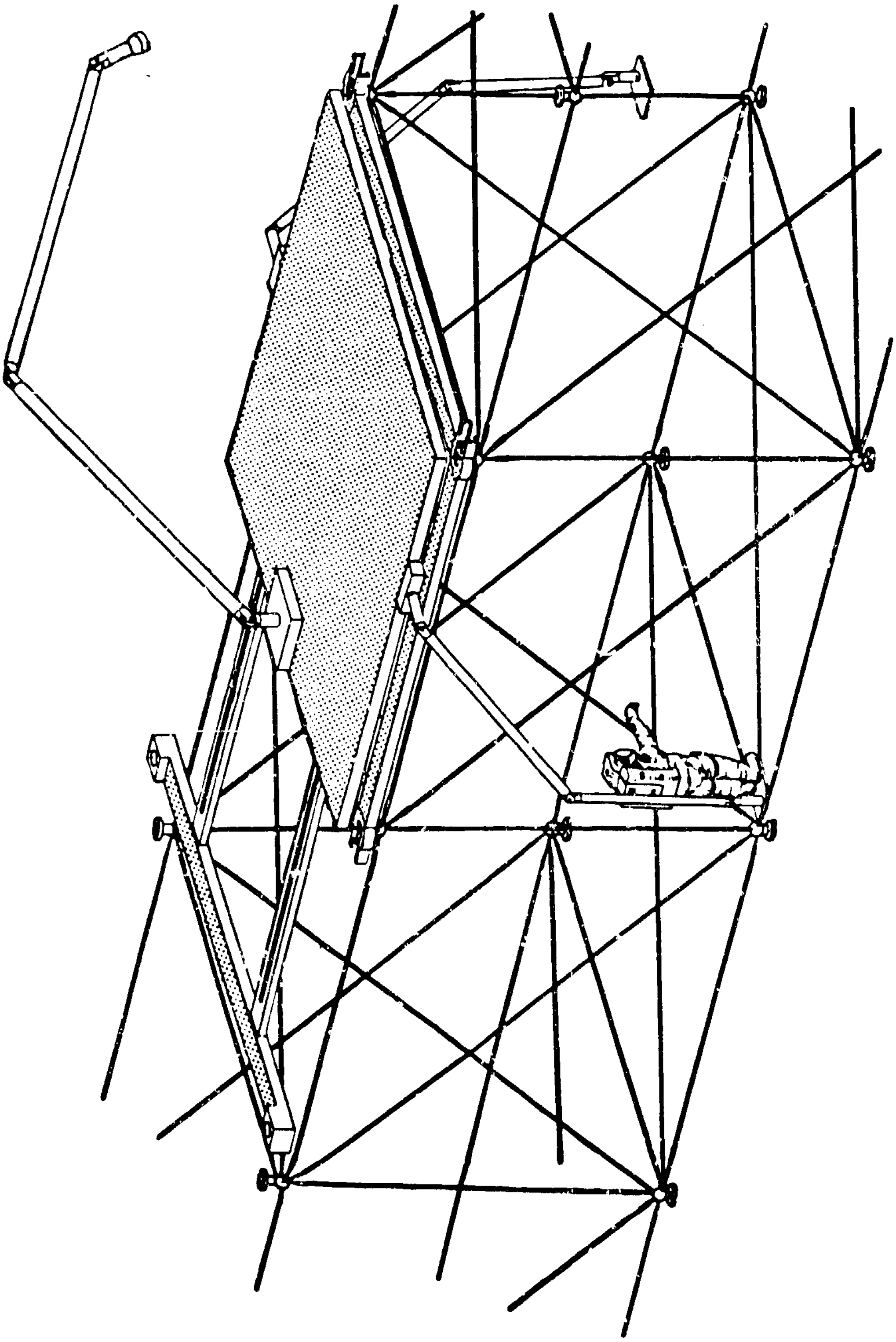


Figure II-5.- Mobile Remote Manipulator System

III. CONSTRUCTION OPERATIONS

Concerns

As part of the Deployable/Erectable trade study, concerns about the construction operations of Space Station were examined. These concerns included; 1) the construction procedures and the feasibility of these procedures, 2) the number of extravehicular activity (EVA) hours required to reach the Initial Operational Capability (IOC) configuration, 3) the ability to package the designated components into the Shuttle cargo bay for each flight, and 4) the Shuttle flights required to accommodate the space station components, and the possible alternatives to the construction procedures and the packaging of the components.

Previously, the construction operations were addressed in the Space Station Reference Document (reference III-1). In the Reference Document suggestions were made for the construction of Space Station using three different truss configurations. In addition, the construction time required to assemble the 9 foot deployable truss structure was presented. This section of the deployable/erectable trade study readdresses the procedures for construction of the IOC using the 9 foot deployable truss structure and also addresses the procedures for construction of the 15 foot erectable truss structure.

Construction Procedures

For the construction procedures, the 15 foot erectable truss structure configuration and the 9 foot deployable truss structure configuration, as seen in figures III-1 and III-2, were used as models. Both are based on the Reference Document Configuration of Space Station, the power tower.

As part of the development of the construction procedures, the assumptions shown in Table III-1 were made. Based on these assumptions and the construction scenario in the reference document, construction procedures for IOC were formulated. The procedures, corresponding assumptions, and references are given in Appendix B.

The erectable and deployable configurations have the same assembly objectives per Shuttle flight. As shown in Appendix B, each flight is broken down into the various construction tasks and each task is allotted an amount of time in which to be accomplished. These times are based on previous EVA experience in space or in neutral buoyancy simulation. Each task is also given a feasibility rating. The rating system is as follows:

1 - has been done in space

2 - has been done in neutral buoyancy (1g weightless simulation)

3 - has been done in 1g

4 - has never been done

These ratings are based on known data and do not attempt to determine whether a task could or could not be accomplished in space. A further breakdown of the feasibility ratings for tasks is shown in Appendix C.

The erectable truss is constructed using a continuous piece by piece assembly operation, while the deployable truss is constructed in sections that are attached in segments and then deployed. All subsystems for the erectable truss must be installed on-orbit. Although some subsystems can be pre-integrated for the deployable structure (see Appendix B), there are some subsystems which must be installed on orbit.

The erectable truss supports a Mobile Remote Manipulator System (MRMS) with a 15-foot square platform while the deployable truss only supports a 9-foot square MRMS platform. Because of the larger area more equipment can be transported in a single trip by the erectable truss MRMS than the deployable truss MRMS. This results in fewer trips by the erectable truss MRMS as can be seen in the procedures, particularly Shuttle Flight II in Appendix B.

Figures (III-3 and III-9) show the space station construction, flight by flight. These figures are of the deployable truss but the components and configuration would be the same as for the erectable truss.

EVA Requirements

For the procedures examined in this study, the EVA requirements were based on the current EVA procedures used for the Space Shuttle. All assembly work was considered done by a two-man EVA team in EMU (Extravehicular Mobility Unit) pressure suits. The maximum time for construction operations for a crewman was six hours per EVA. This time did not include setting up equipment in the cargo bay, adjustment to working in the suits, or clean up of the cargo bay at the end of an activity.

The EVA crew for the erectable truss was actively involved in construction procedures at all times, while the EVA crew for the deployable truss had periods of inactivity in which they were inspecting deployment operations.

The total amount of EVA time required to construct the IOC space station is 111.5 hours for the erectable truss structure and 96.2 hours for the deployable truss-structure (see Appendix B). Figure III-10 shows the total EVA hours required per Shuttle flight and breaks these hours down according to the following eight possible tasks: building/deploying the structure; loading/unloading the MRMS; installing the radiators; installing power cables, ammonia lines, and fuel lines; installing modules and airlocks; installing Utility Power Controllers (UPC)/Main Bus Switching Units (MBSU)/Power Management Controllers (PMC) and antenna systems; MRMS travel time not directly involved with construction of structure or subsystem installation; and all remaining unclassified tasks.

Building the structure for the erectable truss involved the construction of the main truss framework including the three bays encompassing the GN&C, and the power conditioning units (RFC/PWR). Deploying the structure for the deployable truss involved the installation of each section of truss plus the deployment and inspection of the main truss framework. For the erectable structure, it would take 1 minute a strut or 13 minutes a bay to build the structure and for the deployable structure, it would take 5 minutes a bay to deploy the structure. Because of the time involved to install the segments of deployable truss and because there are more 9 foot bays required to equal the same length of 15 foot bay size structure, there is little difference between the two methods in the time to construct the truss structure. The exception is Flight I where the GN&C and power conditioning units were installed for the erectable truss and preintegrated for the deployable truss.

Loading and unloading the MRMS would take more time for the erectable than the deployable truss since the erectable truss had more components to be installed on-orbit.

For both structures the radiators were installed similarly and, therefore, the times do not vary between the two methods of assembly.

The ammonia pipes and hydrazine fuel lines were laid in bay size sections. The power cables are preintegrated in the deployable structure and installed in the erectable structure. Even with the preintegration, again because there are more 9 foot bays than 15 foot bays, the time required to install the ammonia and fuel lines is longer for the deployable structure than the erectable.

The modules, airlocks, UPCs, MBSUs, PMCs, and antennas are installed similarly between the erectable and deployable structure, and there is no large difference between the two construction methods. However, there are several UPC/MBSU/PMC units and antennas for both configurations thus resulting in the large installation times, particularly Flights II and IV.

The MRMS travel time, as already mentioned, is travel not directly involved with construction but involves the transport of equipment from one fixed point to another. The effect on construction time is more pronounced for the deployable structure because the MRMS platform is smaller and cannot carry as much equipment in one trip as the MRMS for the erectable structure.

As a comparison to the previous study on the required EVA time for the deployable 9 foot truss given in the Reference Document, figure III-11 shows the Reference Document time line and this trade study's time line. Much of the additional time now seen in the trade study is due to incorporating the installation of several subsystems not included in the Reference Document procedures. These systems have almost doubled the first predicted time lines.

Figure III-12 shows a comparison between the time to construct the erectable structure and the time to construct the deployable structure for the main truss structure alone. A total of 24.25 hours of construction is required for the erectable truss as opposed to 21.35 hours of construction for the deployable truss. This chart includes any loading and unloading of the MRMS and any travel time of the MRMS that would be required to build the basic truss structure as well as the actual construction times.

The number of EVAs (composed of a team of two crewmen) required to support each Shuttle flight is shown in figure III-13. An estimate of the minimum number of crew and days in flight are indicated based on the assumption of 6 hour EVAs with 24 hours drying time between the use of each EMU. EVAs are assumed to be available on the second day of the flight (a condition not yet practiced). For flights with only three or four EVAs, one EVA crew could fill the requirements, however, on flight requiring five to eight EVAs, two alternating EVA crews would be required. Two EVA crews may not be a realistic approach as they would require five EMU pressure suits and the stowage of these suits in the Shuttle may be difficult to achieve.

Packaging

The construction procedures and the EVA time lines are based on the Space Station components required on a given Shuttle flight, not on the weight or volume of these components. A list of the Space Station components, their packaging sizes, and their weights is given in Appendix D.

Many of the component package sizes were derived from the Reference Document, others were assumed or are unknown. The same considerations were used in determining the weights of these components.

It is assumed the usable envelope of the shuttle cargo bay is 55 feet long and 14.5 feet in diameter for the space station components. The current build-up scenario causes some flights to violate this volume constraint.

For the erectable truss structure Flight V, which includes the logistics module and additions to the transverse boom, the combined length of the radiators and the logistic module violates the 55 foot length restraint, as does the combined diameter of the solar arrays and the power conditioning units (RFC/PWR).

Similar problems are seen for Flight V of the deployable structure. Also Flight I of the deployable structure exceeds the volume requirements with solar array cannisters that extend 17 feet across the cargo bay diameter. Flight II of the deployable structure, although it does not exceed the volume restraints, does just meet the restraints.

In all cases, restraints, pallets, and cradles that may be used in the cargo bay to contain the components and secure them for launch and landing loads have not been included in the sizing of most of the packages, and will have an impact on the final packaging of these components.

The Shuttle can transport up to 65,000 lb of cargo to low Earth orbit and up to 32,000 lb of cargo to a high Earth orbit (see reference III-2). The Reference Document identifies a 270 nmi circular orbit for Space Station. Depending upon whether Space Station is constructed at the 270 nmi orbit or constructed at a lower orbit and boosted to the higher permanent orbit will determine how many of the components the Shuttle will be able to carry to orbit per flight. As can be seen in Appendix D, only Flights I and II of both the erectable and deployable structure are under a 35,000 lb weight. And because of unknown weights in those flights, as well as flights III-VII the total cargo weight will increase.

Because of these volume and weight constraints, it is highly probable the Reference Document's and this trade study's construction procedures will be changed to accommodate the constraints. Although the tasks and the required EVA hours to construct Space Station on each flight may be rearranged, the time to perform the tasks should remain constant.

Shuttle Flights Required and Alternatives

This study uses for a basis the seven Shuttle flight construction scenario outlined in the Reference Document. Because of concerns already addressed in this paper, the number of Shuttle flights required to construct Space Station could change. Table III-2 lists several alternatives to the construction scenario used in this study and their implications on the number of Shuttle flights. Two of the alternatives listed involve construction procedures incorporating the MRMS capibilities.

For the erectable construction approach as outlined by the scenario for Shuttle Flight 1, Appendix B, a framework is to be erected across the shuttle cargo bay. The Space Station transverse beam would be erected from this framework. An alternative is to build the docking bay across the cargo bay using the Shuttle manipulator foot restraint and the MRMS as depicted in figure III-14. Once the docking bay is completed with the MRMS attached the transverse beam would be built off the docking bay using the procedures already established in the appendix.

An alternative which uses the MRMS in the deployable truss scenario is shown in figure III-15. Instead of developing a deployer for the truss structure, the MRMS could be used for the same function. The MRMS push-bar would deploy the structure by attaching to the nodal joints and pushing the bay into its deployed position. The MRMS would then move its platform onto the recently deployed bay and proceed to deploy the next bay in the series. By using the MRMS as a deployer, the cost and weight of a deployer mechanism would be eliminated and the research and development involved could be transferred to enhancing the MRMS capabilities. Both of these alternatives would likely decrease EVA time required for construction.

Taking into account the best conditions to the worse conditions to build the Space Station, it is estimated to take from six to nine Shuttle flights for the erectable structure and seven to ten Shuttle flights for the deployable structure. Most of the additional flights would be created to compensate for volume and weight restraints not EVA hours.

Conclusions/Recommendations

This section of the deployable/erectable trade study addressed construction operations of the IOC using the 9 foot deployable truss structure and the 15-foot erectable truss structure. Concerns in this study included 1) construction procedures and their feasibility, 2) EVA hours required, 3) packaging of the Space Station components, and 4) Shuttle flights required and alternatives to construction procedures and packaging.

Out of these concerns two items present themselves as possible discriminators between an erectable and a deployable truss configuration. The first is pre-integration vs. integration on-orbit. In this study, the deployable is able to take advantage of preintegration and save EVA construction time on the first Shuttle flight. However, in the following flights, both structures require sufficient on-orbit integration to negate any further advantage of the deployable over the erectable.

The second discriminator would be the actual tasks performed by the EVA crews. The erectable truss structure requires constant assembly work, where the deployable truss structure does allow the crews to rest during deployment where they are only required to inspect the structure. However, this only amounts to approximately 14.6 hours out of 96.2 hours, 15 percent of the total deployable structure construction time.

These two discriminators are not strong arguments for one truss structure or the other when coupled with the total EVA hours of construction time; 111 hours for erectable vs. 96 hours for deployable. Therefore, EVA in and of itself is not a major discriminator between the two structures.

However, the number of EVAs per flight as shown on the chart in Table III-3 is a deficiency which needs to be resolved. Flights I, II, and IV need to be reconstructed so as to redistribute the EVA hours to three or four EVAs per flight staying within a much more reasonable work envelope for the crew and Shuttle support. Three EVAs per flight allows for 126 hours of crew EVA time, indicating that the 111 hours of erectable truss construction and the 96 hours of deployable truss construction are satisfactory numbers for EVA hours.

A much more serious area of concern is the weight and volume constraints of the Shuttle cargo bay. Depending upon final size and weight of the Space Station components, the number of flights to build Space Station may vary from six to nine flights for the erectable structure and seven to ten flights for the deployable structure. Further consideration in this area is recommended.

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TABLE III-1

ASSUMPTIONS FOR ASSEMBLY SCENARIO

1. REQUIRED COMPONENTS WILL PACKAGE WITHIN SHUTTLE CARGO BAY VOLUME AND WEIGHT CONSTRAINTS.
2. TWO CREWMEN IN EVA AT A TIME.
3. EVAs ARE BASED ON CURRENT SHUTTLE EVA EXPERIENCE.
4. EVA REQUIRED FOR ALL DEPLOYABLE OPERATIONS.
5. NO EVA OVERHEAD TIME ACCOUNTED FOR.
6. NO SYSTEM CHECKOUTS AT THE COMPLETED CONSTRUCTION OF A FLIGHT.
7. UTILITY POWER CABLES, POWER CONDITIONING EQUIPMENT (RFC/PWR), GN&C, FUEL TANKS, α-JOINTS, LOWER KEEL DOCKING RING, AND SOLAR ARRAYS, PREINTEGRATED WITH 9' DEPLOYABLE STRUCTURE.
8. ALL OTHER SUBSYSTEMS AND SPACE STATION COMPONENTS NOT MENTIONED IN ITEM #7 MUST BE INTEGRATED ON-ORBIT.
9. ALL SYSTEMS AND COMPONENTS MUST BE INTEGRATED ON-ORBIT FOR THE 15' ERECTABLE STRUCTURE.
10. MRMS PLATFORM SIZE IS DETERMINED BY THE TRUSS BAY SIZE.
11. ALL FUEL AND AMMONIA LINES ARE CONSIDERED TO BE IN BAY LENGTH SECTIONS.
12. THE INSTALLATION OF ON-ORBIT INTEGRATED COMPONENTS, COMMON TO DEPLOYABLE AND ERECTABLE STRUCTURES, DEPLOYMENT OF THE SOLAR ARRAYS, AND THE OPERATION OF THE MRMS IS THE SAME FOR THE ERECTABLE AND THE DEPLOYABLE STRUCTURE.
13. THE SPACE STATION MODEL USED, INCLUDES THE NEW POWER CONFIGURATION OF 4 RADIATORS AND POWER CONDITIONING UNITS ON THE TRANSVERSE BOOM.
14. FOURTEEN HOURS OF RADIATOR INSTALLATION IS STILL REQUIRED AFTER FLIGHT II WHEN 42 RADIATOR PANELS ARE STOWED.

Table III-2

FLIGHT PROCEDURE ALTERNATIVES

15' ERECTABLE	9' DEPLOYABLE
o PACKAGE ALL RADIATORS ON FLIGHT I MODULE I ON FLIGHT II - DECREASES NUMBER OF FLIGHTS	o BEGIN HABITATION AFTER SECOND MODULE IN PLACE. EXCEPT FOR MODULES AND TRUSS STRUCTURE, REMAINING COMPONENTS INSTALLED BETWEEN FLIGHTS - DECREASE SHUTTLE EVA TIME
o BEGIN HABITATION AFTER SECOND MODULE INSTALLED. EXCEPT FOR MODULES REMAINING COMPONENTS INSTALLED BETWEEN FLIGHTS. - DECREASES SHUTTLE EVA TIME	o WEIGHT LIMITED: STRUCTURE OF FLIGHT IV AND V COMBINED ON ANOTHER FLIGHT. SEND MODULES UP WITHOUT INTERIOR COMPONENTS, INSTALL ON LATER FLIGHT. - INCREASES NUMBER OF FLIGHTS
o WEIGHT LIMITED: STRUCTURE OF FLIGHT IV AND V COMBINED ON ANOTHER FLIGHT. SEND MODULES UP WITHOUT INTERIOR COMPONENTS, INSTALL ON LATER FLIGHT. - INCREASE NUMBER OF FLIGHTS	o EVA LIMITED: REDISTRIBUTION OF TASKS AND COMPONENTS TO FLIGHTS III, VI, VII, OR ANOTHER FLIGHT DUE TO VOLUME CONSTRAINTS. - POSSIBLE INCREASE OF FLIGHTS
o EVA LIMITED: REDISTRIBUTE TASKS AND COMPONENTS TO FLIGHTS III, VI, VII. - NO CHANGE IN FLIGHTS	o VOLUME LIMITED: REDESIGN OR BETTER DEFINE PACKAGING OF COMPONENTS, OR SEND ON ANOTHER FLIGHT - INCREASES NUMBER OF FLIGHTS
o VOLUME LIMITED: REDESIGN OR REDISTRIBUTE TO ANOTHER FLIGHT - NO CHANGE IN FLIGHTS	o USE MRMS TO DEPLOY STRUCTURE - DECREASE WEIGHT, VOLUME, AND SHUTTLE EVA TIME
o USE MRMS TO BUILD 1st BAY: TRANSITION BOOM - DECREASES SHUTTLE EVA TIME	
POSSIBLE FLIGHTS: 6-9	POSSIBLE FLIGHTS: 7-10

TABLE III-3

DEPLOYABLE VS. ERECTABLE TRADE COMPARISON--CONSTRUCTION OPERATIONS

	DISCRIMINATORS	PREINTEGRATED SUBSYSTEMS 9' DEPLOYABLE	"LAYERED" SUBSYSTEMS 15' ERECTABLE	"LAYERED" SUBSYSTEMS 15' PACTRUSS	"LAYERED" SUBSYSTEMS TETRAHEDRAL
CUSTOMR ACMDTNS	GROWTH POTENTIAL				
	PAYLOAD ACCOMMODATIONS				
SUBSYSTEM INTEGRATION	1) POWER CABLES ETC.				
	2) RCS THRUSTERS ETC.				
	3) THERMAL AND PROP. LINES				
	4) INSTALLATION & SERVICING				
	5) ROTARY JOINTS				
	6) MRMS				
	7) SE&I REQUIRED				
CONSTR. OPS.	EVA HOURS	S	S	?	?
	NUMBER OF EVAS PER FLIGHT	D	D	?	?
COST	TRUSS { WEIGHT, PART COUNT; D.D.&T., DEPLOYER				
	CONSTRUCTION				
TRUSS CRITERIA	REDUNDANCY, REPAIRABILITY AND MAINTAINABILITY				
	PREDICTABILITY				
	STIFFNESS				

A - ADVANTAGE, S - SATISFACTORY, D - DISADVANTAGE

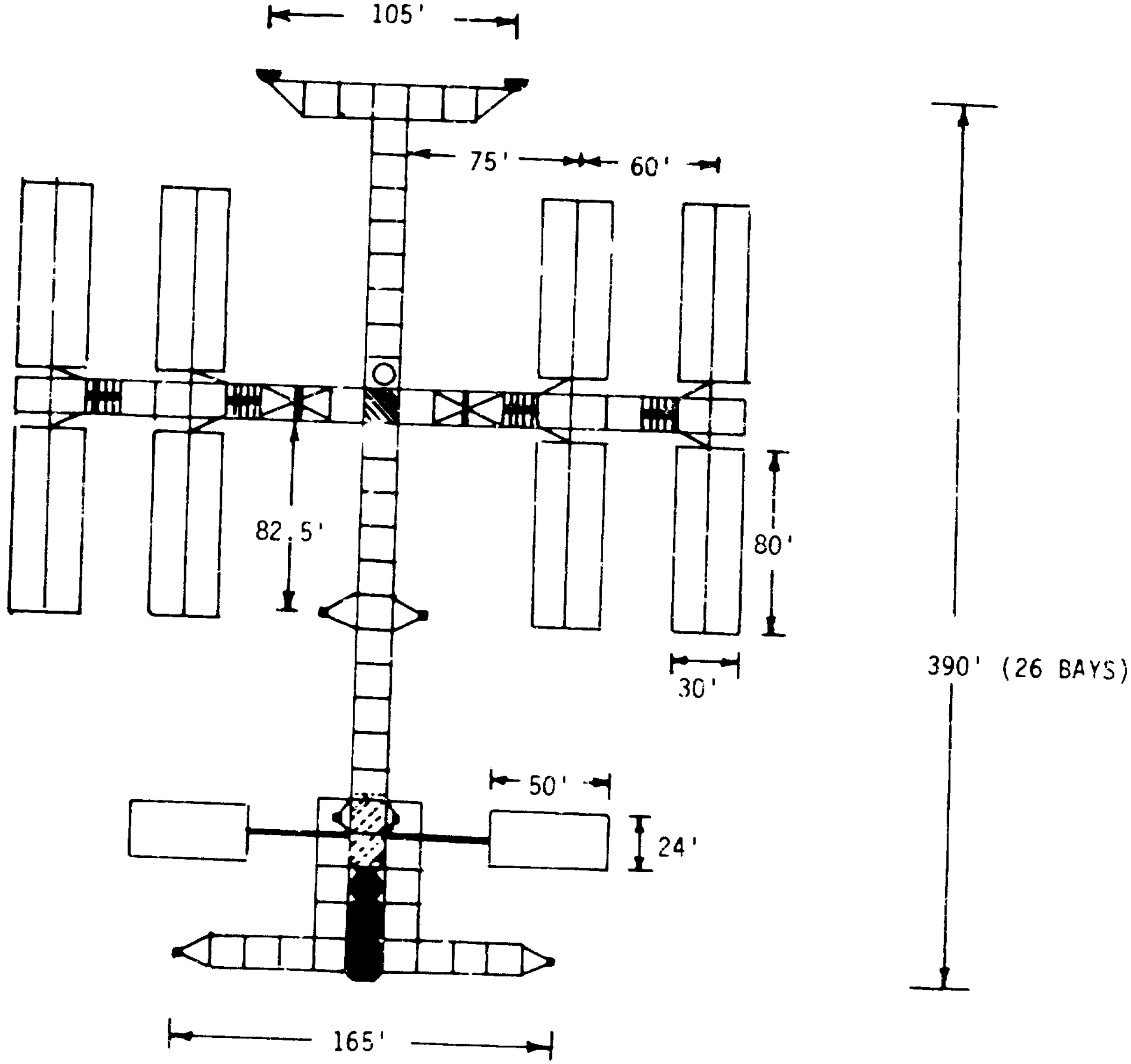


Figure III-1. Sketch of erectable 15-foot truss space station.

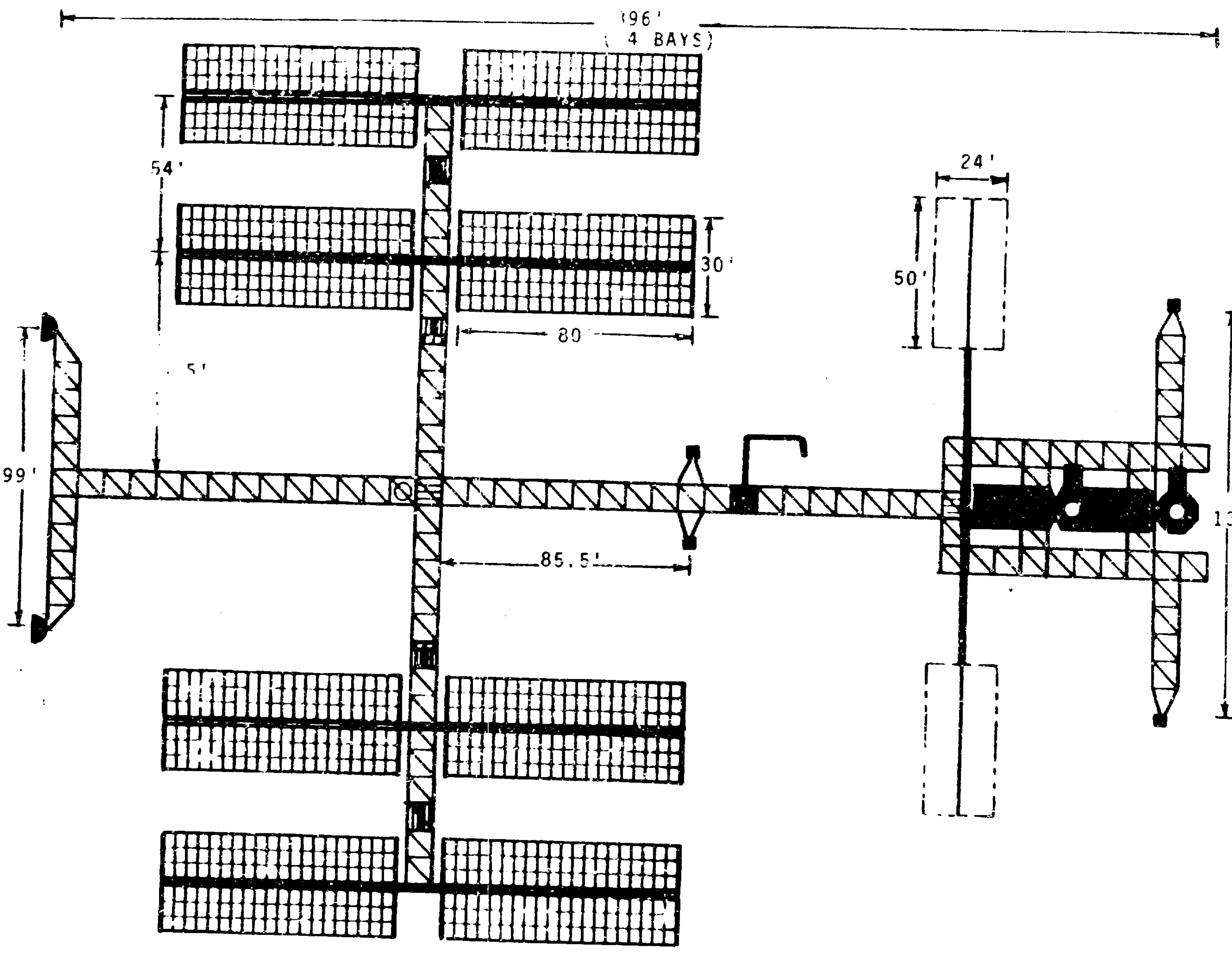


Figure III-2. Sketch of deployable 9-foot truss space station.

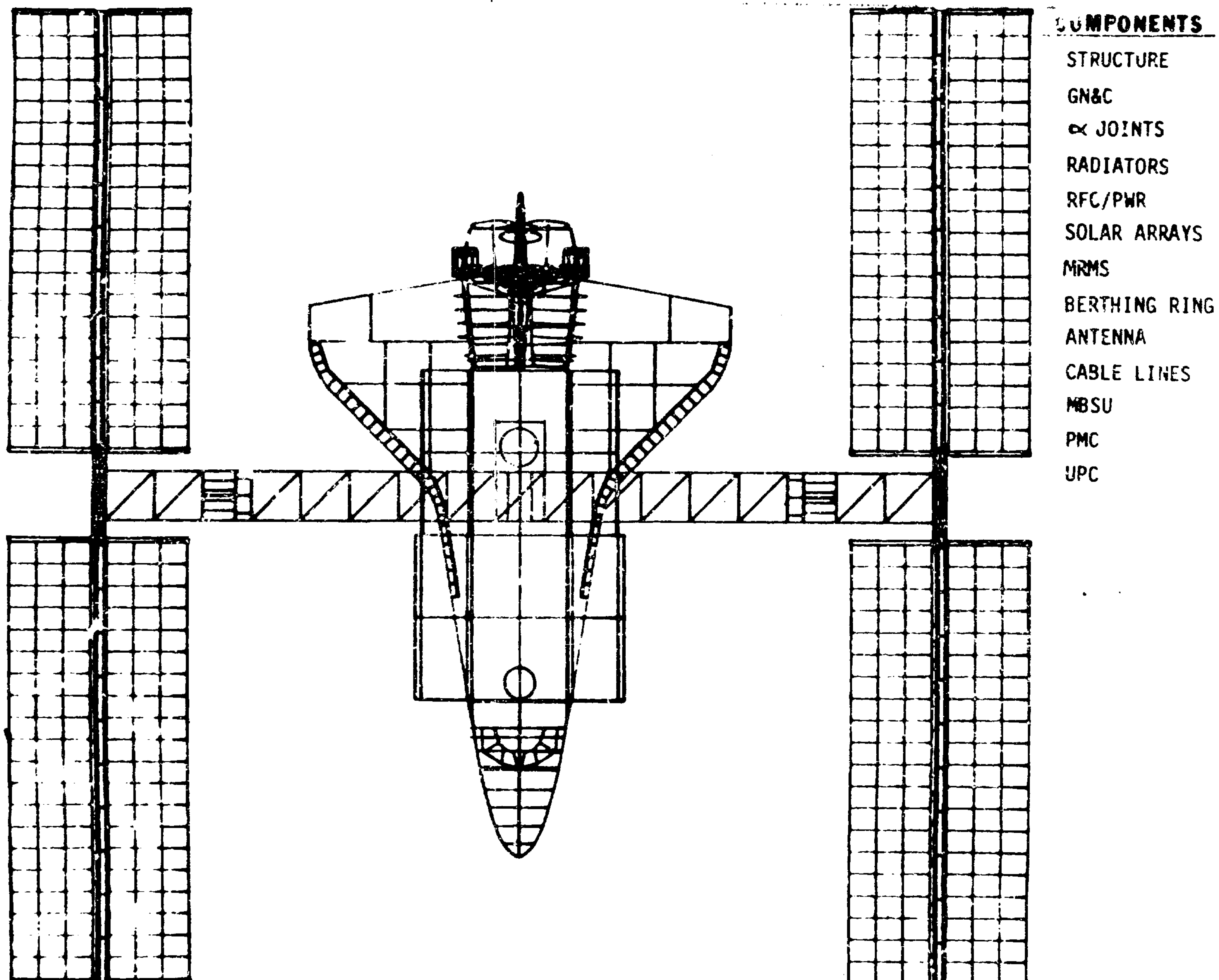


Figure III-3. Completion of Flight I - Transverse boom assembled.

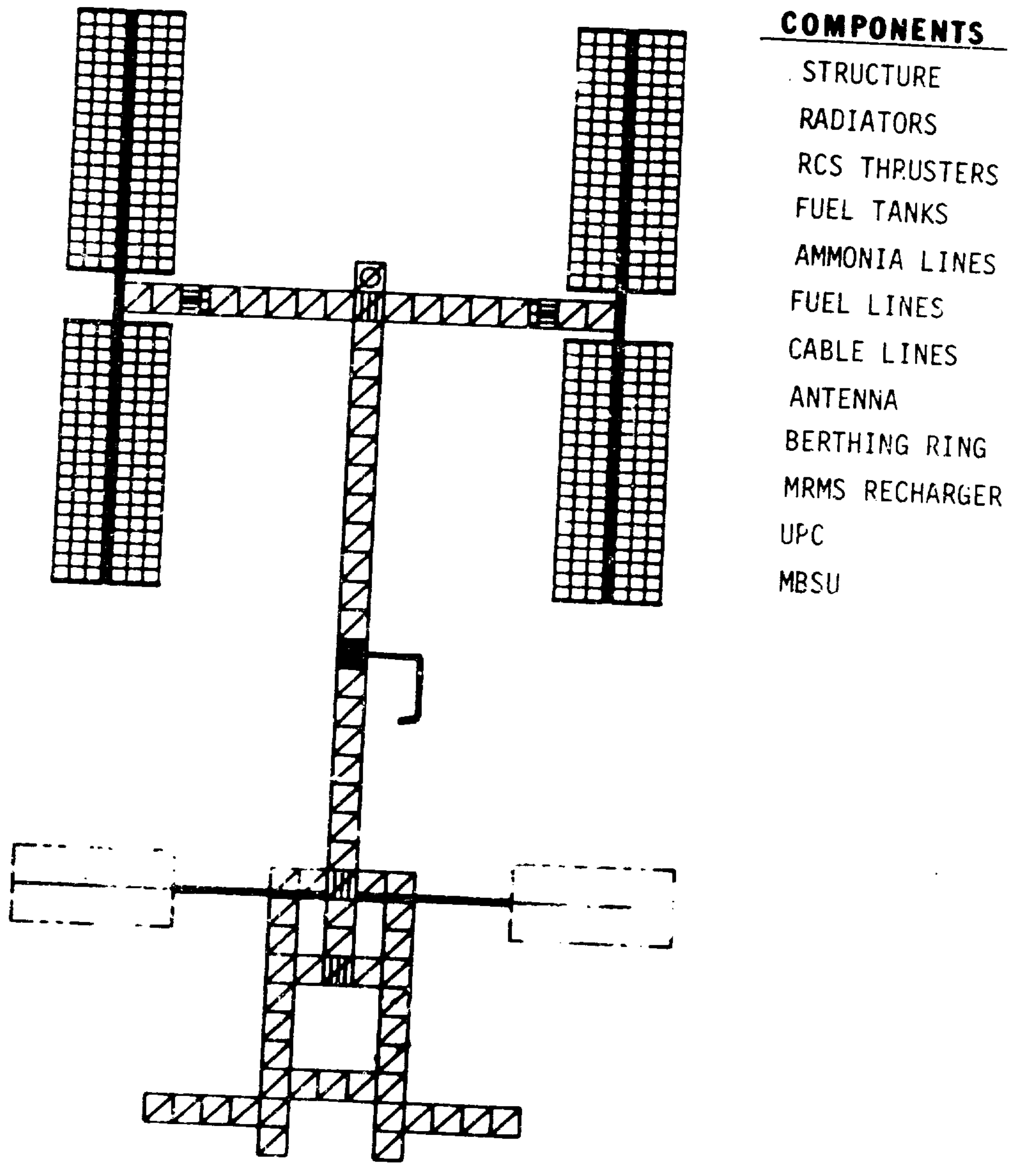


Figure III-4. Completion of Flight II - Lower keel assembled.

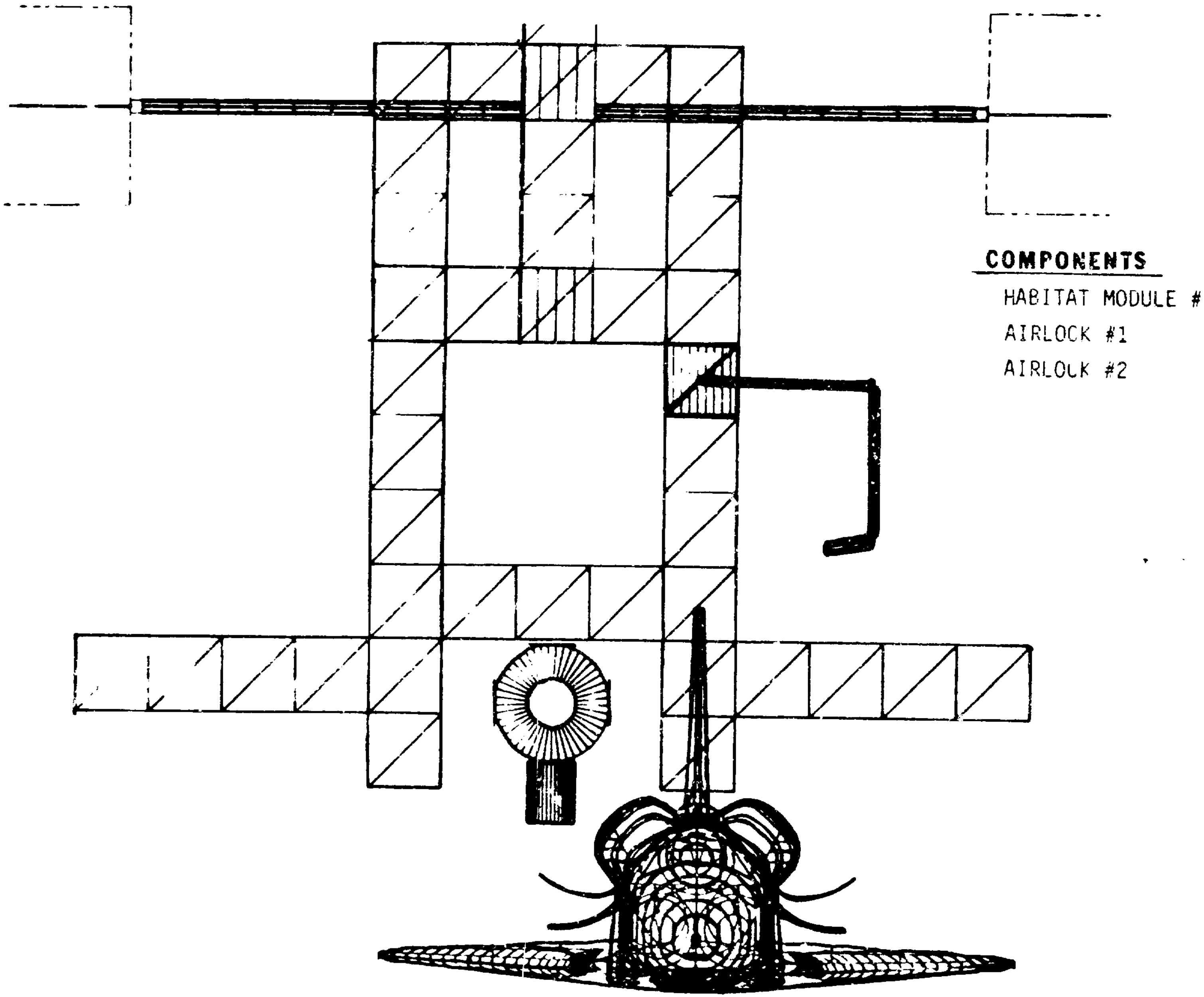


Figure III-5. Completion of Flight III - Habitat module 1 and airlocks installed.

COMPONENTS

HABITAT MODULE #2	CABLE LINES
STRUCTURE	UPC
ANTENNA	MBSU
AMMONIA LINES	

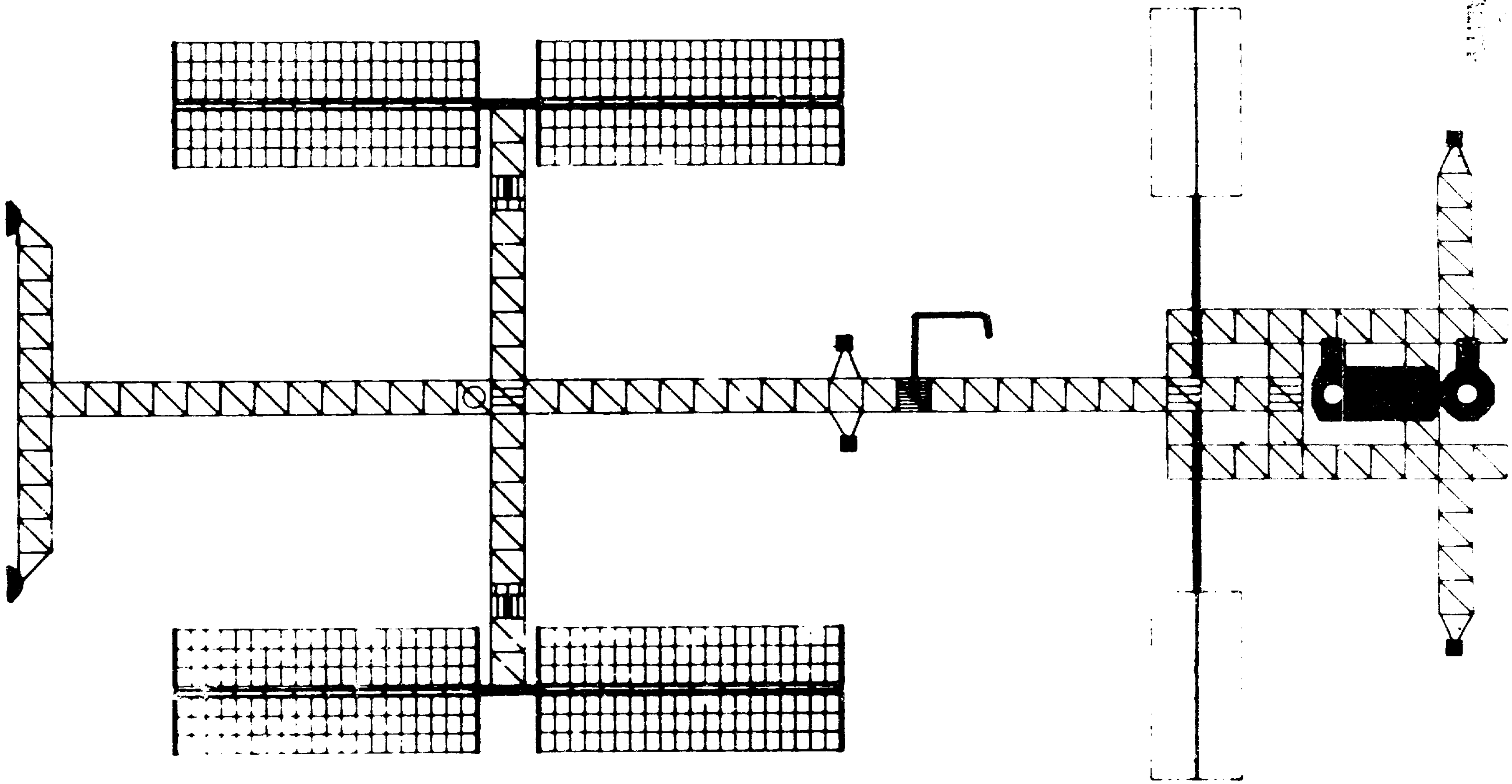


Figure III-6. Completion of Flight IV - Habitat module 2 installed and upper keel assembled.

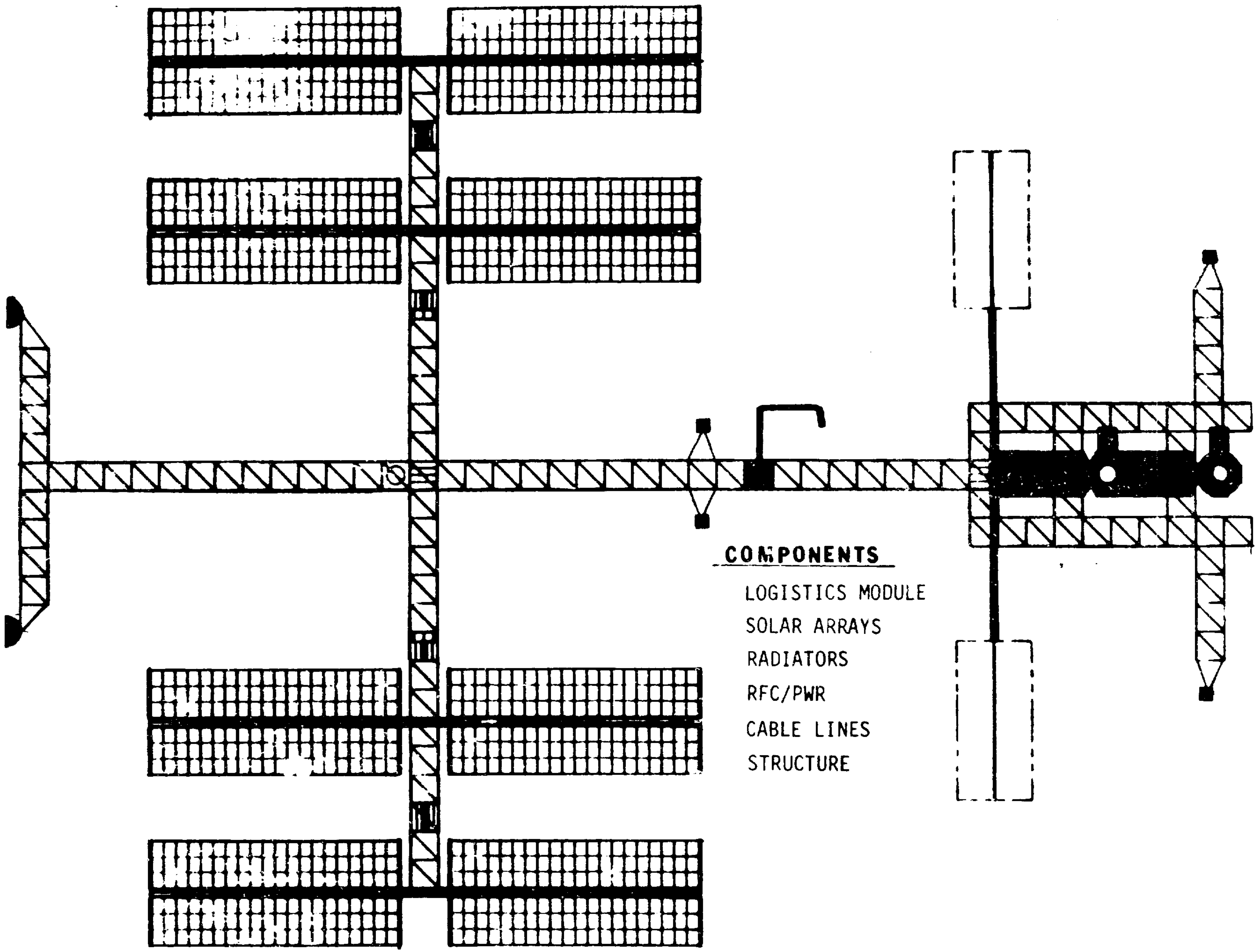


Figure III-7. Completion of Flight V - Logistics module installed and transverse boom extended.

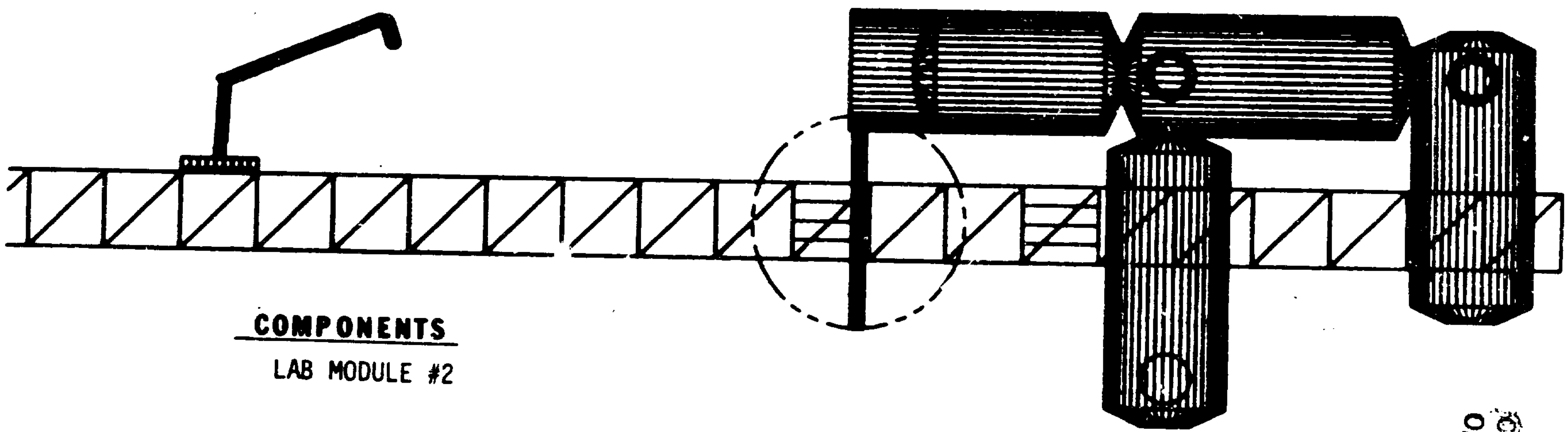


Figure III-8. Completion of Flight VI - Lab module 2 installed.

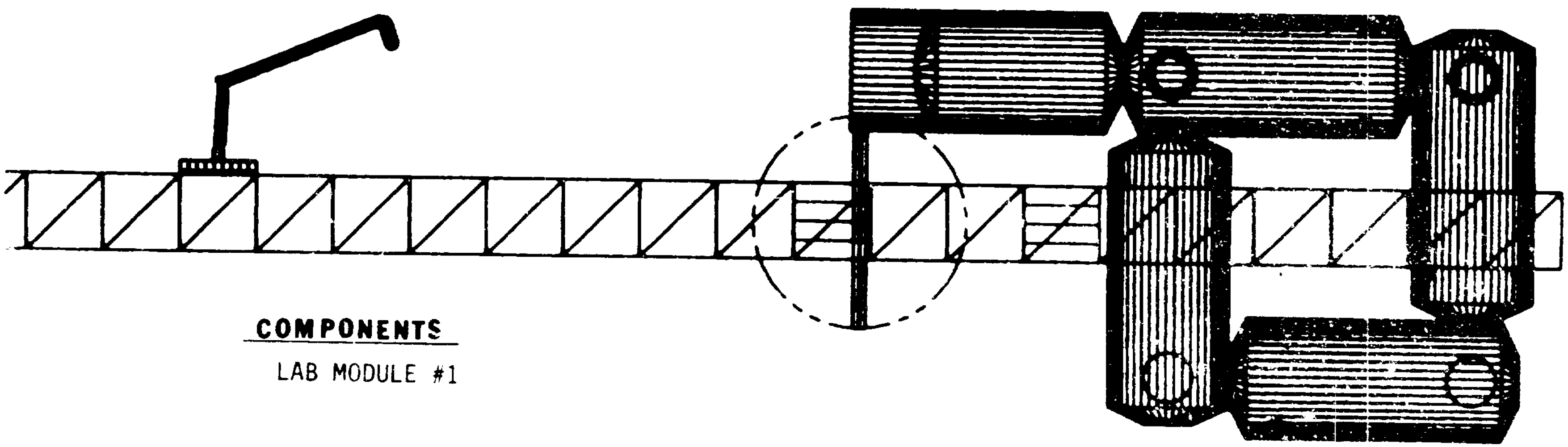


Figure III-9. Completion of Flight VII - Lab module 1 installed.

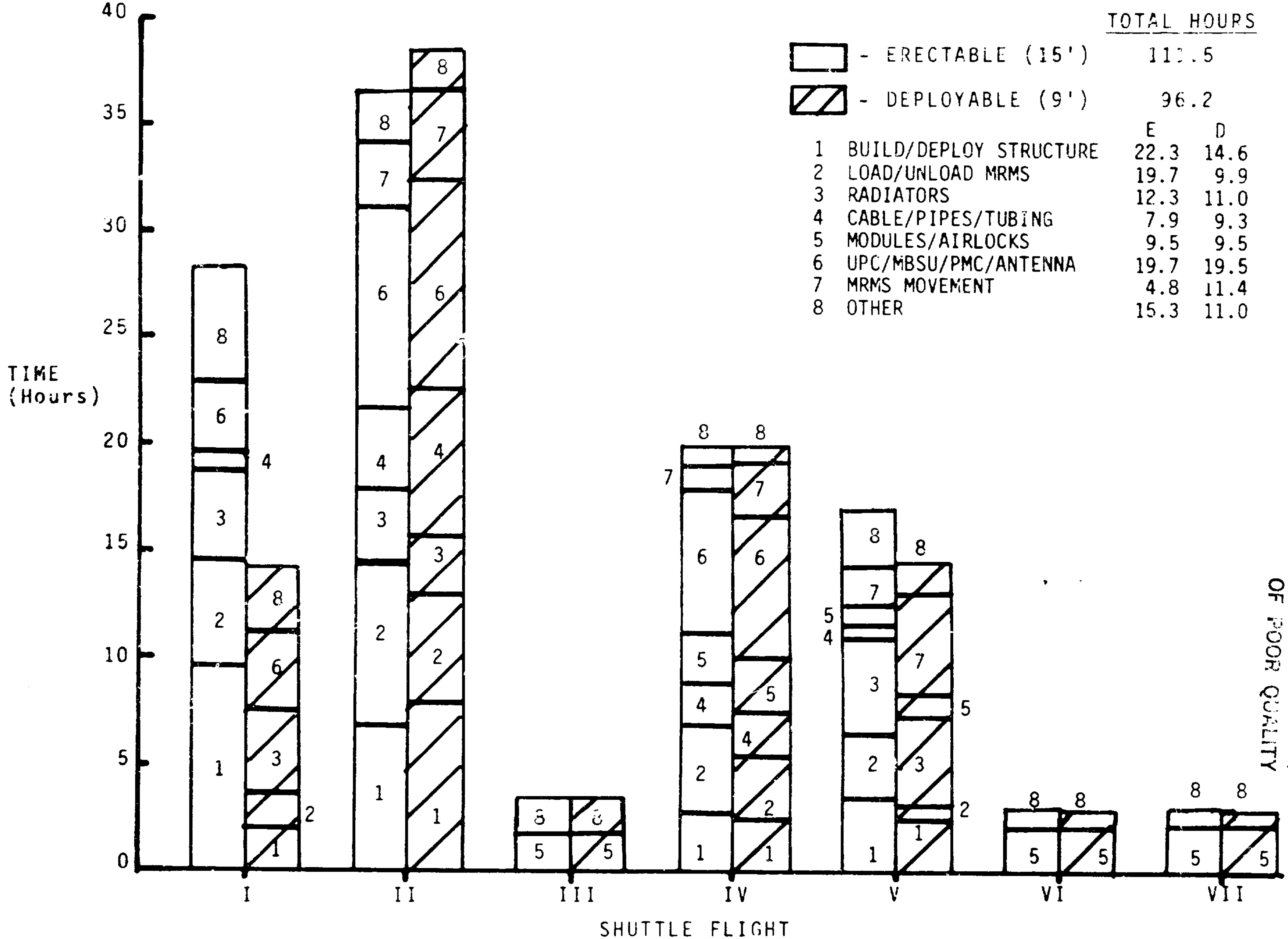


Figure III-10. Comparison of EVA hours per Shuttle flight for erectable (15') vs deployable (9').

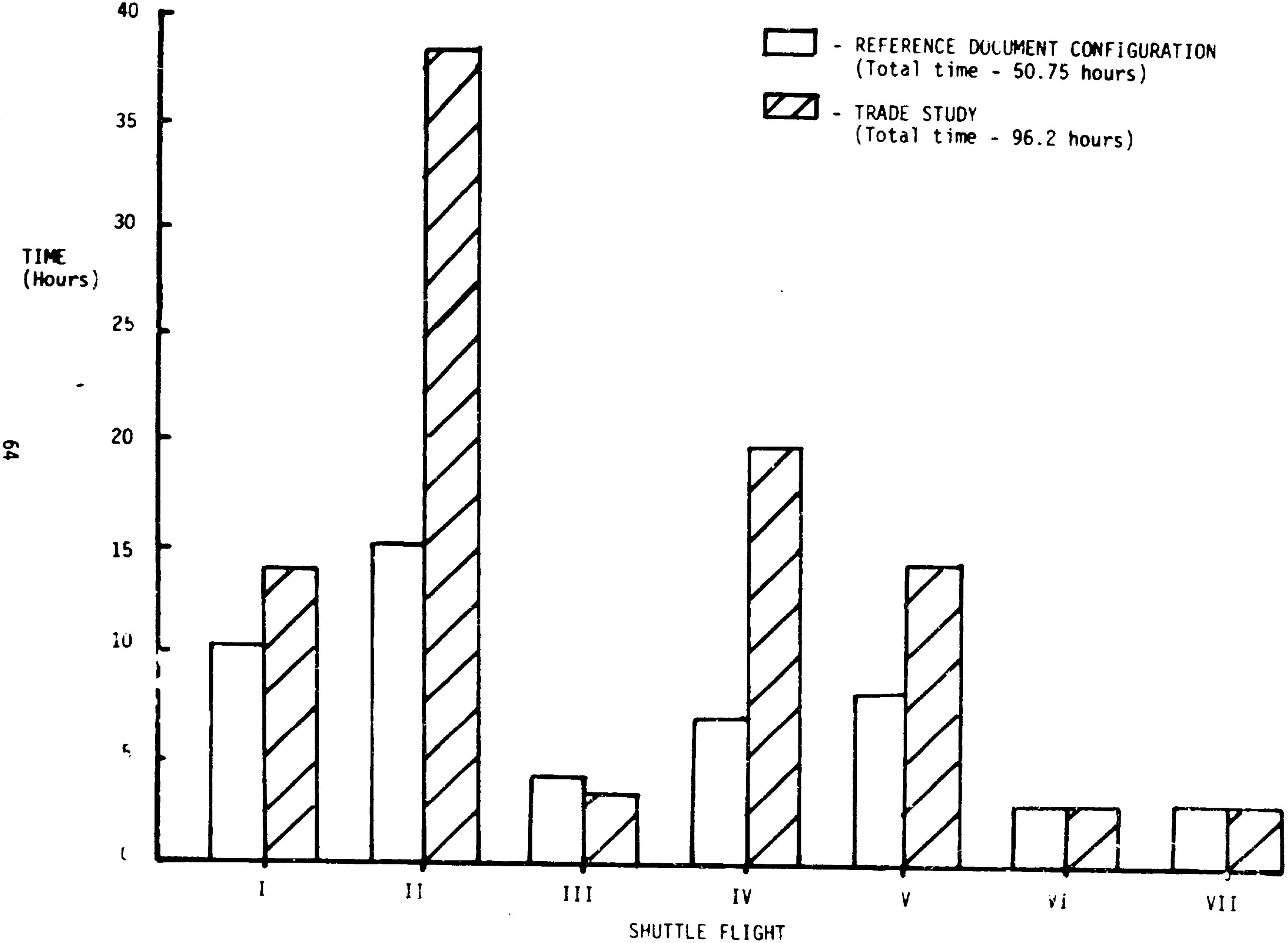


Figure III-11. Comparison of EVA hours per Shuttle flight for 9' deployable truss. Reference Document configuration vs Trade Study configuration.

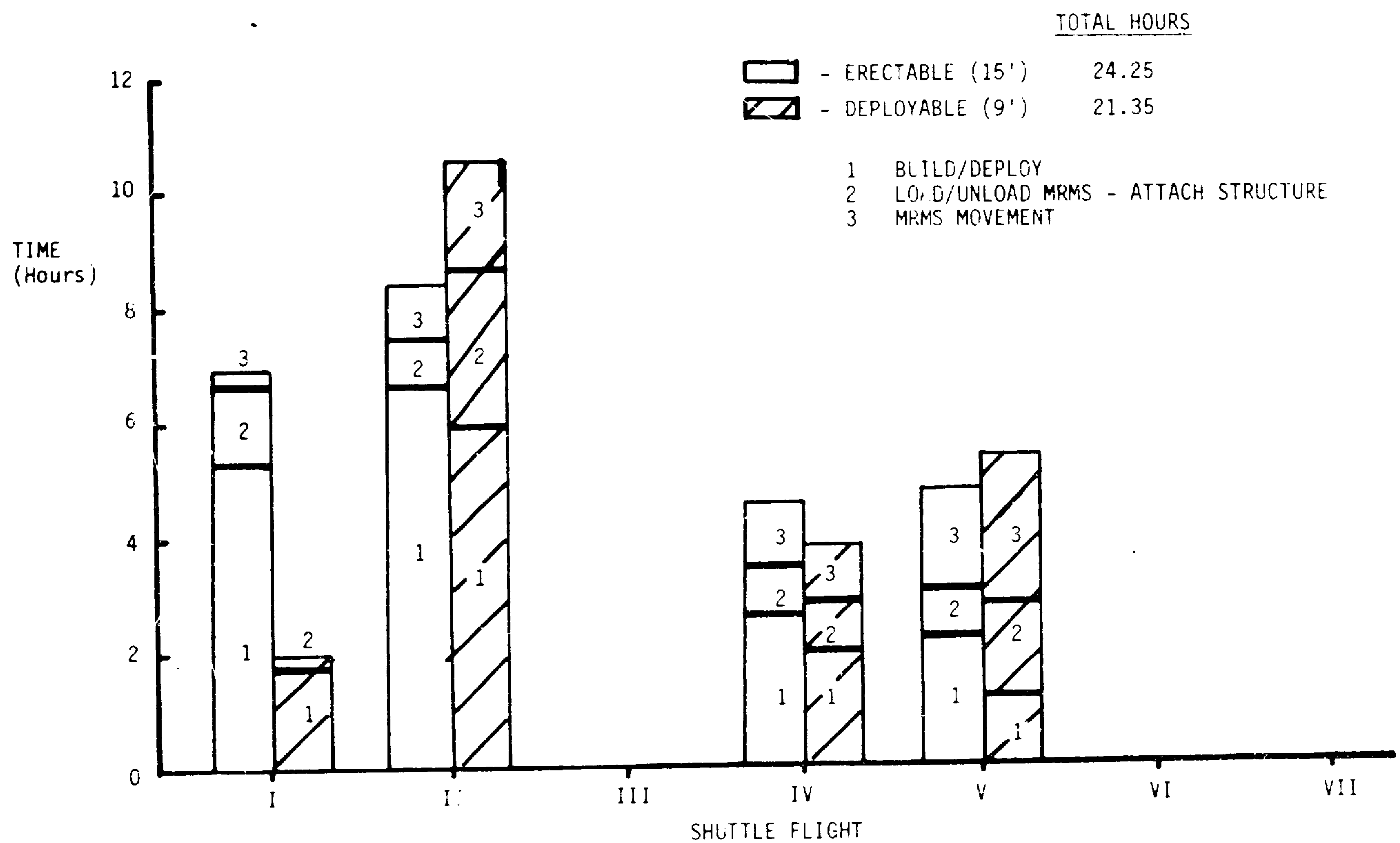


Figure III-12. Comparison of EVA hours per Shuttle flight for structure assembly. Erectable (15') vs Deployable (9').

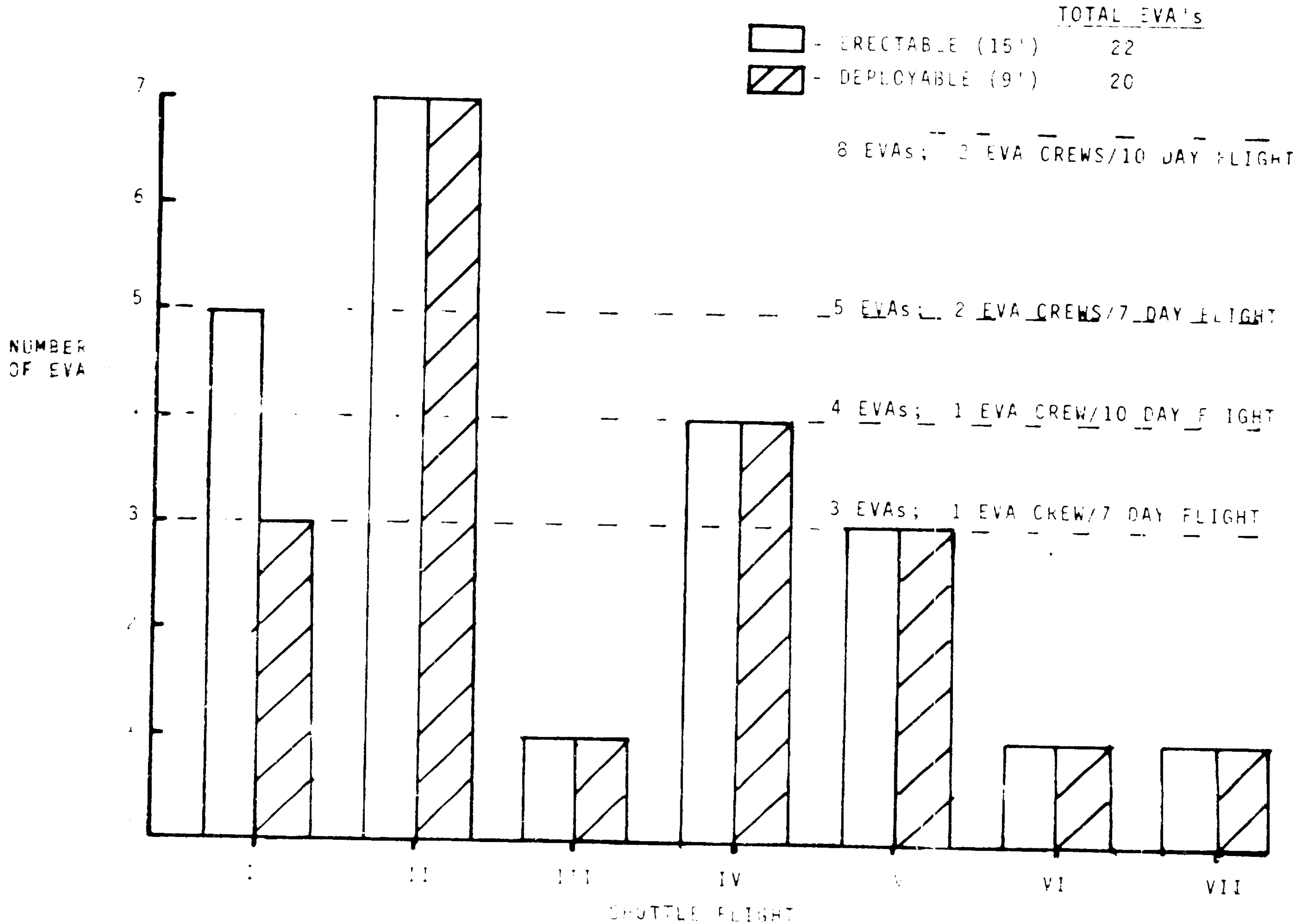


Figure III-13. Comparison of EVAs per Shuttle flight for erectable (15') vs deployable (9').

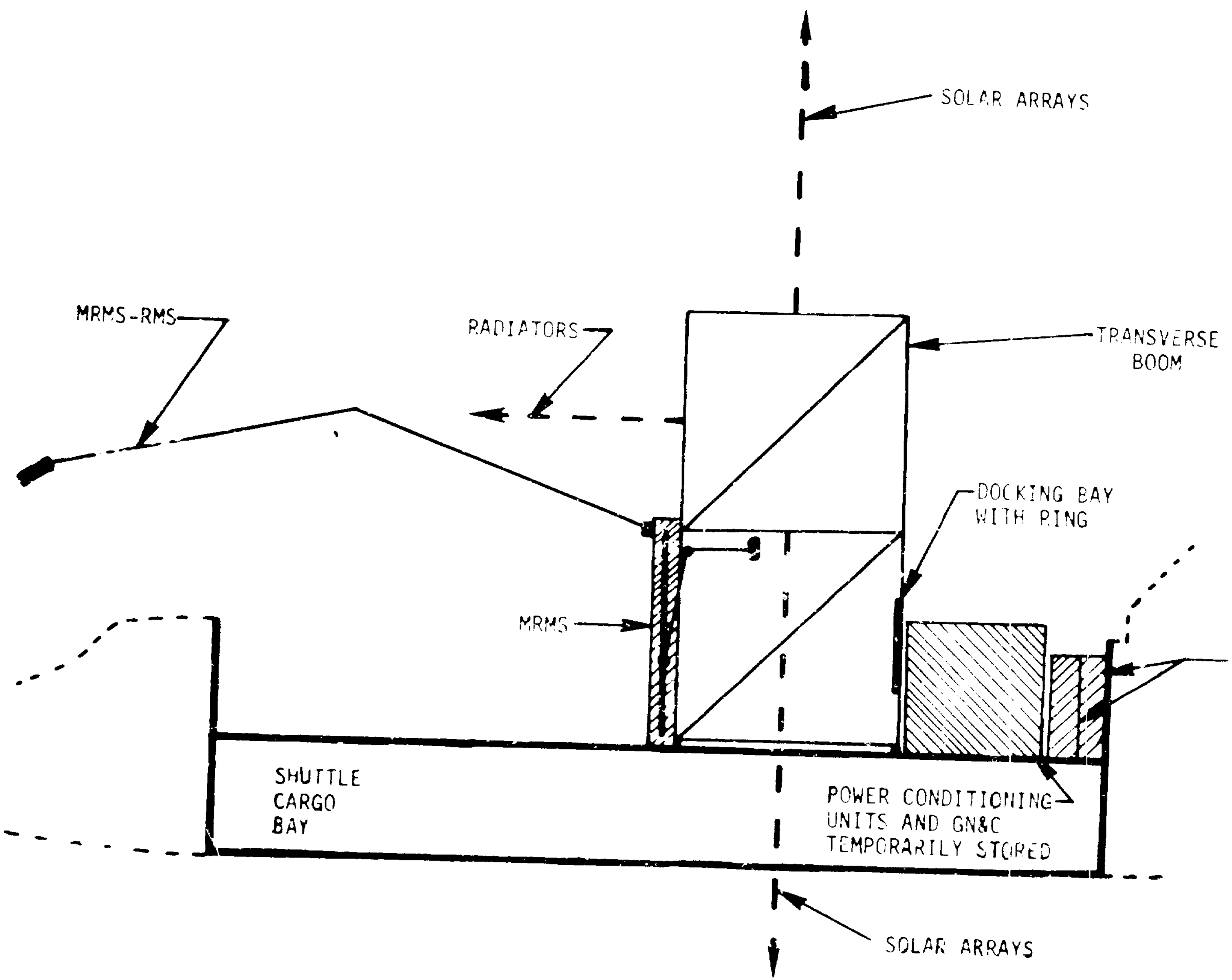
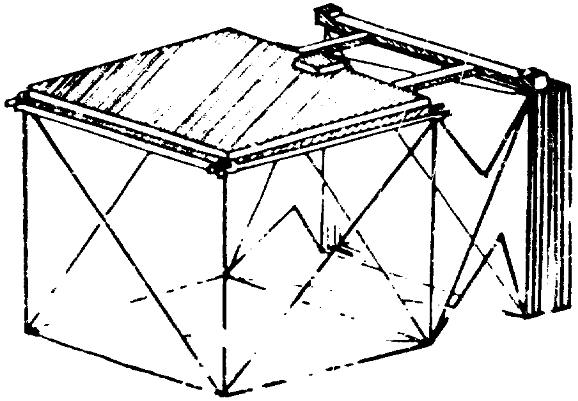
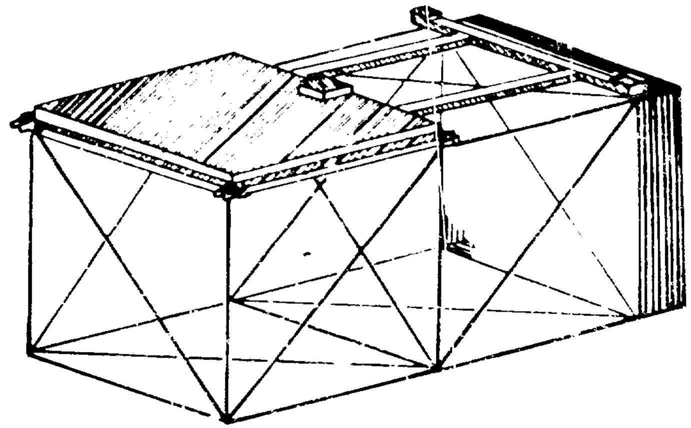


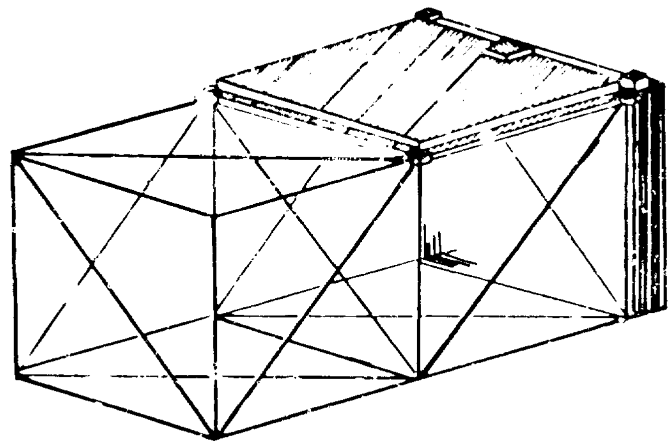
Figure III-14 An alternative procedure to erecting the transverse boom for the erectable truss structure.



MRMS deploying structure



MRMS with deployed bay



MRMS moves to deploy next bay

Figure III-15. The MRMS as an alternative deployer for the deployable truss structure.

IV. COST ANALYSIS

Introduction

The Space Station truss cost trade off analysis represents a four week effort to examine, in as much engineering detail as possible, potential configurations of the primary truss for the Space Station structure. The truss configurations examined are the fifteen foot erectable and the nine foot deployable with deployer.

The conclusions reached are the sole perspective of the estimators and are based on the review of many documents and engineering definition provided by numerous project engineers within NASA. The results presented in this study should be regarded both as a completed first step within the design-to-cost process and as a stepping off point for improving the cost estimates provided here through refined engineering definition, for examining additional truss design alternatives, and for obtaining a better estimate of the cost of the fully integrated truss.

Modeling Approach

Design Assumptions.- The engineering design for the fifteen foot erectable was supplied by the Structural Concepts Branch at the Langley Research Center (LaRC) and is based on the node and node fitting design as shown in figure IV-1. It was assumed that the fifteen foot erectable final assembly would be completed in an extravehicular activity (EVA) environment. An attempt was made during the study to use a detailed description of the most recent Rockwell International truss/deployer design. However, details could not be obtained during the short time frame available. Hence, the nine foot deployable was adapted from a Rockwell International design defined in figures 1.3-2 through 1.3-8 of reference IV-1, which is illustrated by figure IV-2. A bidirection deployer was assumed so the deployer was composed of two back-to-back units of the deployment mechanisms shown in figure IV-3. EVA guidelines were supplied by the LaRC Structural Concepts Branch. The "mushroom" guide pin was assumed to be used for both configurations and was assumed to be machined from aluminum.

Estimating Ground Rules.- The basic estimating ground rules are shown in figure IV-4. It is important to note that a low, medium, and high cost were estimated for each Work Breakdown Structure (WBS) element. These costs are based on the best possible believable, the expected, and the worst possible believable engineering scenarios. The assumptions describing the engineering process for each scenario were used to provide respective costs based on the engineering definition. The low cost may be interpreted as the minimum cost associated with a believable engineering process. Similarly, the high cost may be interpreted as the maximum cost associated with a believable engineering process. As such, no statistical interpretation can be meaningfully attached to these numbers. To do so would imply statistical knowledge which is not available.

No consideration has been given to which budget the money comes from since the intent is to compare resources required to do the job. For example, EVA is considered part of the cost even though it may come out of an operations budget. Budgetary adjustments may be provided by the reader.

No consideration has been given to which contractor will develop and produce the truss. However, the low estimates assume contractors which have performed this work before and have many existing plans and procedures which can be applied. Conversely, the high estimates assume contractors which have few or no existing plans and procedures to apply.

A risk analysis has been applied which is based on the definition of the engineering process by engineers, not on the engineers perception of cost. This results from using the low, medium, and high estimates obtained from the engineering scenarios and applying a statistical process to those cost numbers. For this study, risk is assumed to include both technological/production risk as well as the risk associated with the ability of engineering/estimating personnel to define the bounds within which the engineering process will fall.

The scope of the tradeoff study is shown in figure IV-5. Because of the short estimating time frame, only the primary truss structure, its associated integration and test (I&T), the deployer, its associated I&T, the truss/deployer I&T, the associated construction EVA, the remaining EVA for integration of other systems with the primary truss, and that portion of the system I&T which would be performed by the truss team have been included.

Shuttle flights have not been included since the guidelines provided to the cost estimators for this study do not indicate a difference in the number of flights required between configurations.

A desirable output for the study is a cost estimate for both the truss after assembly in space while awaiting integration with truss attachments and a cost estimate for the activity required to integrate all truss attachments to the truss. The cost of integration can only be estimated after a detailed examination of all attachments and their associated attachment processes. Both the short time available for the study and the lack of available engineering definition of the attachments and attachment processes prohibited completion of such an estimate. A reduced goal of obtaining the cost of the participation of the truss/deployer team within the total system I&T process was realized. This is shown by figure IV-6 which illustrates that the system I&T process is composed of the efforts of a large number of team participants associated with the respective subsystems. Whereas the total system I&T cost could not be estimated within available resources, the truss team's participatory effort could be estimated.

The scope was further narrowed by specifically excluding the rotary joints, the solar arrays, the radiators, the antennas, the modules, other attached appendages, integration and test of sensors and control, all electronics, all software, and all secondary structure for attaching modules, cables, pipes, antennas, etc. It was also assumed that there would be no requirement for the construction of facilities for assembly and test. These assumptions were necessary due to lack of engineering definition and estimating schedule constraints.

Basis of Estimate

Cost Analysis.- The Marshall Space Flight Center Space Station Cost Model (SSCM) and the General Dynamics Convair Division, Large Advanced Space Systems (LASS) Computer-Aided Design and Analysis Program Cost Model defined in reference IV-2 were examined for use as estimating tools. Both are designed to be used at a high WBS level which does not permit estimating cost within subsystems based on detailed engineering definition. Consequently, the RCA PRICE cost estimating model defined by reference IV-3 was used since it permits cost estimating at any WBS level for which calibration data exists. LaRC has been using PRICE for engineering detail based estimates for a number of years and has a reasonable calibration base for the level of detail used in this study.

The groundwork for the study was laid by establishing comparable work breakdown structures as shown in figure IV-7. The primary difference is that the fifteen foot erectable does not require a deployment mechanism.

The analysis was performed at the lowest level in the work breakdown structure at which engineering definition could be obtained in sufficient detail to obtain parameters for the RCA PRICE cost estimating program. This was often the smallest metal or graphite/epoxy component in the assembly process. This is illustrated in figure IV-7 in that the estimating process was applied to the individual metal components of the node fitting in figure IV-1.

Engineering Assumptions.- Each of the WBS elements at which cost is estimated is called a cost generation center and may represent any of a number of types of hardware or software end items as shown by figure IV-8. For this study all were either structural or electromechanical. For each cost generation center a number of engineering based assumptions were made. Although a uniform manned space specification level was assumed, individual considerations at each WBS element determined the number of prototypes, the amount of new design required, the familiarity of the design team with the truss/deployer, the quality of the design team, the amount of design repeat captured, the number of production items, the complexity of the manufacturing process, the number of items integrated and carried to the next higher WBS level, and the complexity of the integration process.

In addition, a large number of engineering process based assumptions were made. The general tendency was to assume that the tasks were partitioned out to engineers familiar with the process. The manufacturing complexities were generated using the PRICE MCPLXS generator based on part tolerances of 10/10000 in. for the low, 5/10000 in., for the medium, and 1/10000 in. for the high scenarios. Appropriate assembly tolerance and production improvement adjustments were made to account for the use of numerical control processes. The contractual process was considered by assuming that parts for the low case would be supplied by a first level subcontractor, for the medium case would be supplied in fifty percent of the cases by a second level subcontractor, and for the high case would be supplied totally by a second level subcontractor. As integration and test approached the system level, more of the effort was assumed to be performed by the prime contractor with less second level subcontractor participation.

All configurations were costed using aluminum (low cost), stainless steel (medium cost), and titanium (high cost) since there is uncertainty as to which would be used or if some combination of all three would be used.

Two percent of the base parts were added as prototypes for individual evaluation and testing. Eight percent of base parts were added to production for testing and spares. Five percent of base parts, which were included in the eight percent above, were assumed to be fully integrated in the next higher assembly. The remainder were for individual piece part testing and spares.

All diagonals and longerons were assumed to be made of a 60/40 mix of pitch 75 graphite fiber and epoxy. The excess laminate in the work breakdown structure accounts for the cost of graphite/epoxy above $20 per pound which is the value that the PRICE MCPLXS complexity generator uses. All longerons and diagonals were reduced in length to compensate for the length of the node (end) fittings. Additional tooling in production was accounted for by using an extra tooling ratio of 2.0 for the low case, 2.5 for the medium case, and 2.9 for the high case.

The fifteen foot erectable truss part count and mass properties are shown in figure IV-9. The nine foot deployable truss part count and mass properties are shown in figure IV-10.

EVA Assumptions.- For EVA astronaut training cost has been assumed the only development cost since shuttle technology use is the baseline assumption. The production cost is based on an application of the Shuttle Reimbursement Guide (reference IV-4) to EVA timelines supplied by the LaRC Structural Concepts Branch. Due to lack of definitive information during the study, wide bounds were assumed with the intent of providing refined engineering definition later.

EVA was split into two WBS elements. The first element is the EVA necessary for the construction of the truss only. The second includes all other EVA time such as attaching modules, integrating power, etc. The intent is to distinguish between resources necessary to deliver a finished truss and resources required for system I&T so that trusses may be compared in a like manner. The percentage of EVA cost for each WBS element was determined based on the percentage each function represented of the total.

For astronaut training a baseline CER from the LASS cost model for space construction crew training was scaled up to 1987 dollars. The low assumption was that the cost per trainee would be only eighty percent of the CER value, that only four astronauts would be trained, and that those astronauts would go on each flight. The medium assumption was that the cost per trainee would be that of the CER and the five astronauts from four (20 total) different crews would be trained. The high assumption was that the cost per trainee was thirty percent more than the CER and that all seven astronauts would be trained for each of the seven flights (49 total).

For EVA production cost the cost of a unit of EVA is based on the Shuttle Reimbursement Guide (reference IV-4) which when scaled up to 1987 dollars costs a minimum of 156,000 dollars and a maximum of 261,000 dollars. The geometric mean of 202,000 dollars was used for the medium. An EVA unit consists of suits for two astronauts plus a spare and all consumables for the flight.

The EVA guidelines provided were assumed to correspond to the low cost. The medium was based on 25 percent additional hours. The high was based on 75 percent more hours. When more than twenty-four team hours of EVA were required on a flight, it was assumed that a second crew would be required for that flight, thus requiring two units of EVA. When more than 42 team hours were required, it was assumed that the excess hours were to be added to the next flight.

For the fifteen foot erectable truss the number of EVA units assumed to be required for the seven flights for the low assumption was nine, for the medium assumption was ten based on trouble in only one flight meeting the timelines, and for the high assumption was eleven based on trouble meeting timelines on two flights.

For the nine foot deployable truss the number of EVA units assumed to be required for the seven flights for the low assumption was eight, for the medium assumption was nine based on trouble in only one flight meeting the timelines, and for the high assumption was ten based on trouble meeting timelines on two flights.

Cost Risk Analysis

Cost Risk Analysis Model.- All of the previously discussed assumptions, plus additional engineering assumptions, were put into the PRICE model which provided costs which were then put into a spreadsheet program where the markup factors were applied to generate inputs to the risk analysis program. This estimating process is illustrated by figure IV-11.

A cost risk analysis was performed for each configuration. The objective was to get an approximation of the distribution of possible projects costs and to obtain an estimate of the expected delivered cost.

Often the estimator is requested to provide the cost of the delivered project. The only possible way the final cost of a project could be provided prior to its initiation would be to know the final configuration of the deliverables and also the exact process by which that configuration was realized. At this stage of the design process this is clearly impossible.

The engineering process by which the project is brought into being is dynamic. A possible model for this process is a network in which each node is a decision point. As the decision is made at each node a particular path is taken. The path resulting from the combination of all decisions within the project defines the path representing the finished project. The network of all paths represents the totality of all possible projects which could have ensued from the beginning of the project. A cost risk analysis examines this network with the intent of approximating the range and distribution of all project costs.

The project cost distribution has been approximated representing each cost generating center by three paths associated with the most optimistic, the expected, and the most pessimistic engineering process assumptions as seen by the engineering/estimator staff. The low, medium, and high costs for each cost generating center are thus functions of the PRICE parameters which correspond to the most optimistic, the expected, and the most pessimistic engineering process assumptions. The cost produced from the cost generating center is then selected from the associated low, medium, and high cost for that center with equal probability. Many other selection weightings are possible, but none seem more justifiable prior to detailed examination of the probability distribution of each center than an equally weighted selection which assumes that no information about the distribution is available. The probability density and cumulative distribution functions are then determined as described for the typical cost risk analysis based on the collection of a thousand random project cost sums. This approximation was feasible within the time frame since the low, medium, and high costs were estimated in order to bound the range of possible project cost. Thus, the risk analysis was performed by running three complete PRICE runs for each configuration and then using the available data.

Since the cost estimating relationships in PRICE are monotonically increasing functions of their parameters we are assured that the sum of the lowest values for all cost generation centers is the lowest of all possible sums. Similarly, the sum of the highs of all the cost generation centers is the highest of all the sums. Thus, the low and high runs also properly bound the range of believable project costs as desired.

Cost Risk Analysis Summary.- The expected delivered costs for the unintegrated trusses are summarized in figure IV-12. The expected delivered costs for the integrated trusses including the truss team participation in the system I&T is shown in figure IV-13. The numbers on these figures have been normalized to the high cost of figure IV-13.

The lows for each configuration represent the lowest believable cost, the mediums represent the cost based on the expected engineering scenario, and the highs represent the highest believable cost. All are based on specific point designs which represent the early phases of the design process and are thus subject to refinement based upon improved engineering definition. As such, these estimates represent a first step in the design-to-cost process. Note that the risk estimate is the expected delivered cost to NASA based upon the risk analysis.

Conclusions

Figures IV-14 and IV-15 show the relative distributions of cost for structure, the EVA associated with truss assembly, the EVA associated with truss system integration activities, and the truss team system I&T contribution.

Figure IV-16 indicates clearly that the deployer can add significant cost to the project and should certainly be examined for innovative cost reduction designs should that option be chosen. It also indicates that based on current timelines, EVA is not a major discriminator between truss design configurations.

Table IV-1 provides a summary of the cost ratings in the standard report comparison form. The nine foot deployable point design as estimated in this study was rated deficient because of the large addition to cost generated by the required deployment mechanism. The fifteen foot erectable was given an advantage for two reasons. First, a fifteen foot concept has less mass than a comparable nine foot concept and will cost less based on the reduced size, material requirement, and part count. Second, the erectable concept will cost less because it does not require a complicated deployment mechanism, thus reducing size, material requirement, and part count further. The fifteen foot PACTRUSS and the tetrahedral were not rated.

REFERENCES

IV-1. Greenberg, H. S.: "Development of Deployable Structures for Large Space Platform Systems." NASA CR-170689, December 1982.

IV-2. Leondis, A.: "Large Advanced Space Systems Computer-Aided Design and Analysis Program." NASA CR-159191-1, July 1980.

IV-3. PRICE H Reference Manual, RCA Corporation, 1985.

IV-4. "Space Transportation System Reimbursement Guide." JSC-11802, May 1980.

Table IV-1. Deployable vs. Erectable Trade Comparison

	DISCRIMINATORS	PREINTEGRATED SUBSYSTEMS	"LAYERED" SUBSYSTEMS		
		9' DEPLOYABLE	15' ERECTABLE	15' PACTRUSS	TETRAHEDRAL
CUSTOMR ACMDTNS	GROWTH POTENTIAL				
	PAYLOAD ACCOMMODATIONS				
SUBSYSTEM INTEGRATION	1) POWER CABLES ETC.				
	2) RCS THRUSTERS ETC.				
	3) THERMAL AND PROP. LINES				
	4) INSTALLATION & SERVICING				
	5) ROTARY JOINTS				
	6) MRMS				
	7) SE&I REQUIRED				
CONSTR. OPS.	EVA HOURS				
	NUMBER OF EVAS PER FLIGHT				
COST	TRUSS { WEIGHT, PART COUNT; D.D.&T., DEPLOYER	D	A	?	?
	CONSTRUCTION				
TRUSS CRITERIA	REDUNDANCY, REPAIRABILITY AND MAINTAINABILITY				
	PREDICTABILITY				
	STIFFNESS				

A - ADVANTAGE, S - SATISFACTORY, D - DISADVANTAGE

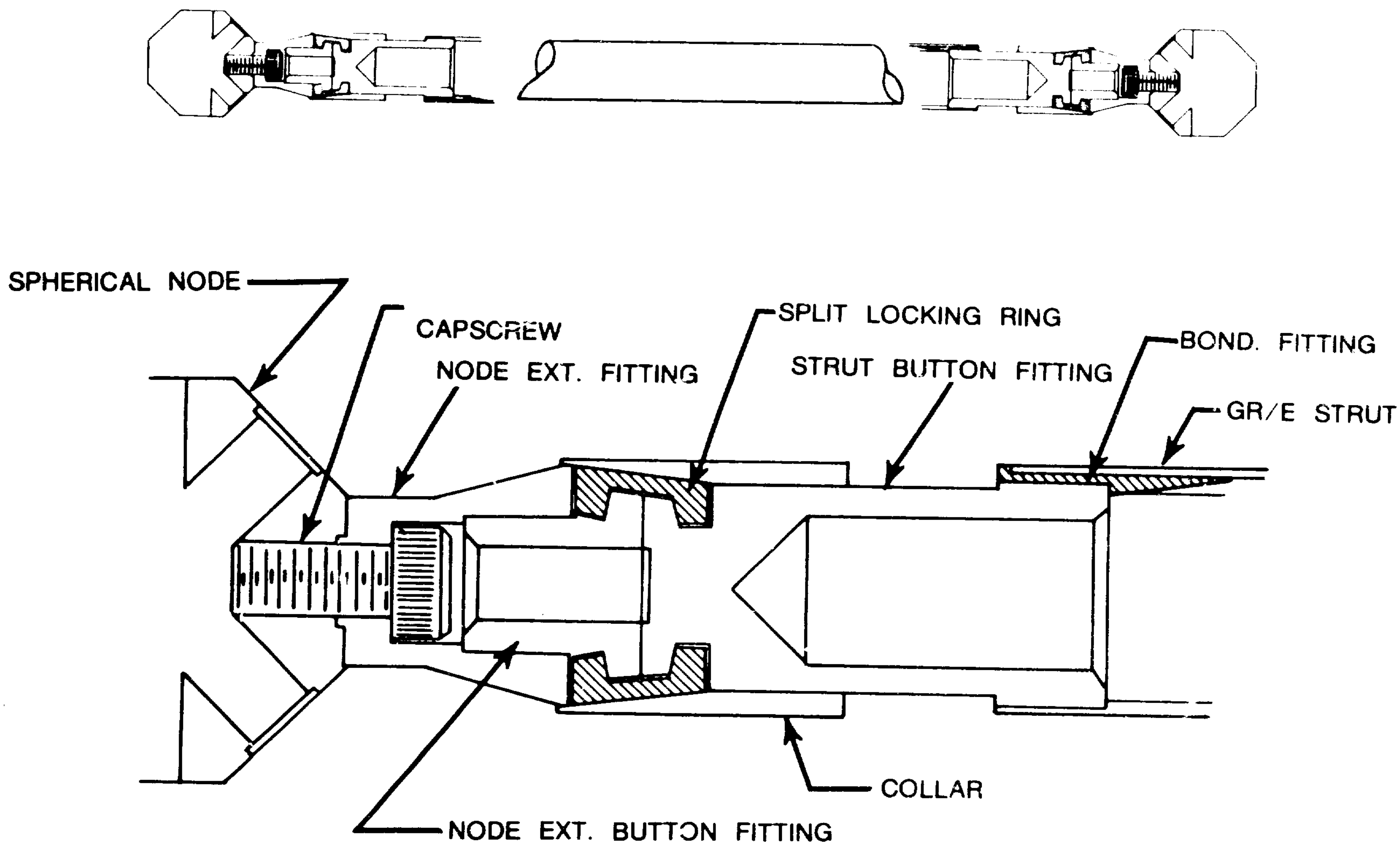


Figure IV-1. 15 Foot Node and Node Fitting Diagram

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TEST ARTICLE DESIGN CONFIGURATION

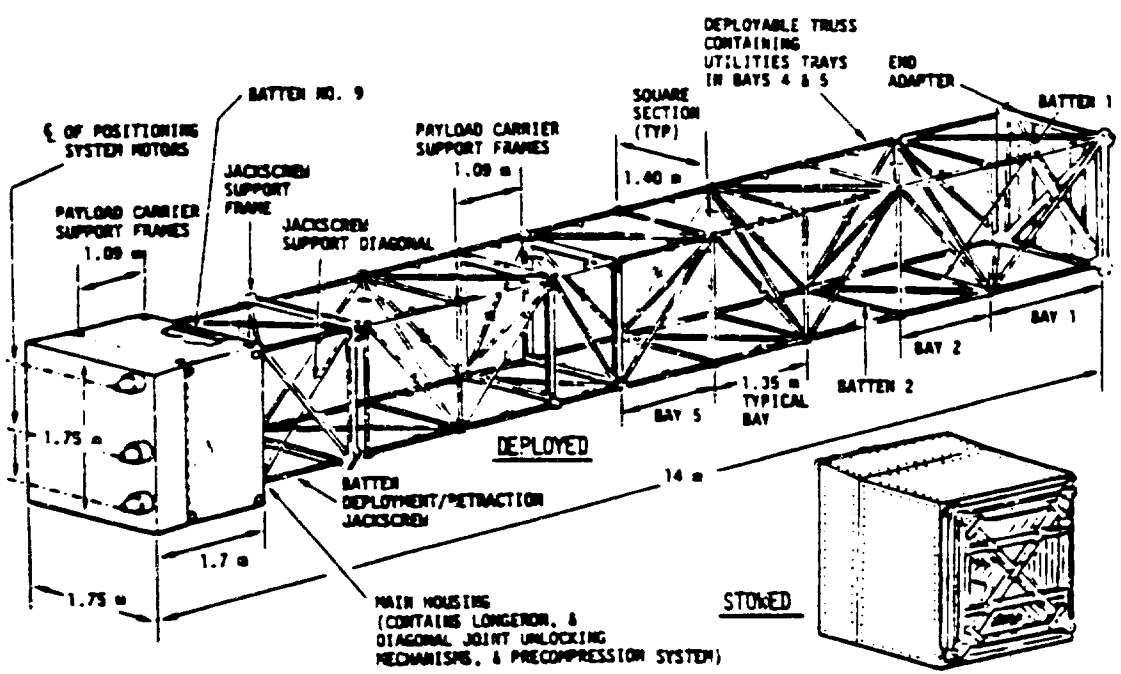

Figure IV-2. Nine Foot Deployable Truss Baseline

DEPLOYMENT/RETRACTION MECHANISM DETAILS

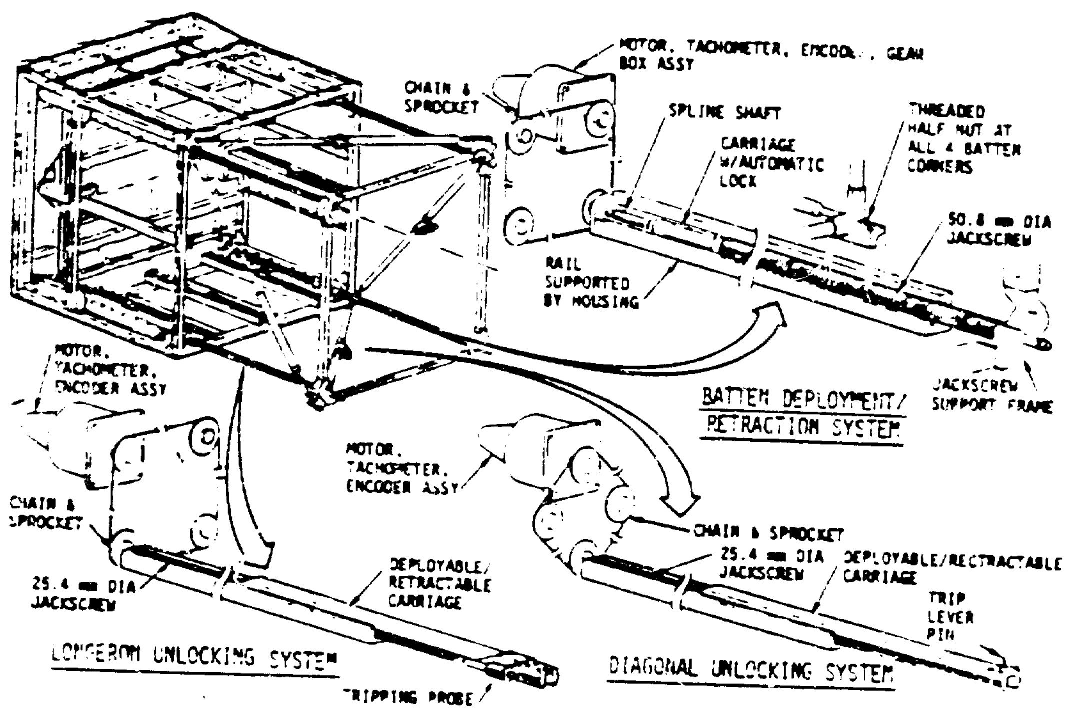

Figure IV-3. Nine Foot Deployable Deployer Baseline

Estimating Ground Rules

- All Costs Shown in 1987 Fixed Year Dollars
- Costs are shown in $K unless otherwise specified
- Technology assumed to be that at beginning of Phase C/D
- Provide Estimate Based on Detailed Engineering Definition
  - Provide Estimate at Lowest Possible WBS Element
- Bound Possible Costs for Each WBS Element
  - Best Possible Believable Engineering Scenario (Low Cost)
  - Expected Engineering Scenario (Medium Cost)
  - Worst Possible Believable Engineering Scenario (High Cost)
- Perform Cost Risk Analysis using Cost Bounds for each WBS Element

Figure IV-4. Estimating Ground Rules

Scope

- Included
  - Truss & Deployer
  - Truss Related System Integration & Test (I&T)
    - Truss Development Team System I&T Contribution
  - Extravehicular Activity (EVA)
- Excluded
  - Non-Truss Related System I&T
    - Truss Attachment Development Team System I&T Contribution
  - Shuttle Flight Costs
  - Truss Attachment Costs
    - Power Subsystem
    - Rotary Joints
    - Command & Data System Components
    - Modules
    - Secondary Structure
  - MRMS

Figure IV-5. Scope of Estimate

SYSTEM INTEGRATION & TEST

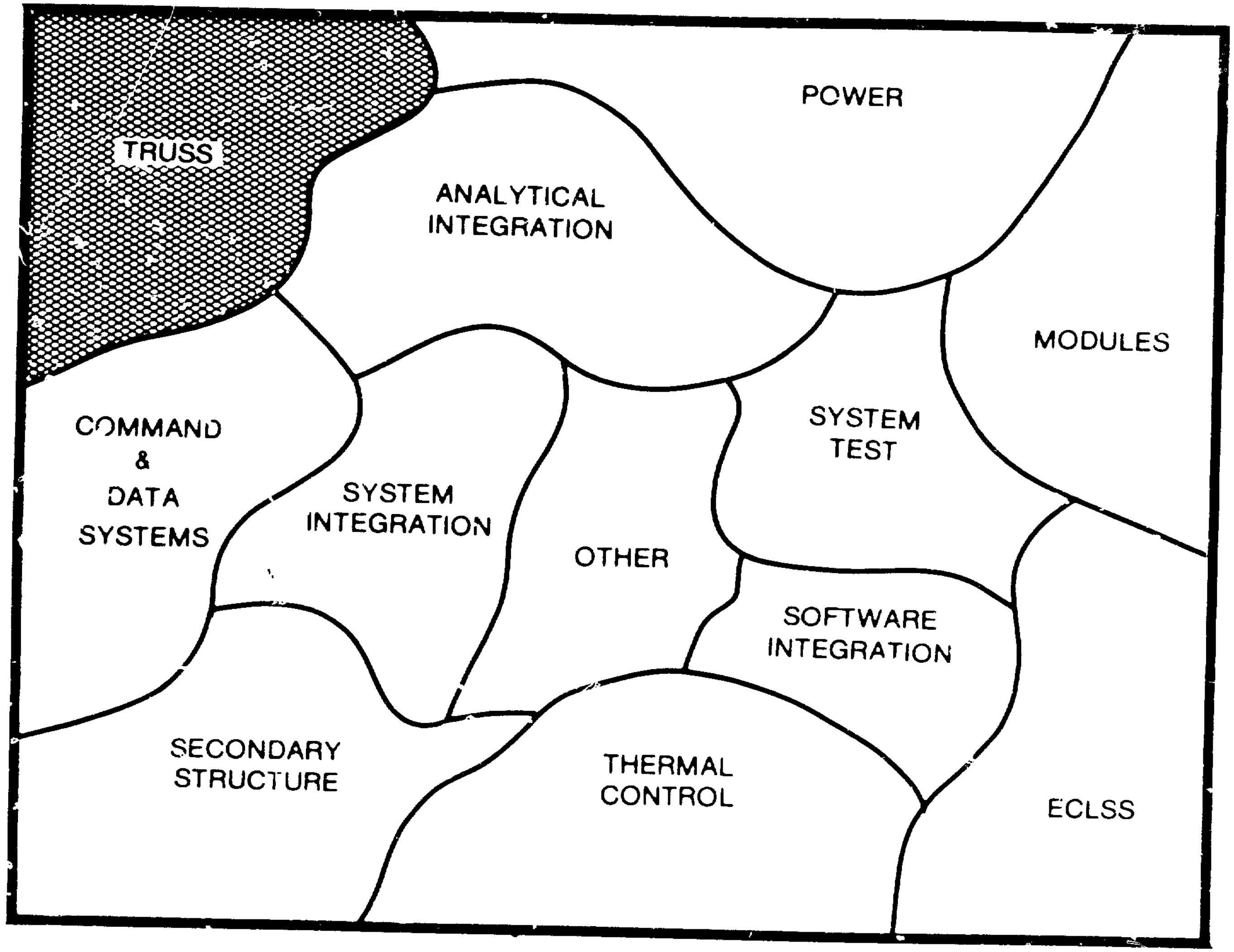

Figure IV-6. Truss Team Participation in System I & T

15 Foot Erectable	9 Foot Deployable
Longerons	Batten Longerons
Diagonals	Batten Diagonals
Node Fittings	Diagonal End Fittings
Attach Capscrew	Longeron Clevis
Node Exten Fitting	Diagonal Clevis
Split Locking Ring	Longerons
Strut Button Fitting	Hinges, Center
Bond Fitting	Diagonals, 2 inch
Collar	Diagonals, 1.75 inch
Node Ext Button Fit	Telescoping Joints
Nodes	Transition Sections
Guide Pins	Turnbuckles
Bolts	Guide Pins
Excess Laminate	Bolts
Structure I&T	Excess Laminate
	Structure I&T
	Deployment/Retraction System
	Jackscrew and Support Structure
	Unlocking System
	Pretension System
	Motors & Equipment
	Dep./Ret. I&T
	Struct. & Dep. I&T
EVA Structure	EVA Structure
EVA System	EVA System
System I&T	System I&T

Figure IV-7. Work Breakdown Structure

Applies to ☐ Development and/or Production Hardware

- ☐ Structure
- ☐ Electronic
- ☐ Electro/Mechanical
- ☐ GFE
- ☐ Purchased
- ☐ Modified
- ☐ Hardware/Software Integration
- ☐ Integration & Test
- ☐ Component Engineering (Purchased Items)

ENGINEERING CONSIDERATIONS	PARAMETER
SPECIFICATION LEVEL	PLATFORM (manned space, unmanned space, commercial airborne, MIL-SPEC airborne, mobile, ground)
ENGINEERING EFFORT	PROTOTYPE QUANTITIES EXTENT OF DESIGN DESIGN REPEATS ENGINEERING COMPLEXITY
MANUFACTURING EFFORT	PROTOTYPE QUANTITIES PRODUCTION QUANTITIES MANUFACTURING COMPLEXITY WEIGHT
INTEGRATION & TEST	ANALYTICAL INTEGRATION COMPLEXITY (structural/electronic) PHYSICAL INTEGRATION COMPLEXITY (structural/electronic) QUANTITIES AT NEXT HIGHER LEVEL SCHEDULE

Figure IV-8. Cost Generation Center Considerations

15 Foot Erectable (Single Bay Keel)

	Number	Unit Mass(lb)	Total Mass(lb)
Longercns	464	3.94	1828
Diagonals	296	5.67	1678
Node Fittings	1520	1.41	2143
Nodes	246	1.77	435
Guide Pins	492	0.61	300
Bolts	2012	0.16	322
	Truss Mass(lb)		6706

Figure IV-9. Part Count and Mass Properties

9 Foot Deployable (Single Bay Keel)

	Number	Unit Mass(lb)	Total Mass(lb)
Batten Longerons	470	2.49	1170
Batten Diagonals	118	3.11	367
Diagonal End Fittings	236	0.82	194
Longeron Clevis	235	1.25	294
Diagonal Clevis	235	2.30	541
Longerons	262	2.37	621
Hinges, Center	262	2.00	524
Diagonals, 2 inch	373	1.70	634
Diagonals, 1.75 inch	373	1.49	556
Telescoping Joints	373	1.29	481
Transition Sections	1270	0.41	521
Turnbuckles	1270	1.00	1270
Guide Pins	940	0.61	573
Bolts	940	0.16	150
Truss Mass(lb)			7896
Deploy./Ret. System	8	407.00	3256
Jackscrew & Support	2	229.00	458
Structure	2	1760.00	3520
Unlocking System	16	60.00	960
Pretension System	2	124.00	248
Motors & Equipment	6	81.00	486
Deployer Mass(lb)			8928
Truss w/Deployer Mass(lb)			16824

Figure IV-10. Part Count and Mass Properties

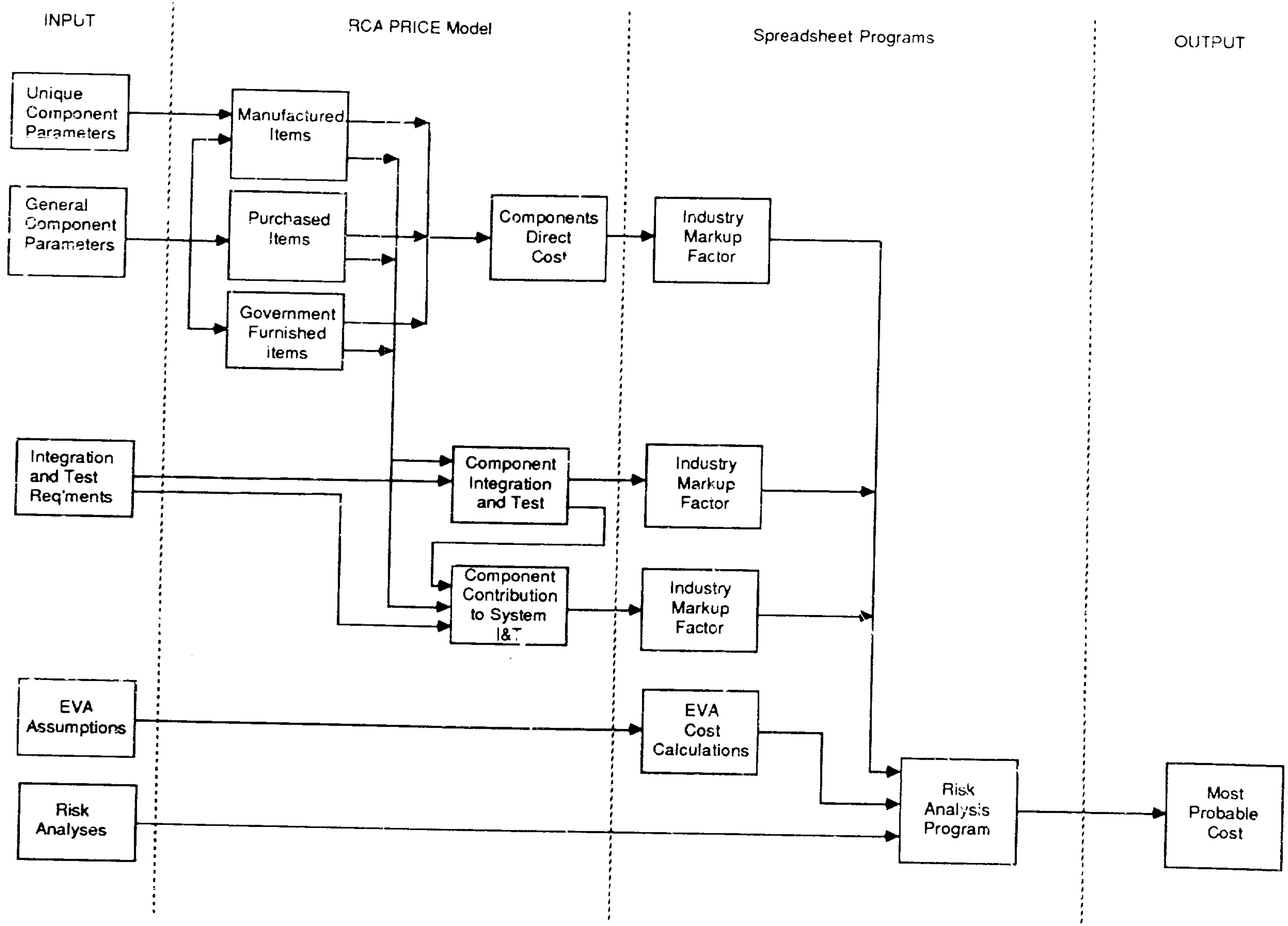

Figure IV-11. Cost Estimating Process

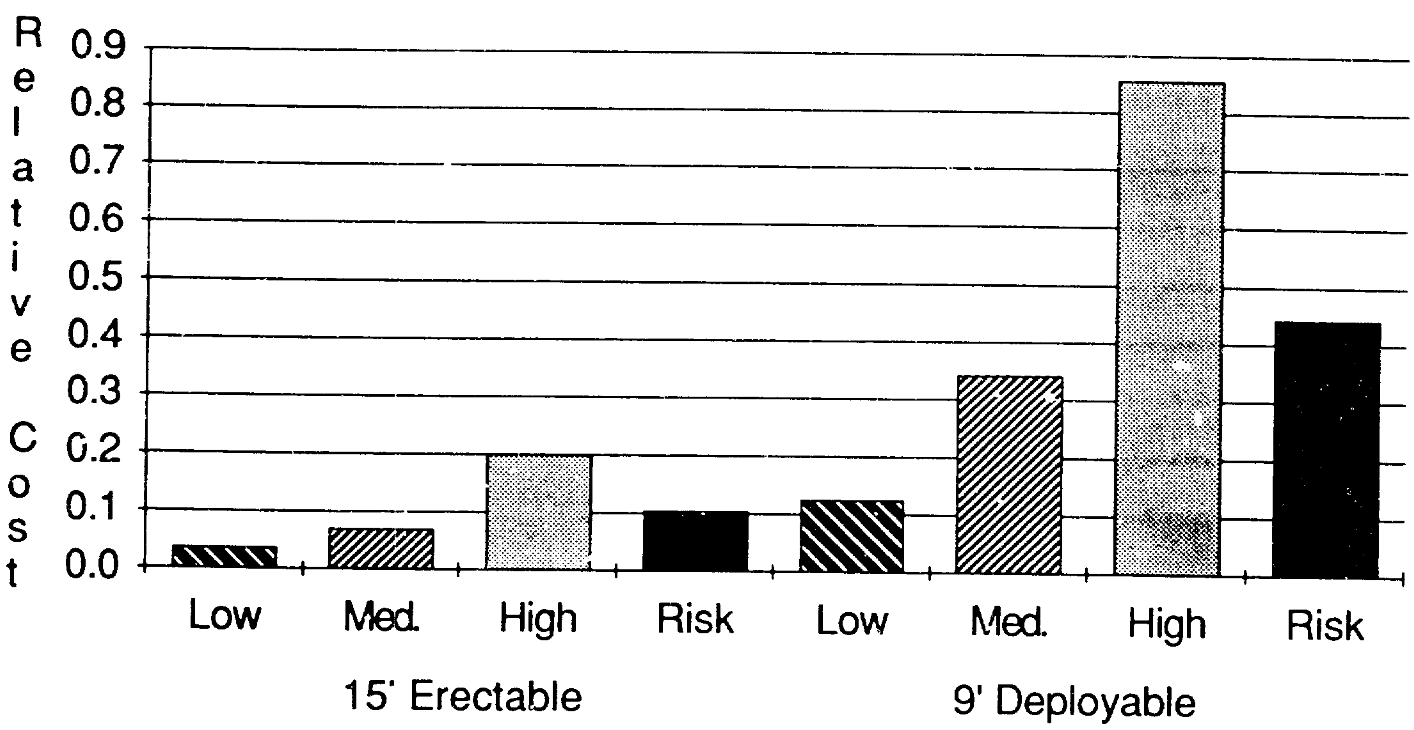

Figure IV-12. 15' Erectable vs 9' Deployable Costs
w/o Systems Integration

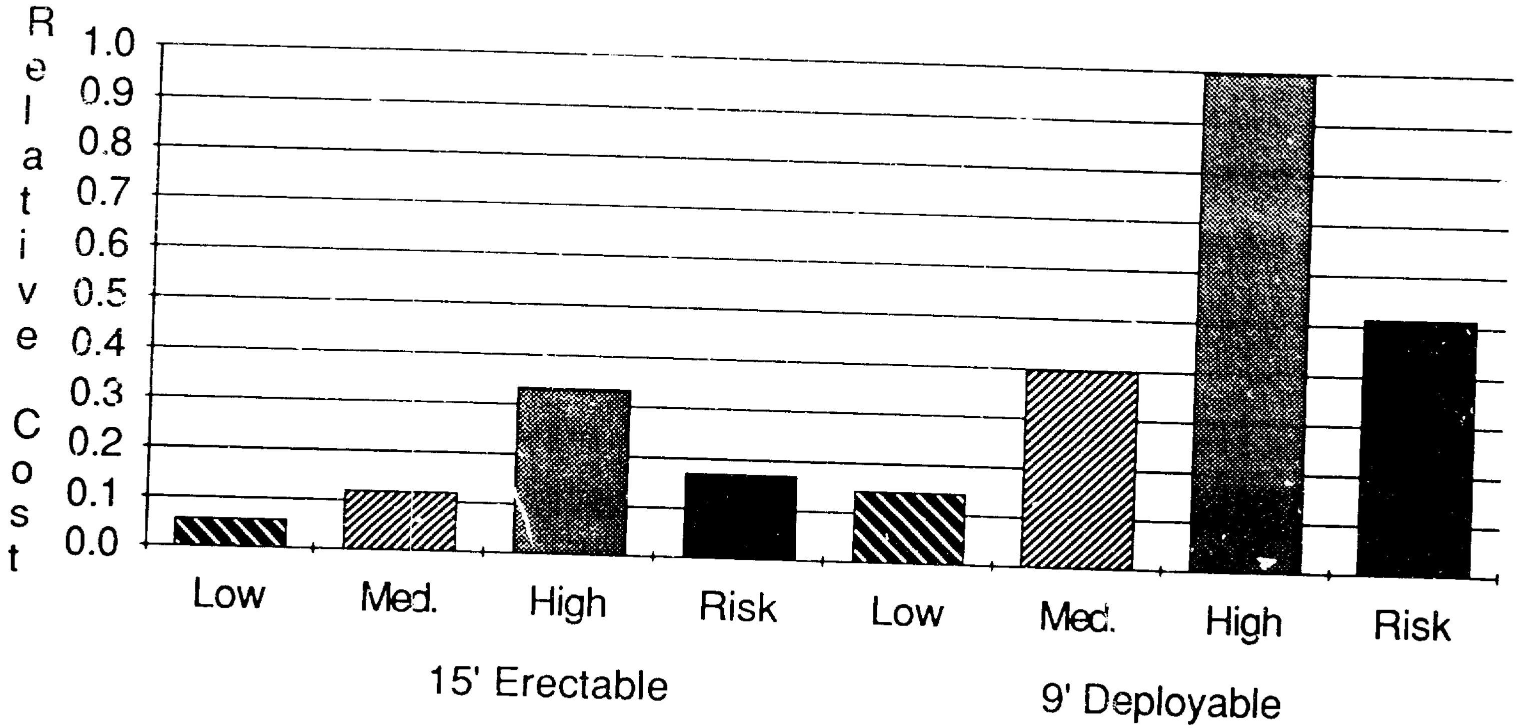

Figure IV-13. 15' Erectable vs 9' Deployable Costs including Systems Integration

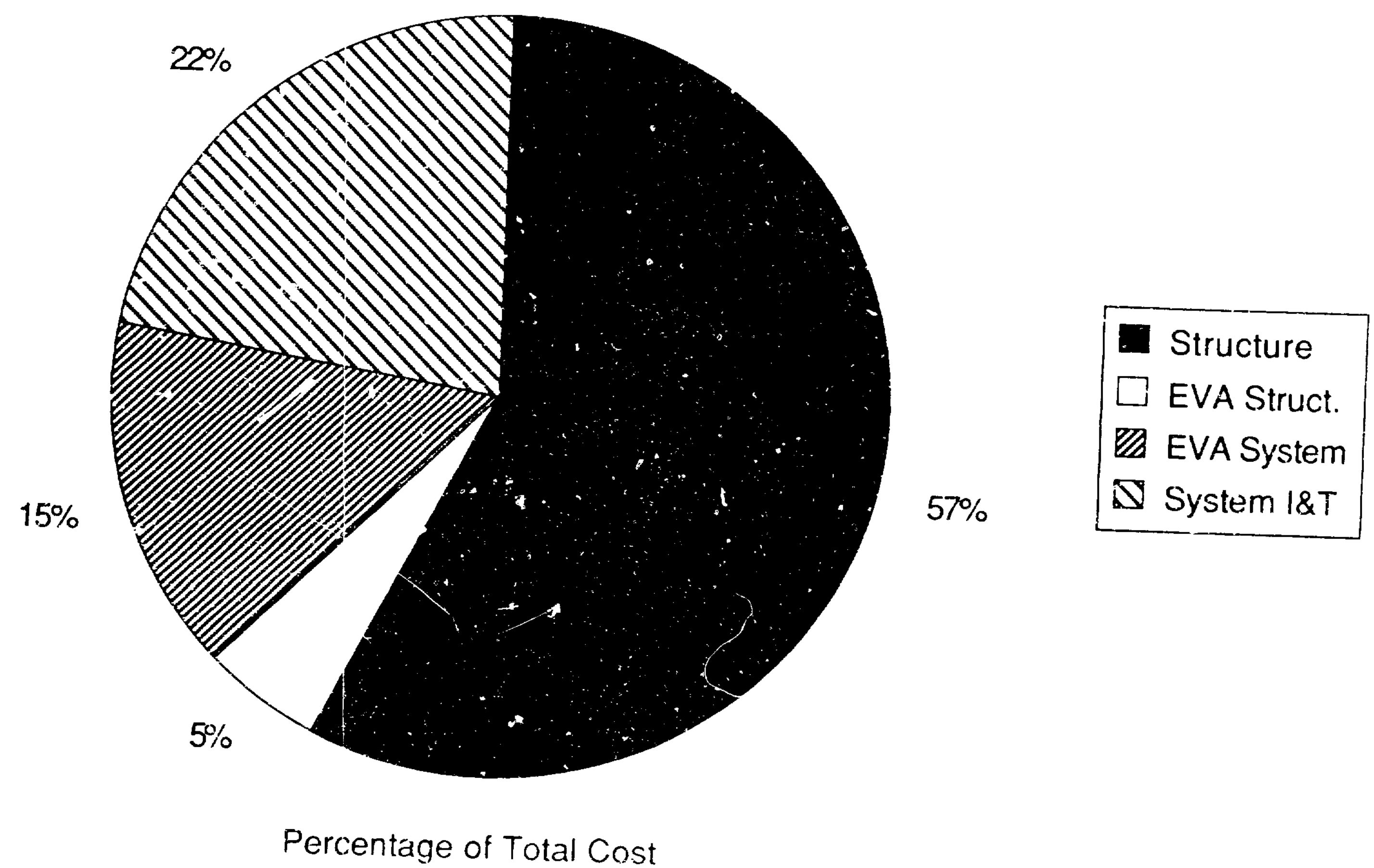

Figure IV-14. 15' Erectable Risk Estimate

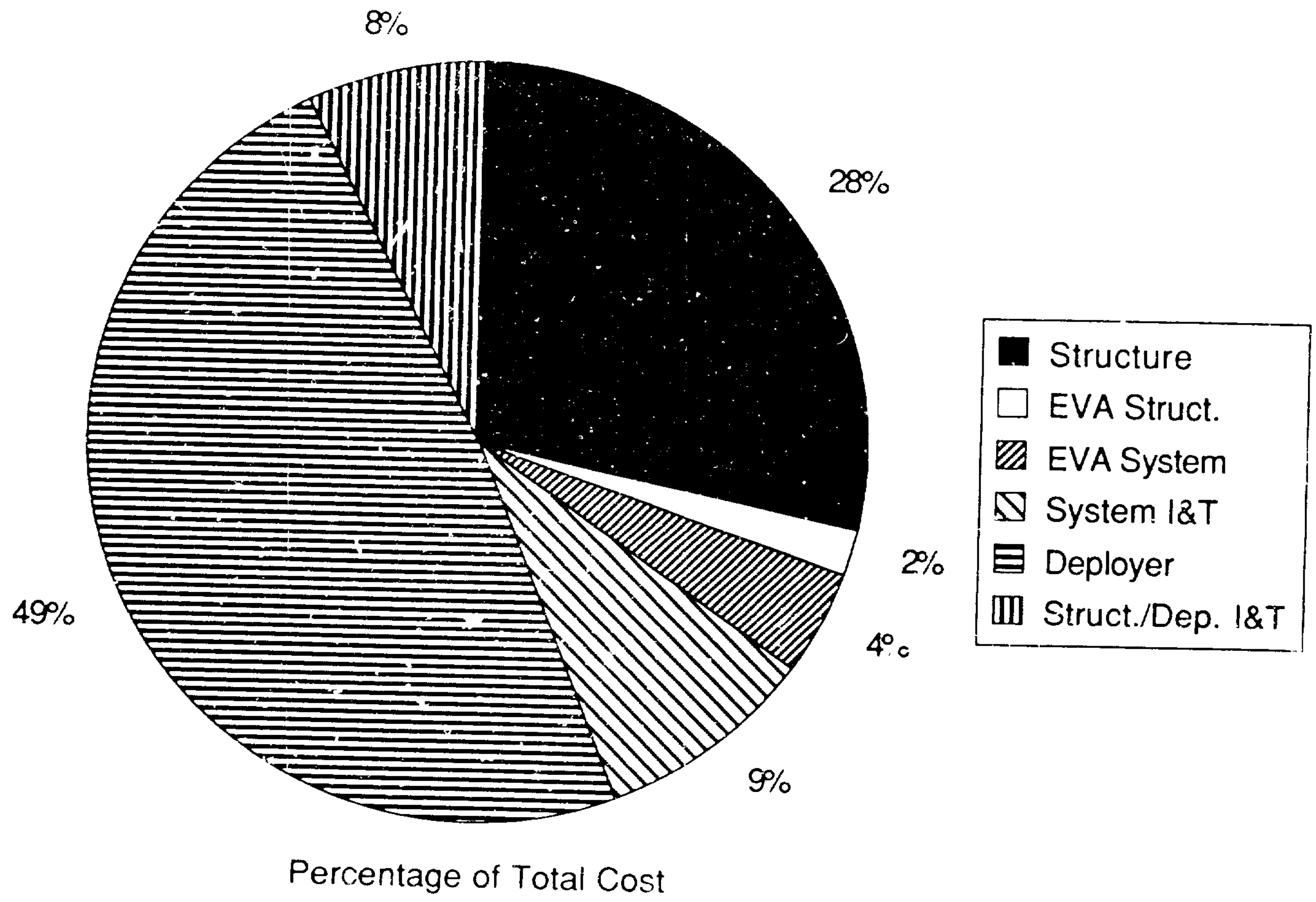

Figure IV-15. 9' Deployable Risk Estimate

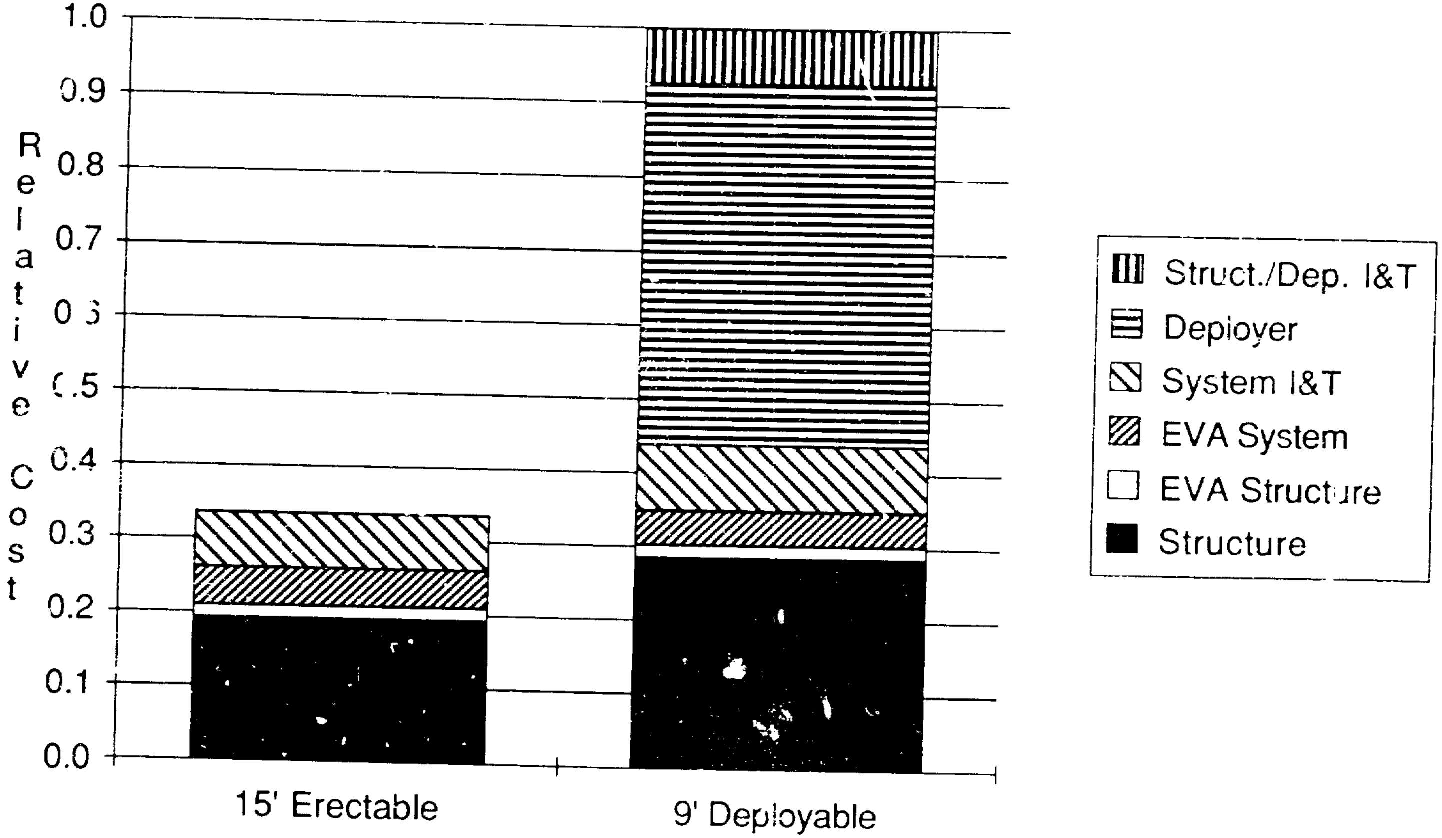

Figure IV-16. Comparison of Truss Cost Risk Estimates

V. TRUSS CRITERIA

Several Space Station truss structure considerations which could aid in the discrimination between erectable and deployable concepts are discussed in this section. Structural redundancy and its influence on safety, orbital operations, reliability, and ease of repair and maintenance will be addressed. Complexities due to variations in joint stiffness, nonlinear characteristics, and design detail and how they effect the accuracies of analytical and model test methods in predicting the Space Station response to loads are discussed. Results from modal analyses and transient response studies for various expected loading conditions on the reference configurations are presented and compared. These results are used to investigate possible structural flexibility influences on rigid body attitude control systems. Quantitative information is provided as an aid in assessing the risk involved in deploying the orthogonal tetrahedral truss beam components of the single-fold reference configuration. Also provided are discussions of a rigid body control analysis and a truss thermal analysis.

V-A-1. Structural Redundancy

The main concerns with structural redundancy are considered to be safety in the case of an accident, and reliability of the deployment or erection process. A summary chart is presented in Table V-A-1.

Safety.- Safety issues are more strongly influenced by the structural type (i.e., single vs. multibay keel) than the construction approach, such as deployable or erectable. Loss of a longeron strut from a single bay keel (reference configuration) reduces by approximately 50% the beam stiffness and load carrying capability (see figure V-A-1) whereas the loss of a node results in a 100% reduction of stiffness and load carrying capability. Due to structural redundancy, a multibay keel retains its structural integrity with slightly reduced capabilities for either a longeron strut or node loss.

Orbital Operations.- Safety concerns are paramount during all orbital operations. Therefore, operations on a single bay structure which is susceptible to a critical accident due to lack of structural redundancy will probably be greatly restricted. However, operations on a multibay structure which is much less susceptible to a critical accident due to high structural redundancy, will probably be less restricted.

Reliability.- Deployment of a redundant structure requires that sufficient joint freedom or clearance be provided during the deployment process to permit the reliable lockup of all folding or telescoping members and joints. The resultant reduction in stiffness that occurs requires the addition of a pretensioning system, with its attendant complexity and reliability features. Alternately, structurally tight joints may be used but the resulting high frictional forces requires the addition of a system for applying high deployment forces with its attendant complexity and reliability features. Conversely, the erection of redundant structures has been proven by experiment (reference V-A-1) to be both efficient and reliable using joints designs that display essentially zero free play and linear behavior (see paragraph V-B).

V-A-2. Repairability and Maintainability

The main concern with structural repair and maintenance is the ability to easily replace structural truss components on orbit. A summary of the salient findings is presented in Table V-A-2.

Longeron or Diagonal Replacement.- The effect of joint free play requires that deployable structures with and without joint preload systems be considered. To date, the only deployable joint preload concept proposed employs a tension cable which is tensioned after deployment to remove free play in the structure. Deployable trusses without a pretension system require tighter joints, which will require special tools and some difficulty to remove the hinge pins in order to change the strut. Reinsertion of a new strut, in this case, could require additional fixtures to align the new strut hinge pin holes with the existing structure hinge pin holes if movement has occurred due to thermal or station keeping loads.

Deployable trusses with pretension cables inside the struts are considered to be extremely difficult to replace. Station operation is affected in that the pretension system must be relaxed (with attendant impact on the station stiffness and operations) to permit the necessary operations of pin removal, cable breaking and reattachment, and structural realignment/pin insertion to take place. Moving the pretension cable outside the strut removes the problem of breaking and reattaching the cable, however, all other difficulties remain. Pretension cables outside the struts, however, add an increased risk during deployment (i.e.- cable management problem) and an eccentric load to each strut. Pretension cables anywhere result in a reduction of load carrying capability of the preloaded strut.

Replacement of an erectable structure diagonal or longeron is accomplished by simply reversing the assembly process. It is recognized that strut length variations due to thermal or station keeping loads could occur but are more easily accommodated by design features of the side attachment joints which permit insertion under worst case conditions. Underwater assembly tests of struts which underwent length changes due to hygroscopic effects was accomplished with little or no difficulty (reference V-A-1).

Node or Batten Replacement.- With a single fold deployable truss, such as the example shown in figure V-A-2, which has rigid batten frames, it is essentially impossible to replace a batten or node on orbit without breaking the station structure or bridging around the frame with an auxilliary structure. All previous discussion concerning pretension cables, tools and fixtures also apply here. The addition of a field break (i.e.,- erectable joint) in each batten member would ease the batten replacement problem (while adding mass), but nodal replacement difficulties remain due to the pin joints and pretensioning cables attached to every node.

Erectable truss node or batten replacement is accomplished by simply reversing the assembly process and has been demonstrated by test (reference V-A-1).

EVA Repair and Maintenance Capability.- An EVA repair and maintenance capability is required by both the deployable and erectable structural approaches, and is, therefore, not a discriminator between the two approaches. However, past experience during assembly tests has demonstrated the necessity for a device such as the MRMS shown in figure V-A-3. A multipurpose device, the MRMS positions the astronaut as needed at a work site and provides a force and moment capability between the astronaut and structure. It also serves as a utility truck or platform supporting construction and payload attachment or servicing as well as repair and maintenance functions (see references V-A-2, V-A-3).

V-A-3. Trade Comparison

A summary of the deployable vs. erectable trade study results is shown in Table V-A-3. The erectable truss was found to display a distinct advantage in repair and maintenance capability. All deployable trusses considered were found to be repairable but with much greater difficulty and/or greater mass, complexity and cost penalty. The ease of repairing an erectable structure, and conversely, the difficulty of repairing a deployable structure is also related to the growth and/or reconfiguration capability of each structural approach.

REFERENCES

V-A-1: Heard, W. L., Jr., et. al.: A Mobile Work Station Concept for Mechanically Aided Astronaut Assembly of Large Space Trusses. NASA TP-2108, March 1983.

V-A-2: Mikulas, M. M., Jr., et. al.: A Manned-Machine Space Station Construction Concept. NASA TM-85762, February 1984.

V-A-3: Bush, H. G., et. al.: Conceptual Design of a Mobile Remote Manipulator System. NASA TM 86262, July 1984.

Table V-A-1. STRUCTURAL REDUNDANCY SUMMARY

CONCERN		DEPLOYABLE	ERECTABLE
SAFETY	SINGLE BAY	o STRUT LOSS REDUCES STIFFNESS AND STRENGTH. STRUCTURAL INTEGRITY MAINTAINED	
		o NODE LOSS RESULTS IN TOTAL LOSS OF STRUCTURAL INTEGRITY	
	MULTIPLE BAY	* STRUT LOSS REDUCES STIFFNESS AND STRENGTH. STRUCTURAL INTEGRITY MAINTAINED. LESS SEVERE THAN SINGLE BAY. * NODE LOSS REDUCES STIFFNESS AND STRENGTH. STRUCTURAL INTEGRITY MAINTAINED. MUCH LESS SEVERE THAN SINGLE BAY.	
ON-ORBIT OPERATIONS	SINGLE BAY	o OPERATIONS IMPEDED OR PRECLUDED DUE TO CRITICAL NATURE OF STRUT OR NODE LOSS	
	MULTIPLE BAY	o LESS RESTRICTIVE OPERATIONS POLICY IS PROBABLE DUE TO NON-CRITICAL NATURE OF STRUT OR NODE LOSS.	
RELIABILITY	o DEPLOYMENT CAN BE HINDERED UNLESS JOINT FREEPLAY IS PROVIDED TO INSURE LOCKING OF ALL MEMBERS		* ERECTION OF REDUNDANT STRUCTURES PROVEN BY PAST EXPERIMENTS.

Table V-A-2. REPAIRABILITY AND MAINTAINABILITY SUMMARY

CONCERN	DEPLOYABLE	ERECTABLE
LONGERON OR DIAGONAL REPLACEMENT	o (1) W/O CABLE PRETENSION - STRUT REMOVAL DIFFICULT. REQUIRES SPECIAL TOOLS TO REMOVE PINS. INTERFERENCE FIT FOR STIFFNESS INCREASES REMOVAL DIFFICULTY. ALIGNMENT JIG AND TOOLS PROBABLY REQUIRED TO REPLACE PINS.	* SIMPLE - REVERSE ASSEMBLY PROCEDURES. PROVEN IN PAST EXPERIMENTS.
	o (2) PRETENSION CABLE INSIDE STRUT - EXTREMELY DIFFICULT. REQUIRES CABLE BREAK AT EVERY NODE PLUS TOOLS TO SEPARATE CABLE. MUST RELAX CABLES AND LOSE SS STIFFNESS TO REPLACE. TOOLS NEEDED FOR PIN REMOVAL MUST RETHREAD & READJUST PRETENSION CABLE IN NEW STRUT WITH TOOLS.	
	o (3) PRETENSION CABLE OUTSIDE - MUST RELAX CABLE AND LOSE SS STIFFNESS TO REMOVE PINS. ALSO SEE (1) ABOVE.	
NODE OR BATTEN REPLACEMENT	o (4) ESSENTIALLY IMPOSSIBLE WITH RIGID BATTEN FRAME WITHOUT BREAKING SS STRUCTURE OR BRIDGING WITH ERECTABLE TRUSS. ALSO SEE (2) AND (3) ABOVE.	

Table V-A-3. DEPLOYABLE VS. ERECTABLE TRADE COMPARISON

DISCRIMINATORS		9' DEPLOYABLE	15' ERECTABLE	15' PACTRUSS	TETRAHEDRAL
CUSTOMR ACMDTNS	GROWTH POTENTIAL				
	PAYLOAD ACCOMMODATIONS				
SUBSYSTEM INTEGRATION	1) POWER CABLES ETC.				
	2) RCS THRUSTERS ETC.				
	3) THERMAL AND PROP. LINES				
	4) INSTALLATION & SERVICING				
	5) ROTARY JOINTS				
	6) MRMS				
	7) SE&I REQUIRED				
CONSTR. OPS.	EVA HOURS				
	NUMBER OF EVAS PER FLIGHT				
COST	TRUSS WEIGHT, PART COUNT D.D.&T., DEPLOYER				
	CONSTRUCTION				
TRUSS CRITERIA	REDUNDANCY, REPAIRABILITY AND MAINTAINABILITY	S-	A	S-	S-
	PREDICTABILITY				
	STIFFNESS				

A - ADVANTAGE, S - SATISFACTORY, D - DISADVANTAGE

EFFECT OF FAILED STRUT ON ALLOWABLE LOAD OF FOUR LONGERON SPACE STATION KEEL BEAM DETERMINED

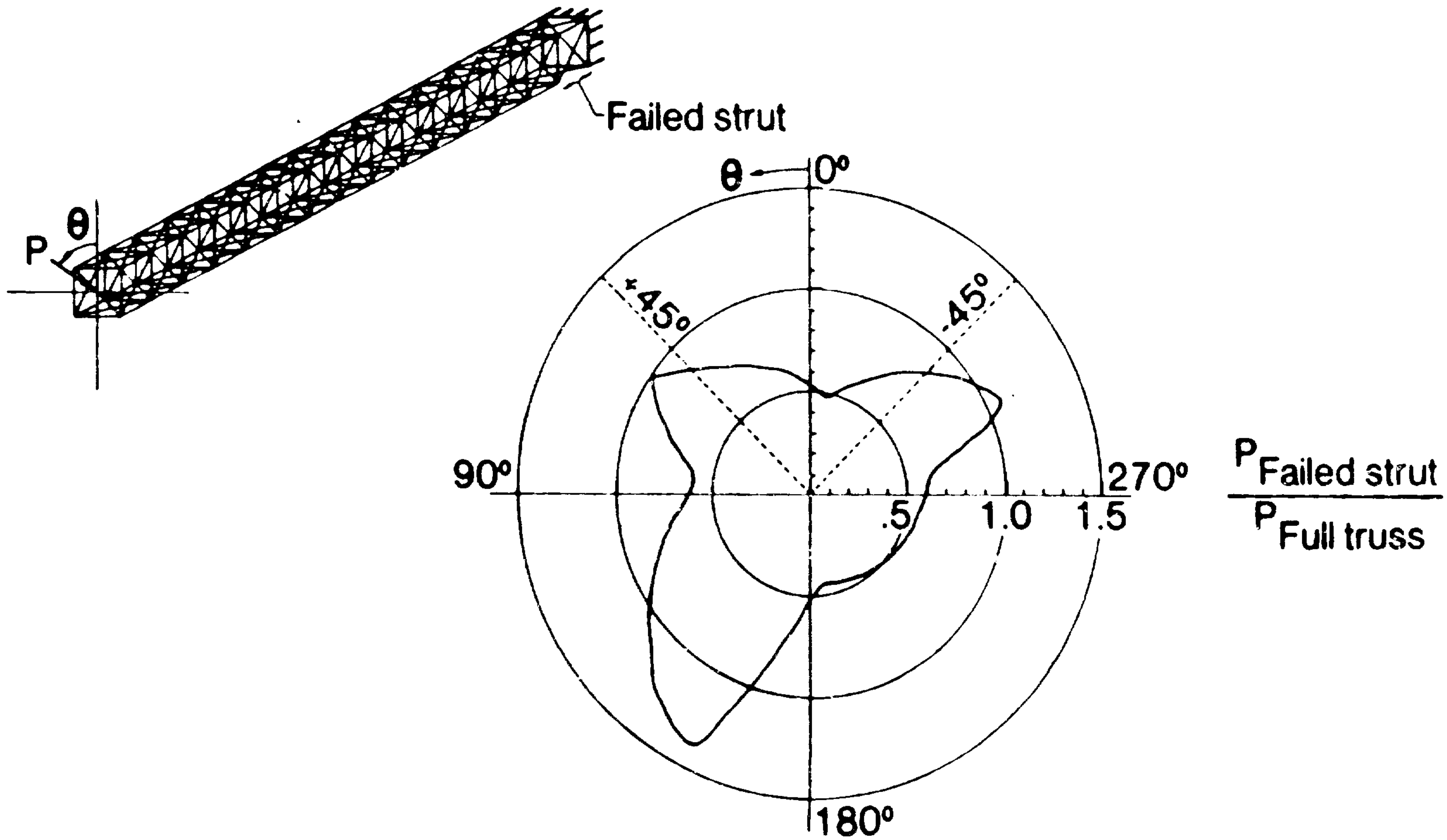

Figure V-A-1. Keel Beam Allowable Load.

DEPLOYABLE TRUSS AND UTILITIES TRAYS CONCEPT

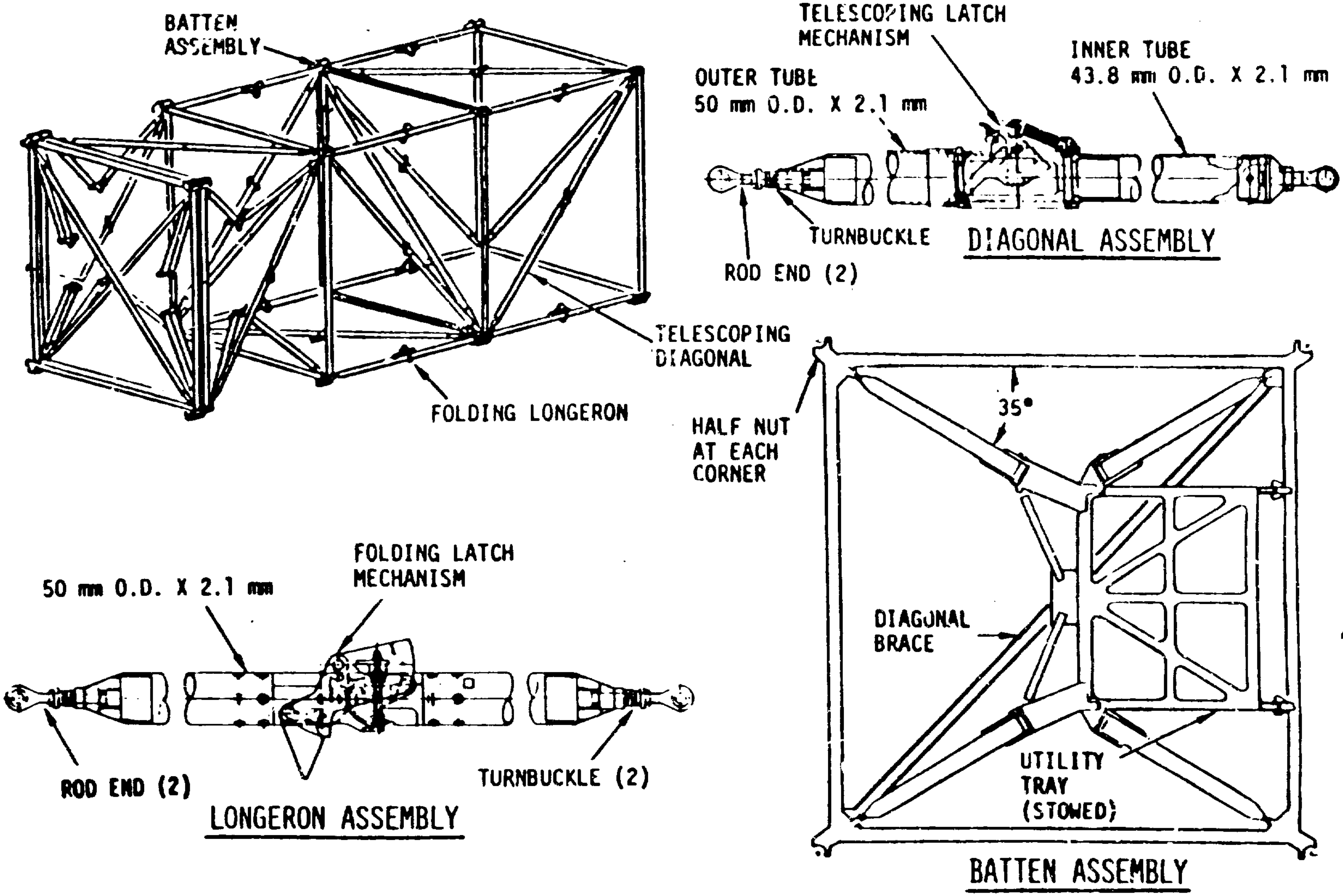

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Figure V-A-2. Typical Single Fold Deployable Truss Batten Frame.

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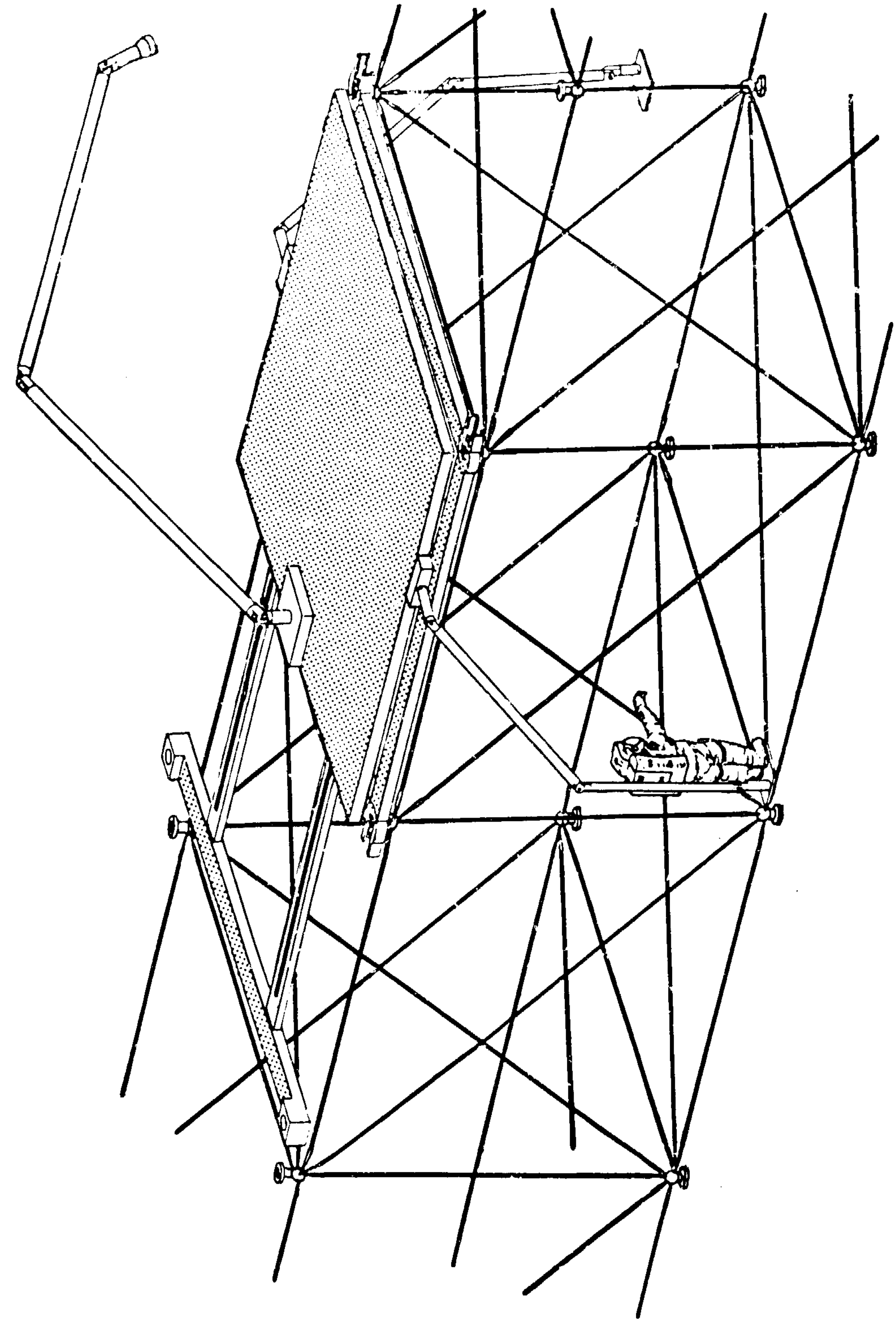


Figure V-A-3. Mobile Remote Manipulator System.

V-B. Predictability

There are a number of areas of concern regarding structural predictability associated with joints and some of these concerns are noted in the chart of Table V-B-1. The first three items serve as discriminators between the three truss configurations under review and are discussed subsequently. The last three concerns are general technology needs, and as such are independent of the structural configuration or deployment/erection scheme. The most significant aspect of these last three concerns is model scaling. There is interest in performing experimental dynamic studies on scale models of the space station structure. However, there is a very limited database on joints and no data on truss beams is currently available that is representative of the type of joint dominated structures being considered. It is unclear if nonlinear load/displacement response and/or hysteresis measured in tests of joint models will scale from the models to full size hardware. Some preliminary experimental programs should be conducted on simple joint models to examine scaling effects before initiating a test program on scale models of a truss beam.

No stiffness requirements for the space station keel beam have been established, however, it is a generally accepted premise that both station controllability and the operation of experiments will be enhanced by the use of a very stiff keel truss beam. The stiffness of truss structures is controlled to a large extent by the separation of the load carrying longeron members. The effect of member separation, i.e, beam depth, on bending and torsional stiffness is shown in the figure V-B-1. As indicated by the curves, significant increases in both bending (EI) and torsional (GJ) stiffness can be obtained by modest increases in beam depth. Tick marks are noted on the abscissa for the three configurations under review. The tetrahedral truss with 10 ft members has the lowest stiffness because the member orientation gives the truss an effective depth of slight over 8 ft. A 15 ft truss has a potential stiffness that is nearly three times that of the 9 ft single fold or 10 ft tetrahedral.

Some reduction in structural stiffness is likely to be associated with the joints. Although this is not included in the curves depicting EI and GJ, it could be a very significant factor (as much as 50%) depending on the number and type of joints required by the truss. Also shown on figure V-B-1 are the results contained in the space station reference document for the 9 ft single fold and the 10 ft tetrahedral. The band shown for these configurations include a joint knockdown factor to 50 percent. It is clear from these results that it is desirable to begin space station planning with a configuration that offers the maximum potential stiffness possible, especially since joints can have such a significant knockdown. Also, bending and torsional stiffness obtained by increasing beam depth adds very little in either cost or mass whereas stiffness increases obtained by increasing the axial stiffness (AE) of the members are generally expensive and add significantly to the mass. Therefore, a 15 ft truss beam is a significant advantage.

The truss keel beam configuration currently being considered has a large number of members. A finite element analysis of the configuration even with one element per member can be large and if multielements per member are required to include joint effects, the analytical model quickly becomes unwieldy and is expensive to run, especially for parametric studies. One method to account for joint offsets is to consider an effective axial strut stiffness ($\overline{AE}$) using the relationship shown in figure V-B-2. As indicated the effective strut stiffness is dependent on the relative lengths of the joint and members, as well as their relative stiffnesses. Shown on the carpet plot of the figure are regions where erectable and deployable truss beams are expected to lie. These regions are based on some preliminary test data and an examination of a number of joint concepts. The effective axial strut stiffness for deployables are expected to be lower than erectables for the following reasons:

1) Erectable trusses require two joints per member whereas most deployable trusses require three joints per member. The third joint is frequently required in the center of a longeron to permit folding.

2) The load transfer path through erectable joints is generally simple and involves direct shear as shown in a subsequent figure. For some deployables such as the 9 ft reference configuration, the load transfer path is complicated and involves a complex combination of bending and shear.

3) The joint design of an erectable has a single requirement, to transfer load in an efficient manner, whereas the design of a deployable joint is generally a compromise as necessary to meet the several requirements of deployment, load transfer, packaging and automatic locking.

4) For erectables, one joint fits all including attachment of peripheral equipment and experiment modules. The deployables being considered, however, require a number of joint designs for both hinging and telescoping members and several of the joints must latch automatically for the beam to carry load.

Due to the higher stiffness knockdown for deployables, the predicted structural response could be significantly in error which would complicate control system design and operation.

One potential problem associated with joint dominated structures is free play in the joints. Some free play in deployable structures may be required to permit smooth deployment using a low drive force deployer. The amount of free play is also associated with machining accuracy requirements. To understand the effect of free play on keel beam deflection a simple analysis was conducted and the results are shown in figure V-B-3. The analysis is based on the assumption of small deflection so that the resulting curvature is equal to the second derivative of the deflection with respect to the length.

Although no criterion for keel distortion has been established it is clear from figure V-B-3 that the 15 foot erectable beam which is deeper and has fewer joints has significantly less distortion than either of the two deployable concepts. The 10 foot tetrahedral beam does not lie on either of the curves shown because the orientation of the truss provides a geometric amplification which significantly increases the distortion effect.

The results of a preliminary study to reduce the free play in a deployable joint is shown in figure V-B-4. Tests were conducted on two simple aluminum clevis joints with hardened steel pivot pins. One joint was fabricated with a 5/16 in. diameter reamed hole that provided a slip (or sliding) fit with the pivot pin. The joint response indicates some free play near zero load and some nonlinear effects at loads to about 500 lbs which are attributed to pin seating. At loads above about 500 lbs the load/displacement is linear.

The second joint with the same dimensions was drilled and reamed for a press fit with a 3/8 in. dia. pivot pin. The 20 percent larger diameter pin has twice the pin bending stiffness of the 5/16 in. dia. pin. The test results for the joint with the press fit pin are bilinear and have a higher stiffness in both tension and compression. Although the press fit pin gives significantly better predictability the joint has greater resistance to deployment motion than the joint with the slip fit pin. A combined analytical and experimental program should be conducted to evaluate the significance of the various factors that affect deployable joint stiffness. Because of the difference in compression and tension load paths, however, it is unlikely that one will be able to eliminate the bilinear behavior of an efficient deployable joint.

Results of similar tests conducted on the erectable joint discussed in the reference document are shown in figure V-B-5. The loading is for a moderate level, however, the load displacement results are linear throughout the test region. Special consideration was taken in the joint design to ensure that the load transfer path was the same in both tension and compression. No attempt was made to have a high axial stiffness (EA) through the joint and the stiffness is well below what might be expected for the truss keel beam.

A new quick-attach erectable joint concept has recently been developed at the Langley Research Center. A photograph of a development model is shown in figure V-B-6. The concept is for a side entry joint that is loaded internally during the joining process. Some attributes of this new joint are (1) the components are simple, inexpensive to fabricate, and easy to inspect; (2) the joint is easy to assemble and has positive latching that will not loosen due to vibration or loading; and (3) it is capable of being fabricated for use with structural members over a large range of sizes. The load transfer link in the joint is a split ring with tapered internal sides. A matched taper is machined on an end-bell of each tube. A collar attached to one member has an internal taper to match an external taper machined on the perimeter of the split ring. The collar is forced over the split ring thereby forcing the end-bells together to internally load the joint.

Some preliminary test results conducted on this developmental model are shown in the figure. The load/displacement results indicate a higher stiffness in compression than in tension. The slope of the load/displacement line changes at approximately 200 lbs tension which indicates that substantial preload can be generated using this joint concept.

This new joint has been incorporated into a multimember structural node and a photograph is shown in figure V-B-7. The multimember aspect of the node is the spherical center section. The sphere permits any member attached to contact the node radially so that all force lines pass through the center of the joint. All joints used in the construction of the keel beam would be spot faced, drilled and tapped at locations so that a member could be attached at 45^{o} to any other member. Special joints could be made to permit attachment at other angles without changing the attachment method or character of the node. Thus, the concept while being simple also has a high degree of versatility.

The assessment of predictability is shown in Table V-B-2. Based on the aspects of effective stiffness, joint complexity, and joint free play it is clear that a 15 ft erectable will have a higher stiffness and greater predictability than either of the reference deployables. While some of the disadvantages of the deployables are resolvable to some degree, often the solution of one problem raises another. For example, eliminating free play in a joint due to a press-fit pin causes the joint to be more difficult to deploy and may cause binding.

Table V-B-1. PREDICTABILITY SUMMARY

JOINT STIFFNESS AND LINEARITY

CONCERN	9 FT DEPLOYABLE	SYNCHRONOUSLY DEPLOYABLE TETRAHEDERON	15 FT ERECTABLE
Effective Stiffness	Longeron and diagonal center joints may significantly reduce structural stiffness		Joint length small & controlled by astronaut accessibility. Have high potential stiffness.
Joint Complexity	Joint design configuration and size dependent on deployment scheme		Joint design general
	Indirect coupled shear and bending load paths		Simple direct shear transfer load paths
	Require multiple joint designs with load carrying latch system		One joint fits all
Free play	Removal in joints increases deployment loads		
	Removal in structure requires complex 2 dimensional cable system--redundancy increases complexity		Incorporated in joint connectivity
	Minimizing free play requires high tolerance machining		
Analysis Technique	Accurate nonlinear analysis models or joints need to be developed and incorporated in finite element models		
	Limited data base on joints available		
Long Term Operation	Cold welding may change structure response, reduce joint damping; stress relaxation will shift preload		
Model Scaling	Joint response may not be amenable to test of scale models		

Table V-B-2 DEPLOYABLE VS. ERECTABLE TRADE COMPARISON

		PREINTEGRATED SUBSYSTEMS	"LAYERED" SUBSYSTEMS		
DISCRIMINATORS		9' DEPLOYABLE	15' ERECTABLE	15' PACTRUSS	TETRAHEDRAL
CUSTOMR ACMDTNS	GROWTH POTENTIAL				
	PAYLOAD ACCOMMODATIONS				
SUBSYSTEM INTEGRATION	1) POWER CABLES ETC.				
	2) RCS THRUSTERS ETC.				
	3) THERMAL AND PROP. LINES				
	4) INSTALLATION & SERVICING				
	5) ROTARY JOINTS				
	6) MRMS				
	7) SE&I REQUIRED				
CONSTR. OPS.	EVA HOURS				
	NUMBER OF EVAS PER FLIGHT				
COST	TRUSS { WEIGHT, PART COUNT D.D.&T., DEPLOYER				
	CONSTRUCTION				
TRUSS CRITERIA	REDUNDANCY, REPAIRABILITY AND MAINTAINABILITY				
	PREDICTABILITY	S-	A	S-	S-
	STIFFNESS				

A - ADVANTAGE S - SATISFACTORY, D - DISADVANTAGE

KEEL BEAM STIFFNESS COMPARISON

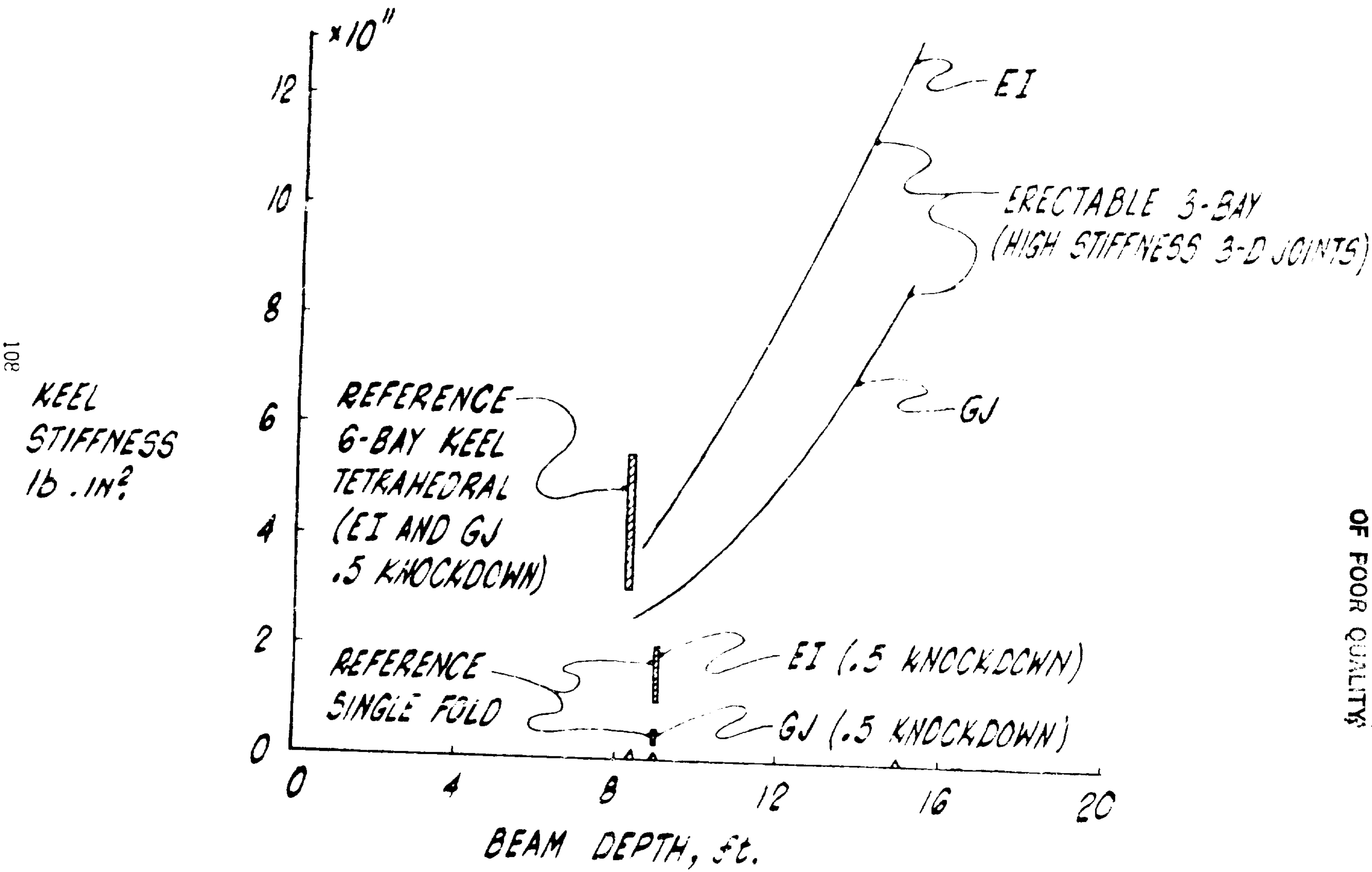
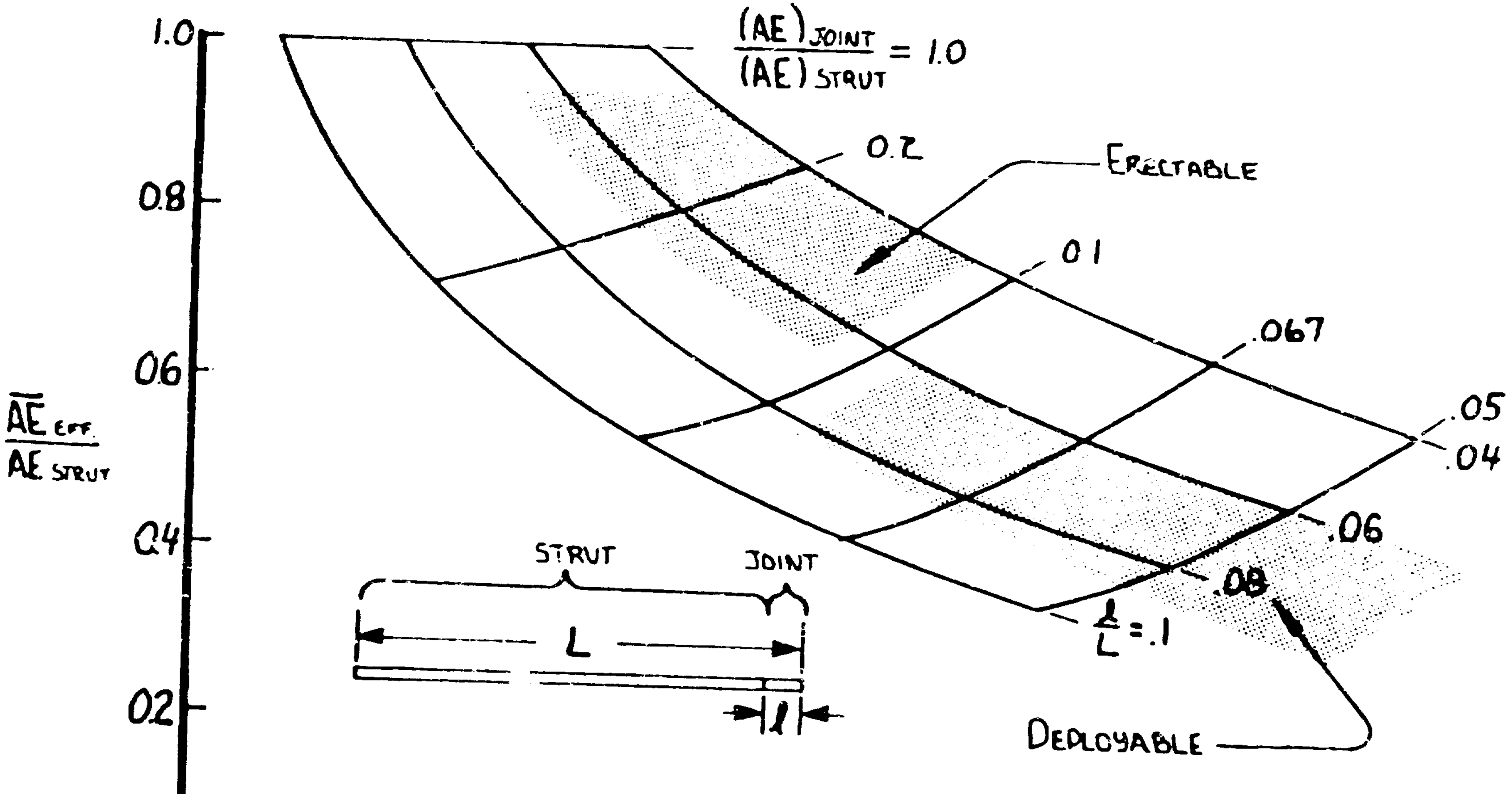


Figure V-B-1 The effect of beam depth on keel beam stiffness.

EFFECTIVE STRUT STIFFNESS CONSIDERING
JOINT EFFECTS



$$\frac{\overline{AE}_{EFFECTIVE}}{AE_{STRUT}} = \frac{1}{1 + \frac{l}{L}\left(\frac{AE_S}{AE_J} - 1\right)}$$

Figure V-B-2 The effect of joint stiffness on the effective axial stiffness of a strut member.

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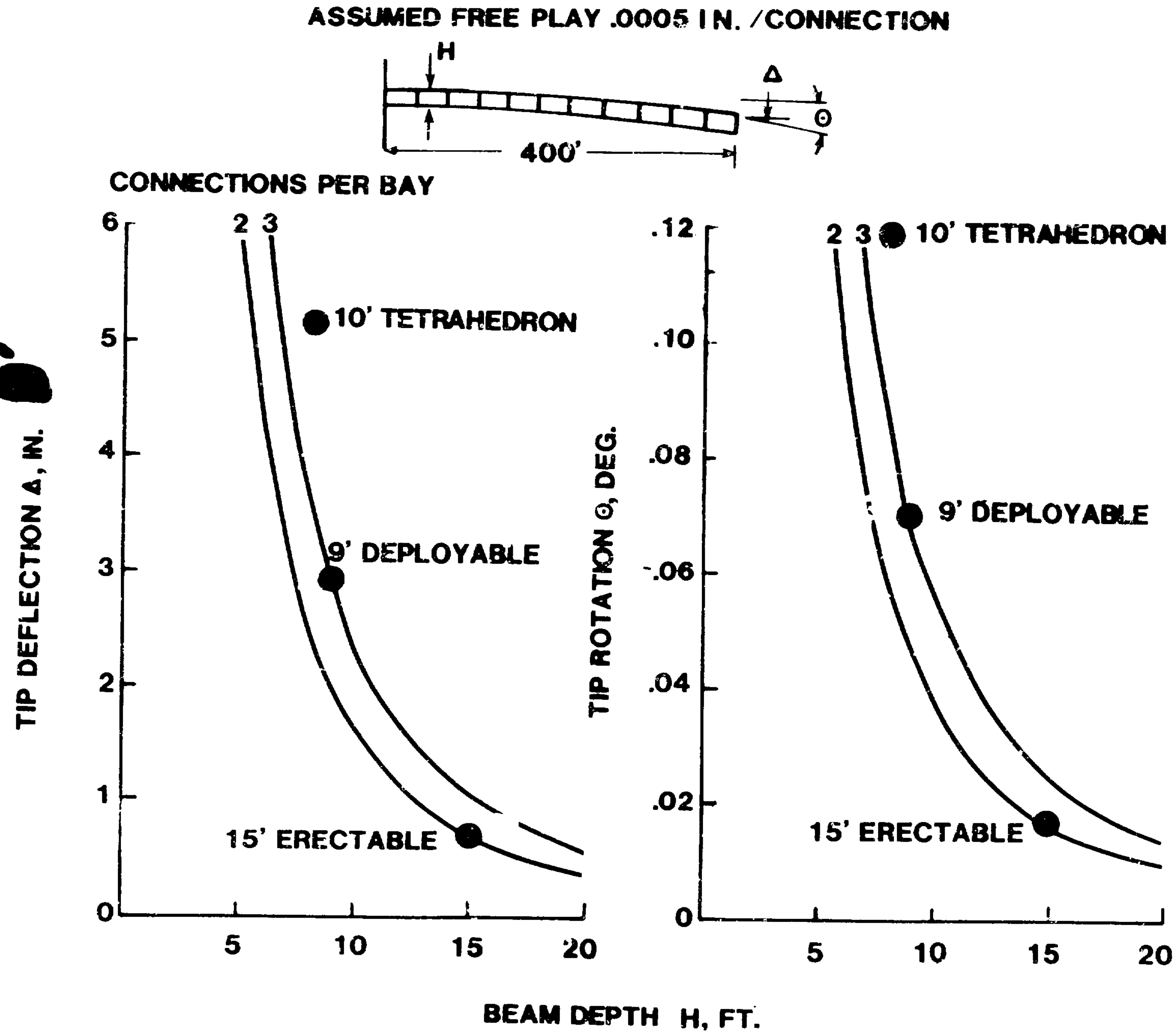

Figure V-B-3 Distortion of the keel beam due to joint free play.

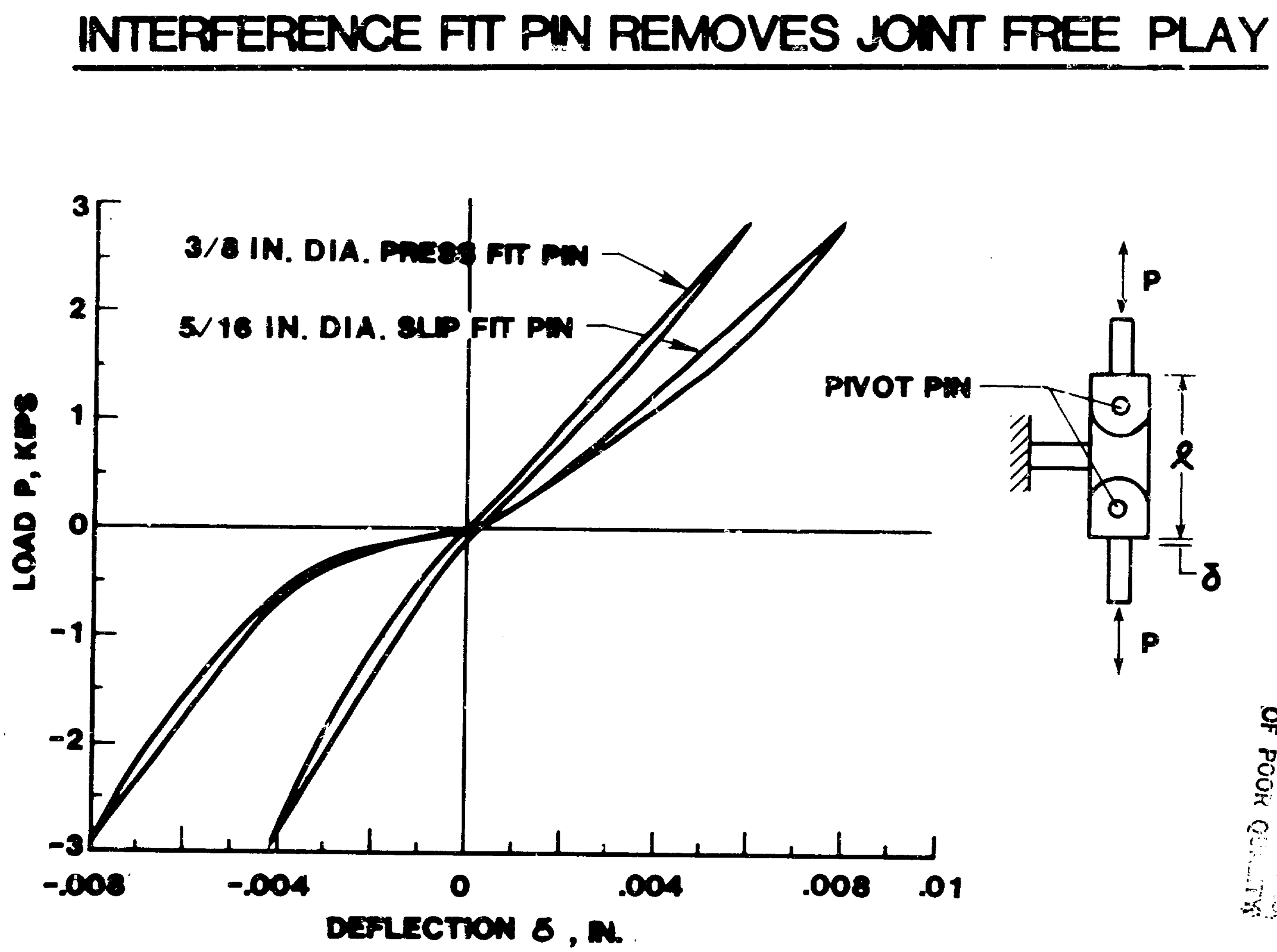

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Figure V-B-4 The effect of pin fit on free play in a deployable clevis joint.

REFERENCE ERECTABLE JOINT SHOWS LINEAR BE'AVIOR

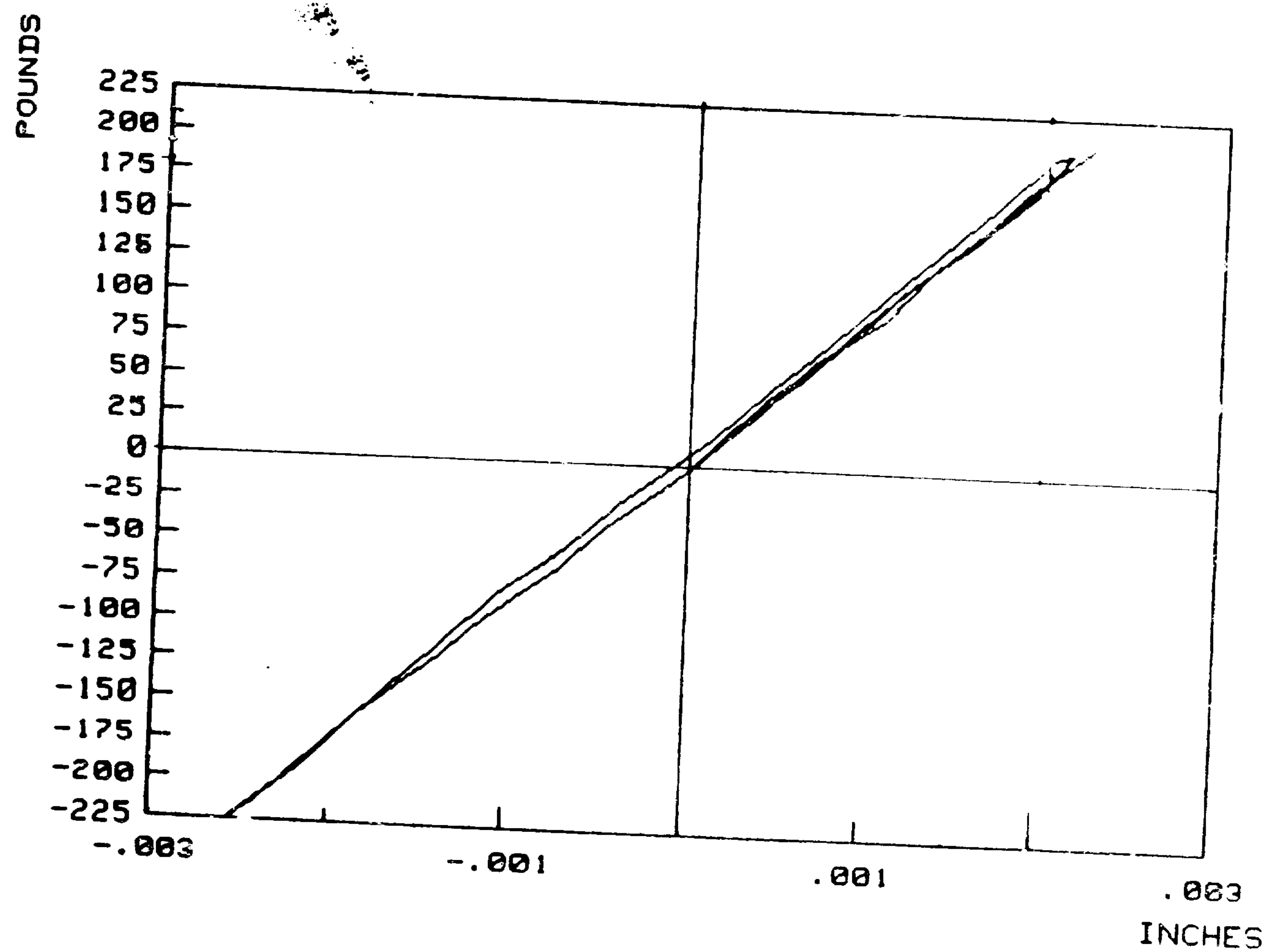

Figure V-B-5 Load displacement response of the reference erectable joint.

ERECTABLE JOINT PRELOADS CONNECTION

DEVELOPMENT MODEL

PRELIMINARY TEST RESULTS

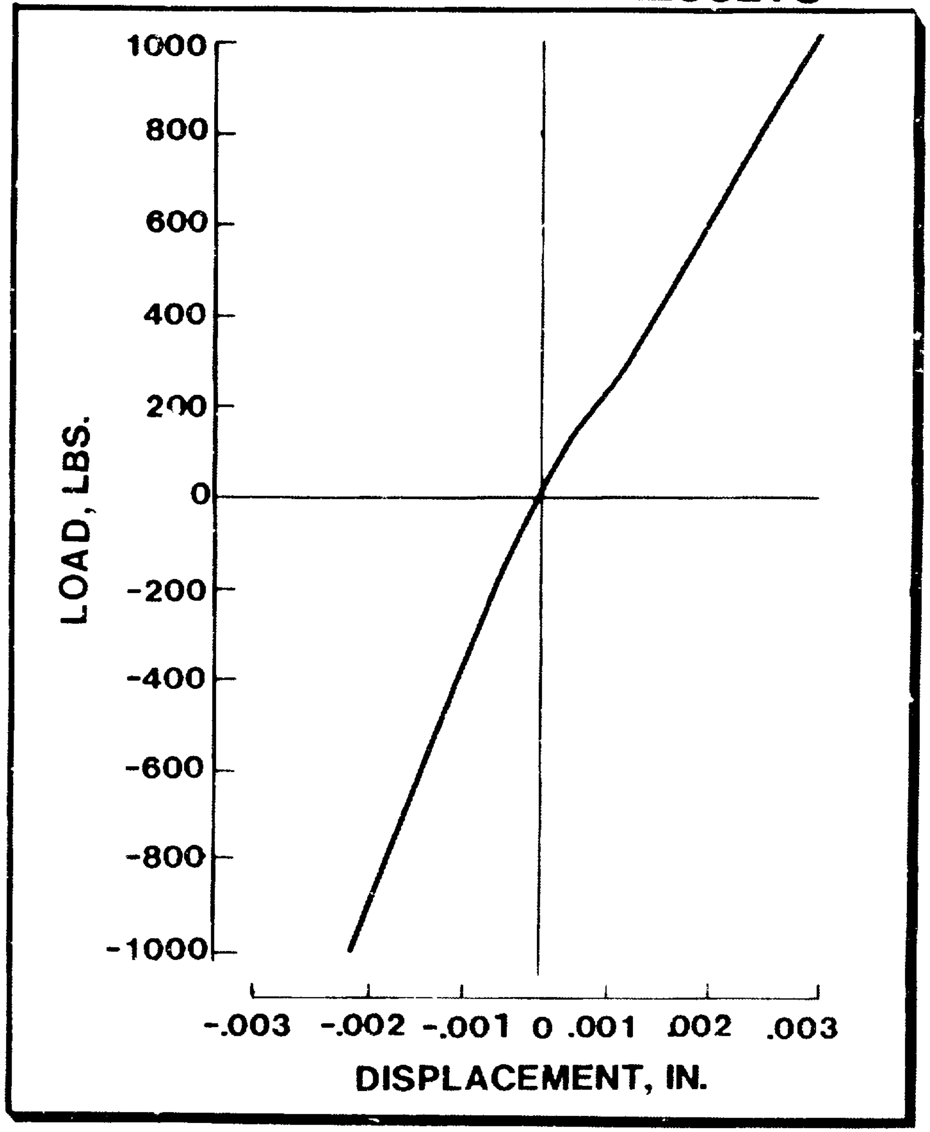

Figure V-B-6 Developmental model and preliminary test results for an improved erectable joint.

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JOINT INCORPORATED IN MULTIMEMBER NODE

- INEXPENSIVE FABRICATION
- SIDE ENTRANCE MATING
- SIMPLE LOAD TRANSFER
- POSITIVE LATCHING

Figure 1-2-7 Photograph of the improved erectable joint incorporated in a multimember structural node.

V-C. Stiffness Considerations

Three finite element models of Space Station reference configurations were developed to investigate possible structures/control interaction and to investigate the dynamic response of the station to various expected external disturbances and active controller moments. The models (shown in figures V-C-1 to V-C-3) were the 15 foot bay 75 KW reference configuration with 300 joints and 879 dynamic degrees of freedom, a 15 foot bay 300 KW growth version with 709 joints and 2055 dynamic degrees of freedom, and the 9 foot bay 75 KW reference configuration with 514 joints and 1542 dynamic degrees of freedom. In these models the pressurized modules were modeled as beams with the equivalent stiffness and lineal density of a 14.5 foot outer diameter aluminum cylinder with a wall thickness of 0.115 inch. Nonstructural masses were added to represent the internal module equipment masses bringing the total mass of each module to the mass given in the reference document. Discrete masses were applied at each node of the model to represent the various nonstructural components expected to be in place on the station such as control moment gyros, power management and distribution units, antennas, RCS thrusters, joint nodal clusters, and distributed utility lines for heat, data and power transmission. The mass characteristics of each model are given in Table V-C-1.

The truss members were represented by rod (axial stiffness) elements with equivalent density and stiffness properties of a high modulus graphite epoxy tube with a two inch diameter and a 0.06 inch wall thickness. The assumed axial modulus of the rods was 40×10^6 psi reference V-C-1. All joint nodes were treated conservatively as pin-connected. The appendages, radiators and solar arrays, and their support structure were modeled as beams as were the CMG and RCS thruster supports and module truss connections. No stiffness reductions due to joint flexibility were included in the models.

Frequency Distributions.- At least the first one hundred natural vibration modes and frequencies were calculated for each configuration. A plot of the modal densities up to 0.8 Hz is given in figure V-C-4. Rigid body control frequencies up to about 0.01 Hz were considered in the analysis. As shown on figure V-C-4, this range is well below both the fundamental appendage frequency and the fundamental structural frequency for all three configurations. The thermal radiators exhibited the lowest frequency responses for all models. The radiator responses differed between the 9 foot bay model and the 15 foot bay models since the 9 foot bay model had a large radiator situated on the keel near the habitation modules whereas all the radiators for the 15 foot models were situated on the transverse booms outboard of the rotary joints. The lowest structural mode of the 9 foot bay truss was keel torsion and was well below the corresponding keel torsion mode of the 15 foot IOC model. The 15 foot bay growth model had several transverse boom modes below the lowest structural mode of the IOC 9 foot bay model.

Effect of Structural Stiffness on Transient Response Performanc. The dynamic response of the three models when subjected to four loading conditions were investigated and some results of the analyses are presented in Table V-C-2. The loading conditions were crew motion, orbit reboost, a 1 degree attitude control command and a shuttle failed dock (where the orbiter attempts a docking maneuver but fails to complete the docking so that subsequent motion of the station does not include the mass inertia of the orbiter). A description of the applied loads is given in the reference document. Three potential discriminators for truss stiffness are peak transient displacements, accelerations, and stresses in the structure. Natural damping of 1/2 percent was assumed. Results at three locations on the station are presented; the nodal point at the experiment module where there are constraints on allowable accelerations, the tip of the outboard solar array where maximum displacements are expected and the location of the CMGs. It should be emphasized that the truss joint effects were not included and that truss stiffness reduction due to these joint effects could have a sizable influence on the transient response.

The first set of columns in the table shows that for virtually all locations on the structure and all applied loadings considered, the peak deflections of the 9 foot station are greater than those of the 15 foot station. However, this comparison is not subject to any displacement criteria since none have been established as yet. Therefore, it is possible that even the larger displacements of the 9 foot truss are acceptable.

The second set of columns in the table show comparisons between accelerations for the two truss sizes. Two conclusions can be made from these results. First, for all input loads considered, with the exception of the attitude control command, the peak transient acceleration at the experimental module violates the 10^{-5} G requirement which was initially established for the station as an environmental criteria for micro-G experiments. Second, comparison of peak accelerations at all locations inspected shows that no trend exists to aid in the discrimination between the two truss sizes on the basis of accelerations. This was also illustrated in the reference document, and is due to the fact that local accelerations are influenced by factors other than truss stiffness.

Finally, in considering transient stresses induced in the structure, the lower stiffness 9 foot bay structural configuration in general had higher stresses. An example of the increase in stress for the less stiff structure is indicated in the table with a comparison of the peak bending stress at the base of an outboard solar array astromast caused by a failed dock loading.

<u>Effect of Rigid Body Attitude Control on Transient Response</u>.- Two attitude control systems were investigated for the IOC 9 foot and 15 foot models to determine structures/control interaction. First, an attitude rate feedback system was used to drive the CMGs to maintain attitude during the Shuttle failed-docking maneuver. Second, the orbit reboost maneuver discussed in the reference document that uses continuous firing of the upper thrusters and intermittent firing of the lower thrusters to maintain attitude was studied.

Attitude Control Using Control Moment Gyros: No significant structures/controls interactions were observed for either the 9 or 15 foot stations when using the control moment gyro system. This is because the rigid body control frequency was low compared to the fundamental structural frequencies as shown in figure V-C-4. For example, consider the transient response results given in Table V-C-2 for a shuttle failed-docking maneuver. The results shown are for an uncontrolled case and give a peak attitude angle of almost 16 degrees. Including rigid body attitude control with a closed loop frequency and a damping ratio of 0.004 Hz and 28 percent respectively results in an applied peak control torque of 650 ft-lb and a peak angle of 0.81 degrees. The transient response results of Table V-C-2 were essentially unchanged when the attitude control system was used in conjunction with docking disturbance. This non-interaction of structures and rigid body controls is also illustrated by the rigid body command results shown in the table. For this case (frequency = 0.004 Hz, 70 percent damping) a peak torque of about 500 ft-lb yielded very small elastic deflections as shown in the table. It should be noted that control of the station after a failed dock is an extreme maneuver which would lead to saturation of the CMG controllers and require use of the RCS attitude control system to desaturate the CMGs.

Reaction Control System: Reboost maneuvers resulted in some interaction between the RCS thrusters and the structural modes and results are shown in Table V-C-2. These results were taken from a 500 second reboost maneuver with a deadband of 1 degree and hysteresis of 0.05 degrees. While peak displacements were generally larger for the 9 foot model, no tendency for the displacements to increase with time was observed for either station model. For example, the peak displacements shown in the table occurred before about 220 seconds during the 500 second reboost maneuver.

On-Orbit Operation of the MRMS.- Movement of the Mobile Remote Manipulator System (MRMS), under consideration as an onboard utility vehicle, was investigated to determine its operational limitations if the maximum acceleration at the attachment point of a laboratory module is not allowed to exceed 10^{-5} G. The station was treated as a rigid body and the acceleration of the MRMS across a bay was assumed to be sinusoidal. Figure V-C-5 shows the time required for an MRMS carrying a given payload to translate across one 15 foot bay such that the reactive force causes a 10^{-5} G maximum acceleration of the station. Times range from a minimum of slightly below 50 seconds (no payload transported) to a time of almost 250 seconds (a payload of 50,000 lbs transported). The acceleration at the laboratory module due to the reactive force caused by the MRMS transporting a 30,000 lb payload was computed for the 15 foot bay finite element model using rigid body and elastic modes. The applied reactive force was computed from the rigid body study. The total acceleration response including the rigid body and elastic accelerations for a one bay MRMS transfer is plotted in figure V-C-6. The accelerations computed were very nearly equal to the rigid body accelerations since the loading period was too long to excite any significant elastic response.

Modeling Accuracy.- The space station structures analyst should consider modeling the joint effects mentioned in Section V-B when preparing a finite element model. Since no joint effects are included in the current space station models discussed in this section, the models will appear stiffer than the actual structure they represent, with the amount of error being a function of the number of joints and magnitude of joint effects present in the particular truss.

In the current space station finite element models, no distinction can be made between a deployable or erectable truss structure since no joint effects are included. It is difficult to add realistic joint effects since they are strongly influenced by local design considerations and final joint designs have not been established. Any stiffness and dynamic response comparisons which are used to discriminate between deployable and erectable trusses based on an analysis which does not include joint effects is suspect.

Because of the large number of joints in the space station truss structure, it is not practical to increase the fidelity of the model at each joint in the structure. It may be possible to obtain an acceptable representation of the stiffness reduction by calculating a reduced linear strut stiffness based on both the strut and joint effective axial stiffnesses. Whether nonlinear behavior, which would include joint freeplay and hysteresis, must be included in an analysis or whether a linear analysis with modified stiffness will give acceptable results will depend on the degree of the nonlinearity.

To present an illustration of the potential inaccuracies associated with a model that neglects joint effects, in particular joint freeplay, consider the Space Station keel beam. Assume that the magnitude of freeplay in each joint of the truss is .0005 in. In general, this keel beam can undergo no-load deflections due to the accumulation of freeplay (as previously shown in figure V-B-3). The keel truss deformations due to freeplay presented in this figure are replotted in figure V-C-7 and compared with peak transient displacements based on finite element models of the 9 foot and 15 foot Space Station which do not include the joint freeplay. The transient displacements are due to three anticipated load scenarios: crew motion, a failed shuttle dock and orbit reboost, and, in all cases, displacements are less than the no-load displacements that would be possible due to the assumed joint freeplay. It is thus possible that the actual truss deformations will be dominated by joint freeplay, and the accuracy of a linear analysis that neglects joint effects may be highly suspect if these effects are large.

Deployable vs. Erectable Trade Comparison.- No station operational criterion has been identified which would not be met satisfactorily by the trusses considered in relation to stiffness. There is, however, a definite benefit to having the increased stiffness of the 15 foot bay truss which can provide a more stable platform. The 15 foot bay truss with its lesser number of joints will also have less decrimental joint dominant effects. The Table V-C-3 evaluation reflects these considerations.

REFERENCES

V-C-1 Mikulas, M. M., Jr.; Croomes, S. D.; et.al.: Space Station Truss Structures and Construction Considerations. NASA TM-86338, July 1984.

Table V-C-1. Mass characteristics of models.

MODEL	MASS lb	C.G. LOCATION* (x,y,z),in	MASS MOMENTS OF INERTIA, $lb \cdot in \cdot s^2 (x10^8)$					
			I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
IOC 9 foot	262,866.	8.,0.,2311.	8.49	7.88	1.10	-.000037	-.011	-.0020
IOC 15 foot	257,462.	14.,0.,2171.	8.39	7.57	1.39	-.00012	-.164	0.0029
300kw 15 foot	528,432.	-11.,0.,2153.	50.2	25.4	26.1	-.00021	-.590	-.0087

* Measured from center of keel, transverse boom intersection.

Table V-C-2. Comparison of transient response data

		PEAK DISPLACEMENTS, IN.			PEAK ACCELERATIONS, g's($\times 10^5$)			PEAK BENDING MOMENT, IN.LB.
		EXPERIMENT MODULE	SOLAR ARRAY TIP	CMG LOCATION	EXPERIMENT MODULE	SOLAR ARRAY TIP	CMG LOCATION	ASTROMAST BASE
SHUTTLE FAILED DOCK	15 foot	.054	1.25	.11	301.	1060.	256.	2355.
	9 foot	.27	2.33	.17	276.	1340.	186.	3945.
CREW MOTION	15 foot	.0021	.039	.0029	12.0	34.2	9.47	
	9 foot	.0072	.060	.0046	10.2	31.8	5.73	
ORBIT REBOOST	15 foot	.44	2.04	.21	191.	1110.	928.	
	9 foot	.33	3.68	.28	648.	1790.	578.	
1° ATTITUDE COMMAND	15 foot	.0007	.014	.0018	.856	9.37	4.78	
	9 foot	.0065	.018	.0022	.997	10.90	4.91	

Table V-C-3. DEPLOYABLE VS. ERECTABLE TRADE COMPARISON

		PREINTEGRATED SUBSYSTEMS	"MODULARIZED" SUBSYSTEMS		
	DISCRIMINATORS	9' DEPLOYABLE	15' ERECTABLE	15' PACTRUSS	TETRAHEDRAL
CUSTOMR ACMDTNS	GROWTH POTENTIAL				
	PAYLOAD ACCOMMODATIONS				
SUBSYSTEM INTEGRATION	1) POWER CABLES ETC.				
	2) RCS THRUSTERS ETC.				
	3) THERMAL AND PROP. LINES				
	4) INSTALLATION & SERVICING				
	5) ROTARY JOINTS				
	6) MRMS				
	7) SE&I REQUIRED				
CONSTR. OPS.	EVA HOURS				
	NUMBER OF EVAs PER FLIGHT				
COST	TRUSS { WEIGHT, PART COUNT D.D.&T., DEPLOYER				
	CONSTRUCTION				
TRUSS CRITERIA	REDUNDANCY, REPAIRABILITY AND MAINTAINABILITY				
	PREDICTABILITY				
	STIFFNESS	S	A	A	S

A - ADVANTAGE, S - SATISFACTORY, D - DISADVANTAGE

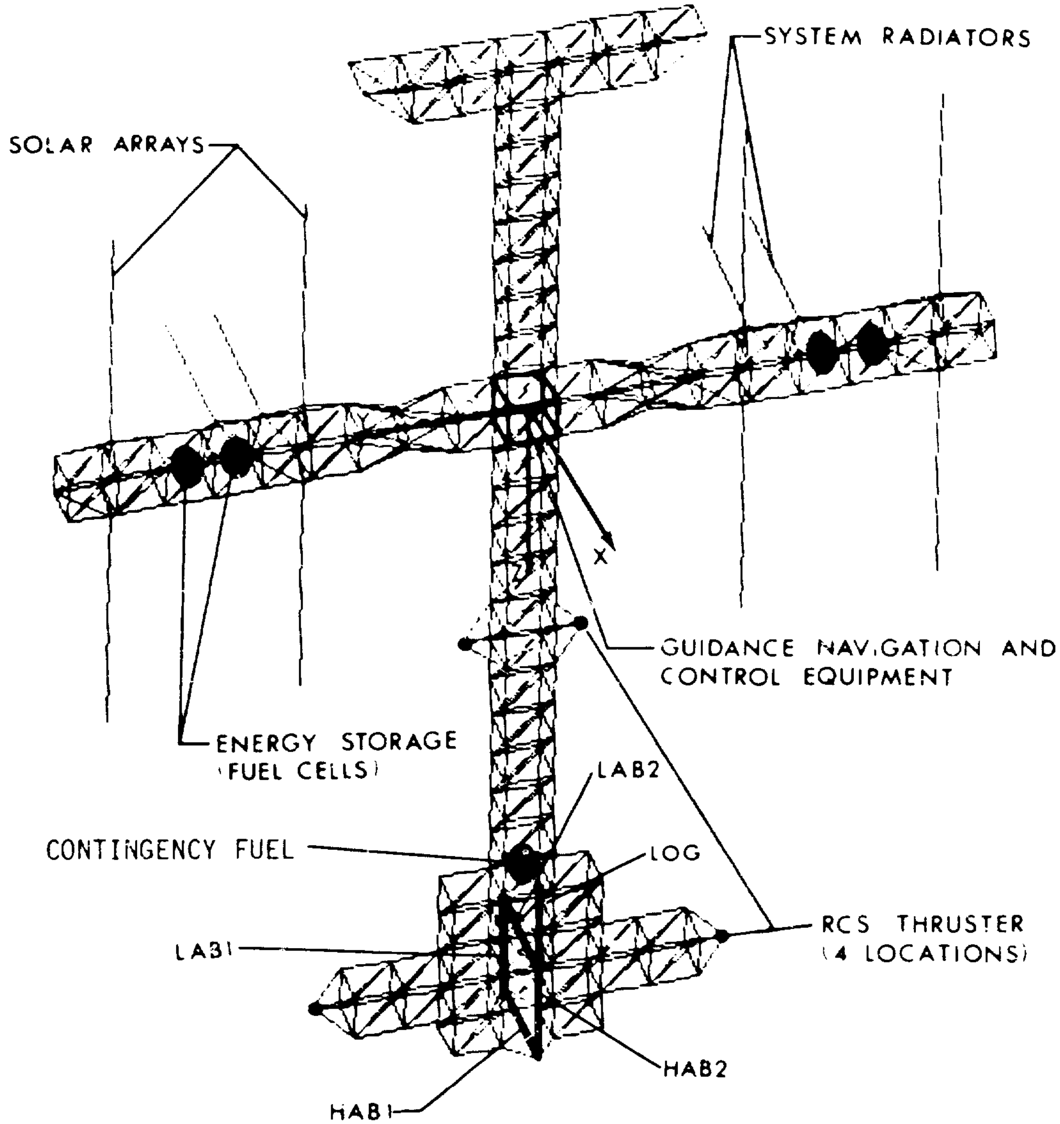

Figure V-C-1. IOC model - 15 foot bays

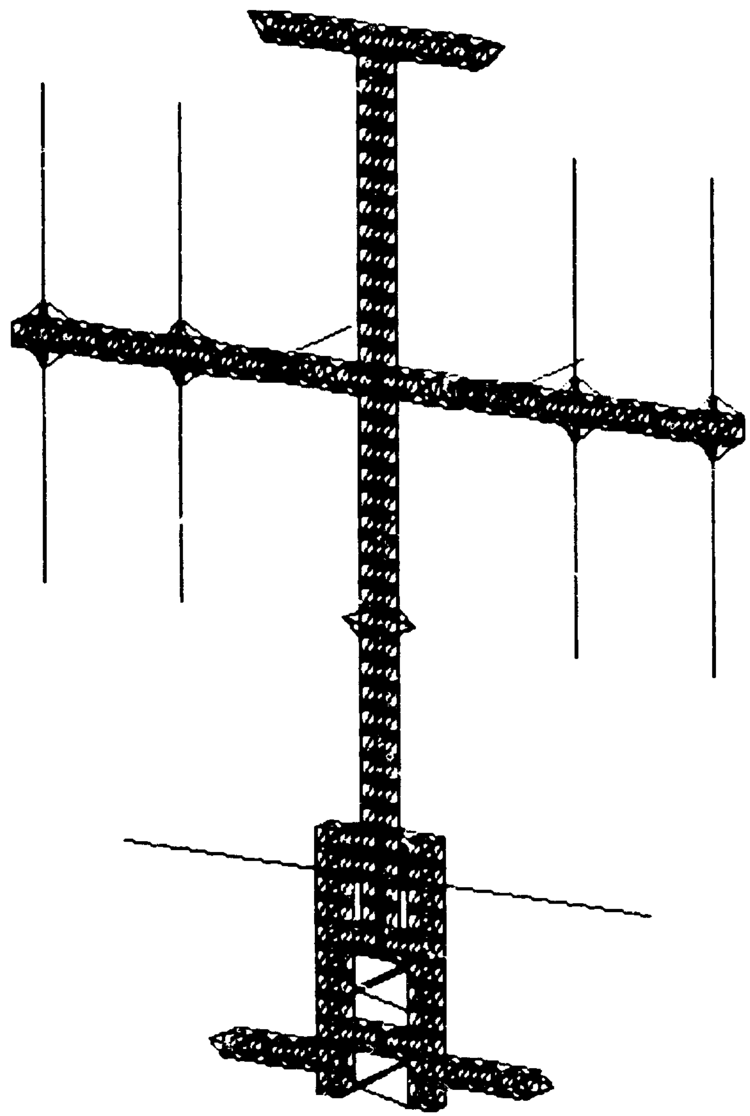

Figure V-C-2. IOC model - 9 foot bays

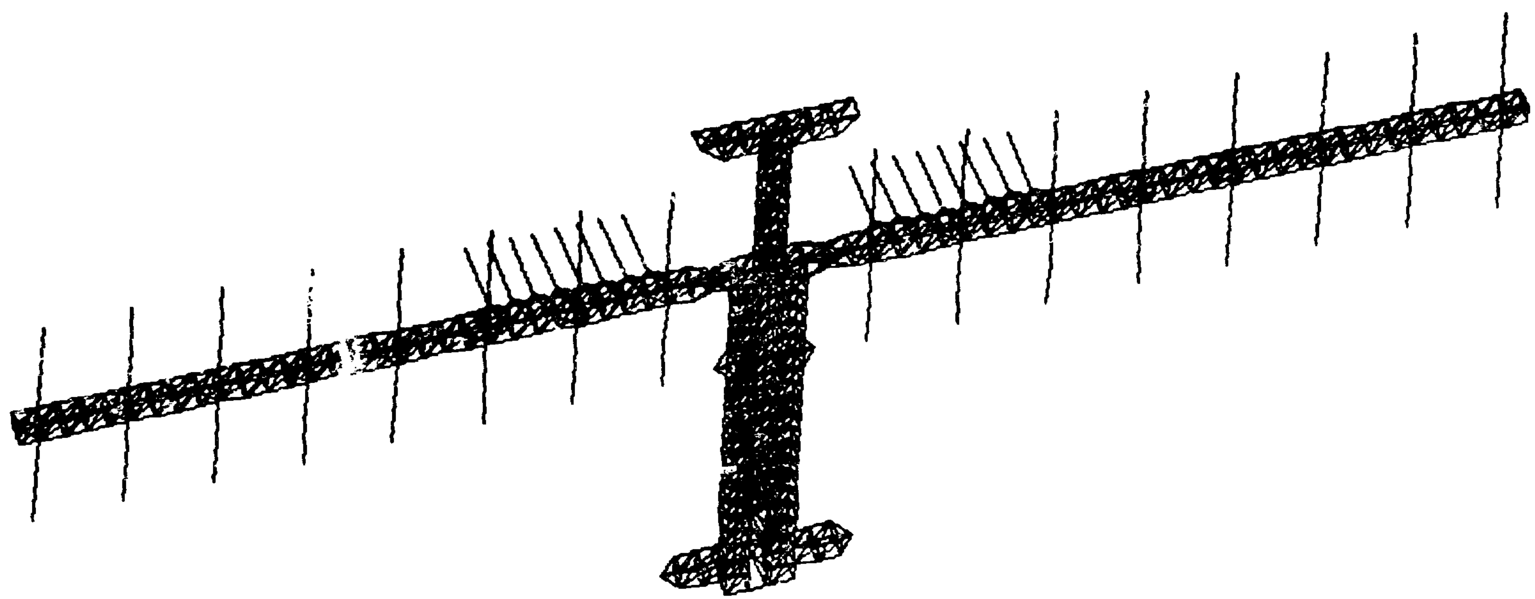

Figure V-C-3. 300 kw growth model - 15 foot bays

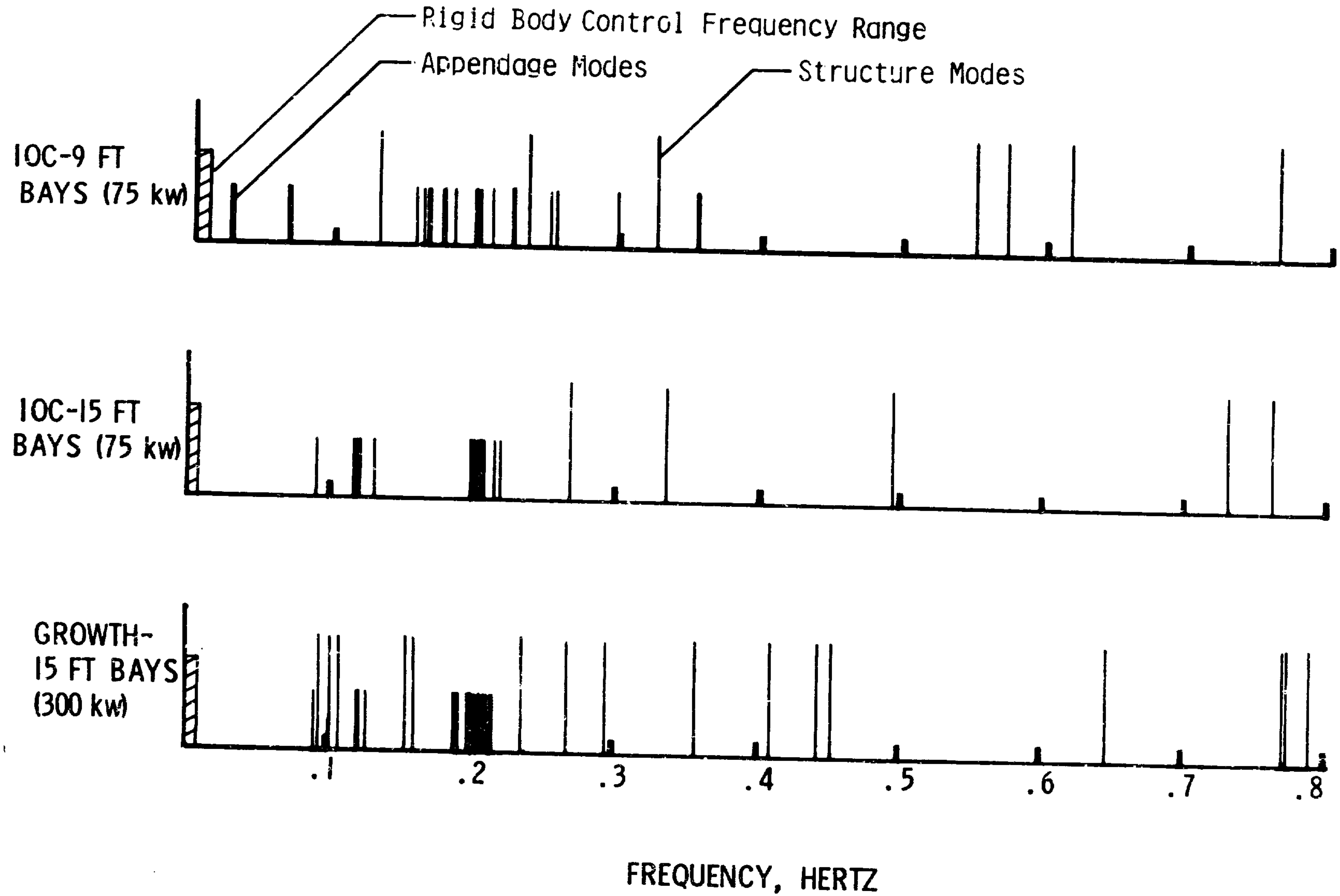

Figure V-C-4. Structural frequency distributions.

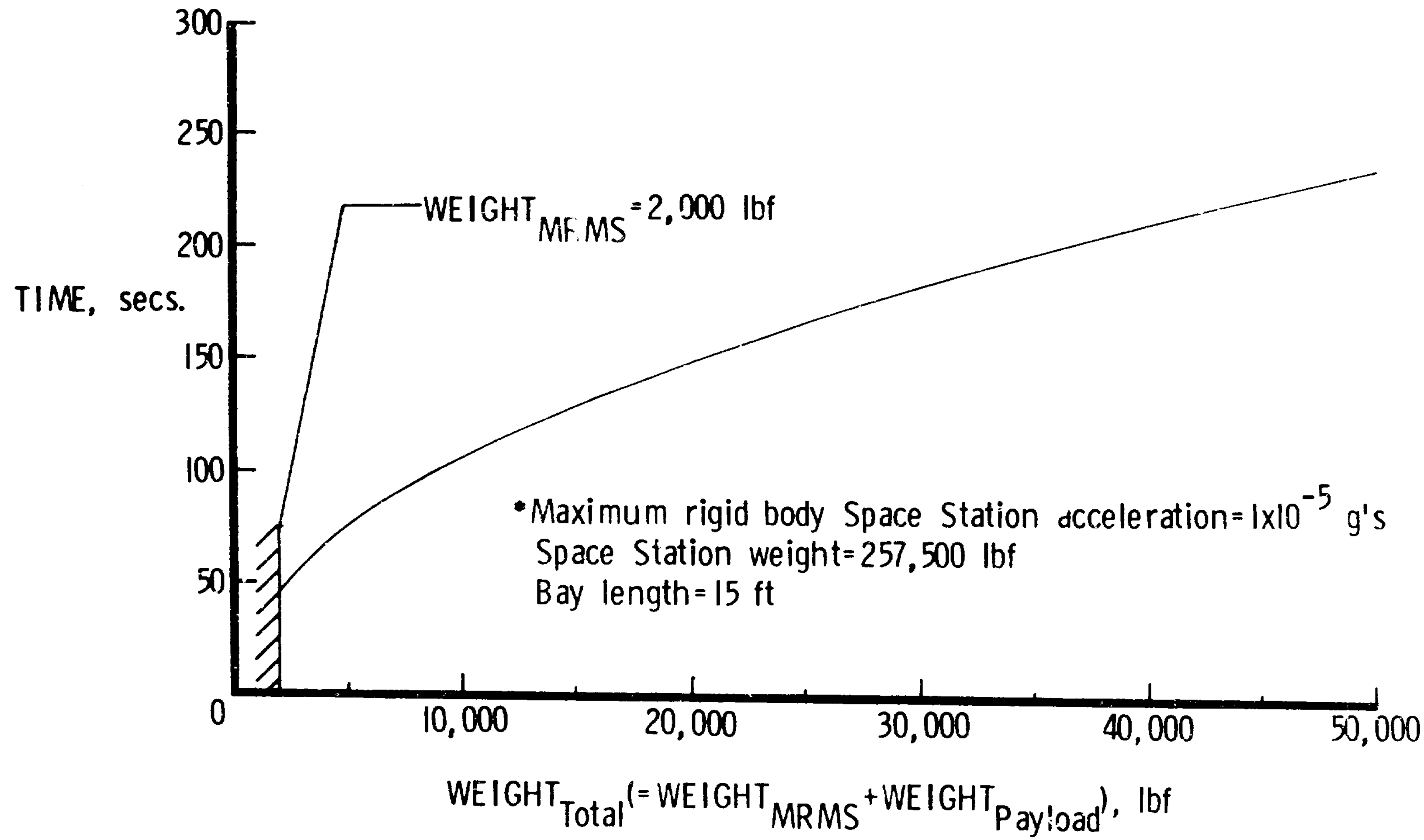

Figure V-C-5. Allowable time for MRMS to traverse one bay*.

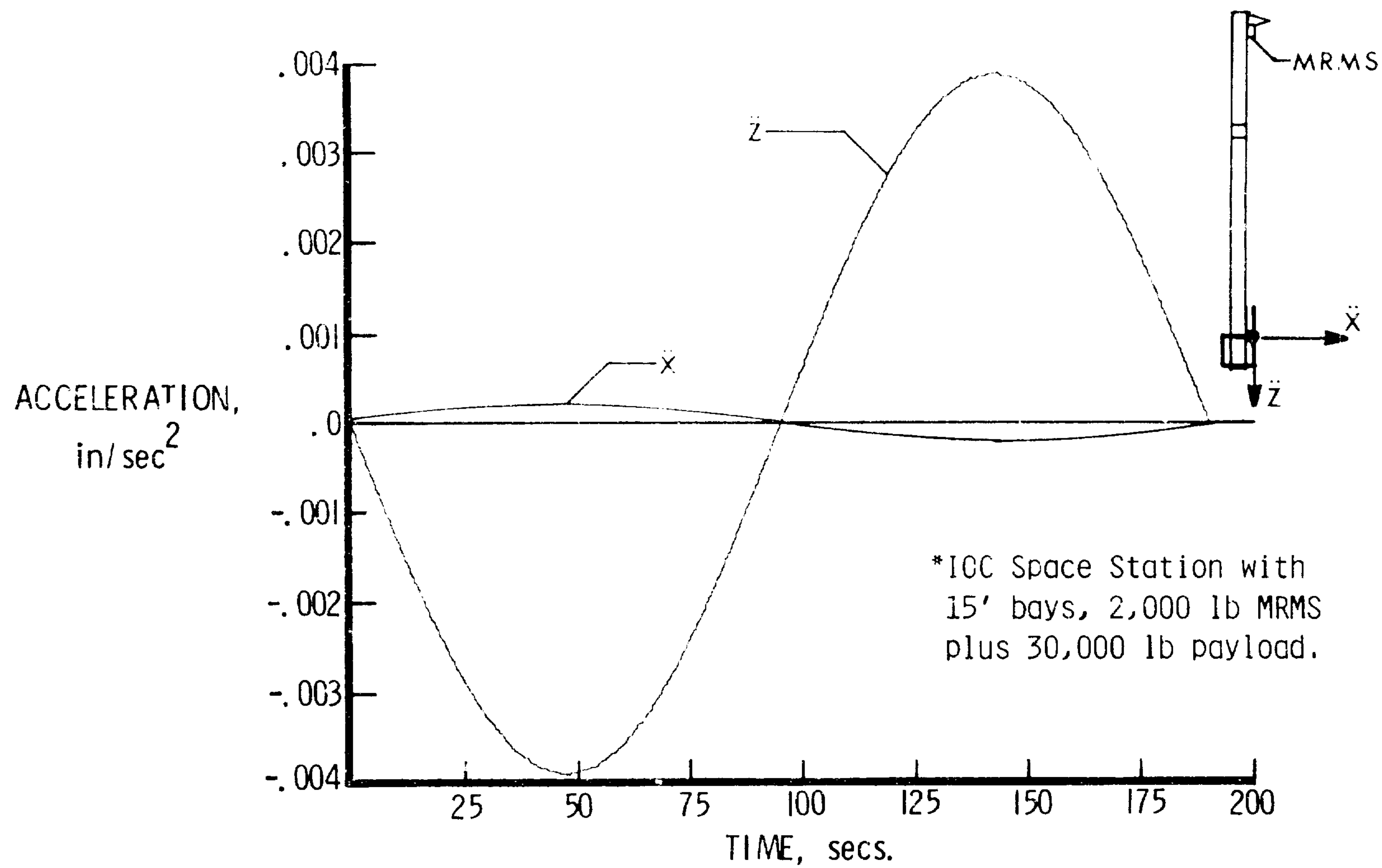

Figure V-C-6. Accelerations at laboratory module due to MRMS translation.

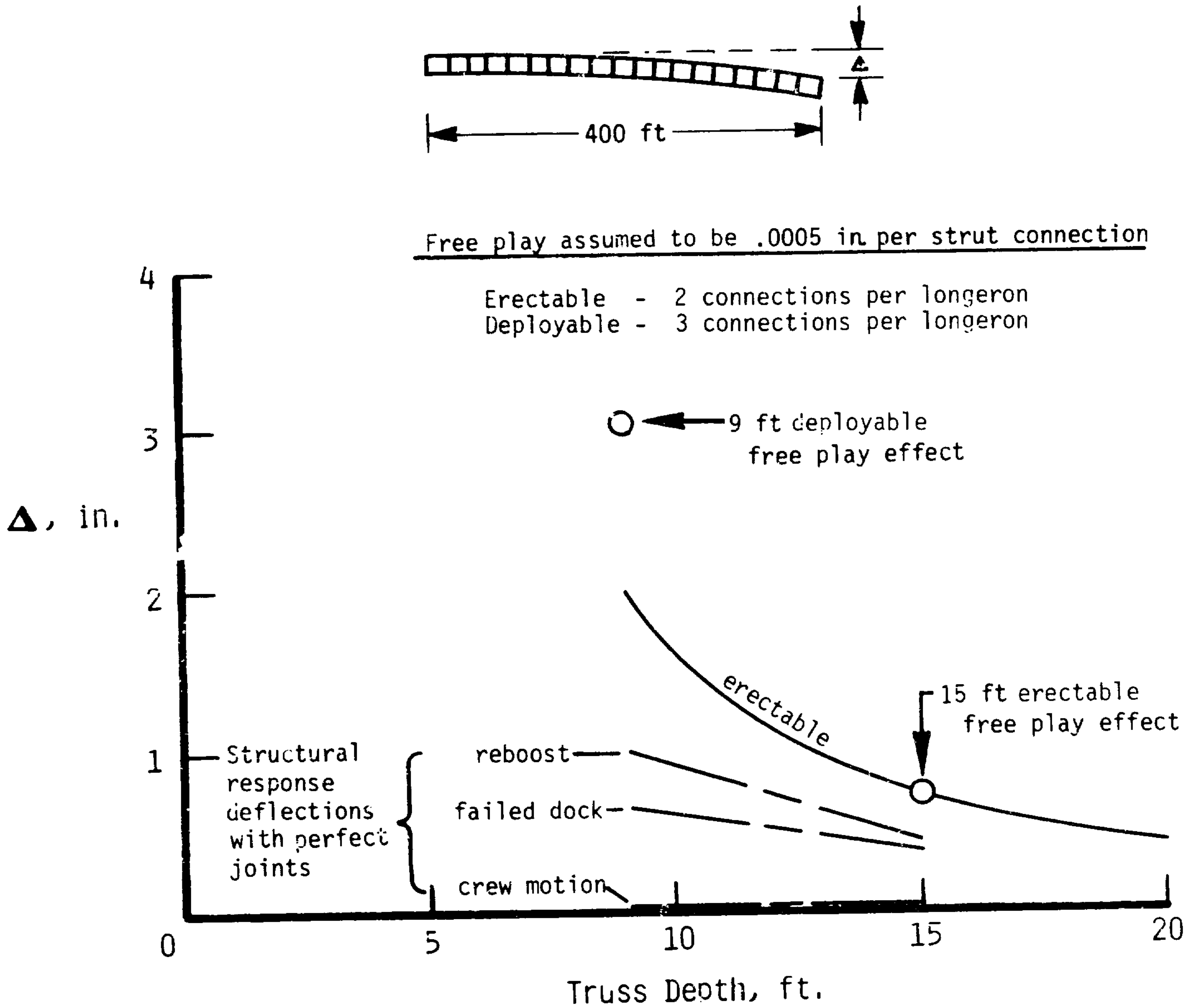

Figure V-C-7. Comparison of keel deflections due to joint free-play and structural response to loads.

V-D. DEPLOYMENT ANALYSIS OF A 9 FOOT DEPLOYABLE SINGLE-FOLD TRUSS

The objective of this task is to provide quantitative information as an aid in assessing the risk involved in deployment of the components of the reference 9 foot single fold deployable truss. It is assumed in this task that such components would deploy in a controlled bay-by-bay fashion; that is, sequentially. Further, for simplification, a planar deployment model is assumed to be adequate for risk assessment.

Figure V-D-1 depicts the deployment of a single bay after several other bays have been successfully deployed. The deployment of a bay is assumed to be accomplished through the simultaneous unfolding of the longerons and telescoping of the diagonals. The longerons have hinge joints at their centers which permits unfolding. The hinge is assumed to lock up once the unfolding of the longeron sections is complete. Lateral velocity of the hinge joint provides the momentum necessary for locking. The diagonals are also assumed to lock up rigidly when fully extended.

Once the station is fully deployed and operational, the truss members will carry tensile or compressive loads with little or no bending present since all joints are assumed to be pinned. The only bending moments that can arise would be due to local vibrations of the truss members. Thus, the bending moments in the members is not a design consideration for normal operation of the station. Furthermore, during deployment the bending moments in the members will be very small provided the bays deploy successfully. However, if for some reason, a longeron hinge joint were to stick, bending moments in the members would result, the magnitude of which will depend upon the extensional deployment rate of the truss-beam component at the time the joint sticks.

To accomplish the unfolding of the bays, an applied control force is necessary. This control force could come from a screw or other type of mechanism. The control force, which varies during the deployment of a bay, is assumed to act at the forward hinge joints of the unfolding bay as shown in figure V-D-1.

<u>Deployment Analysis With an Assumed Stuck Hinge Joint</u>.- Analysis of the extending truss-beam when a hinge joint sticks was carried out using the LATDYN finite element code of reference V-D-1. This code allows for large rigid body motions and large deformations. Large rigid body rotations of the truss members occur during deployment. When a hinge joint sticks rigid body rotations of the members are limited, but can still occur.

Bending moments will be largest when the mass being pushed by the deployment mechanism is greatest. Thus, 18 deployed bays, representing the reference configuration keel, are placed ahead of the extending bay. They are simulated in the model by a single beam whose stiffness is that of the deployed truss-beam. In addition, a large mass representing a full fuel tank weighing 5000 pounds is placed at the tip of the 18 bay deployed portion of the truss-beam.

Initial conditions for the execution of the dynamic analysis are determined from figures V-D-2 and V-D-3, and temporal variation of the control force is determined from figure V-D-4. In generating these figures, four different procedures for unfolding a single bay were considered, namely,

nearly uniform extensional rate

sinusoidal extensional rate

nearly uniform unfolding rate

linear unfolding rate

Both the initial conditions and control force influence the bending moments induced when a hinge joint sticks. Thus, in order to choose cases for detailed analytical investigation, consideration was given to those extension profiles and control force profiles which appeared to produce worst case situations. Using figures V-D-2 through V-D-4, three worst cases were chosen. The first case was that which leads to the maximum initial extensional rate. This occurs under the assumed sinusoid extension rate if a joint sticks when the bay is about 50 percent extended. The second case and third cases were chosen to maximize the control force. These also occur under an assumed sinusoid extension rate if a hinge joint sticks when the bay is either about 10 percent or 90 percent extended.

The resulting peak dynamic bending moments, which occur at the stuck hinge joint, are shown in figure V-D-5 over a range of average extensional rates. The bending strength of the truss members is not precisely known at this time, but it is safe to assume that it is greater than 2000 foot pounds. Nominal extensional rates are considered to be below 1 bay per minute. Thus, figure 5 indicates that at such slow deployment rates, member failure will not occur if a hinge joint sticks. The results also indicate that this deployment rate is very conservative and higher rates may be considered.

REFERENCE

V-D-1 Housner, J. M.: Convected Transient Analysis for Large Space Structures Maneuver and Deployment. 25th Structures, Structural Dynamics and Materials Conference, AIAA Paper No. 84-1023CP, May 1984.

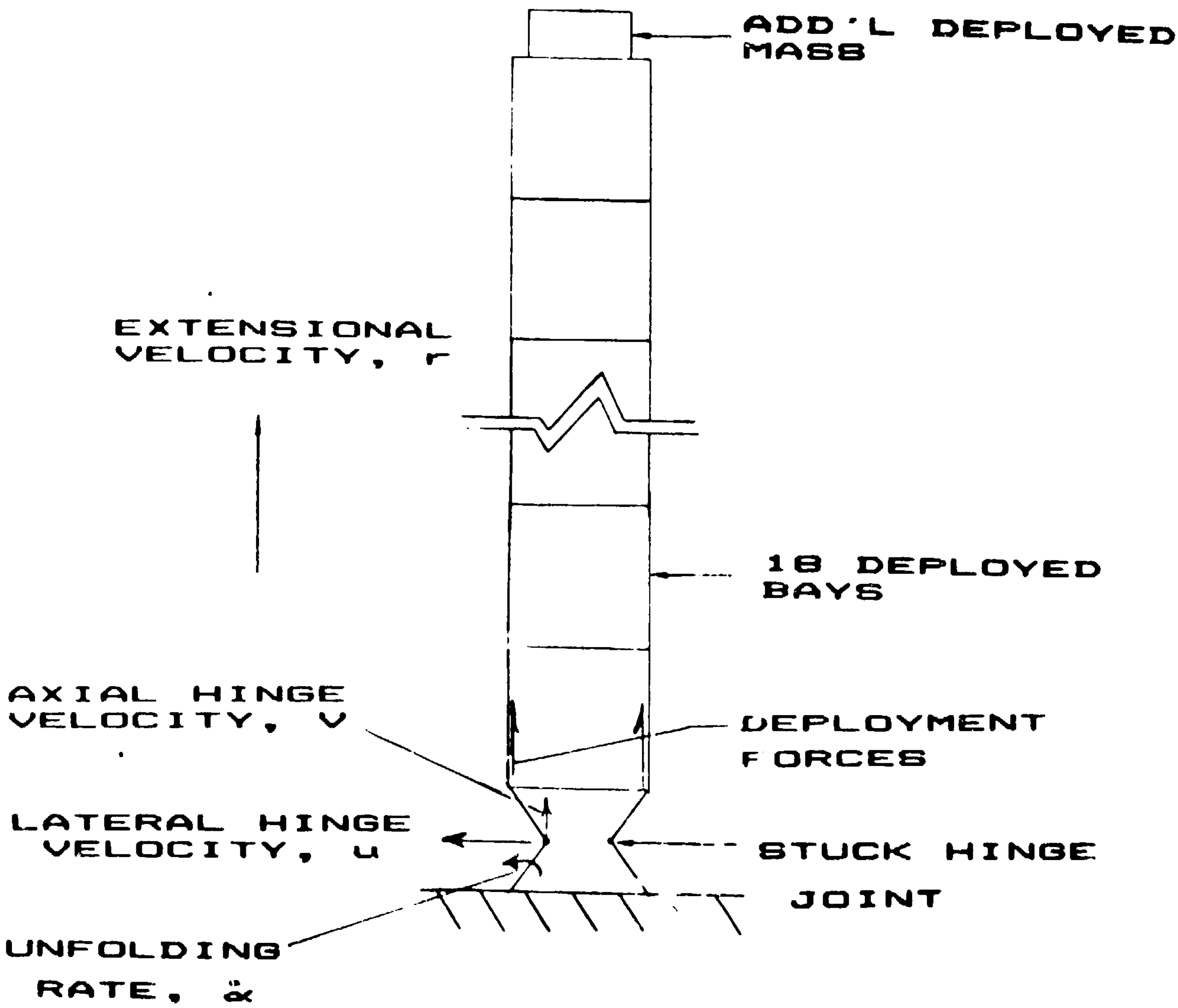

Figure V-D-1. - Keel deployment for risk assessment study.

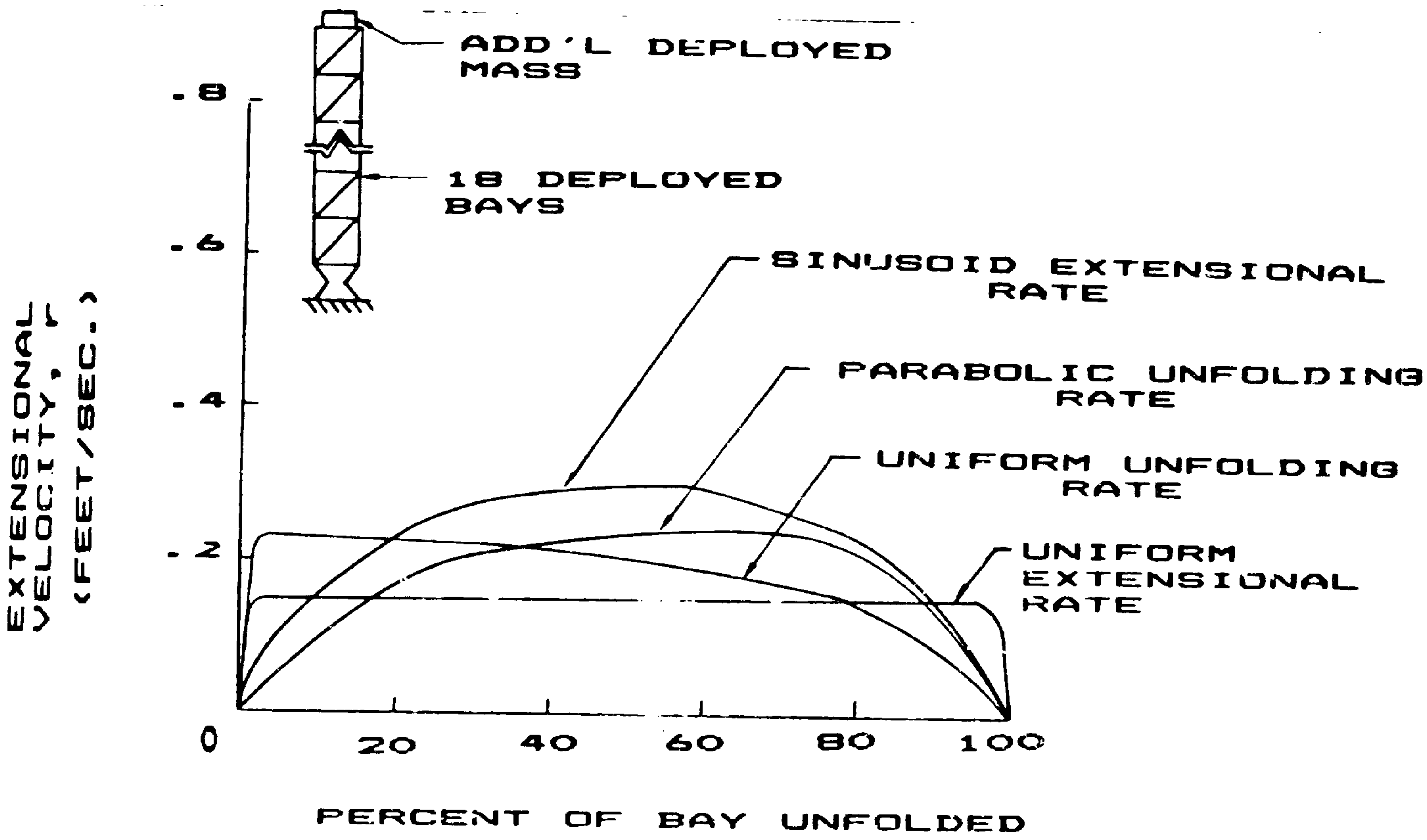

Figure V-D-2. - Assumed variation of extensional rate during unfolding of a single bay prior to hinge sticking for an average one bay/minute deployment.

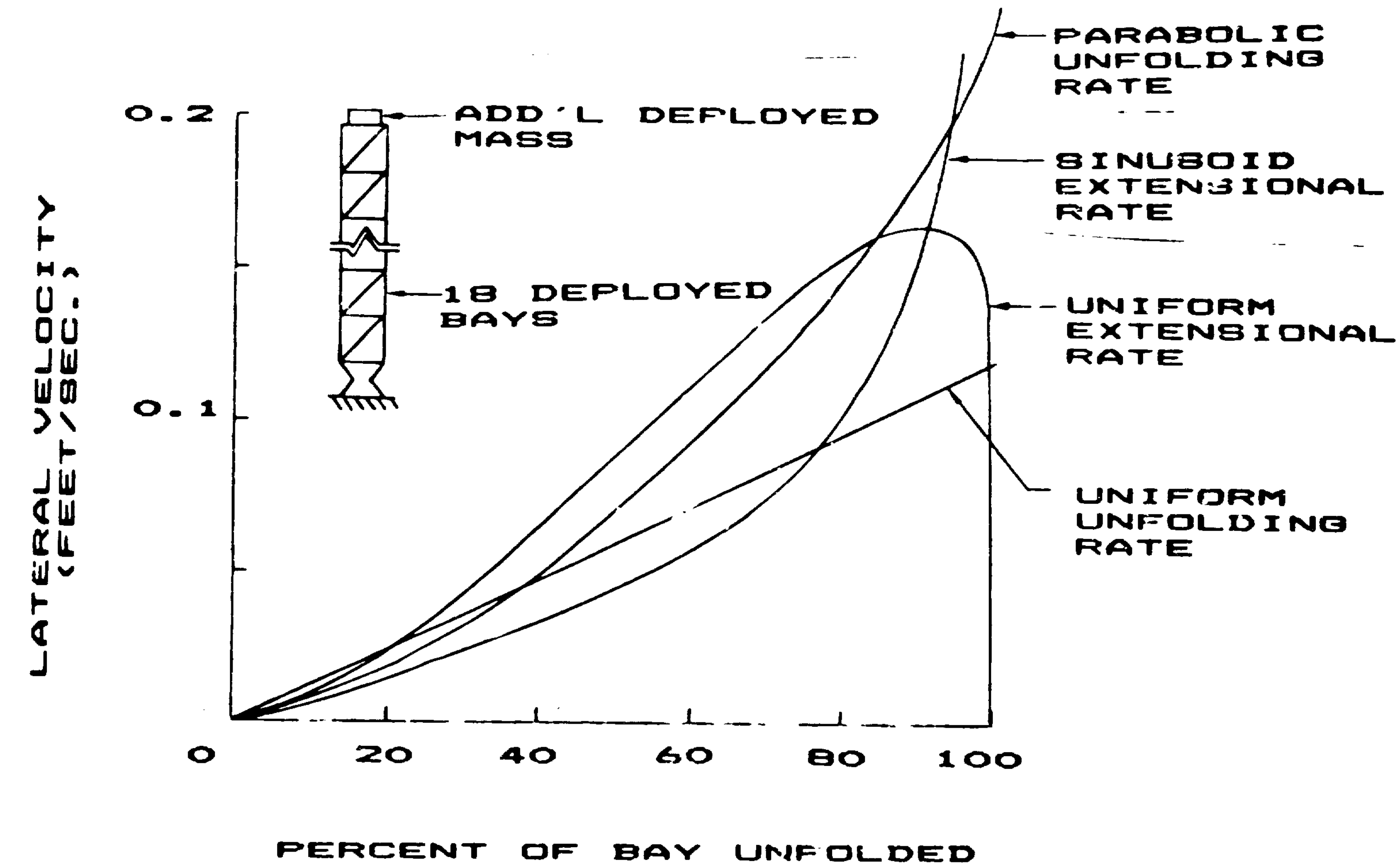

Figure V-D-3. - Variation of hinge joint lateral velocity during unfolding of a single bay prior to hinge sticking for an average one bay/minute deployment.

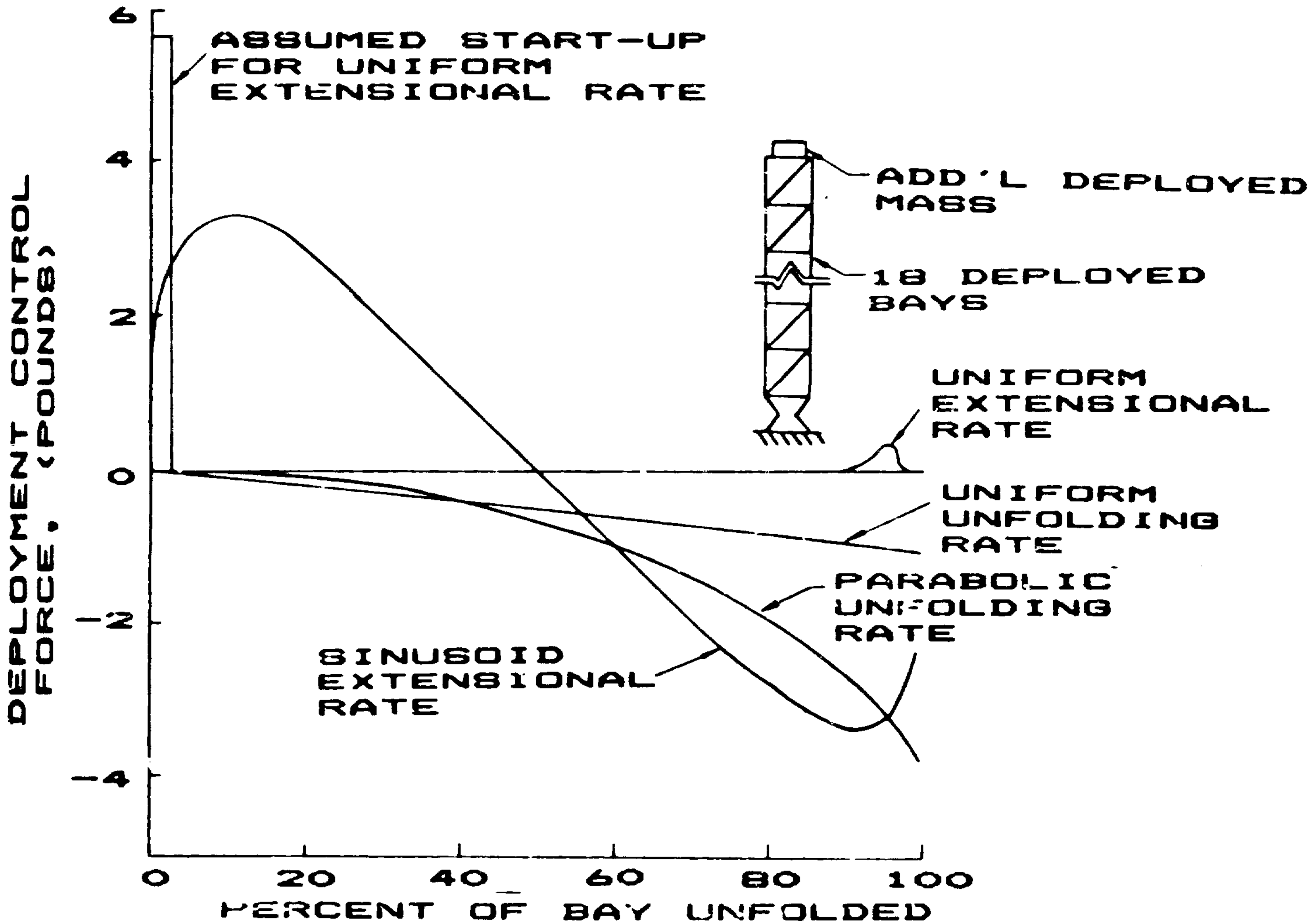

Figure V-D-4. - Variation of a control force during unfolding of a single bay prior to hinge sticking for an average one bay/minute deployment rate.

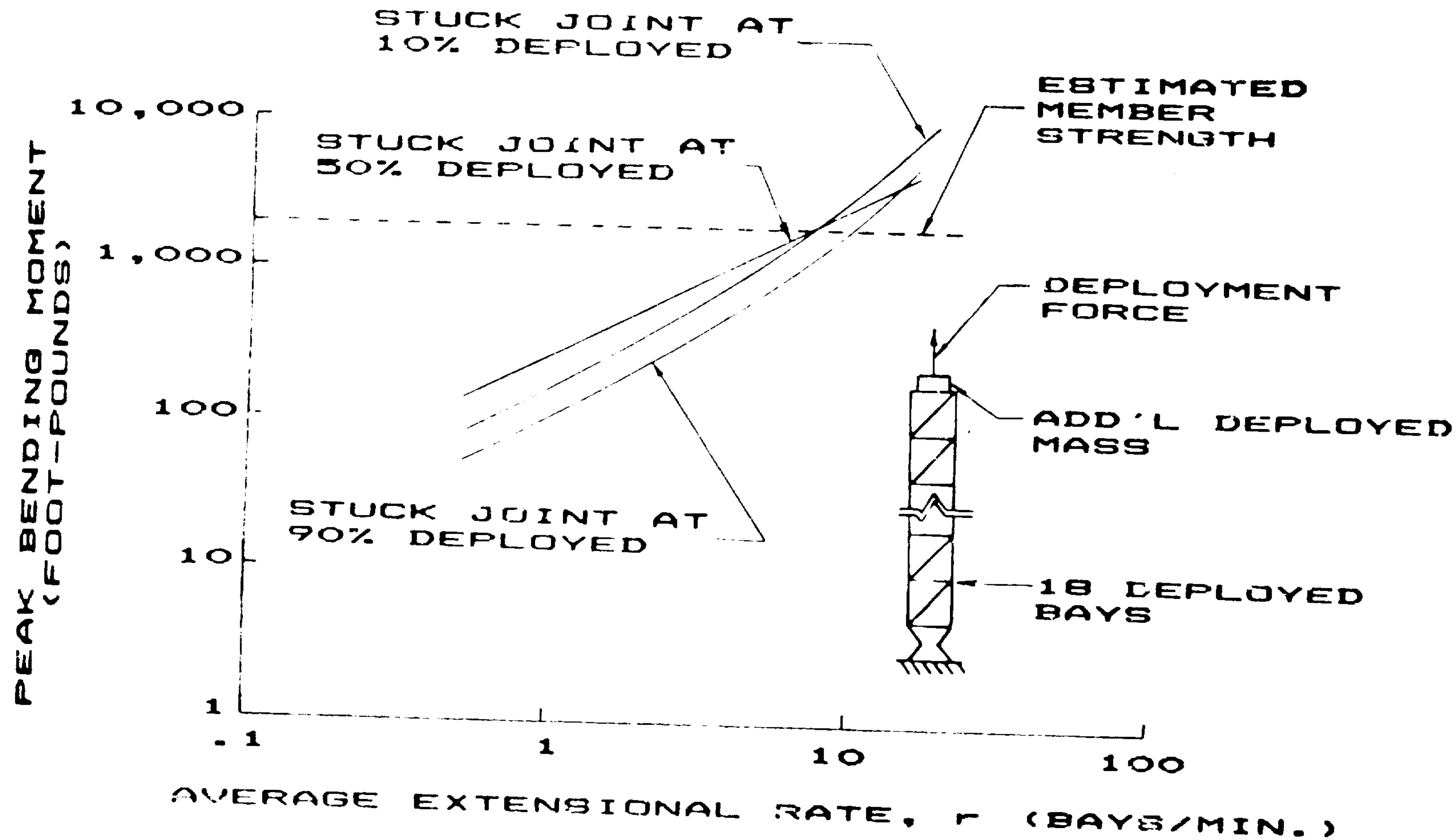

Figure V-D-5. - Variation of peak bending moment with average extensional rate due to a stuck joint.

V-E. RIGID-BODY CONTROL AND THERMAL ANALYSIS

Rigid Body Controllability Analysis.- A rigid-body controllability analysis was performed in order to determine to what extent the overall momentum storage system requirements would be affected due to the two structural concepts. The Rigid-Body Control Dynamics (RCD) module of the Interactive Design and Evaluation of Advanced Spacecraft program (IDEAS) (ref. V-E-1) was used to calculate the on-orbit environmental forces, maneuver forces, and corresponding torques on the structure at specified orbital altitudes, orientations and mission durations. It then determines the momentum storage and desaturation requirements, control system sizing, and propellant required for stationkeeping, attitude control, and other maneuvers. The principal features of RCD are shown in figure V-E-1. The total torque and force time histories are analyzed to determine cyclic and secular momentum buildup for momentum exchange system sizing and desaturation requirements. Momentum desaturation requirements are met using reaction control system (RCS) thrusters. The RCS requirements are also determined for stationkeeping.

The mass properties summary, environmental force and torque summary, propellant requirements and momentum storage requirements for the deployable and erectable concepts are shown in Table 1. The RCD analysis was performed for three operational altitudes; 220NM, 250NM, and, 270NM. The overall mass properties for each of the IOC concepts are similar to the Reference configuration. The maximum aerodynamic forces are experienced when the solar arrays are perpendicular to the direction of flight. The corresponding torques are then experienced about the axis perpendicular to the orbital plane. By integrating the torques around a complete orbit, both cyclic and secular momentum vectors are determined. The cyclic momentum vector is used to determine the number of equivalent Skylab CMG's necessary to absorb the momentum. The worst case conditions occurred at the 220NM altitude, where the number of CMG's required for momentum storage is at its highest. The number of CMG's required at this altitude is 6 for both the 15 foot and 9 foot concepts.

The amount of propellant required for stationkeeping for both concepts are within one percent of each other. The propellant requirement for the CMG desaturation shows that approximately 5 percent more propellant is required for desaturation of the CMG's on the 9 foot deployable concept than for the 15 foot erectable concept at 220NM altitude. This percentage reflects in an additional 400 pounds of fuel to be carried along for each 90-day resupply interval.

Thermal Analysis.- Thermal analysis of both concepts was performed in order to identify any deficiencies in overall integrity of the support structure. This was achieved through the use of the Thermal Analysis (TA) module in IDEAS. TA calculates the transient temperature response for each structural member at a given position in the spacecraft's orbit. Heat sources are solar radiation, Earth albedo, and Earth thermal radiation. The balance between absorption of energy of the elements and the emmittance of energy from the elements out into deep space is used to determine the transient thermal response. Earth shadowing is included. Three major assumptions are made in this type of analysis. First, each element is considered to be an isothermal element. Secondly, the radiation exchanges between structural members are neglected due to small radiation view factors. Finally, structural member-to-member shadowing is neglected. Input into this module consists of the model geometry, each material's thermal characteristics and the position in orbit where the analysis begins and ends. Output yields elemental tempratures and heating rate time histories.

Since each support structure consists of repetitive structural elements, a 15 foot and a 9 foot structural cube was created to simplify the analysis. Members in the cube are shown in figure V-E-2. The cubes were defined to have thermal properties of graphite/epoxy. The cubes were placed in a 270NM orbit and the analysis was then performed at 16 points throughout the orbit. Also, the thermal-induced stresses and loads were computed. The thermal stresses are less than 0.1 psi and are, therefore, negligible.

REFERENCES

V-E-1. Ferebee, Melvin J., Jr.: IDEAS, Multidisciplinary Computer-Aided Conceptual Design System for Spacecraft. Presented at NASA Langley Research Center Symposium on Recent Experiences in Multidisciplinary Analysis and Optimization. April 24-26, 1984.

TABLE V-E-1. SUMMARY OF MASS PROPERTIES AND RIGID-BODY CONTROL REQUIREMENTS

Hydrazine System :Isp = 220 sec
Graphite Epoxy material

	UNITS	15 ft.			9 ft		
WEIGHT	KG		292748			273506	
INERTIAS							
IXX	10**6 SLG-FT2		82.75			72.60	
IYY	10**6 SLG-FT2		74.54			69.65	
IZZ	10**6 SLG-FT2		12.56			5.56	
IXY	10**6 SLG-FT2		.00			0.00	
IXZ	10**6 SLG-FT2		0.76			0.52	
IYZ	10**6 SLG-FT2		-0.03			0.00	
MAXIMUM TORQUE VECTOR		X	Y	Z	X	Y	Z
270 NMI	FT-LB	0.00	24.92	0.01	0.00	25.35	0.00
250 NMI	FT-LB	0.00	36.20	0.01	0.00	37.10	0.00
220 NMI	FT-LB	0.00	73.40	0.02	0.00	76.60	0.00
MAXIMUM MOMENTUM VECTOR							
270 NMI		X	Y	Z	X	Y	Z
CYCLIC	FT-LB-SEC	67.14	4204.28	122.05	66.71	4415.77	116.43
SECULAR	FT-LB-SEC	5.71	0.00	19.08	7.35	0.00	22.21
CMG REQUIREMENT	@ 2300FT-LB-SEC		2.00			2.00	
250 NMI		X	Y	Z	X	Y	Z
CYCLIC	FT-LB-SEC	160.10	6290.61	287.84	7.35	6608.67	5.66
SECULAR	FT-LB-SEC	7.01	0.00	44.29	7.48	0.00	33.34
CMG REQUIREMENT	@ 2300FT-LB-SEC		3.00			3.00	
220 NMI		X	Y	Z	X	Y	Z
CYCLIC		175.91	13135.71	293.42	3.96	13908.62	3.16
SECULAR	FT-LB-SEC	104.79	0.00	45.08	1.58	0.00	0.15
CMG REQUIREMENT	@ 2300FT-LB-SEC		6.00			6.00	
C.P./C.G. OFFSET	FT.	0.00	0.03	-164.50	0.00	0.00	-172.77
C.G. LOCATION	FT.	1.36	-0.03	175.13	0.03	0.00	183.43
AREA PROJECTION	SQ. FT.	25703.59	491.47	470.69	25789.70	504.49	488.45
PROPELLANT REQUIREMENTS							
ORBIT KEEP							
270 NMI	LB		4657			4668	
250 NMI	LB		7011			7069	
220 NMI	LB		14797			14914	
CMG DESAT.							
270 NMI	LB		2807			2948	
250 NMI	LB		6512			6842	
220 NMI	LB		6633			7023	

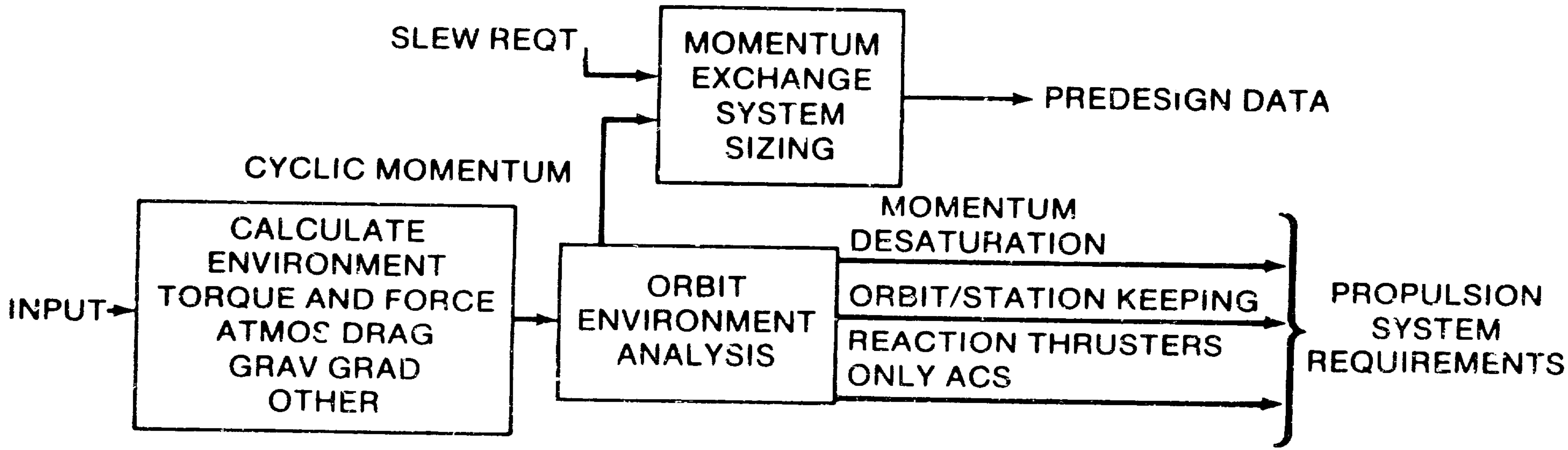

Figure V-E-1. Rigid-Body Control Dynamics Module (RCD)

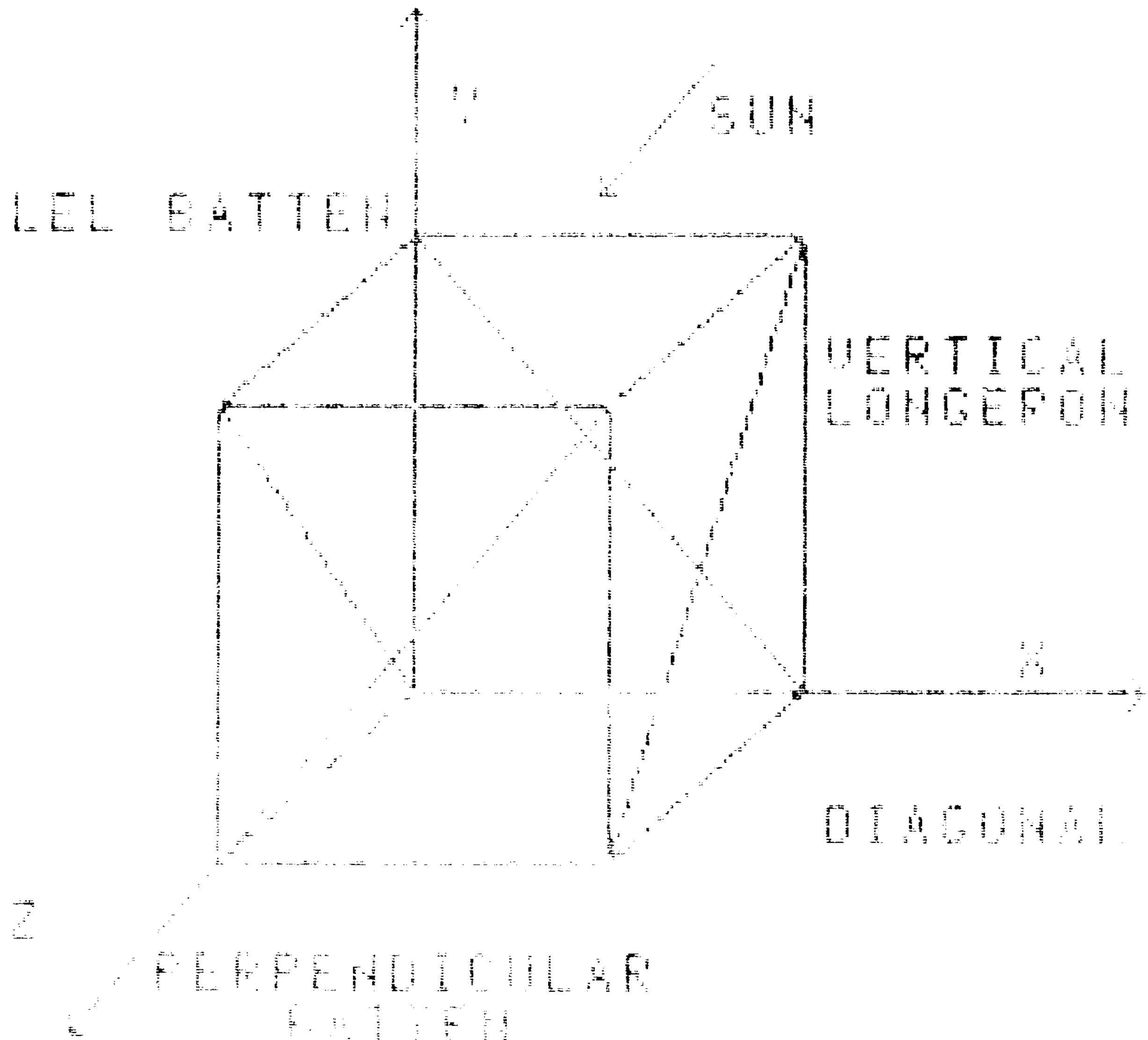

Figure [illegible] Cube Element Definition

CONCLUDING REMARKS

The present paper presents results of a trade study which was conducted to compare four different trusses for constructing the reference gravity-gradient Space Station. A set of discriminators was established and each of the four trusses were rated for each discriminator on an adjective basis. A summary of the evaluation is presented in Table C-1. In the summary the disadvantages for each truss concept are highlighted by cross-hatching. The horizontally cross-hatched disadvantages are characteristics which are potentially resolvable by engineering and development. The diagonally cross-hatched disadvantages are characteristics which are inherent to the truss concept and cannot be significantly improved by further engineering and development. At the beginning of this study, considerable effort was expended on truss criteria such as stiffness and response predictability. Although the deeper trusses have an advantage in this area, no station operational criterion has been found which could not be met satisfactorily by all the trusses considered. Because of the desirability to grow the space station in an evolutionary fashion as needs arise, growth potential was deemed to be the primary truss discriminator. A summary of the major conclusions are as follows:

- 9 foot single fold deployable truss provides:
  - Power cable and small utility line preintegration
  - Rotary joint preintegration
- 15 foot orthogonal truss provides:
  - Excellent growth potential and payload accommodations
  - Minimum interference from payloads with station operations
  - High stiffness and low cost
  - Compact packaging
- Tetrahedral truss provides:
  - Large number of nodes for payload attachment
  - Compact packaging
- EVA hours not prohibitively different between concepts:
  - 9 foot deployable: 94 hours
  - 15 foot erectable: 111 hours
- Erectable, PACTRUSS, and Tetrahedral construction approach with modular subsystem integration simplifies launch package integration and minimizes work package interfacing.

- Number of EVAs per flight too high for all construction scenarios.

In the final analysis, it appears that selection of a truss construction approach for the Space Station becomes a decision between advantages in the initial construction process or operational advantages after the Station is constructed. The 9 foot single fold deployable was found to have some advantage in reduced EVA hours for construction, however, the higher cost of the deployable structure and its deployer more than offset the savings in cost due to the reduced EVA hours. For this reason, strong consideration should be given to the 15 foot truss because of its potential advantages for growth and payload accommodation. Further studies are required to discriminate between the erectable and double fold deployable approach for achieving a 15 foot truss Space Station truss.

For all four construction scenarios, the number of EVAs per Shuttle flight has been estimated as being unsatisfactory. To date, most of the effort on Space Station construction has been spent on estimating EVA construction times for a simplified set of procedures that were developed for the reference station. Very little effort has been expended on developing advanced construction techniques with a goal of minimizing EVA hours. The relatively straight forward development of techniques such as folded or spooled utility lines, and plug-in subsystem modules, along with optimized construction scenarios should significantly reduce the EVA operations. For a spacecraft with a long anticipated life such as the Space Station, all utility lines and subsystems will have to be designed to be maintained or replaced on orbit. This requirement drives the development of simple field joints for the utility lines and quick-attachment "plug-in" modules for the subsystems. What remains is to develop a revised Space Station construction scenario with the goal of reducing EVA operations and evening out the number of EVAs per flight.

A potential alternate Space Station construction scenario is shown in stages in Sketch B. The first phase of this construction approach would be associated with building the truss support structure and attaching a temporary minimal power system, a control system, and a communications system as required to achieve an operational spacecraft. The MRMS would be needed on the first flight to assist in the Station build-up. Additional structure, the power modules, primary utility lines, and other subsystems could be added on the second flight (third, if needed). The pressurized modules and remaining subsystems would be installed on subsequent flights in a manner designed to even out the number of EVAs per flight.

Potential advantages that could result from such an approach would be: (1) minimum work package interfacing, (2) simplified launch package integration, (3) minimized impact of downstream subsystem changes, and (4) evening out of the number of EVAs per flight. These four items could also result in a highly reduced SE&I process. A summary of this scenario is presented in Table C-2.

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TABLE C-1.-DEPLOYABLE VS. ERECTABLE TRADE COMPARISON

		PREINTEGRATED SUBSYSTEMS	"MODULARIZED" SUBSYSTEMS		
	DISCRIMINATORS	9' DEPLOYABLE	15' ERECTABLE	15' PACTRUSS	TETRAHEDRAL
CUSTOMR ACMDTNS	GROWTH POTENTIAL	D	A	A	S
	PAYLOAD ACCOMMODATIONS	S	A	A	A
SUBSYSTEM INTEGRATION	1) POWER CABLES ETC.	A	D	D	D
	2) RCS THRUSTERS ETC.	S	S	S	S
	3) THERMAL AND PROP. LINES	S	S	S	S
	4) INSTALLATION & SERVICING	S	A	A	A
	5) ROTARY JOINTS	A	D	D	D
	6) MRMS	S	S	S	S
	7) SE&I REQUIRED	D	A	A	A
CONSTR. OPS.	EVA HOURS	S	S	S	S
	NUMBER OF EVAs PER FLIGHT	D	D	D	D
COST	TRUSS { WEIGHT, PART COUNT D.D.&T., DEPLOYER CONSTRUCTION	D	A	S?	S?
TRUSS CRITERIA	REDUNDANCY, REPAIRABILITY AND MAINTAINABILITY	S-	A	S-	S-
	PREDICTABILITY	S-	A	S-	S-
	STIFFNESS	S	A	A	S

A - ADVANTAGE, S - SATISFACTORY, D - DISADVANTAGE

D - INHERENT DISADVANTAGE

D - RESOLVABLE DISADVANTAGE

TABLE C-2. ALTERNATE SPACE STATION CONSTRUCTION SCENARIO

CURRENT REFERENCE APPROACH OF ACHIEVING AN ALL UP, 37.5 KW POWER PRODUCING, CONTROLLED, COMPLETELY OPERATIONAL SPACECRAFT ON FIRST FLIGHT IS MAJOR DRIVER IN CONCEPT SELECTION PROCESS.

-- AN ALTERNATE, POTENTIALLY LOWER COST APPROACH, WOULD BE TO:

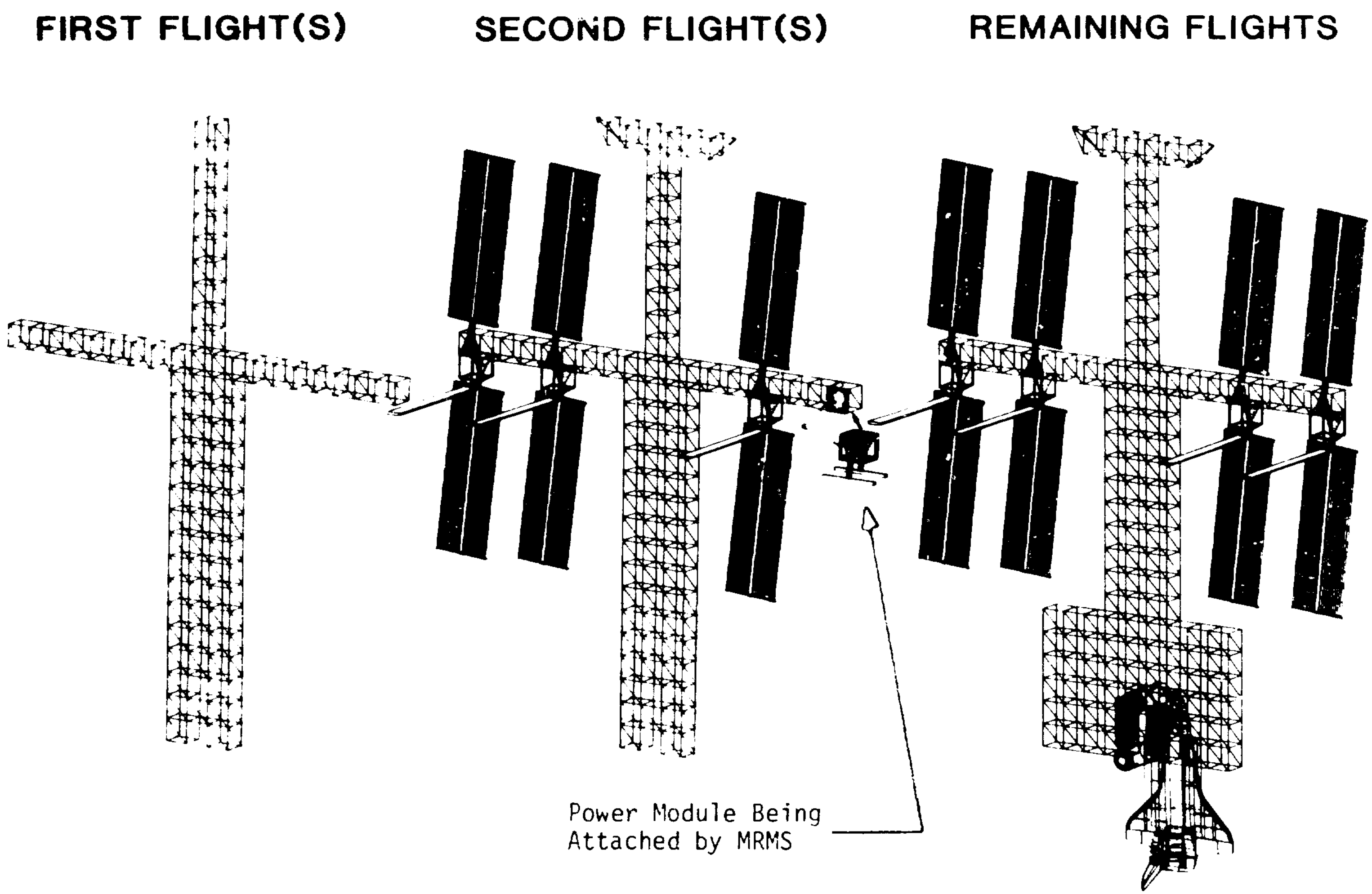
1) PUT UP BACKBONE TRUSS WITH MRMS AND MINIMAL POWER, CONTROL AND COMMUNICATION CAPABILITY OF FIRST FLIGHT
2) INSTALL POWER MODULES ON SECOND FLIGHT
3) INSTALL PRESSURIZED MODULES ON REMAINING FLIGHTS

-- THIS ALTERNATE APPROACH WITH "MODULARIZED" SUBSYSTEMS WOULD HAVE THE FOLLOWING ADVANTAGES:

- o MINIMUM WORK PACKAGE INTERFACING
- o SIMPLIFY LAUNCH PACKAGE INTEGRATION
- o MINIMIZED IMPACT OF DOWNSTREAM SUBSYSTEM CHANGES
- o EVEN NUMBER OF EVAS PER FLIGHT

SIMPLIFIED SE&I PROCESS

ALTERNATE SPACE STATION BUILD-UP SCENARIO



Sketch B. - Schematic showing potential alternate station build-up scenario.

APPENDIX A

PACTRUSS

A new truss concept, the demonstration model of which is called a PACTRUSS has recently been developed at Langley Research Center. The concept is a four longeron box truss that has simple single axis pivot hinges and double-folds for efficient packaging. A photograph of the three bay demonstration model is shown in figure A-1. This box truss configuration has surface diagonals that alternate direction from bay to bay and section diagonals that also alternate direction from bay to bay. Thus, there are only two node types in the truss, nine member nodes designated as node A and four member nodes designated as node B. The longerons, diagonals and horizontal batten members are connected to the two nodes with pin clevis joints. The vertical batten members are rigidly attached to the two nodes, one node type on each end of the batten. The diagonals have a midlength hinge with a near center latch that permits them to be folded for stowage in the packaged configuration. There are no midlength hinges required in the longerons for folding and packaging.

A photograph of the model that illustrates the folding/deployment operation is shown in figure A-2 and several photographs showing the sequence from fully packaged to fully deployed are shown in figure A-3. As indicated in figure A-2, the deployment occurs in a synchronous manner and thus the beam deploys simultaneously in both length and width. The synchronization comes from the fact that the sides of the cube shear and since there are only single degree of freedom joints all faces must shear simultaneously. Note in the sketch of figure A-2 that the projection of the top nodes, battens and longerons into a plane above the beam always form a rectangle with sides of increasing length as the beam deploys. The synchronization is inherent in the configuration and no special devices or added linkage mechanism is required. During deployment the diagonal members unfold about the midlength hinge to their fully extended straight position and the midlength hinge locks via a near-center latch thus securing the beam in the fully deployed position. The folding technique just described and incorporated in the demonstration model is applicable to flat planar trusses with bays added both longitudinally and laterally. The additional lateral bays across the width fold in the same manner as described for the beam. Thus structures of large expanse can be double-folded into a compact package and synchronously deployed.

The demonstration model shown in figures (A-1 through A-3) was designed for maximum packaging efficiency. A planar truss of this configuration would retract to a compact package approximately two bays long with a thickness of 4 member diameters/bay plus one member for the end bay (all members in this model are the same diameter). The width of the beam package is 2 1/2 member diameters/ bay plus one diameter for the end bay. A preliminary examination of the packaged configuration for the space station keel beam has been conducted based on the packaging concept noted for the demonstration model. The keel beam truss is shown in figure A-4. The truss is a nominal 15 foot cube and is assumed to have all 2 inch diameter members. The packaged configuration for the keel beam truss is shown in figure A-5 in relation to the diameter of the Shuttle cargo bay. The packaged configuration easily fits within approximately one-fourth the volume of the cargo bay. It should be noted that for this packaged configuration (figure A-5) the beam was assumed to have a package thickness of five members per bay instead of the more compact four members per bay to give extra room in the package to preintegrate utility lines. The structure is estimated to require about 13,000 feet of tubing. The structural mass is about 14,000 pounds based on a 0.188 inch thick graphite/epoxy tube and an allowance of 50 percent of the tube mass for the hinge joints.

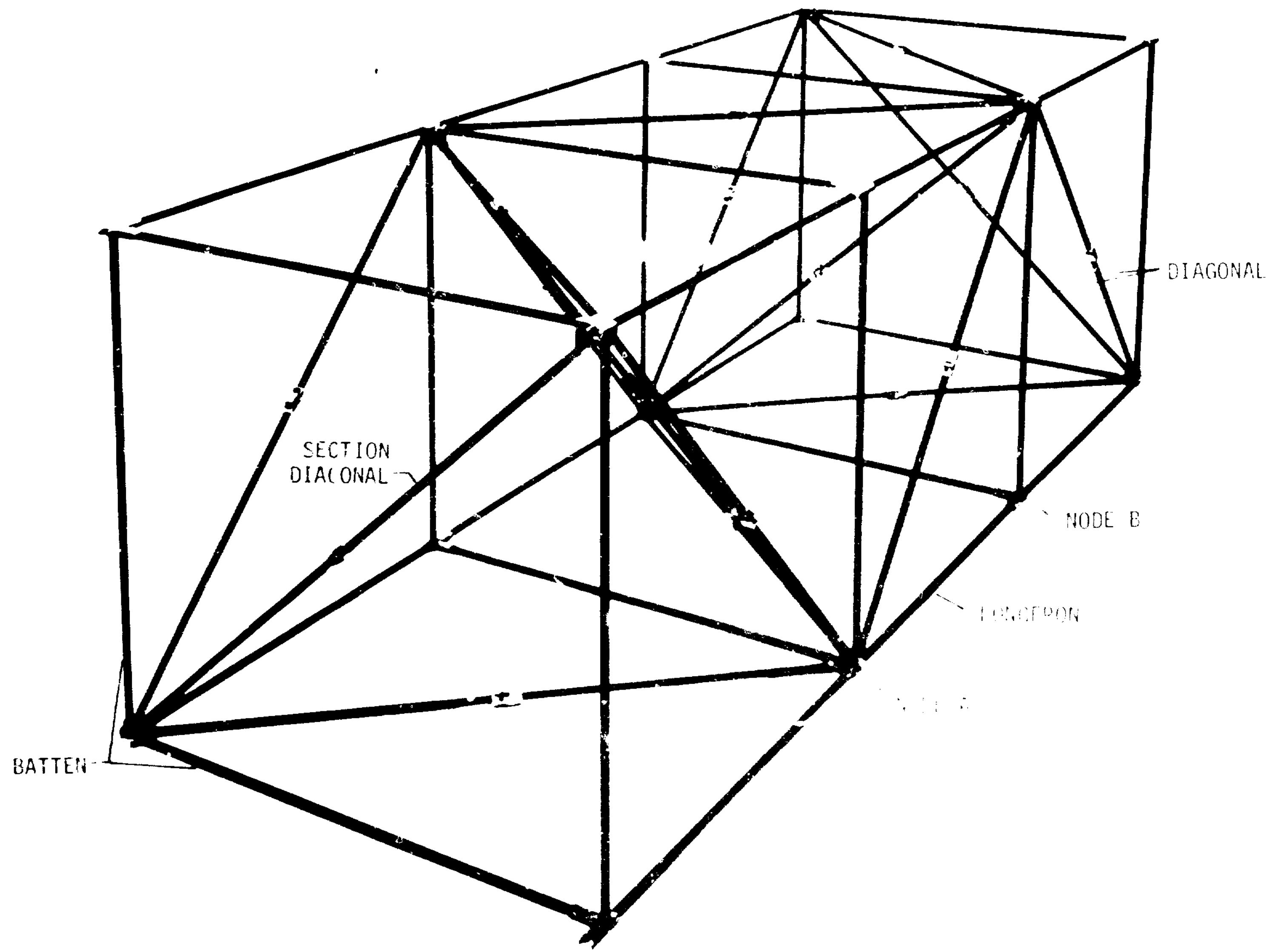


Figure A-1. [illegible]

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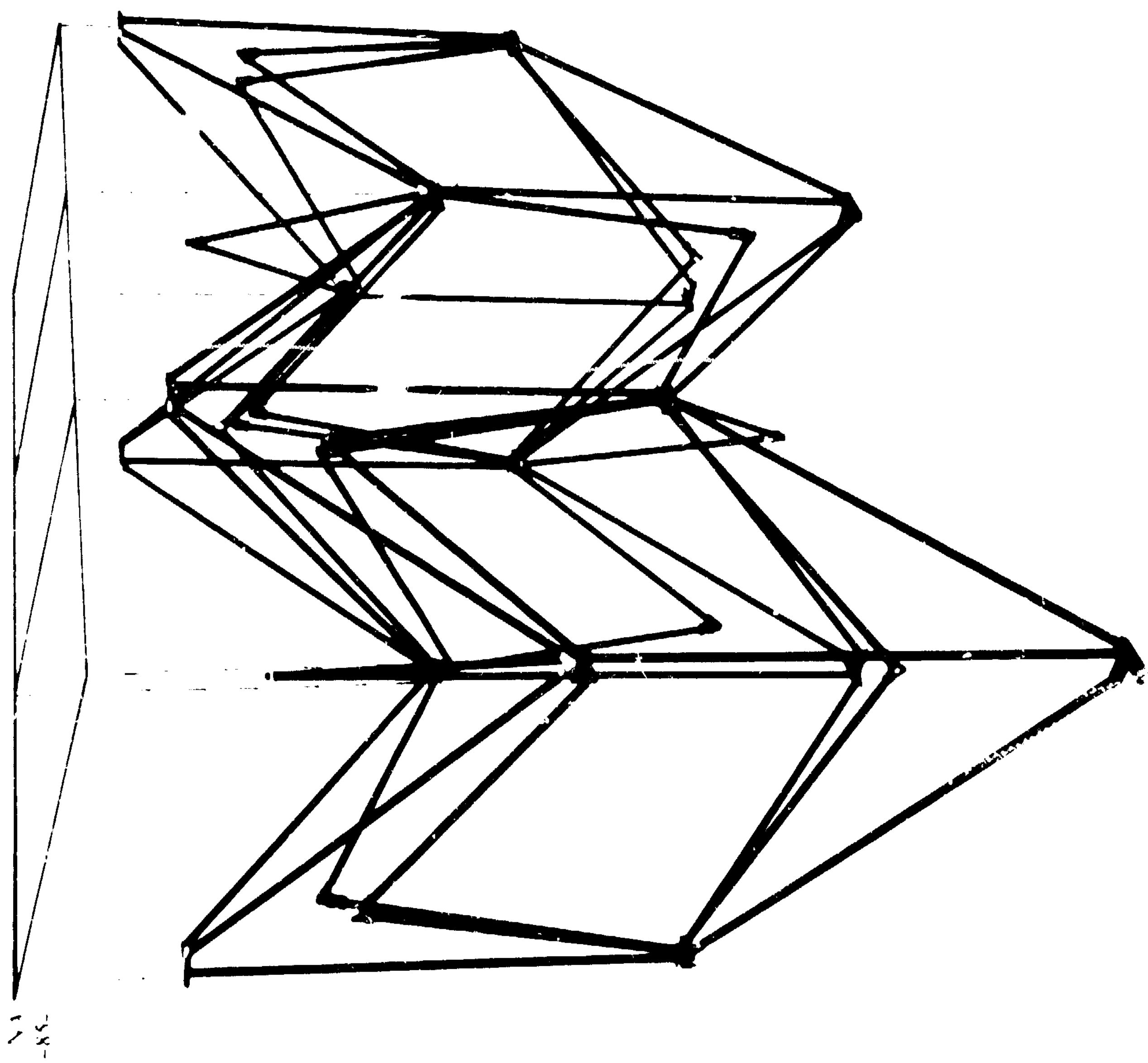

Figure A-2. PACTRUSS model during deployment.

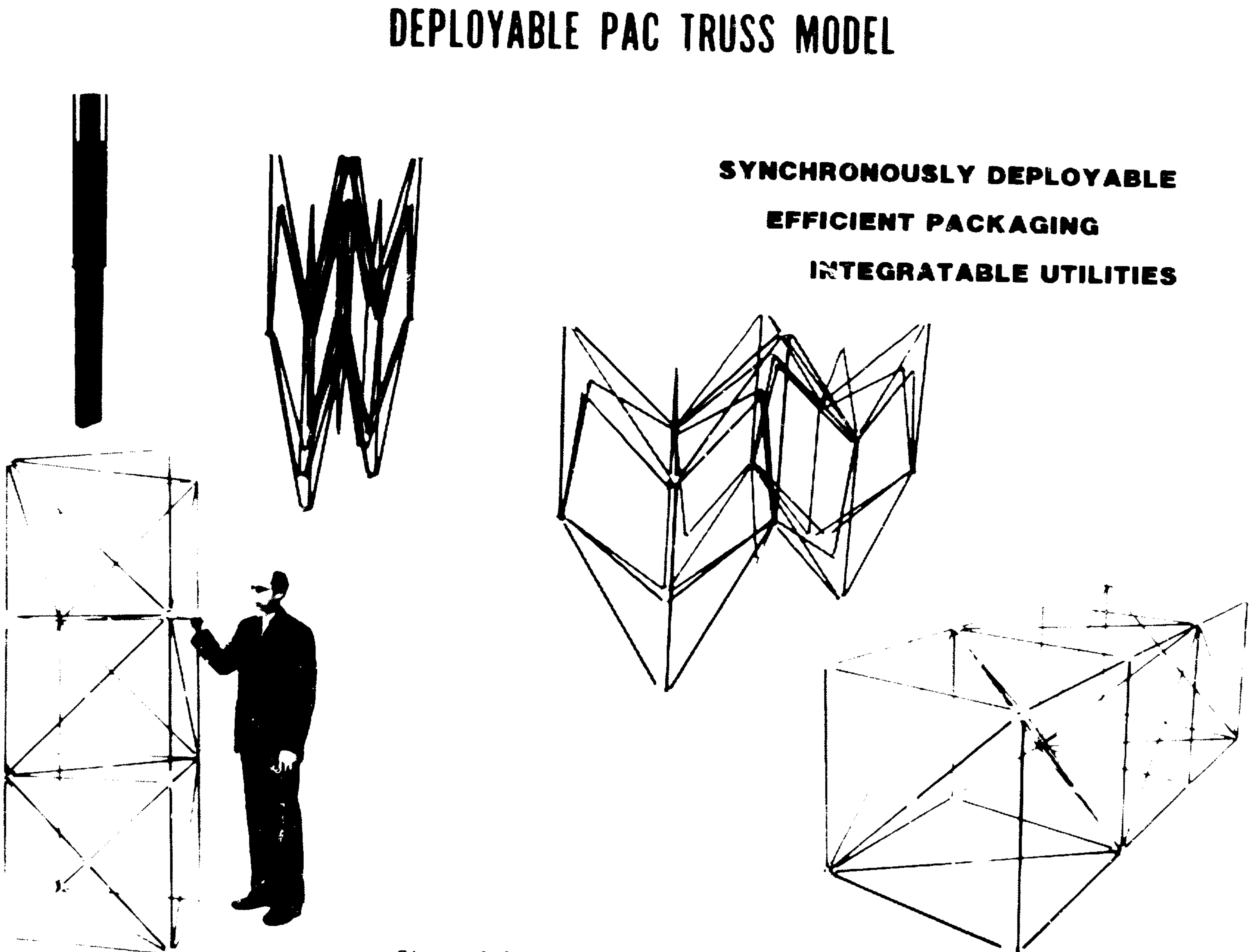

Figure A-3. PACTRUSS deployment sequence.

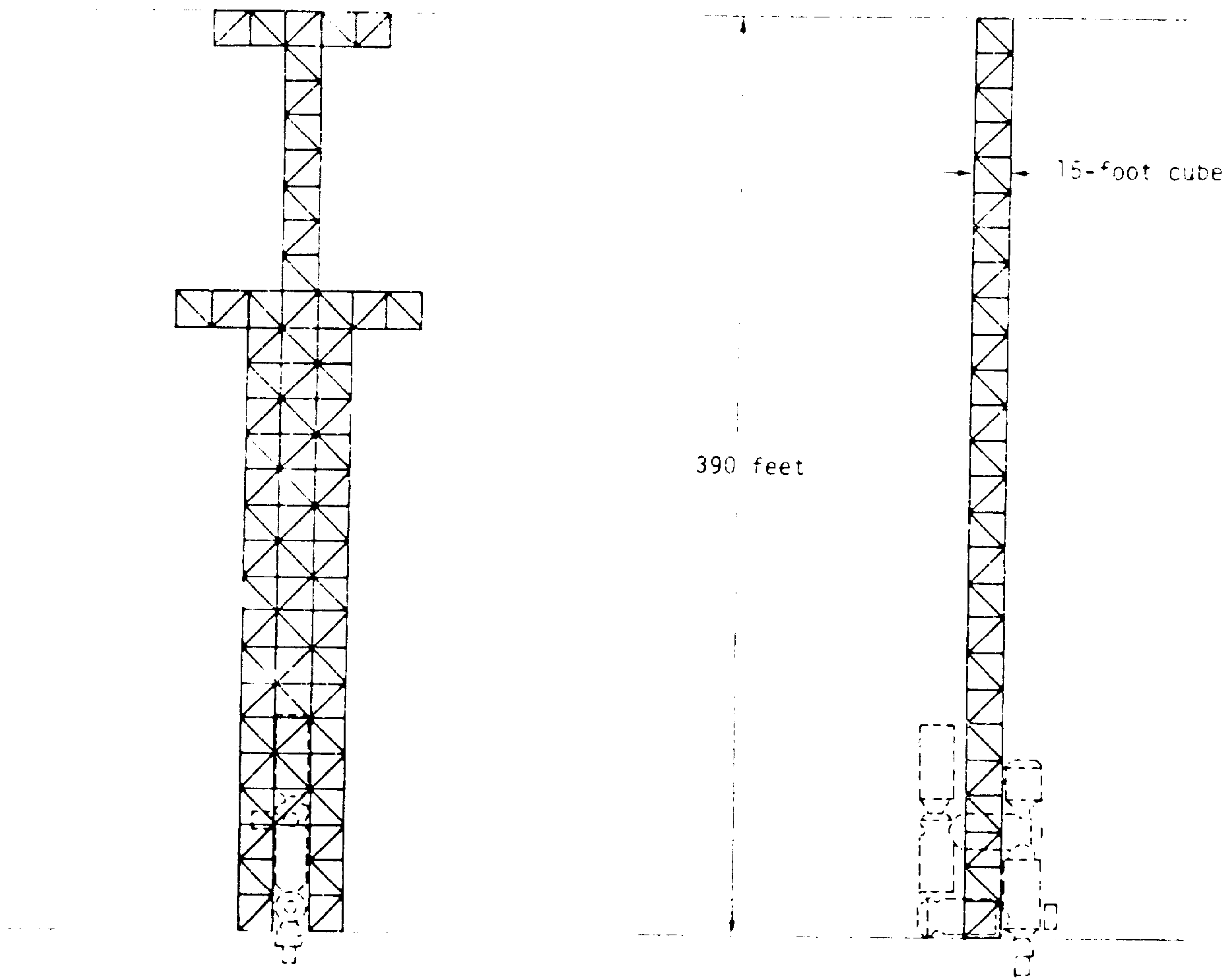

Figure A-4. Space Station structure using the PACTRUSS concept.

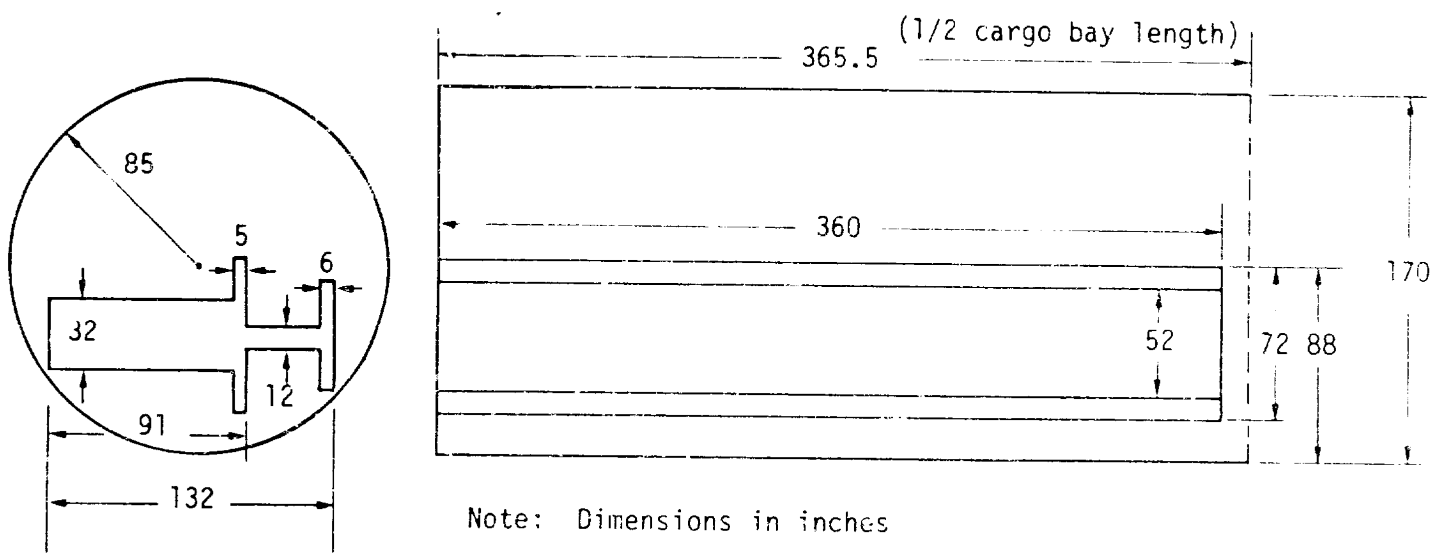

Figure A-5. Packaged Space Station structure in Shuttle cargo bay.

APPENDIX B

This appendix describes the procedures and times required to construct IOC space station for both the erectable and the deployable truss structures. It contains the following:

I. Summary of EVA Hours

II. Assembly Tasks Evaluation

III. Assumptions

I. SUMMARY OF EVA HOURS

FLIGHT	ERECTABLE (HR:MIN)	DEPLOYABLE (HR:MIN)
I	28:08	14:04
II	36:28	38:05
III	3:31	3:27
IV	19:50	19:48
V	17:05	14:26
VI	3:06	3:02
VII	3:12	3:08
TOTAL	111:20	96:13

II. ASSEMBLY TASKS EVALUATION

ERECTABLE 15' TRUSS STRUCTURE

FLIGHT I

COMPONENTS

GN&C (Guidance, Navigation, and Control)
2 α-joints (Rotary Joints)
4 β-joints and Solar Arrays
2 RFC/PWR (Power Conditioning Units)
5 Antenna
5 Communication (Comm.) Units
MRMS (Mobile Remote Manipulating System)
Docking Ring

Struts and Nodes
12 Radiator Panels and Related Mounting Equipment
2 MBSU (Main Bus Switching Unit)
2 PMC (Power Management Controllers)
1 UPC (Utility Power Conditioner)
Power Cable Lines

TASK	TIME (HR:MIN)	*FEASIBILITY RATING	ASSUMPTIONS
1) Unstow framework/strut-node Package I with RMS (Remote Manipulator System)	0:12	1	E3
2) Build frame with MFR (Manipulator Foot Restraint) (15 struts)	0:45	2	E4b
3) Unstow strut-node package II with RMS	0:12	1	
4) Build center bay with GN&C a) Position GN&C b) Assemble bay with GN&C (50 struts)	3:25 (0:05) (3:20)	4	 F1 E4b,c
5) Install MRMS a) Unfold b) Position c) Install on center bay d) Install RMS on MRMS e) Checkout MRMS	2:14 (0:11) (0:13) (0:20) (1:00) (0:30)	4	E8
6) Load MRMS - 9 packages (solar arrays, RFC/PWR, struts & nodes, MBSU, PMC, UPC, cable)	1:44	1	

* See Appendix C

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
7) Build port bay 1 (13 struts)	0:13	2	E4a
8) Assemble port α-joint	0:47	4	
a) Position α-joint	(0:10)		
b) Build inboard transition truss (12 struts)	(0:12)		
c) Build outboard transition truss (25 struts)	(0:25)		
9) Assemble port RFC/PWR converter bay	0:52	4	
a) Position RFC/PWR unit	(0:07)		E1
b) Assemble bay (45 struts)	(0:45)		E4a
10) Build port bay 5 (13 struts)	0:13	2	
11) Install port solar arrays	0:42	4	
a) Position solar array I	(0:07)		E1
b) Install (14 struts)	(0:14)		E4a
c) Repeat a) + b) for solar array II	(0:21)		
12) Install power/utility cable and MBSU/PMC/UPCs back to cargo bay	1:12	2/4	
a) Move 5 bays	(0:09)		E6
b) Install cable	(0:09)	(2)	E5
c) Install units (1 MBSU, 1 PMC, 1 UPC)	(0:45)	(4)	E7
13) Load MRMS - 2 packages (solar arrays, RFC/PWR)	0:23		
14) Repeat steps #7-12 (less 1 UPC) for starboard side	3:44:00		
15) Deploy solar ararys	1:00	1	E8
16) Unload MRMS - 2 packages (cable) Load MRMS - 4 packages (radiators, antenna, communication boxes)	1:10	1	
17) Install port radiators	2:13	4	E8
a) Move to position (3 bays)	(0:05)		
b) Crew in MFR to maneuver radiators	(0:08)		
c) Install 6 radiator panels	(2:00)		

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
18) Move to starboard radiator position, installing antenna	2:00	1	
a) Move 6 bays	(0:10)		
b) Install 5 antenna	(0:50)		E10
c) Install 5 comm. boxes	(0:50)		
d) 10 Connections	(0:10)		
19) Install starboard radiators	2:13		
a) Same as 17 b, c.	(2:08)		
b) Move to cargo bay (3 bays)	(0:05)		
20) Build docking bay	0:31	2	
a) Unload docking ring	(0:10)		
b) Erect docking bay (21 struts and 1 ring)	(0:21)		
21) Unload MRMS - 6 packages (strut and nodes, antennas, comm. units, radiators)	1:12		
22) Detach Framework	1:20	2	E10
a) Detach nodes (4)	(0:20)		
b) Back shuttle away	(0:15)		
c) Disassemble frame	(0:45)		
TOTAL EVA TIME	28:08		

DOES NOT INCLUDE:

1) System checkouts
2) MFR installation and removal
3) EVA overhead

FLIGHT II

COMPONENTS

48 Radiator Panels & Related Mounting Equipment
2 Radiator Booms
Struts and Nodes
Power Cable Lines
Ammonia Lines
Fuel Lines
4 RCS Thrusters (Reaction Control System)
6 Fuel Tanks
8 Antenna
8 Communication Units
Docking Ring
20 UPC
6 MBSU
MRMS Recharger Unit

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) Checkout MRMS	0:30	1	E8
2) Load MRMS - 4 packages(struts and nodes, fuel tanks)	0:46	1	
3) Build lower keel and install fuel tanks	3:11		
a) Build 12 bays (156 struts)	(2:36)	2	
b) Position fuel tanks I	(0:05.5)	1	
c) Build fuel tank support (8 struts, 4 connections)	(0:12)	4	E11
d) Repeat b and c for fuel tank II	(0:17.5)		
4) Return to cargo bay (12 bays)	0:20		
5) Load MRMS - 12 packages (power cable, ammonia lines, lower RCS thrusters, docking ring, antennas, comm. units, fuel lines, UPCs, MBSU)	2:19	1	
6) Move back to fuel bay (12 bays)	0:20		
7) Build lower keel extensions	8:00.5		
a) Build 2 adjoining bays (move 1.5 bays and use 13 struts per bay)	(0:28.5)	2	
b) Build 3 bays (39 struts)	(0:39)	2	
c) Build port extension (6 bays - 78 struts) and docking ring (8 struts)	(1:26)	2	

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
d) Install port RCS thrusters (4 struts)	(0:14.5)	4	F12
e) Lay fuel, ammonia and power cable lines to fuel tanks (8 bays)	(1:29.5)	4	E5
f) Move 2 bays	(0:04)		
g) Build starboard extension (move 1 bay, build 7 bays - 91 struts)	(1:33)	2	
h) Install starboard RCS (4 struts)	(0:14.5)	4	
i) Lay fuel, ammonia and power cable lines to fuel tanks (8 bays)	(1:29.5)	4	
j) Move to cargo bay (13 bays)	(0:22)		
8) Lay fuel lines (6 bays), ammonia lines (11 bays), power cable (11 bays) on way to cargo bay	1:30	4	
9) Install 8 antenna and 3 comm. units on way back to cargo bay.	2:56	4	
10) Install 12 UPC and 5 MBSU on way back to cargo bay	4:15	4	
11) Unload MRMS - 9 packages (power cable, ammonia lines, antennas, comm. units, fuel lines, UPC, MBSU)	1:44	1	
12) Load MRMS - 9 packages (MRMS recharger, RCS thrusters, radiators, radiator booms, radiator mounting equipment, UPC, MBSU)	1:41	1	
13) Move to radiator location (13 bays)	0:22		
14) Install radiators	3:35		E8
a) Install and deploy starboard booms and heat exchangers	(0:30)	3	

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
b) Install starboard radiators (3 panels)	(1:02)	4	
c) Move to port position (2 bays)	(0:04)		
d) Repeat a) and b)	(1:32)		
e) Stow 42 radiators along port keel extension	(0:27)	4	E13
15) Install MRMS recharger	0:15	4	E8
16) Move to upper RCS thruster (7 bays)	0:12		
17) Install RCS thrusters (8 struts)	0:29	4	
18) Return to cargo bay	2:27		
a) Move 7 bays	(0:12)		
b) Install 8 UPCs	(2:00)	4	
c) Install 1 MBSU	(0:15)	4	
19) Unload MRMS - 5 packages (radiator, UPC, struts and nodes)	0:59		
20) Return MRMS to recharger	0:36		
a) Move MRMS 14 bays	(0:24)		
b) Plug MRMS in	(0:05)	3	E8
c) Crew translates back 14 bays	(0:07)	1	E14
TOTAL EVA TIME	36:28		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead
3) Installation of remaining 42 radiator panels

FLIGHT III

COMPONENTS

Habitat Module #1
Airlock #1
Airlock #2
Module Mounting Structure

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) Retrieve MRMS	0:24.5		
a) Crew translates 5 bays	(0:02.5)	1	
b) Activate MRMS	(0:15)	1	
c) Move MRMS to cargo bay (4 bays)	(0:07)		
2) Install module mounting structure	0:40	2	E8
3) Install Habitat #1	0:30	4	E8
4) Connect Utilities	0:50	3	E8
5) Ammonia pump hookup	0:12	3	E15
6) Install airlock I	0:20	4	E8
7) Install airlock II	0:20	4	
8) MRMS to recharger panel	0:14.5		
a) Move MRMS 4 bays	(0:07)		
b) Plug into recharger	(0:05)	3	
c) Crew translates back to cargo bay (4 bays)	(0:02.5)		
TOTAL EVA TIME	3:31		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead time

FLIGHT IV

COMPONENTS

Habitat Module #2
Module Mounting Structure
Struts and Nodes
9 Antennas
2 TDRS (Antenna)
11 Communication Units
Ammonia Lines
Power Cable Lines
9 UPC
1 MBSU

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) MRMS activation	0:24.50		
a) Crew translates to MRMS (4 bays)	(0:02.5)	1	
b) Activate MRMS	(0:15)	1	
c) Move MRMS to shuttle (4 bays)	(0:07)		
2) Install mounting structure	0:50	2	
3) Install Habitat #2	1:15	4	
4) Connect side panel utilities	0:25	3	
5) Remove airlock II from Habitat I and berth to Habitat II	0:20	4	
6) Load MRMS - 12 packages (struts and nodes, antennas, comm. boxes, TDRS, ammonia lines, power cable, UPC, MBSU)	2:20	1	
7) Install upper keel and cross boom	3:10	2	
a) Move MRMS 18 bays	(0:30)		
b) Install upper keel to port (10 bays-130 struts)	(2:10)		
c) Move MRMS 2 bays star board	(0:04)		
d) Build 2 bays (26 struts)	(0:26)		
8) Install upper boom utilities	4:57		
a) Move MRMS 5 bays	(0:09)		

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
b) Install: power cable lines ammonia lines	(0:38)	4	
c) Install 2 TDRS antenna (8 struts, 2 antennas, 2 comm. units)	(0:52)	3	E16
d) Install 9 antennas and 9 comm. units	(3:18)	4	
9) Install upper keel utilities	3:39		
a) Move 10 bays	(0:17)		
b) Install power cable lines and ammonia lines	(0:52)	4	
c) Install 9 UPCs and 1 MBSU	(2:30)	4	
10) Return to cargo bay (18 bays)	0:30		
11) Unload MRMS - 9 packages (struts and nodes, antennas, comm. units, ammonia lines, power cable, UPC)	1:45	1	
12) Return to charger	0:14.5		
a) Move MRMS 4 bays	(0:07)		
b) Plug-in MRMS	(0:05)	3	
c) Crew translates 4 bays	(0:2.5)		
TOTAL EVA TIME	19:50		

DOES NOT INCLUDE:

1) Systems checkout
2) EVA overhead time

FLIGHT V

COMPONENTS

Logistic Module and 3 Fuel Tanks
4 β-joints and Solar Arrays
12 Radiator Panels and Related Radiator Mounting Equipment
Power Cable Lines
2 RFC/PWR

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) MRMS activation	0:24.5	1	
2) Install Logistics module	1:00	4	
3) Return to cargo bay (3 bays)	0:05		
4) Load MRMS - 10 packages (solar arrays, radiators, radiator mounting equipment, struts and nodes, RFC/PWR, power cable)	1:56	1	
5) Move 22 bays to port outboard array with MRMS	0:37		
6) Build 2 bays (26 struts)	0:26	2	
7) Build bay with RFC/PWR module (52 struts)	0:52	4	
8) Build 1 bay (13 struts)	0:13		
9) Install solar arrays (14 struts)	0:42	4	
10) Build outer bay (13 struts)	0:13		
11) Move to starboard outboard array	2:43		
a) Move 4 bays	(0:07)		
b) Install power cable lines	(0:04)	2	
c) Install radiators (6 panels)	(2:13)	4	
d) Move 11 bays	(0:19)		
12) Repeat steps 6-11c	4:50		

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
13) Deploy solar arrays (4)	1:00	1	
14) Return MRMS to cargo bay (23 bays)	0:39		
15) Unload MRMS - 6 packages (struts and nodes, power cable, radiators)	1:10	1	
16) Return MRMS to charger	0:14.5	3	
TOTAL EVA TIME	17:05		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead time

FLIGHT VI

COMPONENTS

Lab Module #2
Module Mounting Structure

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) Activate MRMS	0:24.5	1	
2) Install mounting structure	0:50	2	
3) Install lab module #2	1:15	4	
4) Connect utilities	0:25	3	
5) Return MRMS to charger	0:11.5		
a) Move 2 bays	(0:04)		
b) Plug in MRMS	(0:05)	3	
c) Crew translate to shuttle	(0:2.5)	1	
TOTAL EVA TIME	3:06		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead time

FLIGHT VII

COMPONENTS

Lab Module #1
Module Mounting Structure

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) Activate MRMS	0:24.5	1	
2) Install mounting structure	0:50	2	
3) Install lab module #1	1:20	4	
4) Connect utilities	0:25	3	
5) Return to recharger	0:12.5		
a) Move MRMS 3 bays	(0:05)		
b) Plug in MRMS	(0:05)	3	
c) Crew translate to shuttle	(0:02.5)	1	
TOTAL EVA TIME	3:12		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead time

DEPLOYABLE 9' TRUSS STRUCTURE

FLIGHT I

PRE-INTEGRATED COMPONENTS	ON-ORBIT INTEGRATED COMPONENTS	
GN&C	5 Antennas	1 UPC
2 α-joints	5 Communication Units	
4 β-joints & Solar Arrays	MRMS	
2 RFC/PWR	Docking Ring	
Power Cable Lines	12 Radiator Panels	
Deployable Structure	2 MBSU	
Radiator Mounting Equipment	2 PMC	

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) Install radiators	4:13	4	D1
a) Crew ingress MFR and maneuver to position	(0:08)		
b) Install 6 radiators (I)	(2:00)		
c) Move to radiator II	(0:05)		
d) Repeat b)	(2:00)		
2) Rotate 38' deployable structure package to position	0:11	1	D2
3) Deploy solar array boxes (4)	0:05	1	D1
4) Deploy rail extensions (2 per end)	0:05	1	D1
5) Deploy transverse boom (14 bays)	1:22	4	D1,3
a) Crew check for correct deployment	(0:10)		
b) Deploy boom	(1:12)		
6) Install MRMS	2:03	4	D1
a) Position MRMS	(0:13)		
b) Install MRMS on structure	(0:20)		
c) Install RMS on MRMS	(1:00)		
d) Checkout MRMS	(0:30)		
7) Deploy solar arrays (4)	1:00	1	D1
8) Erect one docking bay (13 struts, 4 connections)	0:19	2	D4

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
9) Load MRMS - 5 packages (antennas, comm. units, MBSU, PMC, UPC)	0:57	1	D5
10) Install antennas a) 5 antennas b) 5 comm. units c) 10 connections	1:50 (0:50) (0:50) (0:10)	4	D6
11) Install 2 MBSU, 2 PMC, UPC	1:15	4	D7
12) Move MRMS 20 bays during installation	0:20		D8
13) Unload MRMS - 2 packages (antenna, comm. units)	0:24	1	
TOTAL EVA TIME	14:04		

DOES NOT INCLUDE:

1) System checkouts
2) MFR installation/removal
3) EVA overhead time
4) Detach from cargo bay

FLIGHT II

PRE-INTEGRATED COMPONENTS	ON-ORBIT INTEGRATED COMPONENTS	
Deployable Structure	4 RCS Thrusters	Struts & Nodes
Power Cable Lines	Ammonia Lines	20 UPC
6 Fuel Tanks	Fuel Lines	6 MBSU
Docking Ring	8 Antennas	MRMS Recharger Unit
Radiator Booms & Related Mounting Equipment	8 Comm. Units	
	48 Radiator Panels	

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) Checkout MRMS	0:30	1	D1
2) Install lower keel structure	2:46	4	D1,3
a) Unstow & position keel	(0:27)		
b) Attach keel to transition boom	(0:20)		
c) Connect utilities	(0:02)		
d) Deploy rail extension	(0:15)		
e) Deploy lower keel (20 bays)	(1:42)		
3) Deploy radiator booms	0:10	3	D1
a) Deploy booms	(0:05)		
b) Deploy radiator heat exchangers	(0:05)		
4) Load MRMS - 3 packages (struts & nodes, radiators)	0:36	1	
5) Move MRMS to radiator booms (20 bays)	0:20		
6) Erect 4 bays (32 struts)	0:52	2	
7) Install radiators	2:38	4	D1
a) Move to port side (2 bays) and position crewman	(0:05)		
b) Install 3 radiator panels	(1:00)		
c) Move MRMS starboard (4 bays)	(0:04)		
d) Position crewman	(0:02)		
e) Repeat b	(1:00)		
f) Stow radiator package (42 panels)	(0:27)		D9

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
8) MRMS to cargo bay (23 bays)	0:23		
9) Load - 1 package (keel extensions)	0:11		
10) Move to end of lower keel (23 bays)	0:23		
11) Deploy keel extensions a) Position port keel extension b) Install keel extension c) Deploy keel extension (12 bays)	1:34 (0:12) (0:20) (1:02)	4	
12) Move to starboard position (4 bays)	0:04		
13) Repeat 11 for starboard keel extension	1:34		
14) Move MRMS to erect internal bays (3 bays)	0:03		
15) Build internal structure a) MRMS moves 6 bays b) Build 4 bays (32 struts) 2 bays (26 struts)	1:04 (0:06) (0:58)	2	
16) Return to cargo bay (31 bays)	0:31		
17) Load MRMS - 7 packages (RCS thrusters, ammonia lines, fuel lines)	1:20		
18) Move MRMS to lower keel port extension (36 bays)	0:36		
19) Install port RCS thruster (4 struts)	0:14.5	4	D10
20) Move MRMS 18 bays	0:18		
21) Lay lines: fuel lines (15 bays) ammonia lines (10 bays)	2:04.5	4	D11

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
22) Move to starboard RCS position (11 bays)	0:11		
23) Install RCS starboard thrusters (4 struts)	0:14.5	4	
24) Move MRMS 13 bays	0:13		
25) Lay lines: fuel lines (15 bays) ammonia lines (10 bays)	1:54	4	
26) Lay lines to upper RCS thrusters a) Move 10 bays b) Lay fuel and ammonia lines	1:41.5 (0:10) (1:31.5)		
27) Install 2 upper RCS thrusters (8 struts)	0:29	4	
28) Lay lines back to cargo bay a) Move 11 bays b) Lay ammonia lines	0:48.5 (0:11) (0:37.5)		
29) Unload MRMS - 3 packages (ammonia lines, fuel lines)	0:36	1	
30) Load MRMS - 5 packages (UPC, MBSU, MRMS recharger unit, antennas, and comm. boxes)	0:57		
31) Move to port keel extension (34 bays) and then starboard keel extension (12 bays)	0:46		
32) Installations a) Antennas (8), comm. units (8), connections (16) b) UPC (20) c) MBSU (6)	9:26 (2:56) (5:00) (1:30)	4	
33) MRMS Recharger a) Move to position (10 bays) b) Install recharger	0:25 (0:10) (0:15)	4	D1
34) Return to cargo bay (24 bays)	0:24		

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
35) Unload MRMS - 6 packages (antenna, comm. units, UPC, MBSU)	1:10	1	
36) Move MRMS to recharger (25 bays)	0:25		
37) Crew translate to shuttle (25 bays)	0:12.5	1	D14
TOTAL EVA TIME	38:05		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead time
3) Installation of remaining 42 radiator panels

FLIGHT III

COMPONENTS

Habitat Module #1
Airlock #1
Airlock #2
Module Mounting Structure

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) Retrieve MRMS	0:23		
a) Crew translates 6 bays	(0:02)	1	
b) Activate MRMS	(0:15)	1	
c) Move MRMS to cargo bay (6 bays)	(0:06)		
2) Install module mounting structure	0:40	2	D1
3) Install Habitat #1	0:30	4	D1
4) Connect Utilities	0:50	3	D1
5) Ammonia pump hook-up	0:12	3	D12
6) Install airlock #1	0:20	4	D1
7) Install airlock #2	0:20	4	
8) MRMS return to recharger	0:12		
a) Move MRMS (5 bays)	(0:05)		
b) Plug into recharger	(0:05)	3	
c) Crew translates back to shuttle (6 bays)	(0:02)		
TOTAL EVA TIME	3:27		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead time

FLIGHT IV

PRE-INTEGRATED COMPONENTS

Deployable Structure
Power Cable Lines

ON-ORBIT INTEGRATED COMPONENTS

Habitat Module #2
Module Mounting Structure
9 Antennas
2 TDRS (antennas)
11 Communication Units

Ammonia Lines
9 UPC
1 MBSU

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) MRMS Activation	0:23	1	
2) Install module mounting structure	0:50	2	
3) Install Habitat #2	1:15	4	
4) Connect panel utilities	0:25	3	
5) Remove airlock #2 from Habitat #1 and berth to Habitat #2	0:20	4	
6) Install upper keel	3:47	4	
a) Load upper keel onto MRMS	(0:16)	2	
b) Translate to upper keel position (32 bays)	(0:32)		
c) Unfold deployment rails	(0:05)		
d) Attach keel to transverse boom	(0:30)		
e) Deploy upper keel (22 bays)	(1:52)		
f) Return to cargo bay (32 bays)	(0:32)		
7) Load MRMS - 8 packages (antennas, comm. units, ammonia lines, UPC, MSBU)	1:32	1	

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
8) Move to upper keel (31 bays)	0:31		
9) Install ammonia lines	2:16	4	
a) Move MRMS 26 bays	(0:26)		
b) Install lines	(1:50)		
10) Install antennas (same time as lines)	3:58	4	
a) 2 TDRS antenna	(0:40)		D13
b) 9 antennas, 9 comm. units, 18 connections	(3:18)		
11) Install 9 UPC, 1 MBSU	2:30	4	
12) Return to shuttle (49 bays)	0:49		
13) Unload MRMS - 5 packages (antenna, comm. units, ammonia lines, UPC)	0:59	1	
14) Return to recharger	0:13		
a) Move 6 bays	(0:06)		
b) Plug MRMS in	(0:05)	3	
c) Crew translates to shuttle (6 bays)	(0:02)	1	
TOTAL EVA TIME	19:48		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead time

FLIGHT V

PRE-INTEGRATED COMPONENTS

Deployable Structure
4 [illegible]-joints & Solar Arrays
2 RFC/PWR
Power Cable Lines
Radiator Mounting Equipment

ON-ORBIT INTEGRATED COMPONENTS

Logistics Module and 3 Fuel Lines
12 Radiator Panels

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) MRMS activation	0:23	1	
2) Install logistics module	1:00	4	
3) Return to cargo bay (7 bays)	0:07		
4) Install port solar array	2:41	4	
a) Load port array on MRMS	(0:11)		
b) Move MRMS (39 bays) to position	(0:39)		
c) Unfold deployment rails	(0:05)		
d) Attach port array	(0:35)		
e) Deploy structure (6 bays)	(0:32)		
f) MRMS back to cargo bay (39 bays)	(0:39)		
5) Install starboard solar array (same as 4)	2:41	4	
6) Deploy arrays (4)	1:00	1	
7) Load MRMS - 1 package (radiators)	0:12	1	
8) Move to port position (43 bays)	0:43		
9) Install port radiators	2:00	4	
10) Move to starboard position (23 bays)	0:23		
11) Connect utilities on way (4 connections)	0:08	3	
12) Install starboard radiators	2:00	4	

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
13) Return to shuttle (43 bays)	0:43		
14) Unload - 1 package (radiators)	0:12	1	
15) MRMS to recharger, crew to shuttle	0:13		
a) Move MRMS 6 bays	(0:06)		
b) Plug in MRMS	(0:05)	3	
c) Crew translate 6 bays	(0:02)	1	
TOTAL EVA TIME	14:26		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead time

FLIGHT VI

COMPONENTS

Lab Module #2
Module Mounting Structure

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) Activate MRMS	0:23	1	
2) Install mounting structure	0:50	2	
3) Install Lab. module #2	1:15	4	
4) Connect utilities	0:25	3	
5) Return MRMS to shuttle	0:09		
a) Move MRMS 2 bays	(0:02)		
b) Plug in MRMS	(0:05)	3	
c) Crew translate to shuttle (6 bays)	(0:02)	1	
TOTAL EVA TIME	3:02		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead time

FLIGHT VII

COMPONENTS

Lab Module #1
Module Mounting Structure

TASK	TIME (HR:MIN)	FEASIBILITY	ASSUMPTIONS
1) Activate MRMS	0:23	1	
2) Install mounting structure	0:50	2	
3) Install Lab #1 module	1:20	4	
4) Connect utilities	0:25	3	
5) Return to shuttle	0:10		
a) Move MRMS (3 bays)	(0:03)		
b) Plug in MRMS	(0:05)	3	
c) Crew translate to shuttle (6 bays)	(0:02)	1	
TOTAL EVA TIME	3:08		

DOES NOT INCLUDE:

1) System checkouts
2) EVA overhead time

III. ASSUMPTIONS

E. Erectable Scenario Time Line Assumptions

E1 - RMS Motion:

a)

Package Weight	Translation Speed	Rotation Speed
MFR	.4 fps	1.5^{o}/sec
10 klb	.3 fps	1.2^{o}/sec
32-62 klb	.15 fps	$.6^{o}$/sec

(In most cases, 10 klb package range assumed)
(Ref. 3)

b) RMS orient and grapple - 2 min.
(Ref. 4)

E2 - Release clamps/latches - .5 min/ea
(Based on Ref. 5 Neutral Buoyancy tests)

E3 - Load/unload package between MRMS and cargo bay (and variations):

a)	RMS translates 40' to package	(E1a)	- 2 min.
b)	RMS orient and grapple	(E1b)	- 2 min.
c)	Release package clamps (4 clamps/2 per crewman)	(E2)	- 1 min.
d)	RMS extract package (translate 15', rotate 90^{o}, translate 30')	(E1a)	- 1 min.
e)	Reattach clamps	(E2)	- 1 min.
f)	Open package locks	(E2)	- 1 min.
		(a-e)	11 min.
		(a-f)	12 min.

E4 - Build Structure:

a) With MRMS (Ref. 6) - 1 min/strut
b) With MFR (Ref. 7) - 3 min/strut
c) Manually (Ref. 7) - 5 min/strut

E5 - Cable/pipe lines installation:

a) Cable - 2 attachments per node per line - 1 min.
1 connection per end of line - .5 min.
(Based on Ref. 5 Neutral Buoyancy tests)
b) Pipes - 2 attachments (1 min) and
1 connection (.5 min) per node per line - 1.5 min.
(Based on Ref. 6 quick attachment joints)

E6 - MRMS assumed to move 9 fpm

E7 - UPC/PMC/MBSU:
Assumed installation of 15 min/unit

E8 - See Reference 1, Assembly task evaluation and assumptions.

E9 - Install antenna:

a) 10 min/antenna (assumed)
b) 10 min/communication unit (assumed)
c) 1 min/connection (assumed
2 connections per antenna (connection between antenna and communication unit)

E10 - Detach framework:
Assumed 5 min/node
(Based on Ref. 5 Neutral Buoyancy tests)

E11 - Fuel tanks:

a) Install struts same as E4
b) 1 min/connection assumed

E12 - RCS thrusters:

a) Install struts same as E4
b) Position
c) 1.5 min/connection (assumed)
(4 connection for RCS thruster to struts)

E13 - 14 hours of radiator panel installation remaining

E14 - Crew translation:
.41 fps
(Ref. 4)

E15 - Ammonia pump hook-up assumed 2 min/line (6 lines)

E16 - TDRS antenna
a) 10 min/antenna
b) 10 min/communication units
c) install struts same as E4
d) 1 min/connection

D. Deployable Scenario Time Line Assumptions

D1 - See Reference 1, Assembly task evaluation and assumptions

D2 - Rotate 38' package (See E1)

a)	Unlatch	(E2)	- 2 min.
b)	Grapple	(E1b)	- 2 min.
c)	Translate 7'	(E1a-32 klb)	- 1 min.
d)	Rotate 90°	(E1a-32 klb)	- 3 min.
e)	Translate 7'	(E1a-32 klb)	- 1 min.
f)	Latch	(E2)	- 2 min.
			11 min.

D3 - Structure deployment

a) 5 min/bay (3 min/bay to deploy, 2 min/bay to inspect)
b) 2 min/section to check set-up.

D4 - Docking bay:

a) See E4 to install struts
b) 1.5 min/connection assumed

D5 - Load/unload: See E3

D6 - Install antennas: See E9

D7 - Install MBSU/PMC/UPC: See E7

D8 - MRMS travel: See E6

D9 - Radiator stowage: See E13

D10 - RCS thrusters: See E12

D11 - Fuel lines/ammonia lines: See E5

D12 - Ammonia pump hook-up: See E15

D13 - TDRS antenna: See E16

D14 - Crew translation: See E14

APPENDIX C

FEASIBILITY OF ASSEMBLY TASKS FOR SPACE STATION

Ratings

1 - Has been done in space
2 - Has been done in neutral buoyancy (1-g weightless environment)
3 - Has been done in 1-g
4 - Has never been done

General

A task is given a rating based on the lowest step rating the task has received. For example, if a task is composed of three steps where one step is rated a 1, one step a 3 and another step a 4, the overall rating is a 4.

A rating for a task does not necessarily indicate a task can or cannot be done, only that the task has or has not been carried out in a certain environment. Current or future studies may prove that certain conceptual tasks will be accomplishable.

STEP	RATING	SOURCE
1. RMS grappling a package	1	Shuttle flight
2. RMS positioning a package	1	Shuttle flight
3. RMS placing a package	1	Shuttle flight
4. Astronaut release package restraints (clamps/latches)	1	Shuttle flight
5. Astronaut secure package restraints	1	Shuttle flight
6. Build structure with MFR	2	Ref. 4, 6
7. Build structure with MRMS	2	Ref. 4, 6, 8
8. Build structure with no mechanical/ motorized assembly aids	2	Ref. 4, 7
9. Assemble a large package to a truss structure	4	
10. Install MRMS on truss structure	4	
11. Install RMS on MRMS	4	

STEP	RATING	SOURCE
12. Checkout MRMS		
a) Mobility/workstations	2	Ref. 6, 8
b) MRMS - RMS	1	Shuttle flight
13. MRMS movement	2	Ref. 6, 8
14. Attach cable/pipe lines to structure	2	Neutral Buoyancy Simulation
15. Connections between sections of cable/pipe lines	1	Shuttle flight
16. Deploying cable inside a deployable structure	2	Ref. 9
17. Install small units (MBSU/PMC/UPC)	4	Unknown configurations and placements
18. Install antennas and communication units	4	
19. Deploy solar arrays	1	Shuttle flight
20. Install radiators	4	
21. Detach (quick-release) of structure from cargo bay	2	Neutral Buoyancy Simulation
22. Stow a package on the truss structure	4	
23. Install module mounting structure	2	Ref. 4, 6, 7
24. Install modules/airlocks	4	
25. Deploy rail extensions	3	Ref. 8
26. Deploy radiator booms	3	Ref. 8
27. Deploy solar array boxes	1	Shuttle flight
28. Attach deployable structure to boom/keel	4	
29. Deploy structure		
a) By outside mechanism	2	Ref. 4, 9
b) Self-powered mechanism	1	Seasat

APPENDIX D

SIZE AND WEIGHT SPACE STATION COMPONENTS

ERECTABLE 15' TRUSS:

COMPONENT	SIZE* (Per Package in ft.)	WEIGHT* (Total lbs)
FLIGHT I		
1) Structure (2 packages) - 358 struts - 48 nodes	22 x 2.3 x 2.5**	3001**
2) GN&C (1 package)	9 x 9 x 9	3779
3) α-joints (2 packages)	14 diameter x 2 thick***	?
4) β-joints and solar arrays (4 arrays/2 packages)	17 x 4.2 x 5	8276
5) RFC/PWR - Power conditioning units (2 packages)	9 x 9 x 9	3228+
6) Antenna (2 packages) - 5 antenna - 5 communication units	1 x 1 x 5	658
7) MRMS (1 package) 15 foot platform	10 x 16 x 3***	?
8) Docking Ring (1 package)	5.8 diameter x 1.5	?
9) Power Cable (2 packages) - 2 lines of cable - 336 feet of cable	2.3 diameter x .5	182
10) Radiators (1 package) - 12, 25 foot panels - 2, heat exchangers (part of RFC/PWR system)	1 x 25 x 1.5	540
11) 2 MBSU (1 package) 2 PMC (1 package) 1 UPC (1 package)	2 x 1 x 1*** 2 x 1 x 1 2 x 1 x 1	?

Total Weight = 19664+

* Unless otherwise indicated all sizes and weights can be found in Ref. 1 and any of its addendums

** Ref. 10 and Section IV, Cost Analysis

*** Assumed

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT II		
1) Structure (2 packages) - 407 struts - 112 nodes	22 x 2.7 x 2.7**	3458**
2)a. Radiators (1 package) - 48, 50' radiator panels	50 x 2 x 3 or 50 x 1 x 6	3360
b. Radiator booms (2 packages)	45 x 2 diameter	812
c. 2 Heat Exchangers (2 packages)	24 x 2 diameter	960
3) RCS Thrusters (4 packages)	1.65 x 1.65 x 1.55	266
4) Fuel Tanks (2 packages) - 3 tanks per package	10 x 3.4 x 3.4	5794 (wet) (1064 - dry)
5) Ammonia Lines (2 packages) - 6 lines - 2700 feet	**** 1.17 x 2.17 x 15.25	371****
6) Fuel Lines (1 package) - 3 lines - 1440 feet	1.7 x 1.7 x 15.25	731
7) Power Cable (2 packages) - 2 lines - 1320 feet	1 x 3.4 diameter	713
8) Antenna (2 packages) - 8 antenna - 8 communication units	4 x 2 x 1	1733
9) Docking Ring (1 package)	5.8 x 1.5	?
10) 20 UPC (1 package) 6 MBSU (1 package)	2 x 2 x 5*** 2 x 3 x 1	? ?
11) MRMS Recharger (1 package)	2 x 2 x 2***	?

Total Weight = 18198+(Wet)
13468+(Dry)

**** Used .1 lb/in^3 density of aluminum for O.D. of .25" and .75"

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT III		
1) Habitat Module #1	34 x 14.5 diameter	37942
2) Airlock (2 packages) - #1 - #2	6.7 x 8.3	2942
3) Module Mounting Structure	?	?

Total Weight = 40884+

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT IV		
1) Habitat Module #2	34 x 14.5 diameter	34163
2) Module Mounting Structure	?	?
3) Structure (2 packages) - 168 struts - 52 nodes	2.17 x 1.7 x 22**	1436**
4) Antenna		
- 9 antenna (1 package)	3 x 3 x 1	?
- 2, 9'-TDRS (2 packages)	4.5 x 1 diameter	180
- 11 communication units (1 package)	3 x 4 x 1	?
5) Ammonia Lines (2 packages) - 6 lines - 1260 feet	**** 15.25 x 1.17 x 1	173****
6) Power Cable (2 packages) - 2 lines - 480 feet	1 x 2.5 diameter	260
7) 9 UPC (1 package) 1 MBSU (1 package)	3 x 3 x 1*** 1 x 1 x 1	?

Total Weight = 36212+

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT V		
1) Logistics module and fuel tanks (1 package)	34 x 14.5 diameter	33884
2) β-joints and solar arrays (4 arrays/2 packages)	17 x 4.2 x 5	8276
3) Structure (2 packages) - 40 nodes - 250 struts	2.17 x 2 x 23**	1958**
4) Radiators (1 package) - 12, 25 foot panels - 2, heat exchangers (part of RFC/PWR system)	1 x 25 x 1.5	540
5) Power cable (2 packages) - 2 lines - 240 feet	.5 x 2.1 diameter	130
6) RFC/PWR - Power conditioning units (2 packages)	9 x 9 x 9	3228+

Total Weight = 48016+

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT VI		
1) Lab module #2	34 x 14.5 diameter	55305
2) Module mounting structure	?	?

Total Weight = 55[illegible]5+

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT VII		
1) Lab module #1	34 x 14.5 diamete	39495
2) Module mounting structure	?	?

Total Weight = 39495+

DEPLOYABLE 9' TRUSS STRUCTURE:

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT I		
1) Transverse boom structure (1 package) - includes GN&C, RFC/PWR's, α-joints, power cables, solar arrays, support **structure (14 bays), heat exchangers	17 x 9 x 32	16715
2) Antenna - 5 antenna (1 package - 5 communication units (1 package)	1 x 1 x 5	658
3) MRMS (1 package)	1.5 x 9 x 9***	?
4) Erectable structure (1 package) - 20 struts - 4 nodes	1.17 x 1 x 13**	159**
5) Radiators (1 package) - 12, 25' panels	1 x 25 x 1.5	420
6) Docking ring (1 package)	5.8 diameter x 1.5	?
7) 2 MBSU (1 package)	2 x 1 x 1***	?
2 PMC (1 package)	2 x 1 x 1	?
1 UPC (1 package)	1 x 1 x 1	?

Total Weight = 17952+

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT II		
1) Deployable structure (1 package) - includes lower keel** structure (23 bays), fuel tanks, radiator booms, heat exchangers, power cable (23 bays)	47.2 x 9 x 9	9802 (wet) (5072 - dry)
2) Deployable structure (2 packages) - includes keel extension** structure (13 bays/pkg), power cable (13 bays/pkg), docking ring	9 x 11.7 x 10.3	2438+
3) RCS Thrusters (4 packages)	1.65 x 1.65 x 1.55	266
4) Erectable struts and nodes (2 packages) - 110 struts - 24 nodes	2.6 x 1.2 x 1.5**	926**
5) Radiators (2 packages) - 48, 50' panels	50 x 1 x 3	3360
6) Ammonia lines (2 packages) - 6 lines (48 bays) - 2592 feet	9.25 x 2.2 x 2.2****	556****
7) Fuel lines (1 package) - 3 lines (41 bays) - 1107 feet	9.25 x 1.2 x 1.1	648
8) Antenna (2 packages) - 8 antennas - 8 communication units	4 x 2 x 1	1733
9) 20 UPC (1 package) 6 MBSU (1 package)	2 x 2 x 5*** 2 x 3 x 1	? ?
10) MRMS recharger (1 package)	2 x 2 x 2***	?

Total Weight = 19529+ (wet)
(or 14799+ dry)

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
Flight III		
1) Habitat module #1	34 x 14.5 diameter	37942
2) Airlocks (2 packages) - #1 - #2	6.7 x 8.3	2942
3) Module mounting structure	?	?

Total Weight = 40884+

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT IV		
1) Habitat module #2	34 x 14.5 diameter	34163
2) Module mounting structure (1 package)	?	?
3) Deployable structure** (1 package) - includes upper keel and boom structure (22 bays), power cable (22 bays)	9 x 13 x 12	2062
4) Antenna		
- 9 antennas (1 package)	3 x 3 x 1	?
- 2, 9'-TDRS (2 packages)	4.5 x 1 diameter	180
- 11 communication units (1 package)	3 x 4 x 1	?
5) Ammonia lines (2 packages) - 6 lines - 1188 feet (22 bays)	9.25 x 1.2 x 2****	164****
6) 9-UPC (1 package)	3 x 3 x 1***	?
1 MBSU (1 package)	1 x 1 x 1	?

Total Weight = 3[illegible]569+

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT V		
1) Logistics module and fuel tanks (1 package)	34 x 14.5 diameter	33884
2) Deployable structure** (2 packages) - includes extensions to transverse boom structure (5 bays per package), RFC/PWR, power cables (5 bays per package) solar arrays (2 per package), heat exchangers	9 x 17 x 10.7	12374
3) Radiators (1 package) - 12, 25' panels	1 x 25 x 1.5	420

Total Weight = 46678+

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT VI		
1) Lab module #2	34 x 14.5 diameter	55305
2) Module mounting structure	?	?

Total Weight = 55305+

COMPONENT	SIZE (Per Package in ft.)	WEIGHT (Total lbs)
FLIGHT VII		
1) Lab module #1	34 x 14.5 diameter	39495
2) Module mounting structure	?	?

Total Weight = 39495+

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16. Abstract

In this paper the results of a trade study on truss structures for constructing the Space Station are presented. Although this study was conducted for the reference gravity gradient space station, the results are generally applicable to other configurations. The four truss approaches for constructing the space station considered in this paper were the 9 foot single fold deployable, the 15 foot erectable, the 10 foot double fold tetrahedral, and the 15 foot PACTRUSS.

The primary rational for considering a 9 foot single-fold deployable truss (9 foot is the largest uncollapsed cross-section that will fit in the Shuttle cargo bay) is that of ease of initial on-orbit construction and preintegration of utility lines and subsystems. The primary rational for considering the 15 foot erectable truss is that the truss bay size will accommodate Shuttle size payloads and growth of the initial station in any dimension is a simple extension of the initial construction process. The primary rational for considering the double-fold 10 foot tetrahedral truss is that a relatively large amount of truss structure can be deployed from a single Shuttle flight to provide a large number of nodal attachments which represent a "pegboard" for attaching a wide variety of payloads. The 15 foot double-fold PACTRUSS was developed to incorporate the best features of the erectable truss and the tetrahedral truss. That is, the 15 foot PACTRUSS will accommodate Shuttle size payloads within each truss bay, yet the whole keel structure can be deployed from a single Shuttle flight.

To provide a basis for comparing these quite different construction approaches, a set of discriminators were established. In the paper, each of the five discriminators are described and each truss is qualitatively evaluated with an adjective rating.

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