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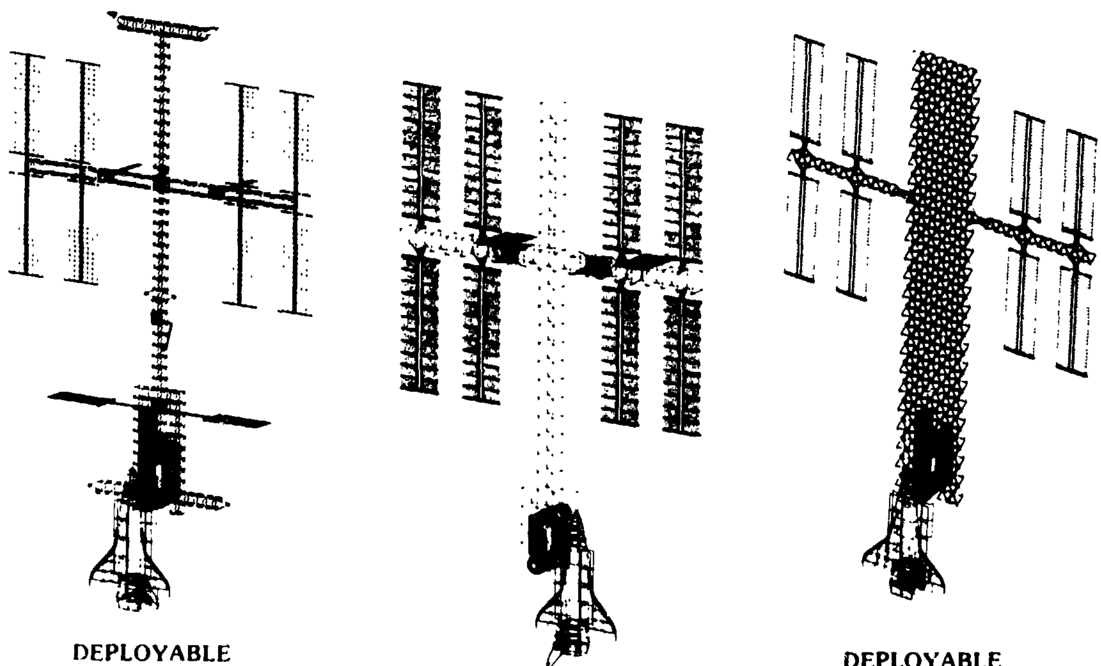

DEPLOYABLE SINGLE FOLD

ERECTABLE

DEPLOYABLE DOUBLE FOLD

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SPACE STATION TRUSS STRUCTURES AND CONSTRUCTION CONSIDERATIONS

by

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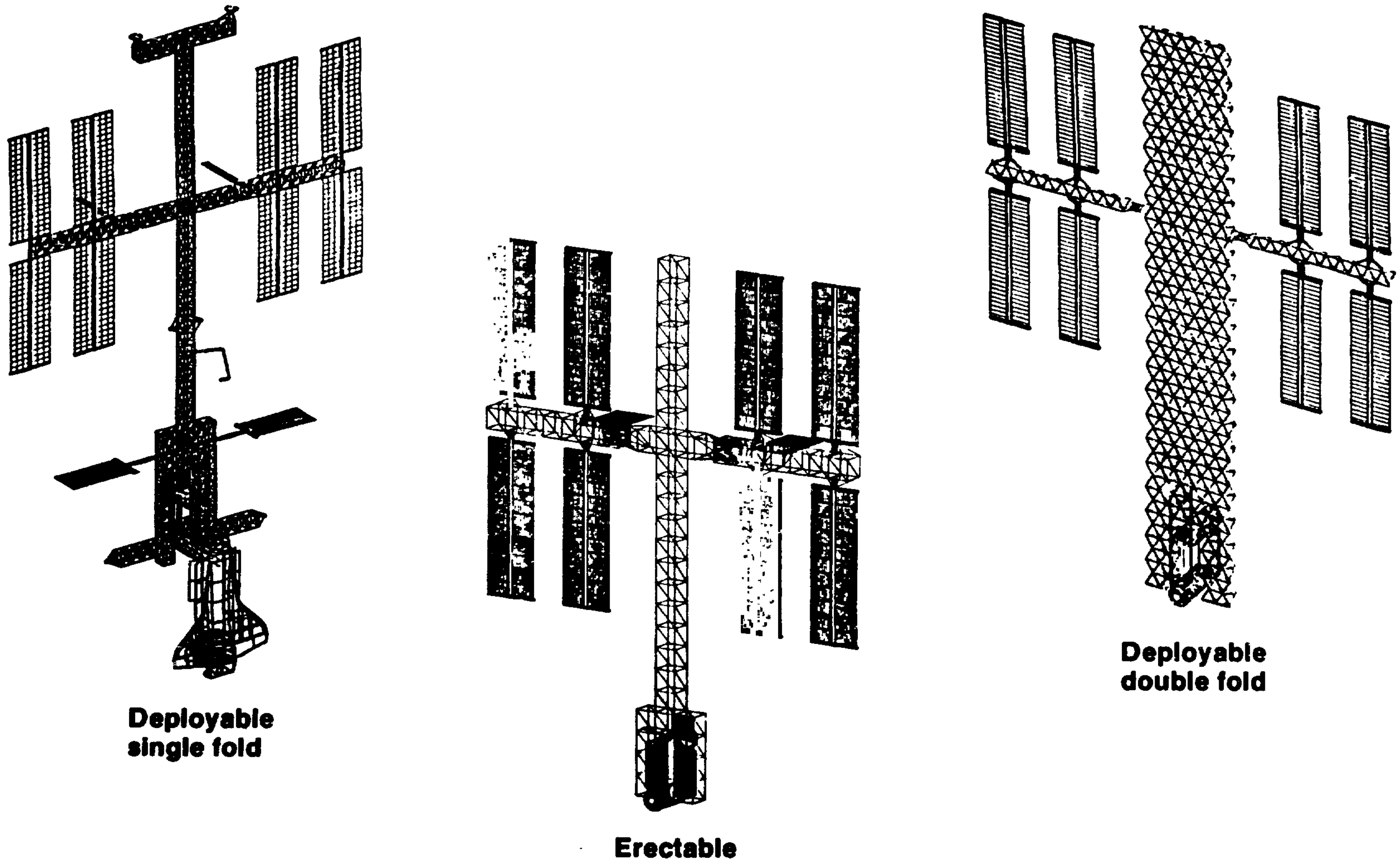
SPACE STATION TRUSS STRUCTURES AND CONSTRUCTION CONSIDERATIONS

INTRODUCTION

Over the past ten years, a considerable effort has been expended on structures for large space systems. Most of the effort has been generic in nature and directed towards large reflector applications (reference 1 and 2). The currently conceived Space Station represents a set of system requirements that are somewhat different than those considered for previous applications, thus, much of the past research is not directly applicable. However, the experience gained on past structural studies provides a wealth of knowledge and insight over a wide range of parameters that can guide the selection process for the Space Station structure.

Although a specific configuration has not been selected for the Space Station, a gravity gradient stabilized station will be considered in this paper as a basis upon which to compare various structural and construction concepts. The scope of this paper will be limited to the Space Station primary truss support structure. Three approaches (see sketch A) which are believed to be representative of the major techniques for constructing large structures in space will be described in detail so that salient differences can be highlighted.



Sketch A. Reference station structural options.

TRUSS CONSTRUCTION APPROACHES

The overall dimensions of the Space Station configuration considered in this paper are shown in figure 1. The solar arrays shown in this configuration are sized to deliver 75 kW continuous power. In addition to addressing the obvious design considerations such as cost and structural stiffness, it is necessary for the structure to accommodate a wide variety of module and payload attachments as well as allow for growth, alteration and maintenance.

A comprehensive study of available deployable truss structures is found in references 3 and 4 and a description of erectable structures is presented in reference 5. A comparison of deployable trusses and erectable trusses is presented in reference 6. For the reference Space Station, three approaches for assembling the primary truss are discussed and contrasted in this paper. The first is a station build-up using deployable single fold beam segments while the second is an erectable approach and the third is a station build-up using deployable truss structures which double fold for maximum compaction. For all three construction approaches it is assumed that there will be a Mobile Remote Manipulator System (MRMS) such as discussed in reference 8 on the structure to assist in the construction process. The next three sections are devoted to discussing the three assembly approaches and the final section is devoted to contrasting the salient features of the three approaches.

Single Fold Deployable Beams

Due to the need for redundancy in the Space Station primary structure, only four-longeron beams are considered. An analysis of the failure of such beams with missing members is presented in reference 7. The results of that study indicate that the maximum reduction in beam strength with any one member missing is 50% in either bending or torsion.

In determining the size of truss beam it is considered desirable to make the beam cross-section as large as possible, within cargo bay constraints, for the following reasons:

(1) Payload and module attachments and Mobile Remote Manipulator System (MRMS) considerations. Since the Space Shuttle will be the transportation system for Space Station it is likely that the pressurized modules and many other payloads to be attached to the station will be in the 14 foot size class (cargo bay limit). It appears that payload attachments would be simpler for larger beam cross-sections. Also, since it will be necessary to transport payloads about the station with the MRMS, larger beams would be desirable since they allow a wider track for the MRMS and thus greater clearance between payloads attached to the sides of the beam.

(2) Utilities integration. A unique feature of a single fold deployable beam is the inherent internal space available to permit

utility lines to be preintegrated. Since it will be necessary to install a considerable number of sizeable power and communication wires, and cooling hoses to accommodate the needs of Space Station, it is desirable to use larger cross-section beams with more available internal area.

(3) Cost. For a fixed geometric pattern, the linear footage of truss struts required to construct a beam of a given length is independent of beam depth. However, the number of joints required decreases linearly with increasing beam depth. Since the cost of a deployable beam is dominated by the joints, larger beams should result in cost savings.

(4) Stiffness. Although dynamic studies to date have not identified strong drivers for making a very stiff Space Station, it is generally believed that increased station stiffness will simplify both the station control problem and the approach to isolate experiments that require low acceleration levels and/or accurate pointing. This is especially true in growth considerations and could ease payload placement concerns relative to mass distribution.

In arriving at beam cross-sectional size, the prime consideration was the 14 foot cargo bay diameter constraints. This diameter constraint establishes a maximum upper limit on an uncollapsed square beam cross-sectional size of about ten feet. For the current study a maximum size of nine feet was chosen for the deployable beam to provide space outside the beam for ready preintegration of external attachments such as folded solar arrays, folded radiator support structure, RCS thrusters, and antennas. Another consideration in beam concept selection was the need to provide accommodations for a mobile remote manipulator system (MRMS) such as discussed in reference 8. For the type of MRMS discussed in that reference, it is necessary: 1) to provide structural guide pins at each nodal joint which guide the MRMS motion, 2) that there be no blockage for the MRMS, and 3) that the bays be square. Finally, it is believed to be desirable to make all elements of the deployable structure as common as possible in order to reduce the amount of structural development and flight qualification required. Consideration was given to deploying a structure several bays wide so that the keel extensions could be integrated with the lower keel to form a single deployable unit. Such a packaged unit would have to be stowed with the multiple bays running lengthwise in the cargo bay. This packaging approach has the disadvantage that the width of the cargo bay now limits what can be packaged in the direction of deployment. Although this approach has not been ruled out it is not considered in the current study because large bay-sized packages could not be integrated into the beam and multiple bay deployment appears to be a higher risk.

With the previously mentioned considerations in mind, a nine-foot single-fold deployable beam was developed for further study and is shown in figure 2. The beam is an orthogonal tetrahedral design, having longerons that fold inward and diagonals that telescope to effect packaging similar to the beam discussed in reference 3. The primary differences between the geometry of the beam in the current paper and that of reference 3-are in the tetrahedral diagonal arrangement and the provision of quick-attachment joints at the side of each bay. These aspects were incorporated to make the deployable beam compatible with an add-on erectable structure which will be discussed later.

The deployment features of the beam under consideration include efficient packaging characteristics, controlled sequential deployment stabilized by the use of guide rails, and the accommodation of in line bay-sized payload packages such as might be required for rotational joints, power conditioning equipment, fuel containers, etc. These aspects are presented in figure 3.

The packaging characteristic of this beam are such that each bay compacts to a dimension equal to two longeron diameters. As an example, a 216 foot long beam with two inch diameter longerons and nine foot bays will originate from an eight foot long package. In the design of an acceptable deployment scheme, it is considered desirable to have a controlled, sequential deployment of the beam in which one bay unfolds at a time and deployment instabilities normal to the deployment direction are prevented. A deployment canister accomplishes both of these tasks, however, it blocks MRMS movement and cannot readily accept bay-sized solid section. Consequently the beam currently under study utilizes a system of rails such as shown in figure 3 as an aid to deployment. The rails are located on one side of the box beam and move over the MRMS guide pins. They are removed after deployment leaving an unobstructed structure for movement of the MRMS. It is necessary that the deployment rails extend at least two bays past the bay to be deployed to maintain complete control during deployment. This could be accomplished by deploying folded rails or by sliding the packaged beam to one side of the support rails. It is also considered necessary to erect an initial bay, or to have a bay sized package at the end of the total package to assist in guiding the partially deployed bay along the rails such as shown in figure 3. Detailed studies of sequential deployment of the nine foot deployable beam discussed in this section have not been conducted, but three deployment schemes are postulated. One deployment concept considered assumes that the energy for deployment is contained in precompressed springs in the joints of each bay. In this case a release mechanism (not defined in this study) would permit the bays to be deployed one at a time. A second deployment concept incorporates a deployment mechanism such as a lead screw or chain which engages one bay at a time, and moves it to full deployment. This procedure is repeated until the beam is fully deployed. A third deployment concept would make use of the available MRMS for positive bay by bay deployment. Use of the MRMS could also eliminate the need for the two bay rail extensions. Selection of the most appropriate deployment scheme will be the result of trade-off and development studies.

As indicated earlier, for future payload attachments, and to permit the option for very general growth, it was considered desirable to provide quick-attachment joints at the side of each bay such as shown in figure 4. These joints, which are discussed in reference 5, provide a convenient capability for attaching small payloads to a single joint or large payloads to multiple points. By providing quick-attachment joints in the proper locations and directions, the initial beam structure can be readily grown or altered by erectable procedures such as shown in figure 5 and discussed in reference 5.

Station Assembly - An exploded view of a gravity gradient stabilized Space Station composed of nine foot deployable beam elements is shown in figure 6. The Roman numerals indicate the Shuttle flight upon which portions of the station will be placed in orbit. The basic philosophy in establishing this assembly scenario is to maximize the preintegration of utilities and attachments thus minimizing the amount of in-space integration necessary. It is also an objective to leave the spacecraft self-powered and controllable after each flight and to achieve early habitability. The payload summary for the major station elements of the first two flights is as follows:

FLIGHT	MAJOR SPACE STATION ELEMENTS
I	inboard solar array wing pairs rotating power joints power conditioning radiator arrays inboard transverse boom structure power conditioning equipment control equipment communication equipment berthing structure MRMS

FLIGHT	MAJOR SPACE STATION ELEMENTS
II	lower keel structure port keel extension structure starboard keel extension structure lower boom structure main radiator booms main radiator panels closeout structure

The transverse boom portion of the Space Station to be constructed on Flight I is shown on figure 6. That portion of the station is shown packaged in the cargo bay in figure 7, and some details of the launch package are shown in figure 8. The package consists primarily of the solar arrays on each end, a bay-sized section on each side containing the rotary joint and power conditioning equipment, a bay-sized section in the middle containing the CMGS, and bays of deployable truss in between those main elements. The three subsystem carrying sections were constrained to be exactly bay-sized so that uniformly space guide pins could be provided for movement of the MRMS without the need to develop special length deployable truss bays. All required utility lines are stowed in the open area of the truss shown in the end-view in figure 2, and deploy as the truss bays are deployed. The package is viewed as being held tightly together with both longitudinal and shear straps to provide a stiff unit for launch. The first step in the construction process is installation of the power conditioning radiators while the package is still in the cargo bay (see figure 7). The individual elements of the radiators are 50 feet long, one inch thick and one foot wide. The elements are installed one at a time using a combination of EVA and RMS operations. The second step in the construction process is removal of the launch package from the cargo bay and attaching it to the bay sides as shown in figure 9.

The third step in the construction process is to deploy the transverse boom off of the guide rails in both directions. There are a number of options for deploying the truss structure as discussed previously. It is also necessary that the guide rails extend two bays out from the packaged structure. This two bay length of guide rail could be provided on this particular package in one of two ways. A two bay length of rails could be packaged along side the rails shown in figure 9 and rotated into position with a simple hinge or, the launch package could be slid to one side in the configuration shown in figure 9 to expose a two bay length of guide rails. In either approach it is viewed that the rails will remain on the transverse boom to assist in attaching the outboard portions of the transverse boom on subsequent flights. The fourth step of the construction process is to deploy the top half of the solar array blanket box. This is viewed as a simple rotation about the center line of the solar array canister. This deployment could either be automated, or it could be accomplished with the MRMS and EVA. In the latter case, of course, the MRMS would have to be installed on the transverse boom prior to this operation. The fifth step of the process is to deploy the solar array blankets. This is viewed as an automated process using a continuous longeron deployable mast as the actuation device. The sixth and final step of the construction process is to erect a bay of the upper keel to attach a berthing ring for the second flight. This erected bay is necessary to offset the transverse boom from the berthing adaptor on the second flight to provide clearance for operation of the SRMS.

The lower keel portion of the station to be constructed on flight II can be seen in figure 6. The launch package containing these elements is shown in figure 14. The second flight Shuttle is shown berthed to the transverse boom in figure 15. The first step in the lower keel construction process is to remove the lower keel from the cargo bay and attach it to the transverse boom. This is accomplished using the SRMS and the MRMS. There are a number of approaches possible for attaching the lower keel to the transverse boom. It would probably be desirable to have an aid such as a one bay long set of guide rails extensions on the upper end of the keel package which could be slid over the guide pins on the transverse boom to positively position the lower keel package for attachment. The second step of the construction process is to deploy a two bay extension of the guide rails from the lower portion of the package to provide positive control of the deploying lower keel.

These rails are not shown on the figure. The keel is then deployed one bay at a time until full deployment as shown in figure 16. The third step of the process is to deploy the radiator booms as shown on the right of figure 16. The two cross hatched bays shown on the lower keel in figure 16 are fixed bay length sections integrated into the deployable keel to provide volume for subsystem elements such as RCS propellant storage and for tool storage. They also provide convenient attachment support for the radiator booms and for a utility plug-in tray that would be built into the lower section. The simple hinge deployment scheme was developed to permit preintegration of the coolant hoses from the radiators to the lower utility tray in the vicinity of the pressurized modules. The fourth step of the construction process is to deploy the radiator arms as shown in figure 17. The fifth step of the process is to erect two bays on each side of the keel around the radiator booms. The sixth step would be to install the lower radiators in a fashion similar to that described for the power conditioning radiators. In this case the MRMS would assist in the process and would be positioned on the outer erected bay.

The seventh step of the process is to install the port keel extension. The operation would consist of the MRMS moving up the keel to retrieve the keel extension from the cargo bay, transporting it down the keel to position it for attachment to the outer erected bay. The eighth step of the construction process would be to deploy the port keel extension as shown on the right hand side of figure 18. For the keel extension package shown in figure 18, a solid bay was provided to permit direct attachment of the packaged port side of the lower boom. It is likely that the boom structure is short enough that guide rails would not be needed to control the deployment process. This may also be true for the keel extension itself, however, this situation would have to be studied in depth. The ninth step is to repeat this process to construct the starboard keel extension. The tenth and final step is to erect the internal support bays as shown in figure 20. If it were found necessary to have RCS after the second flight, these also would have to be installed.

Starting with flight III, 36 foot long, 14 foot diameter pressurized modules would be transported on each flight until the station was complete. Items such as the upper keel and outboard arrays and other needed items would have to be placed in front of the modules in the cargo bay on a priority basis. The completed station is shown in figures 21 and 22.

Erectable Truss Structures

The discussion presented in the previous section for considering large truss elements is also appropriate for erectable trusses. However, for erectable trusses whose cross-section is not limited by cargo bay size constraints, it would appear that limiting the bay size to around 16 feet would be desirable in an effort to keep the truss compatible with payload attachments and to confine the size of the MRMS. In this section two different sizes of erectable trusses will be considered. The first will be an erectable truss with nine foot bay lengths which will be shown to be completely compatible and complementary to the nine foot single fold beam discussed in the previous section. The second will be an erectable truss with bay length of 15 foot which was chosen because it is large enough to accommodate 14 foot payloads within a truss bay. In both cases it was considered desirable to have square bays in the truss to readily accommodate a MRMS that can move in two directions. A triangular faced truss would represent an additional complication to accomplish this.

Nine Foot Bay Size Erectable Truss - During the course of the current study it became apparent that an erectable truss could be substituted for the nine foot single fold deployable truss of the previous section without changing the station assembly scenario in any substantive fashion. All utilities and attachments would be preintegrated into a harness as with the deployable structure. The only difference in the assembly process would be that each bay is erected on the rail system instead of deployed and the harness installed. The existence of such a scenario provides a backup assembly approach for the nine foot deployable beam thus reducing programmatic risks in developing the deployable beam. This approach has merit in its own right in that erectables are a low risk structural development and provide potential for high versatility and growth.

Fifteen Foot Bay Size Erectable Truss - To take full advantage of erectable trusses with regard to stiffness, reduced part count, and payload attachments it is desirable to have bay lengths on the order of 14 to 16 feet. An initial study of the application of erectable trusses to Space Station is presented in reference 9. In that study, a 14 foot bay size was chosen. In the present section a description will be presented of an erectable truss Space Station with 15 foot bay sizes. The increase in bay size to 15 feet was considered desirable to more readily accommodate a 14 foot diameter attached payload within a truss bay. It may even be desirable to go slightly larger in bay size. The specific truss geometry chosen is shown in figure E1. This particular geometry was chosen primarily because the surface hardpoints are in a square pattern - a feature which simplifies movement of the MRMS. An additional advantage is that all cluster joints in the truss would be identical. This truss geometry, which has two different strut lengths, is an orthogonal version of what is commonly called a tetrahedral truss such as discussed in references 10 and 11 and displays very similar structural performance features.

In the current study the struts are assumed to be two inch diameter tubes with quick attachment joints such as discussed in reference 5 and shown in figure E-2. A nodal cluster joint which joins the tubes at each intersection is shown in figure E-3. Also shown attached to the cluster is a guide pin along which the MRMS platform can move.

Station Assembly - The 15 foot bay size erectable version of a gravity gradient stabilized Space Station selected for study in this paper is shown in figure E-4. Assembly studies indicate that the MRMS, the inboard two sets of solar arrays, the transverse boom structure between the arrays and associated rotary joints and power conditioning equipment could be brought into orbit and assembled on the first Shuttle flight. It should be noted that for the erectable station considered in this section, the radiators are on the transverse boom rather than being located near the modules as was the case for the nine foot beam station. The assumption is made that the arrays are unwound on the dark side of the orbit so that coolant hoses could be used across the rotary joint. The placement of the radiators on the transverse boom leaves an unobstructed area for growth in the vicinity of the modules. Final selection of radiator placement will have to be the subject of indepth trade studies. On the second flight, the first pressurized module could be brought into orbit along with the remainder of the structure and the remaining arrays. During the second flight, the keel of the station would be erected and the first pressurized module put in place. A description of the sequential buildup of the Space Station follows.

The initial steps in building the transverse boom on the first flight is shown in figure E-5. The first step, once the Shuttle is in-orbit, is to place a set of construction rails across the cargo bay and erect the first bay using the Shuttle RMS and Mobile Foot Restraints (MFR's) as shown in figure E-5-a. The second step is to mount the MRMS on the bay as shown in figure E-5-b, permitting simultaneous operation of two manipulators. The third step is to erect the second bay and translate the two bays to the left of the cargo bay (figure E-5-C). This could be accomplished using a link chain drive as was proposed in reference 5 or a similar system. It is assumed that the MRMS will have mobile foot restraints (MFR's) such as discussed in reference 8 to assist in astronaut assembly of the structure. In the fourth step (figure E-5-d), the manipulator on the MRMS lifts the rotary joint and attached power conditioning equipment from the payload bay and rotates it 90° for assembly into the transverse boom as shown. This build-up process is continued until the transverse boom with solar arrays and radiators is completed such as shown in figure E-6. One bay at the top of the keel is also erected with a berthing ring for attaching the Shuttle to the partially erected station on the second flight. The completed transverse boom with deployed arrays ready for system checkout is shown in figure E-7.

An important and critical aspect of the overall construction process is the integration of the utility lines. One feasible technique for utilities integration is shown in figure E-8. Due to the linear nature of the Space Station a seemingly logical way of dealing with utility lines would be to develop a wiring and hose harness which could be conveniently spooled for packaging and provide a controlled means of deployment. Such a system could be checked out on the ground and could be designed to have a minimum number of field connections. A depiction of the main utilities being installed by the MRMS during keel erection is shown in figure E-9.

After the keel truss is erected the MRMS removes the pressurized module from the cargo bay, translates it down the keel and assists in its attachment to the truss as shown in figures E-10 and E-11. Attachment details are not presented in this paper, however, it is assumed that the MRMS positions the module for attachment and that standoff strut members will provide support from the truss to the module trunions which will be installed by astronauts using the MFR positioning arms. After installation of the module, the additional struts, solar arrays and radiators are stowed on the side of the keel (see figure E-10) using the MRMS for subsequent construction after the station is manned.

In subsequent flights, the additional modules are brought into orbit and the remainder of the station is constructed with astronauts assisted by the MRMS. The completed station minus a logistics module is shown in figure E-12. Figure E-13 shows the sixth flight docking to a pressure module with a logistics module in the cargo bay.

Station Growth - The undefined requirements for Space Station use in the the future add a new dimension to the design of an initial operational capability (IOC), namely potential growth. The IOC configuration is the foundation on which future station capabilities will be built. Therefore, it is imperative that sufficient system margins be build into the IOC configuration so that future decisions on station use will not be unnecessarily constrained. The erectable approach displays great versatility in meeting future station configuration requirements. Consequently, this approach results in very few constraints on future station growth and use.

Table II shows the structural part count, mass and stiffness characteristics of the three construction approaches considered throughout this paper. It is shown in the table that the addition of 208 struts and 44 nodal cluster joints to the erectable single bay keel structure of Figure E-4, results in the three bay wide keel structure illustrated in Figure E-14. The two extra keel bays provide increased safety against accidental operational structural damage and removes the possibility of a catastrophic single point nodal joint failure. Additionally, the bending and torsional stiffnesses of the three bay keel are factors of 2.3 and 6.6, respectively, times as great as the single bay keel values - features which are extremely important when considering the unspecified pointing and isolation requirements of future Space Station experiments and/or functions. If additional Station area is needed (i.e., - for construction and test of large spacecraft) the configuration shown in Figures E-15 and E-16 requires that 348 struts and 84 nodal cluster joints be added to the configuration of Figure E-14. The entire station structure shown in Figures E-15 and E-16 (1204 struts and 306 nodal clusters) occupies an unassembled volume of approximately 6'x 6' x 21.2' and weighs 6950 lb. The erectable method permits the structure to be added as needed and avoids the deployment of large structural segments near the station. Although not shown, an alternate configuration option, which may be attractive operationally and is possible using the erectable approach, is to construct station support structure perpendicular to the plane of the lower keel platform shown in Figures E-15 and E-16.

Sychronously Deployable Tetrahedral Truss Structures

It is understood that a double fold structure is a more efficient means than a single fold structure for packaging truss structures for launch in the cargo bay. In this section a scenario will be presented for constructing a gravity gradient stabilized Space Station from a double-fold synchronously deployable tetrahedral truss. Because of the high packaging efficiency of the double fold truss it is considered desirable to deploy a large area of truss in orbit initially to minimize subsequent add-ons.

The tetrahedral truss station chosen for study in this paper is shown in figure T-1 and details of the truss are shown in figures T-2, T-3 and T-4. This keel structure is shown as six bays wide with 10 foot long struts. The transverse boom structure is shown as a four longeron, single bay strip taken from the tetrahedral truss. The transverse boom and keel structure are identical. The strut tubes are two inches in diameter. A slot is shown at the bottom of the keel for subsequent attachment of the modules. A close up of a possible strut attachment scheme for the rotary joint and array canisters is shown in figure T-5.

Cargo Bay Packaging - The main elements of the tetrahedral station are shown packaged in the cargo bay in figure T-6. As was discussed earlier, it can be seen that the relatively large amount of truss packages quite compactly in the cargo bay leaving room for solar arrays, power conditioning equipment and radiators, all of which are not shown. This packaging implies that, potentially, the complete station structure can be brought up on one Shuttle flight.

A major difference between the tetrahedral station and the previously discussed stations is that the truss faces have a triangular strut arrangement dictating that a different type of MRMS be developed. This is discussed in appendix A.

Truss Deployment - Two possible deployment scenarios for a synchronously deployable tetrahedral truss are considered. In both cases the deployment energy is stored in prestressed springs at the joints. In the first deployment scenario, the packaged truss is released free in space to self deploy. The synchronous tetrahedral truss possesses a unique theoretical one-degree-of-freedom mechanistic deployment characteristic. Free deployments have been successfully demonstrated. Such a deployment process (aided perhaps by synchronizers such as discussed in reference 6) is likely to be a low risk process. However, it would probably be desirable to accomplish this deployment away from the Shuttle to minimize possible interference problems. This is not viewed as a shortcoming of the whole construction procedure. A second deployment procedure would utilize a set of rails which guide the deployment process and perhaps tethers attached to the outer joints of the truss to provide a controlled deployment process. Since the truss deploys synchronously and distances between the joints in two directions are continuously changing, the guide rail system is somewhat complex and represents a new development. The use of tethers for controlling the deployment of such a truss has never been demonstrated. Trade studies would have to be conducted to determine the best deployment approach from a system reliability point of view.

Station Assembly - In this paper no attempt will be made to provide a detailed end-to-end assembly scenario for the tetrahedral station, however, the apparent necessary steps will be discussed in general. For this assembly scenario a powered and controlled component of the station will be left on orbit after the first Shuttle flight. Consequently, then it will be necessary to install a set of operational solar arrays, power conditioning equipment and CMG's during that flight.

One possible scenario for accomplishing the station build-up on the first flight is as follows:

(1) Release packaged keel truss from Shuttle and freely deploy in space.

(2) Reattach Shuttle to deployed keel structure in vicinity of where the transverse boom will be mounted and place MRMS on keel.

(3) Using erectable struts attach rotary joints and associated power conditioning equipment to keel.

(4) Deploy transfer boom structure and attach to other end of rotary joint.

(5) Move MRMS out on transverse boom and attach solar arrays and power conditioning equipment radiators.

(6) Unspool wiring harnesses between active components.

(7) Attach CMG package to keel truss and complete wiring.

(8) Check out system.

On the second flight a pressurized module would be brought up and attached in the lower slot. The lower radiators, cooling hoses, and the wiring harness from the module area to the CMG's and power equipment would then be installed.

An alternate approach to station construction would be to deploy the keel truss structure on a shared Shuttle flight and gradually add succeeding components as shared Shuttle flights permit. This approach could reduce the required reliability that needs to be built into all the subsystems since any failed component could be replaced on a subsequent flight without jeopardizing the total construction process. Although the station construction process would be spaced out over more Shuttle flights, it could result in reduced program risks and costs.

CHARACTERISTICS OF THE THREE CONSTRUCTION APPROACHES

The three approaches presented in this paper are believed to generally represent the major techniques for constructing the Space Station structure. An attempt will be made in this section to delineate the salient features of each approach to assist in providing a means for comparison.

Part Count, Weight and Stiffness

In this section detailed characteristics of the three structures discussed in this paper are presented. Although the three differently constructed stations are not exactly comparable, they are similar enough that general comparisons can be made. The parameters selected for characterizing each construction approach are part count, weight, and stiffness because of their relationship to the structural design, fabrication costs and performance of the Space Station.

All trusses were assumed to be constructed from 2 inch diameter tubular struts with a wall thickness of .06 inches. The material chosen was graphite/epoxy and was assumed to have an effective laminate modulus of 40×10^6 psi and a density of .063 lb/in^3. These properties, or near values, appear achievable using currently available high modulus graphite filaments and the appropriate laminate construction (see Table I).

Due to design complexity of the joints, the weight of the 9 foot deployable beam was estimated to be 8 lb/ft, based on scaling up a smaller beam design. Weight estimates for the erectable and deployable truss structural were calculated using the tube dimensions and properties above. Nodal Cluster Joint weights including strut end fittings were 3.5 lb/node for the erectable structure and 4.02 lb/node for the deployable tetrahedral truss, both based on fabricated aluminum hardware.

Both one and three bay wide keel versions of the 9 foot deployable beam (2 keel bays erectable) and the 15 foot erectable beam were examined. Only a 6 bay wide keel deployable tetrahedral truss was examined. Table II presents dimensional values of the parameters examined. The results in Table II are also presented in Table III in non-dimensional form in which all quantities are normalized with respect to the corresponding parameter value of the 9 foot deployable beam which was chosen as the reference.

Comparing the results in Table III shows that the 15 foot bay erectable approach results in a structure which has about half as many parts, and weighs half as much as the reference beam yet possesses three time the stiffness. The deployable tetrahedral truss is seen to have 50% or more parts than the reference beam but has only a slightly higher weight. The 6 bay tetrahedral truss is over twice as stiff as the one bay reference beam but only slightly stiffer than the 3 bay reference. On a stiffness to weight basis, the three bay 15 foot erectable is seen to be two to three times as good as the deployable tetrahedral truss or the 3 bay reference beam.

Structural Development

The two items to be addressed in the development of each structural concept will be (1) flight hardware development, and (2) structural predictability. These items are highlighted because of their potential for causing future programmatic disturbances. In all cases it is assumed that the truss struts will be two inches in diameter and made of graphite/epoxy. The choice of graphite/epoxy for the strut elements is primarily made to ease total station thermal expansion concerns both in assembly and operation, while providing increased station stiffness.

Nine Foot Deployable Beam

(1) Flight Hardware Development - The main hardware elements for this beam are: the graphite/epoxy struts, the corner joints, the center joints for the longerons, the telescoping joints for the diagonals, and the deployment mechanism. Details of typical corner joints for this beam are shown in figure 4 and details of the longeron joints and telescoping joints can be found in reference 3. Due to the highly detailed nature of these joints and the desired thermal expansion compatibility with the graphite/epoxy struts for bonding purposes it

would be desirable for these joints to be made from titanium. The same is true for the longeron center joints and the diagonal telescoping joints. It is also considered that the highest risk item in the joint design is the assurance of simultaneous lockup of the folding longeron joints and the telescoping diagonal joints. It is also considered more difficult to assure the final joint lockup in such a beam than it would be in a deployable structure that had all folding joints. When using prestressed springs to deploy a single bay wide structure where each element is essential to the complete performance of the beam, it would be desirable to have a redundant spring mechanism at each joint to insure it would be locked in place. This adds additional development and operational complexity to the design.

The railed deployment scheme shown in figure 3 is untried, but conceptually simple. For the three deployment schemes discussed previously there is likely to be considerable development involved in providing a highly reliable system. Although the development of the deployment scheme is likely to be quite involved, the beam size and one-bay-at-a-time deployment approach means that ground testing will provide a high degree of confidence for orbital deployment.

(2) Structural Predictability - There is a high degree of uncertainty in structural performance of deployable truss which is associated with free play and nonlinearity in the joints. There is no known published data on these effects. Additionally, very little is known about how

much free play and nonlinearity can be tolerated from a control aspect. Under such circumstances it would appear desirable, from a program risk point of view, to have alternate concepts which minimize the joint free play and nonlinear effects if it were found necessary to do so. Preloading the beam with tension members is one means of reducing joint freeplay and nonlinearity, and one such system is discussed in reference 3. However, it is not clear how this will be accomplished in a redundant structure since dimensional tolerances must be accounted for in providing proper preload in all members. Analytical studies, which consider reasonable assumed values for dimensional tolerances could shed considerable light on this issue. Those studies should be relatively straight forward due to the small number of members in the beam cross-section.

Fifteen Foot Erectable Beam

(1) Flight Hardware Development - The main hardware elements of this beam are the graphite/epoxy struts, the quick attachment joints, and the nodal cluster fitting. All joints and nodal cluster fittings of the orthogonal tetrahedral truss are identical thus minimizing the developmental part count. Details of an existing quick attachment joint are shown in figure E-3. A nine point nodal cluster design which is compatible with the quick attachment joint is shown in figure E-4. Both one and two inch diameter versions of the design shown in figure E-3 have been fabricated from aluminum. The two inch joint design has

been used extensively in simulated zero-g assembly studies (neutral buoyancy tests) which are discussed in reference 5. Compatibility with pressure suited astronaut use of this joint in EVA was successfully demonstrated in these tests.

Thermal compatibility between the graphite/epoxy struts and the threaded joint fitting for bonding purpose may dictate that the bonded fitting be titanium. However, operative joint components and the nodal cluster could potentially be aluminum. The use of left and right hand threaded fittings bonded into opposite ends of the graphite struts permits post-fabrication adjustment of the strut lengths accurately and economically. A breakdown of the part count and estimated mass properties is presented in Table II.

(2) Structural Predictability - Erectable joints need not exhibit the freeplay which characterizes deployable joints. Appropriate design can remove free play and significantly reduce non-linear structural behavior. The wedging feature of the quick attachment joint shown in figure E-3 is one simple feature which results in a tight joint and eases mating of the joint halves during assembly. Structural test results of a large truss component (36 struts) using eighteen foot long struts and two inch diameter joints similar to figure E-3 are discussed in reference 6. Also shown in reference 6 are typical results from joint stiffness tests which illustrate the slight joint non-linearity effects present. The joints shown were fabricated in separate pieces

for testing versatility and economy. Nodal clusters were assembled using shouldered threaded fasteners to connect joint halves and cluster fittings. Alternate techniques such as riveting, or welding, may eliminate fastener bearing and further reduce joint non-linearity.

Tetrahedral Truss

(1) Flight Hardware Development - The main hardware elements for this structure are; the graphite/epoxy struts, the strut ends, the nodal clusters, the center joints for the longerons, and the self contained spring system required for deployment. Details of these elements are shown in figures T-2, T-3, and T-4. If a rail assisted deployment were selected, the rails and associated mechanisms would also have to be developed. Because of a desired thermal expansion compatibility with the graphite/epoxy struts, the strut ends and center joints should be made from titanium or graphite/epoxy. In contrast the nodal clusters could be made of aluminum since there is no direct bonding to graphite/epoxy elements. A breakdown of part count and truss weight is presented in Table I. Due to the high degree of redundancy in the tetrahedral truss the assurance of lockup at each joint is less critical than it was in the case of the nine foot deployable beam.

(2) Structural Predictability - As discussed in the section on nine foot deployable beams, there is a high degree of uncertainty associated with free play and nonlinearity in the joints, and there is the same

concern with controls as there was with the nine foot deployable beam. Preloading the tetrahedral truss with tension members is one means of reducing free play and nonlinearity in the joints. This is likely to be difficult to achieve in the tetrahedral truss due to the high degree of redundancy in the truss structures. Another potential problem with preloading the tetrahedral truss using tension members is that the tension members would have to be offset from the strut center lines by an amount equal to the radius of the struts. This would cause eccentric loads where the tension members were anchored with a resulting moment being applied to the anchor cluster. A comprehensive, analytical and experimental program would have to be conducted to evaluate the structural predictability of the deployable tetrahedral truss.

SPACE STATION ASSEMBLY, MAINTENANCE, AND GROWTH

Nine Foot Deployable Beam - As mentioned previously, the basic philosophy in the development of the station construction approach using the nine foot deployable beam was to maximize preintegration of attachments and utility lines, and to minimize field connections. In other words an attempt was made to come as close as possible to developing a completely deployable spacecraft. This philosophy was established with the thought in mind of minimizing EVA operations. Of the three construction approaches considered in this paper, this approach will have the least needed EVA assistance in station assembly.

However, the necessary compact and integrated nature of such a deployable spacecraft places many design constraints on the attached subsystems and associated utility lines and could result ir increased program costs. The integrated nature of this beam could also be a hinderance to maintenance and repair. The growth of the nine foot deployable beam presented herein would be similar to the erectable station because of the quick-attachment joints that were provided at the nodes of the beam for that purpose. The main differences being that the number of pieces to be erected would be much higher for the smaller truss, and the resultant stiffness would be one third of the deeper erectable truss.

Fifteen Foot Erectable Beam - The objectives of this construction approach were to minimize structural part count, complexity and mass, to use the compact packaging of erectable structure to reduce Shuttle cargo bay volume requirements, and to take advantage of a developed and demonstrated technology to reduce operational risk during the Space Station assembly phase. This approach potentially requires the greatest EVA of the methods considered. However, experiments discussed in reference 5 have demonstrated the efficiency at assembling components designed with the pressure-suited astronauts capabilities and limitations in mind. Additionally, the non-integrated, sequential nature of the construction process has favorable implications for reducing programmatic development costs and risks. Assembling the Space Station system by system reduces the interface design complexity.

Developmental (SE&I) costs of insuring the deployment reliability of a highly pre-integrated, mechanistic, system are avoided with the component level assembly of Space Station. Operational development of the assembly process is essentially reduced to insuring geometric compatibility of all elements, a lower risk and cost advantage.

On-orbit maintenance and/or repair of Space Station systems (including structure) is enhanced and simplified as a direct result of using the sequential construction approach. Components installed on-orbit are, by design, more accessible and therefore, more easily maintained or replaced than those encapsulated in a highly pre-integrated approach.

Space Station growth and/or reconfiguration is accomplished as a continuation of the original assembly procedure using the same on-orbit capabilities. Intimate physical control of all added structure and/or componentry is maintained using the MRMS - a low risk, sequential approach which preserves growth versatility and could have significant cost reduction potential.

Tetrahedral Truss - The basic philosophy in the development of the station construction approach using a synchronously deployable tetrahedral truss is to take advantage of the high packaging efficiency of a double fold structure to place a large area of truss on orbit on the first Shuttle flight. Such a truss would provide a convenient "peg board" for attaching modules and payloads, and provide adequate space for large space construction. Because of the high packaging efficiency of the tetrahedral truss, it would seem prudent to deploy extra truss initially rather than trying to grow the station. However, if in a growth version it were desired to add additional modules below the ones shown in figure T-1-b, it would be necessary to add support structure, since the area below the modules must be left open for Shuttle docking. A three sided version of this station is discussed in Appendix B.

As was mentioned previously, there are two possible approaches for deploying such a truss structure. The first is to use a set of guide rails and the second is to release the truss freely in space. In the first case a relatively complex rail mechanism system would have to be developed. In the second case the truss would have to be released away from the Shuttle which would require docking with the deployed structures. There is a risk that the deployed truss would develop some rotational motion that could complicate or make it impossible to achieve docking. It would appear, however, that a relatively simple control system could be attached to truss before release to eliminate this problem.

Total assembly of a double fold deployable tetrahedral truss Space Station is similar to the erectable truss Space Station in that essentially no preintegration of utilities or subsystems with the structure is possible. This has the obvious disadvantage that higher EVA time will be associated with total station assembly than would be the case with the highly preintegrated 9 foot deployable beam station discussed earlier. On the other hand separating the various functional aspects of the total station would permit much greater freedom in the individual design or selection of each of the functions or subsystems. In a preintegrated approach to total station design, the highly compact and integrated packaging places severe design constraints on most of the subsystems being integrated together. As was the case with the erectable truss Space Station, there is almost unlimited flexibility with the tetrahedral truss station in choosing subsystem dimensions and packaging arrangements. Since utilities such as power lines and cooling hoses can be laid down from large diameter spools such as shown in figure E-9, there will be more freedom to choose from available materials than is likely to be the case where all lines must be tightly packed in a preintegrated system. The separated aspect of the station functions also has implications on maintenance and repair. The very nature in which all of the utilities are assembled permits easy access for inspection, maintenance, and replacement.

Another possible advantage to be accrued from a nonintegrated station is the programmatic possibility of constructing the station in a sequential fashion to take advantage of utilizing partial Shuttle flights over a long period of time. For example, the structure could be placed in orbit initially, and gradually added to in a low risk approach. In a preintegrated approach to station construction, a high degree of reliability must be placed into each subsystem to assure program success. The longer term sequential approach to station construction would ease reliability requirements in the various subsystems which could result in significant cost reductions.

A sequentially constructed Space Station such as the erectable or tetrahedral truss station could also reduce considerably the total SE&I function by easing restraints and interactions on the many subsystem interfaces. In a highly preintegrated design, a change in design parameters of almost any subsystem could have cascading effects on the total station design. Such changes late in the program could have serious cost implications.

CONCLUDING REMARKS

In the present paper three different structural approaches for constructing a gravity gradient stabilized Space Station were described and contrasted. The three approaches chosen are believed to be representative of the major approaches for constructing large truss structures in space. The first construction approach is one in which the station is built-up from segments, each of which is a deployable single fold beam. In this construction approach, utility lines, and subsystems are preintegrated into the beam. The second construction approach is one in which the station is erected from individual struts and utility lines and subsystems are installed as the station is built. The third construction approach is one in which the primary structure is a deployable double fold truss. In this construction approach, the utility lines and subsystems are installed after the truss is deployed. The primary differences between the three construction approaches are as follows:

Part count, weight and stiffness

Because of the larger strut length achievable with erectable structures, this construction approach inherently results in the lowest part count and weight. Due to the greater depth structure of the erectable it has a stiffness to weight ratio that is twice that of the other two construction approaches.

Structural Development

To date, no large truss structures have been qualified for space use. Although segments of various large deployable trusses have been built, there are no published results on their structural performance. There is a high degree of uncertainty in the structural performance of deployable trusses associated with free play and nonlinearity in the joints and this issue should be dealt with early in the development of any deployable truss. A large erectable truss has been built, and ground testing demonstrated that built in wedging features of the quick attachment joints eliminated free play and resulted in small joint nonlinearity.

Space Station Assembly, Maintenance, and Growth

Due to the preintegrated nature of the single fold deployable structure, its use would result in the lowest EVA time required to construct the Space Station of the three approaches considered. The amount of EVA required for total station construction would be higher but similar for the other two approaches, due primarily to the similar approach used for installation of utilities and subsystems. Repair of the erectable truss is simple due to the use of the quick attachment strut joints which are readily removed and replaced. Replacement of a damaged member in a deployable truss is likely to be a more involved process. On-orbit maintenance of the Space Station utility lines and subsystems will be a simpler process for the erectable or deployable tetrahedral truss approach than for the nine foot deployable beam station. Components installed on-orbit are, by design, more accessible and, therefore, more easily maintained or replaced than those encapsulated in a highly preintegrated approach.

Space Station growth and/or reconfiguration is accomplished as a continuation of the original assembly procedure for the erectable construction approach. Growth of the nine foot deployable beam station presented herein would be similar to the erectable station because of the quick-attachment joints that were provided at the nodes of the beam for that purpose. The main difference being that the number of pieces to be erected would be much higher for the smaller truss. The basic philosophy associated with the double-fold deployable tetrahedral truss construction approach was to place enough truss in orbit initially to accommodate growth considerations.

System Considerations

Although the study reported upon in this paper was limited to structures and construction considerations, a few observations were made relevant to the total system. The nine foot deployable single-fold beam Space Station construction approach with preintegrated utility lines and subsystems is a continuation of past experience in putting spacecraft in orbit, the basic philosophy being to build and checkout as much of the spacecraft as possible on the ground to minimize on-orbit operations. The other two construction approaches are new in the sense that final integration of the utility lines and subsystems is accomplished on-orbit, obviously involving more initial on-orbit operations. The second "non-integrated" approach provides: (1) greater flexibility in the selection of utility lines and subsystems since they do not have to be preinstalled in as tightly packaged integrated system, (2) greater flexibility in packaging since all subsystems and the structure are not preattached, and (3) greater flexibility in the launch and assembly sequence of station components. Assembling the Space Station system by system reduces interface design complexity thus having a potential significant effect on the SE&I function. For example, a downstream design change in a particular subsystem is less likely to have a large impact on other subsystems in an unintegrated system than in highly preintegrated system. Such considerations should be the subject of trade studies early in the design process of such a large, multi-launch system such as the Space Station.

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TABLE I.

ESTIMATED MATERIAL PROPERTIES FOR GRAPHITE/EPOXY LAMINATES

(VOLUME FRACTION = 60%, PLY THICKNESS = .003", LAMINATE THICKNESS = .060")

LAMINATE CONSTRUCTION	E_x 10^6 lb/in^2	E_y 10^6 lb/in^2	G_{xy} 10^6 lb/in^2	ν_{xy}	α_x 10^{-6}/°F	α_y 10^{-6}/°F	DENSITY lb/in^3
FIBER MODULUS = 75×10^6 lb/in^2							
0_{20} *	45	0.90	.70	.28	-.6	16	.063
$(90/0_9)_s$	40.7	5.32	.70	.048	-.49	2.01	.063
$(90/\pm45/0_7)_s$	33.4	7.44	2.83	.31	-.53	1.06	.063
$(90/\pm45/0_{16}/90)$	37.1	6.41	1.77	.20	-.51	1.53	.063
FIBER MODULUS = 100×10^6 lb/in^2							
0_{20} *	60	0.90	.70	.28	-.82	16	.068
$(90/0_9)_s$	54.1	6.82	.70	.037	-.74	1.24	.068
$(90/\pm45/0_{16}/90)$	49.4	8.28	2.14	.20	-.76	.85	.068
$(90/\pm45/0_7)_s$	44.4	9.63	3.58	.32	-.79	.48	.068

* SEE REFERENCE 13

TABLE II

DETAILS OF DIFFERENT CONSTRUCTION APPROACHES

CONSTRUCTION APPROACH	NO. OF STRUTS		NO. OF CLUSTERS		WEIGHT		KEEL STIFFNESS			
	1 BAY KEEL	3 BAY KEEL	1 BAY KEEL	3 BAY KEEL	1 BAY KEEL	3 BAY KEEL	EI		GJ	
							1 BAY	3 BAY	1 BAY	3 BAY
9' DEPLOYABLE BEAM STATION	1329	1645	380	448	7820	8943	2×10^{11} lb in^2	4.6×10^{11} lb in^2	0.4×10^{11} lb in^2	2.9×10^{11} lb in^2
							1 BAY	3 BAY	1 BAY	3 BAY
15' ERECTABLE BEAM STATION	648	856	178	222	3777	4955	5.6×10^{11} lb in^2	12.8×10^{11} lb in^2	1.2×10^{11} lb in^2	8.1×10^{11} lb in^2
	6 BAY KEEL		6 BAY KEEL		6 BAY KEEL		6 BAY KEEL		6 BAY KEEL	
DEPLOYABLE TETRAHEDRAL TRUSS STATION 10' STRUT LENGTH	2637		677		10,405*		5×10^{11} lb in^2		5.6×10^{11} lb in^2	

* CONTAINS 684 LBS FOR FOLDING CENTER JOINTS.

TABLE III
COMPARISON OF DIFFERENT CONSTRUCTION APPROACHES
(NORMALIZED TO REFERENCE CONFIGURATION VALUES OF TABLE II)

CONSTRUCTION APPROACH	NO. OF STRUTS		NO. OF NODES		TOTAL WEIGHT		KEEL STIFFNESS			
							BENDING - EI		TORSION - GJ	
	1 BAY KEEL	3 BAY KEEL	1 BAY KEEL	3 BAY KEEL	1 BAY KEEL	3 BAY KEEL	1 BAY KEEL	3 BAY KEEL	1 BAY KEEL	3 BAY KEEL
NINE FOOT BAY DEPLOYABLE	1	1	1	1	1	1	1	1	1	1
FIFTEEN FOOT BAY ERECTABLE	.49	.52	.47	.50	.48	.55	2.8	2.78	3	2.79
	6 BAY KEEL		6 BAY KEEL		6 BAY KEEL		6 BAY KEEL		6 BAY KEEL	
TEN FOOT BAY DEPLOYABLE TETRAHEDRAL	1.98	1.60	1.78	1.52	1.33	1.16	2.47	1.08	14.2	1.92

APPENDIX A

Mobile Remote Manipulator System For A Tetrahedral Truss

INTRODUCTION

A conceptual design is presented for a mobile RMS platform that can traverse a tetrahedral truss in a 0° and 90° direction, is reversible, and can be driven at a uniform velocity.

Space Station studies to date have focused on configurations that have a large work area for the purpose of servicing OTV vehicles, satellite repair, manufacturing ,etc. This large work area is readily provided by using deployable tetrahedral panels. Areas greater than 100,000 square feet can be provided in just one Orbiter flight. Quite obviously, to utilize such large areas requires that means for transporting the astronauts and a remote manipulator about the station must be provided. In essence, the manipulator can be mounted to a moving platform and this platform can either move on a dedicated rail system or can have an integral set of rails built in and then move along the truss surface on specially designed guide pins.

A device which walks on nodes and employs stationary tracks on the mobile platform itself has been studied in Reference 1. It utilizes a push-pull device to provide movement. The system discussed here utilizes a retractable chain drive system together with a stationary sprocket attached to the node guide pin to provide movement. This gives a near uniform traversing velocity resulting in less dynamic loading on the manipulator system. Even though the face members are in three different directions (i.e., 0°, 120° and 240°) this moveable platform can be designed to move in two orthogonal directions. This platform utilizes a chain drive with reversible motors and also be designed to change work planes as will be described later.

TETRAHEDRAL TRUSS ARMS

In figure 1 is shown a three-sided tetrahedral truss platform (item 1). Shown as item 2 on the visible face of this truss is the MRMS (Mobile Remote Manipulator System) consisting of a moving platform and a Shuttle RMS. Items 3 and 4 are pivoting platforms for plane changing and this will be discussed later.

A schematic of the rail system (item 5) which is attached to the underside of the MRMS platform (item 2) is shown in figure 2. These rails engage specially designed guide pins (item 6) and slide along these pins in a longitudinal direction. Note that there are three rails engaging these pins and that at any position, at least three guide pins are engaged. The platform can also be moved transverse to this direction by means of three rails transverse to the first three rails.

At the appropriate location, the platform is stopped and the direction changers (item 7) are rotated 90 (see figure 3). The platform is then free to move in the transverse direction as shown in figure 4.

Figure 5 shows a partially exploded view of the platform and rail system. Note that the rails have "T" slots cut in them and that these slots are flared at each end for proper engagement of the guide pins. This figure also shows a schematic of how this vehicle can be propelled along the guide pins by using a chain drive (item 9). These chain drive boxes pivot up or down about hinges (item 10).

View A is shown in figure 6 and shows how the guide pin (item 6) is being engaged by the flared mouth of the "T" slotted rail (item 5). Note that this guide pin has an engagement sprocket (item 13). This sprocket could be square so that more teeth could be engaged by the drive chain. As the platform moves to the right the drive chain (item 9) engages the guide pin sprocket (item 13). There is at least one guide pin and sprocket being engaged at any one time by the two drive chain boxes.

Since there are two sets of chain drives for transverse and longitudinal movement, one set of the chain drives must be engaged while the other set is in a disengaged position. When the direction is changed, the two sets of chain drives are reversed. A close-up of section B-B of figure 5 is shown in figure 7. The chain drive (item 9) is shown as an end view. When its engaged with item 13 it is in the down position. To disengage, this box is rotated 180° CW about point A. In order to do this, gaps in the rail must be opened to permit passage. This is done by pivoting rail segments (item 11) about point B out of the way. This is shown more clearly in figure 8 which shows an enlarged view of the middle of the rail system. Note that two chain drives are down in the engaged position and two are pivoted in the up disengaged position. Also notice that the two drive boxes overlap slightly and that they are located on opposite sides of the guide rail.

Figure 9 is the enlarged view D showing the direction changer (item 7). The rail junction would have a cylindrical cavity into which this item would fit. A specially designed actuator or gear and pinion drive would rotate this 90° each time a direction change is desired.

Figure 10 shows a schematic of the chain drive. All four boxes need to be synchronized so they will not interfere with each other as the drives are switched.

To change direction then, the following must be done:

a. Direction changers (item 7) rotated 90°.

b. Rail segments (item 11) pivoted up.

c. Chain drive boxes (item 9) rotated 180°.

d. Rail segments (item 11) pivoted back down.

PLANE CHANGE

To properly use this MRMS on a truss structure such as shown in figure 1 where six work platform faces exist, the MRMS must be able to change work planes. In this configuration, there are three outer work planes and three inner work planes. This transfer from plane to plane can be accomplished using specially designed pivoting platforms.

Figure 11 is a schematic of going from one outer plane to another outer plane by going around the apex. The succession of views show how this is done using item 3, the pivot platform. This platform would have the same basic pattern of guide pins mounted to it so that the MRMS can be driven onto it. Once on the platform, the platform and MRMS combination is pivoted 120° at which position the MRMS can transfer onto the adjacent plane.

A procedure for transferring from an outer plane to an inner plane is shown in figure 12. This is the same basic concept as before except that this pivot platform has to rotate 180° and also has to translate five feet along the axis of rotation to align guide pins.

APPENDIX B

Delta Tower

INTRODUCTION

An alternate approach for constructing a gravity gradient Space Station that has a large area for accommodating a variety of payloads, servicing satellites and OTV's is shown in figure B-1. The large triangular keel shown in the figure can be a deployable tetrahedral truss design that can be packaged in one Shuttle flight. This concept provides a very stiff structure as well as a large work area. The total weight of this truss would be around 20,000 lbs. assuming 2" diameter struts with -035" thick walls. This appendix addresses the option of deploying three long tetrahedral truss panels attached to each other to form a delta shaped keel.

DELTA TOWER CONFIGURATION

The central keel of this concept consists of three tetrahedral trusses that are 60 ft. wide, 416 ft. long, and 8.16 ft. thick. Transverse to the keel are tetrahedral truss beams that are attached to the delta through the rotary joints. The station being discussed in this section is identical to the tetrahedral truss station discussed in the text and shown in figure 1-1-a with two additional truss planes added to form the delta keel. As can be seen in figure B-1 the modules are attached at the delta. This arrangement shows the command hab., and logistics module attached to one apex and laboratory modules attached to the other two apexes. Shown on the near face of the delta column is a mobile remote manipulator system (MRMS) that can traverse in both direction and can be transferred to all six inside and outside planes as discussed in Appendix A. This MRMS can also be designed to cross the rotary joint and traverse the solar array truss for operations on the array boom.

Since the delta keel is made up of trusses that are 60 ft. wide, the inside of this column can be used as comoartmented protective enclosures that could be used for servicing large spacecraft.

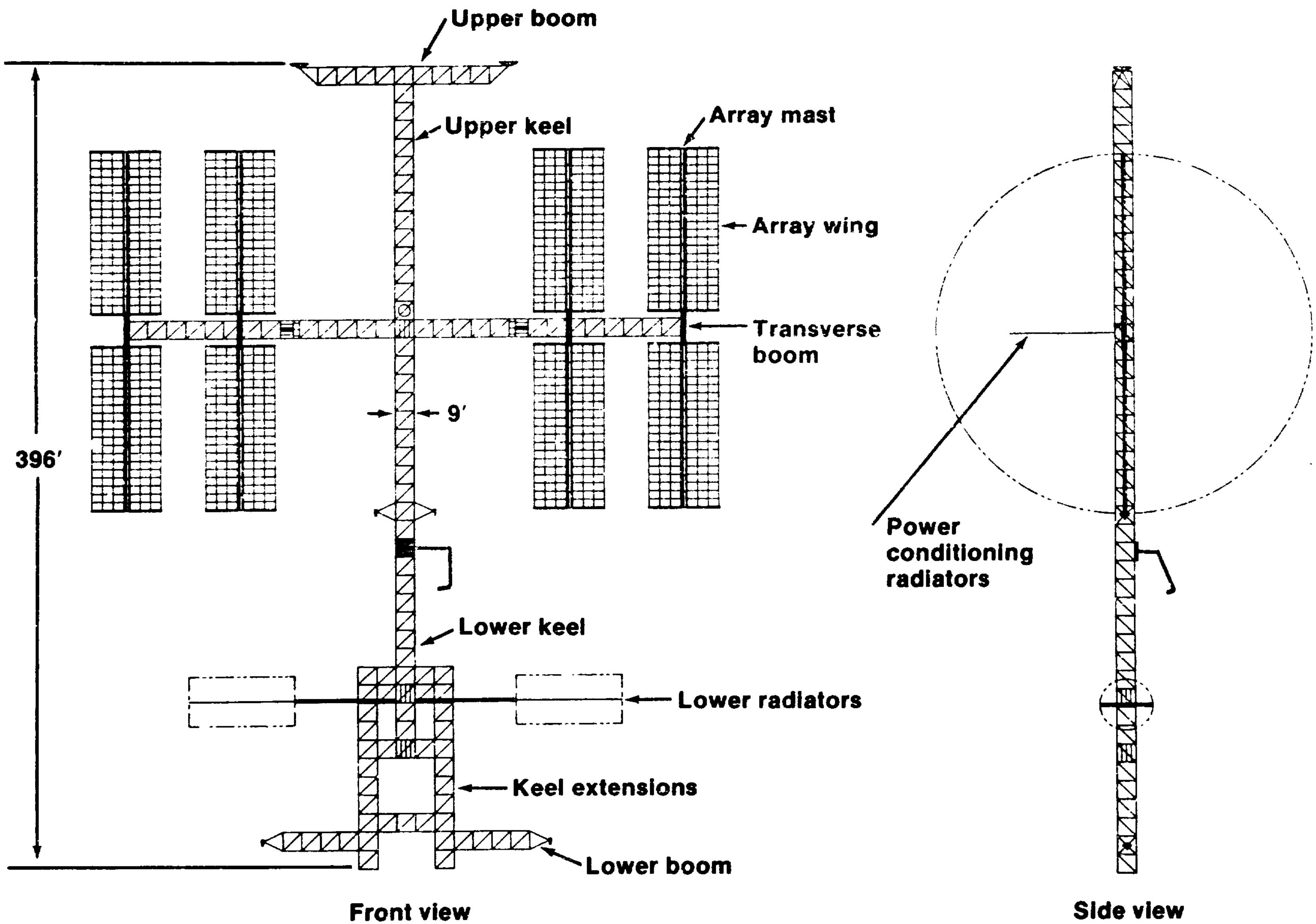


Figure 1. Overall space station dimensions and nomenclature.

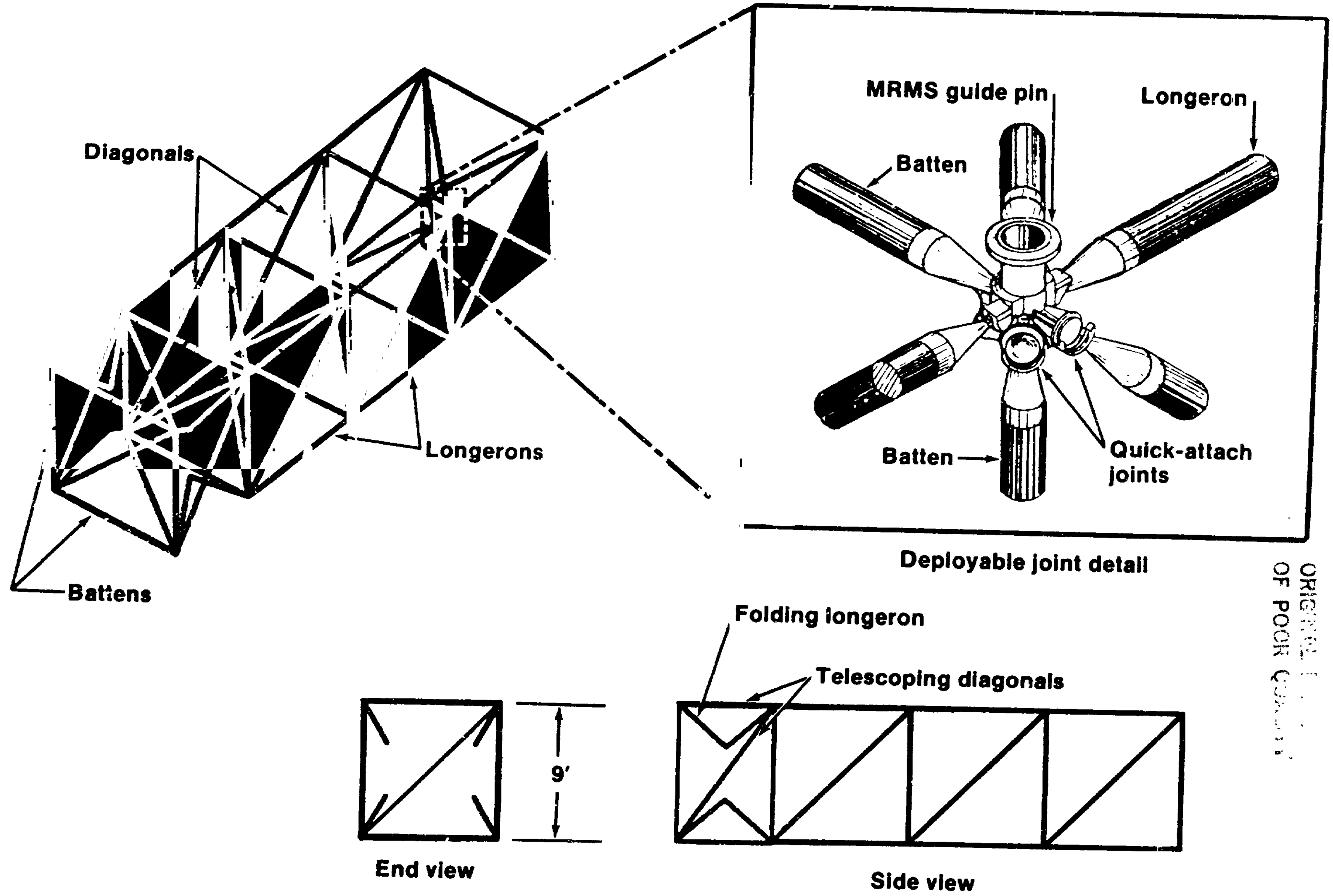


Figure 2. Schematic of deployable beam showing one bay being deployed and detail of joint.

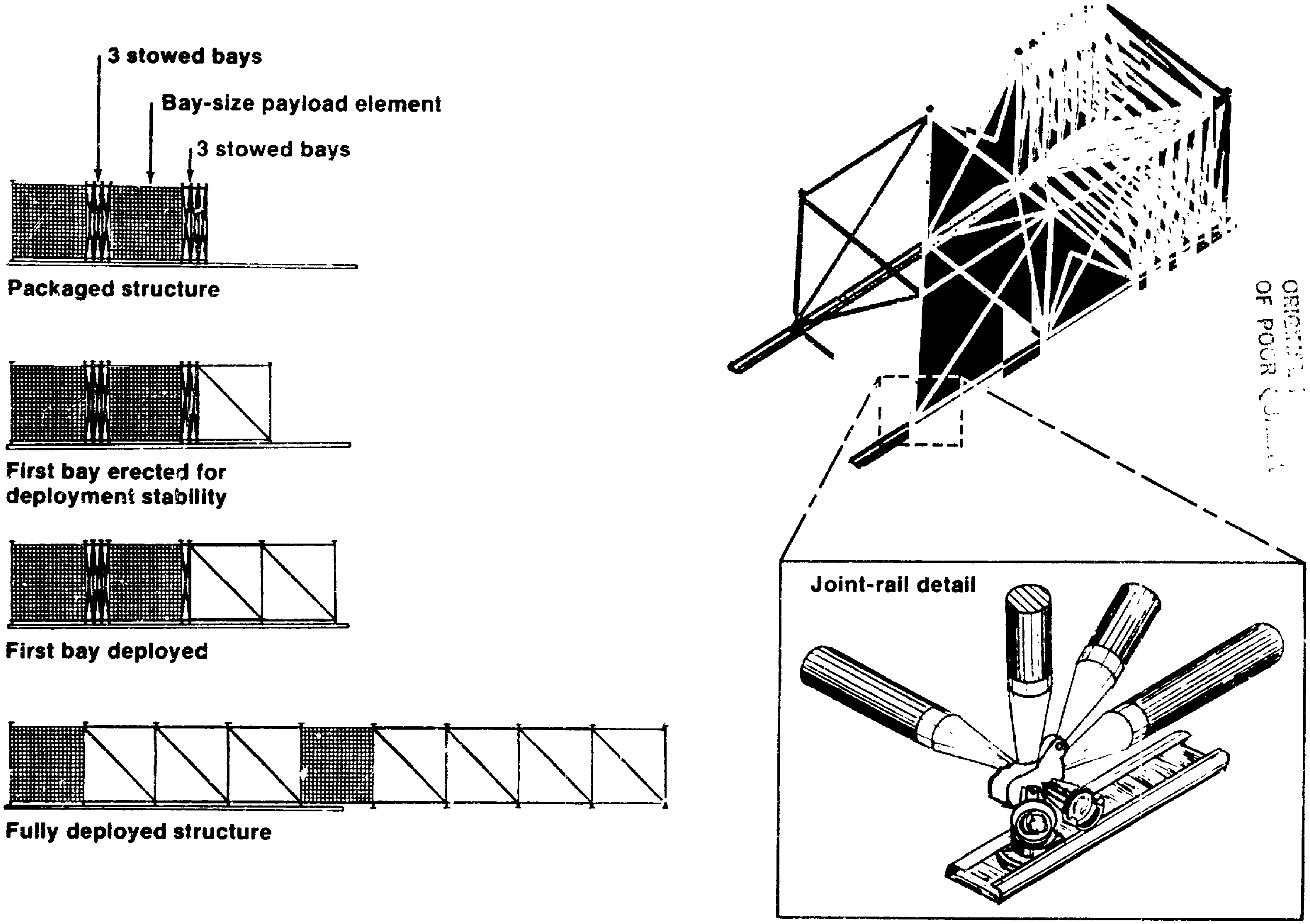


Figure 3. Truss deployment sequence and rail detail.

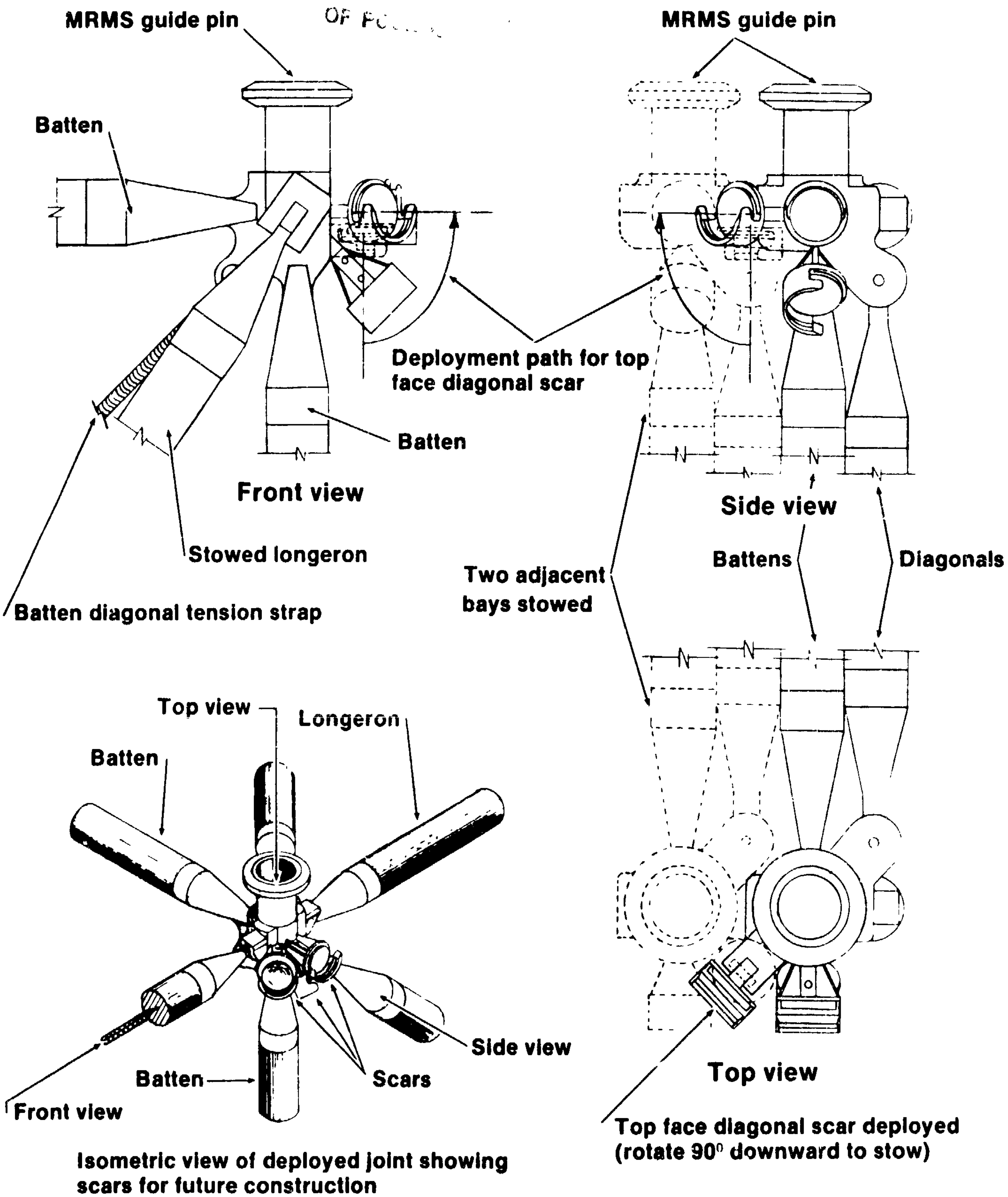


Figure 4. Details of a deployable joint showing attached MRMS pin and erectable side joints ("scars").

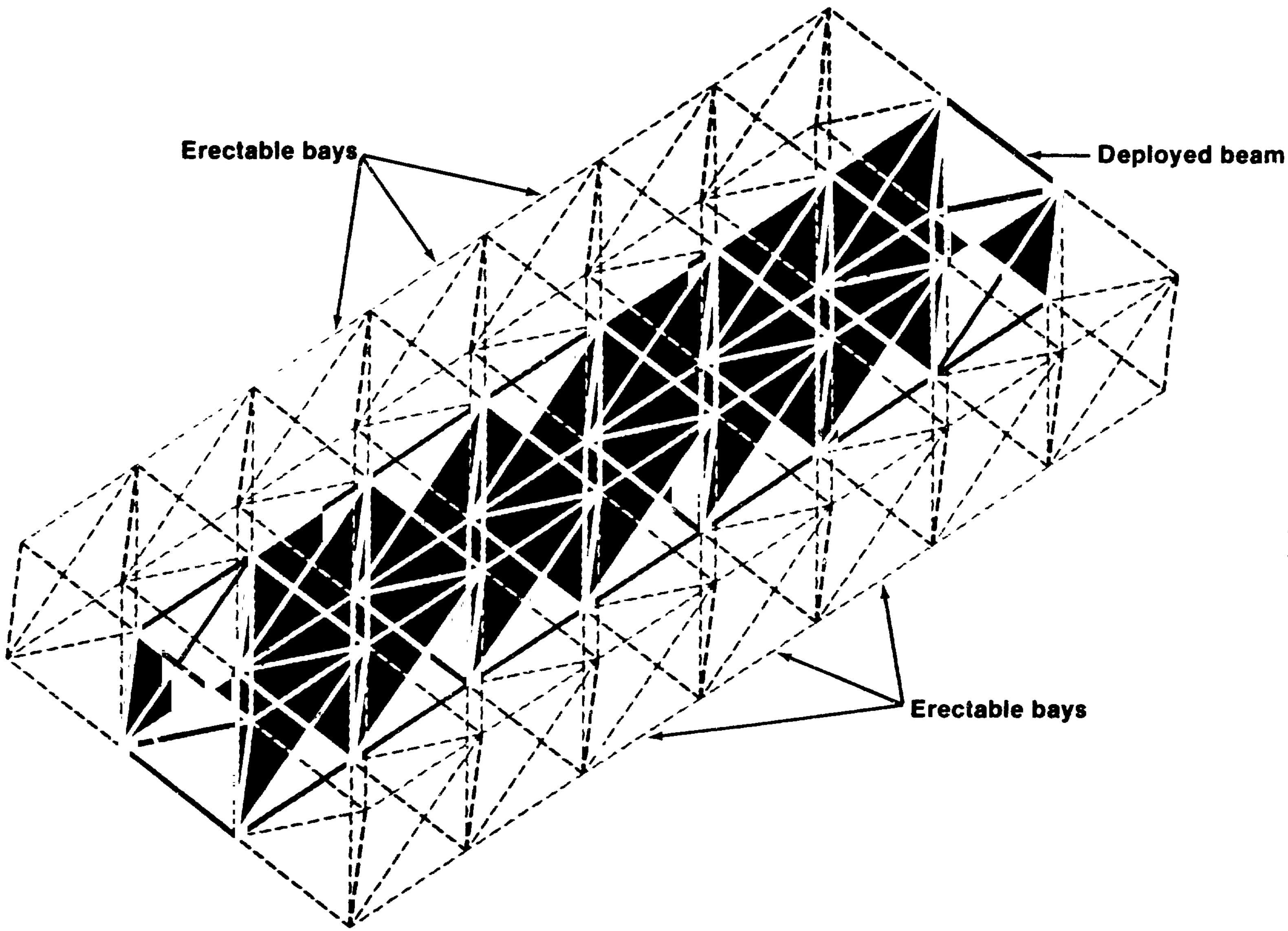


Figure 5. Schematic showing deployed beam and added erectable structure.

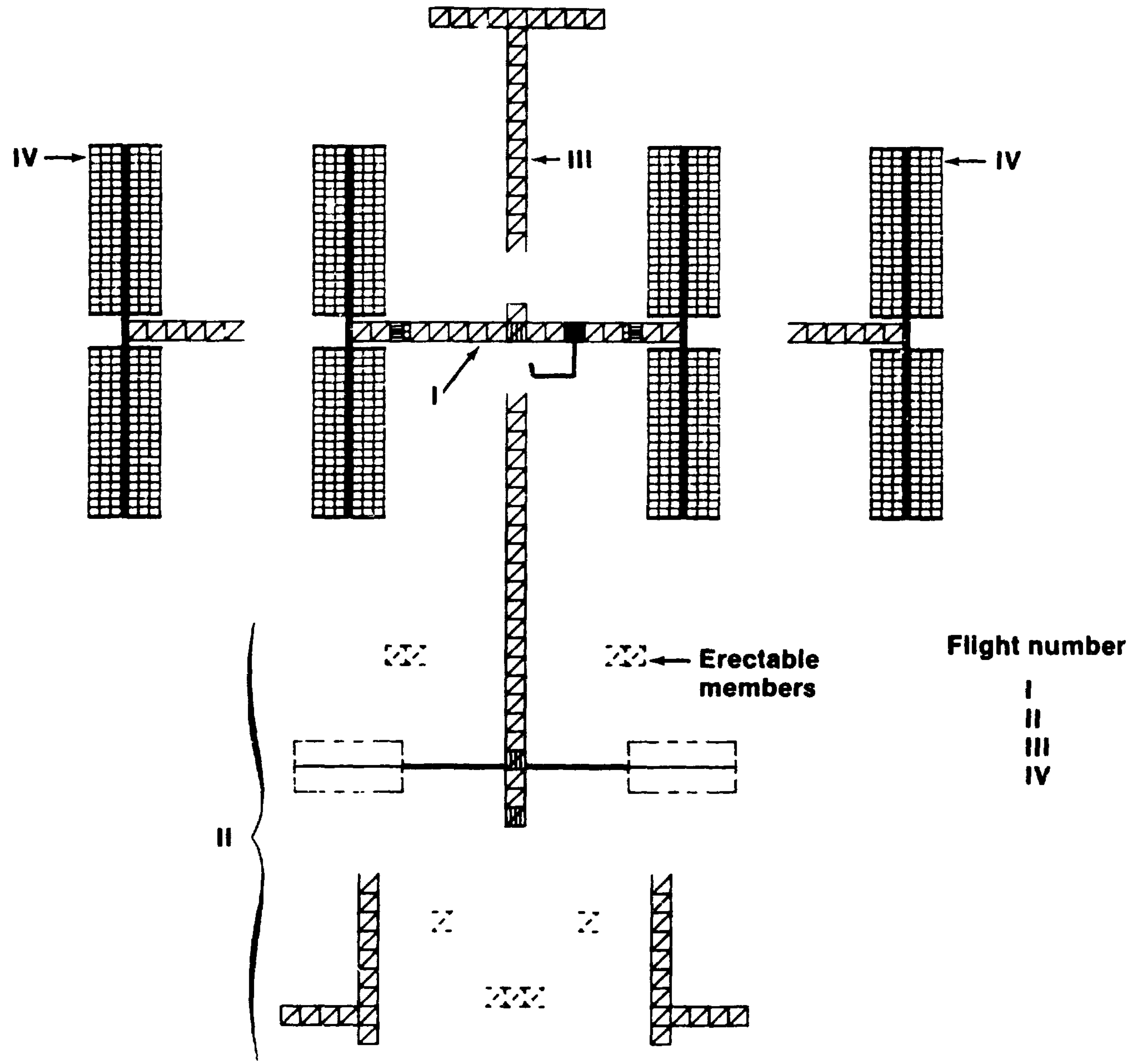


Figure 6. Launch sequence for various elements of the space station.

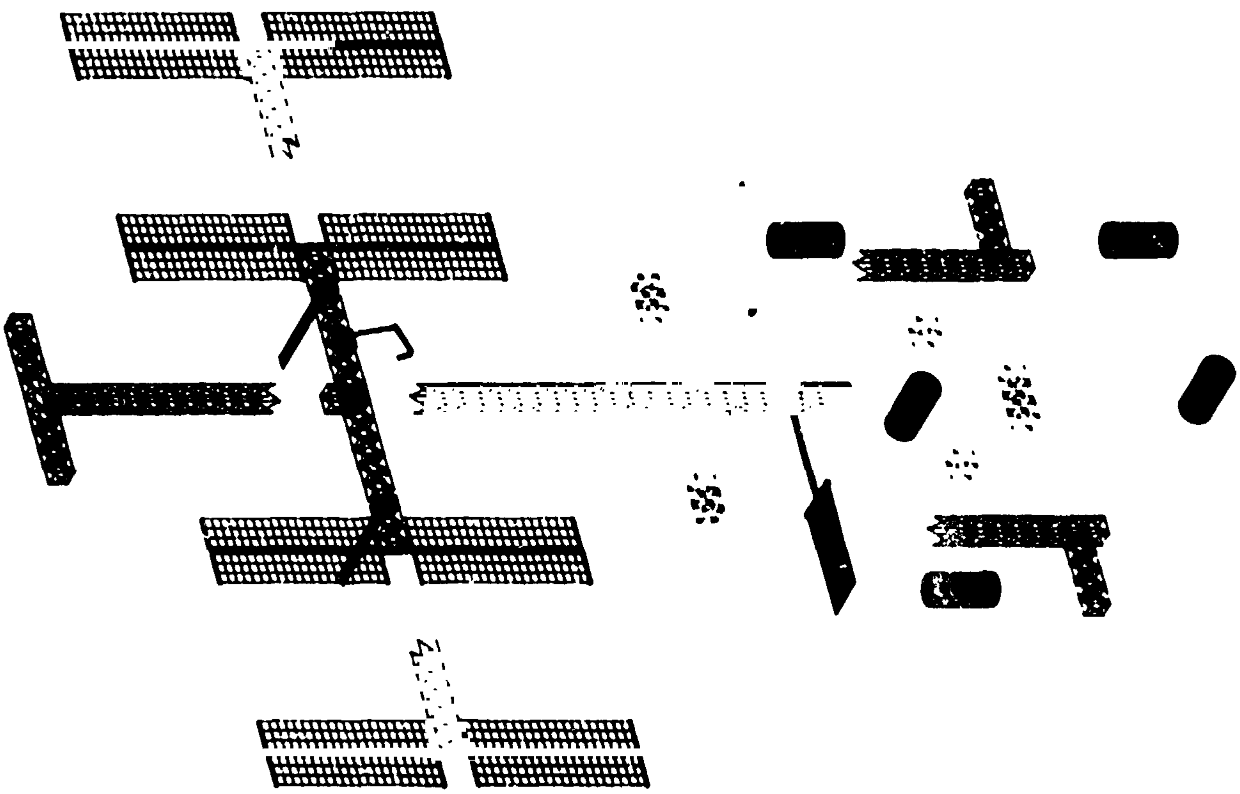


Figure 6 (cont.). Oblique view showing modules.

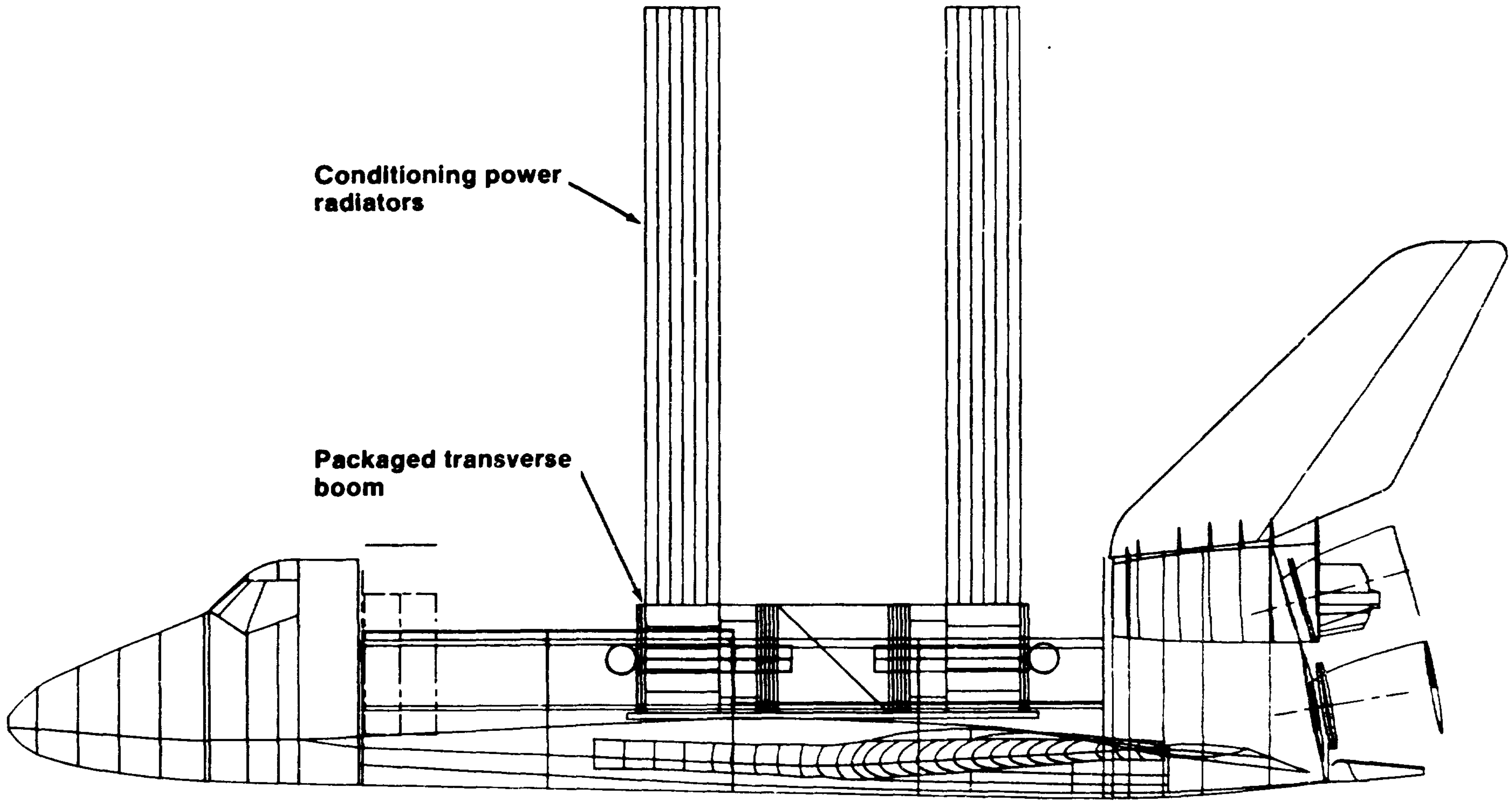


Figure 7. Power conditioning radiations shown installed on first launch package while still in cargo bay

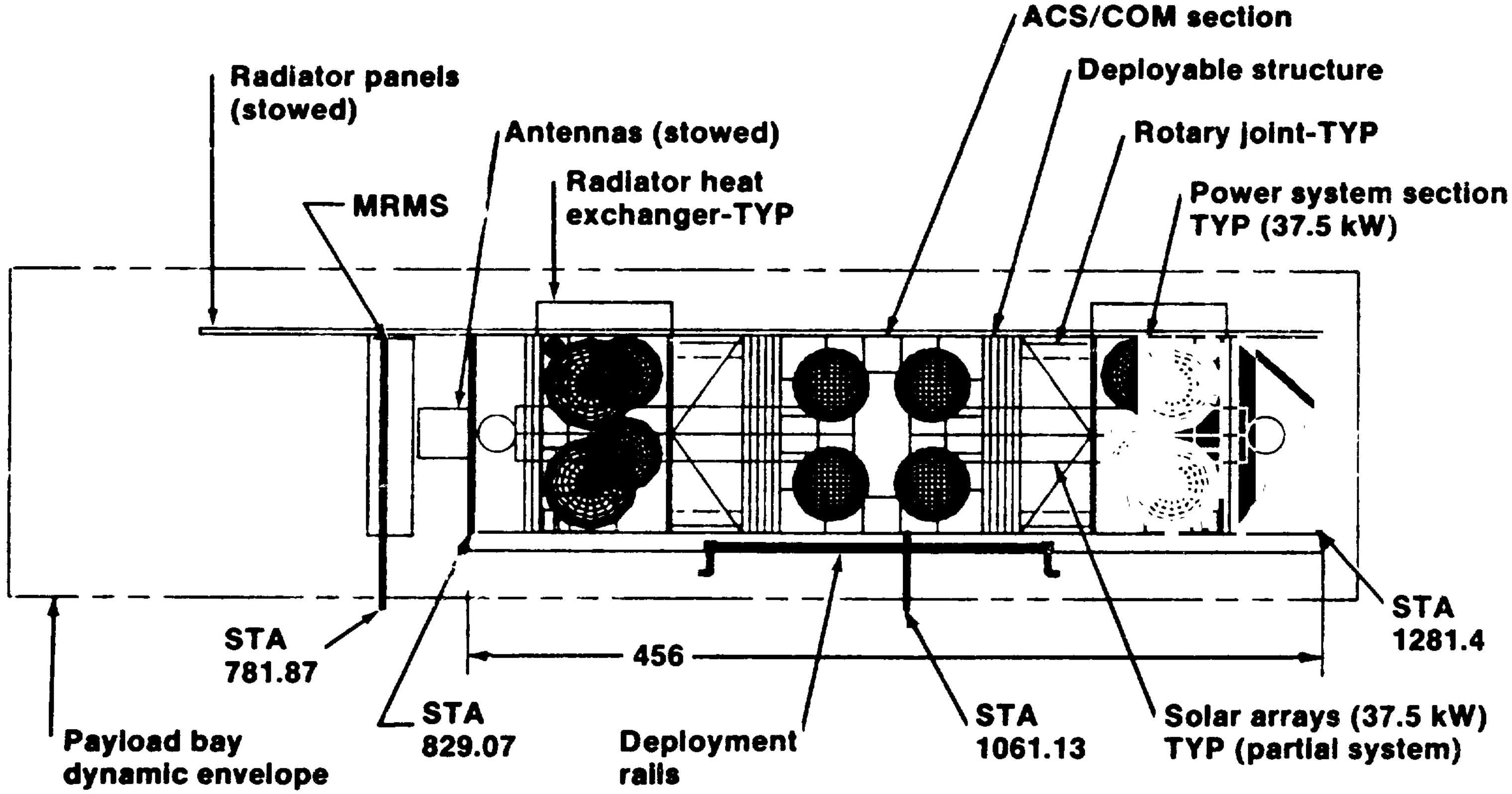


Figure 8. Transverse boom, first launch package.

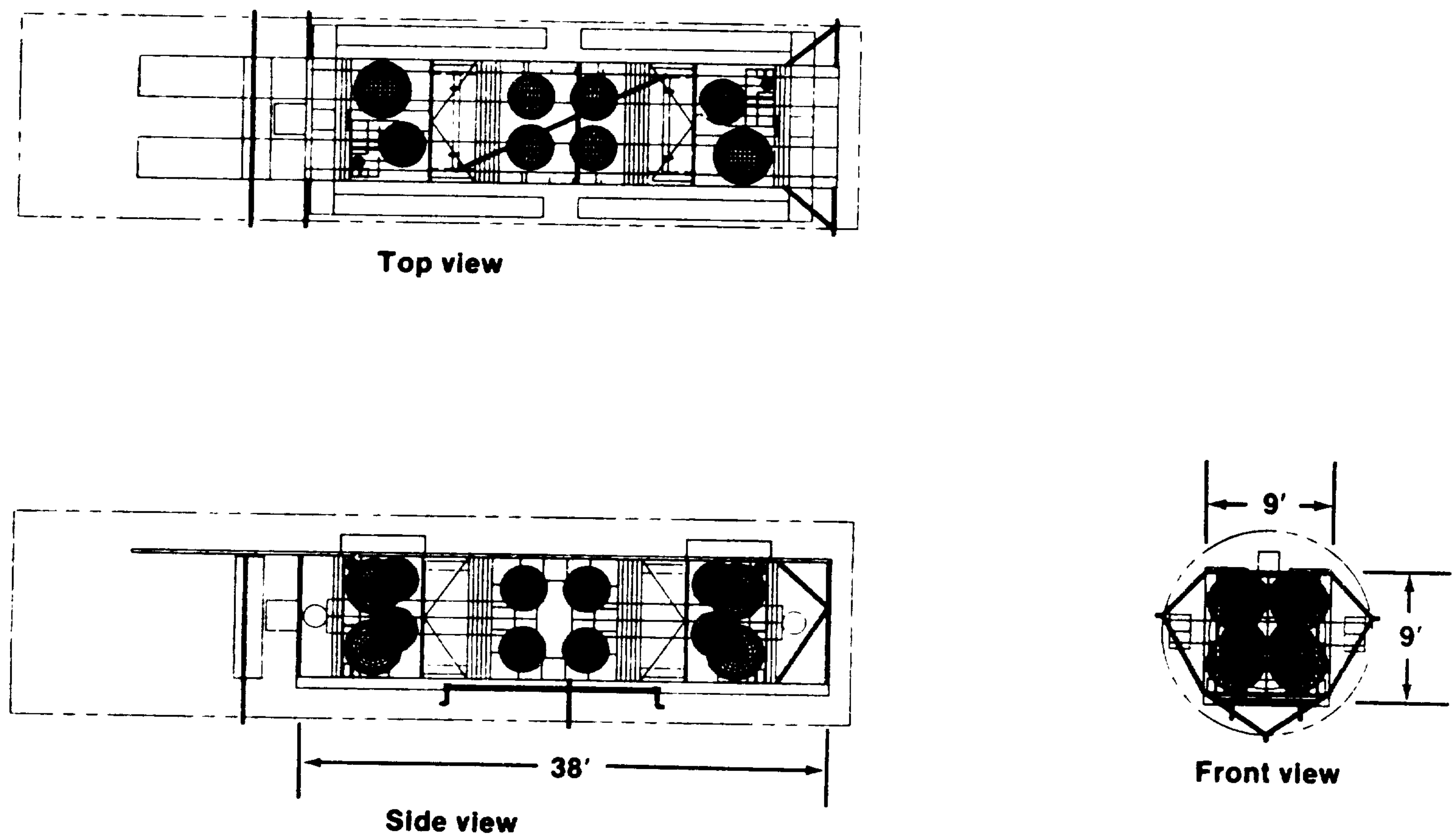


Figure 8 (cont.). Three views of first launch package.

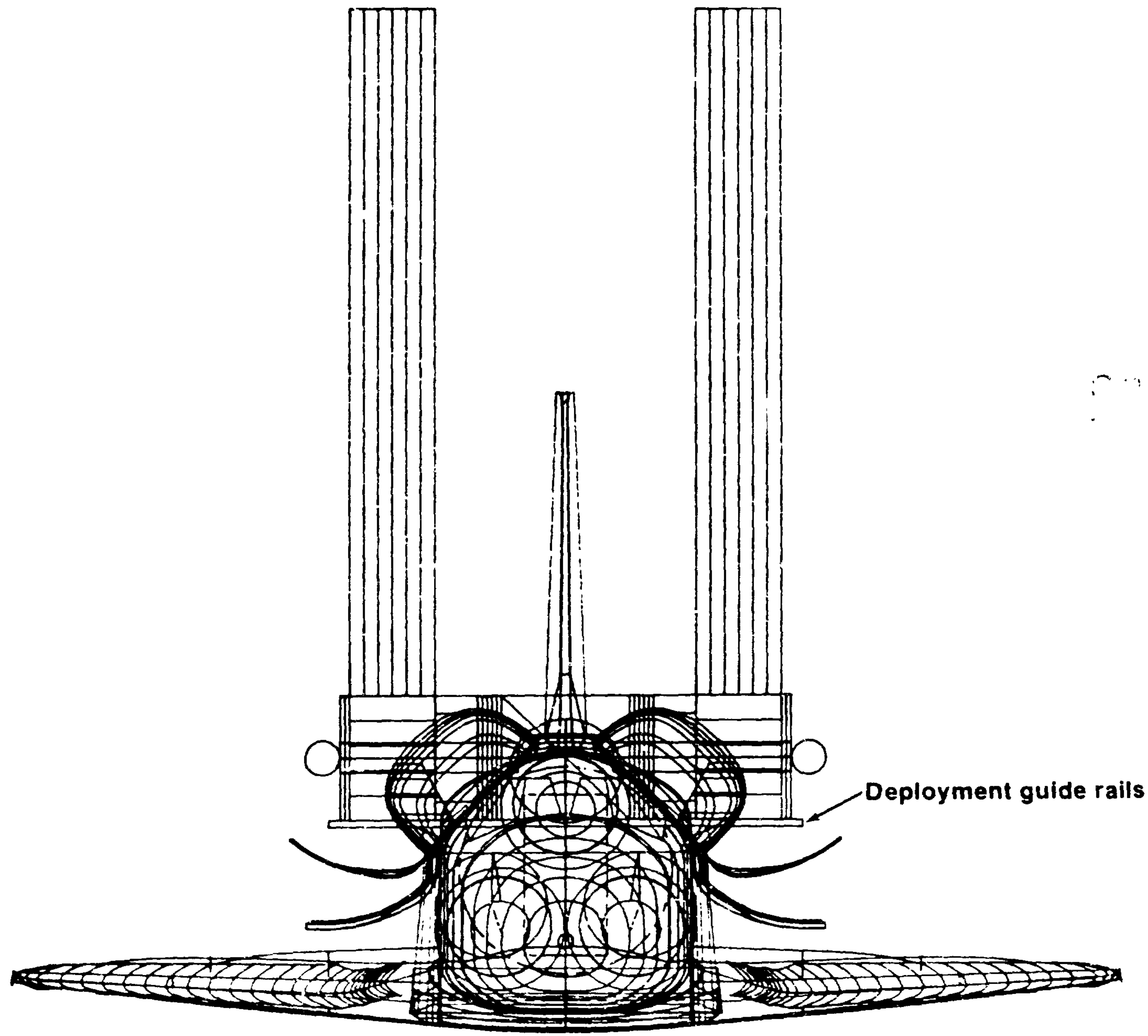


Figure 9. Launch package removed from cargo bay using SRMS, rotated 90° and attached to cargo bay sides.

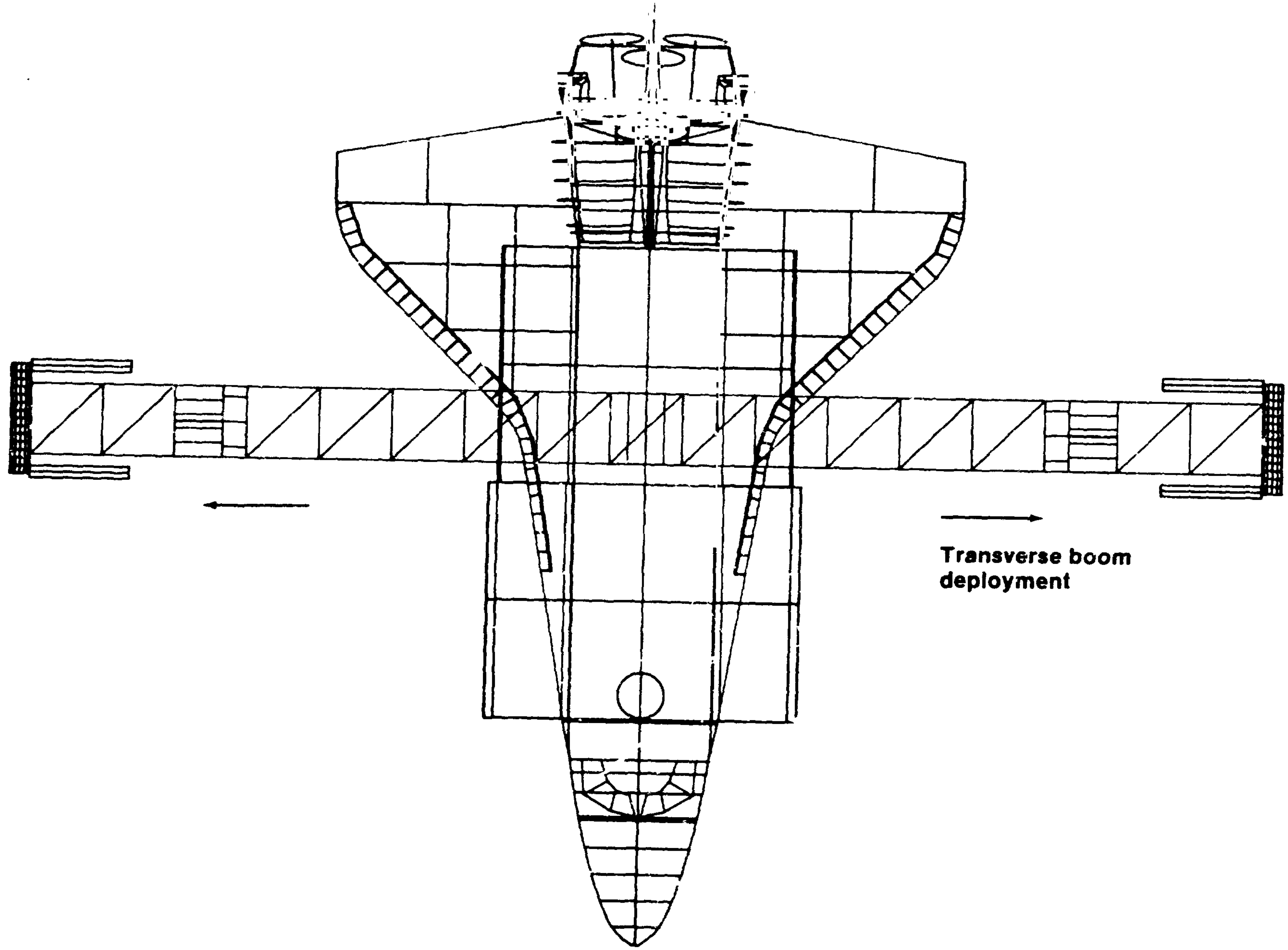


Figure 10. Transverse boom deployed from guide rails.

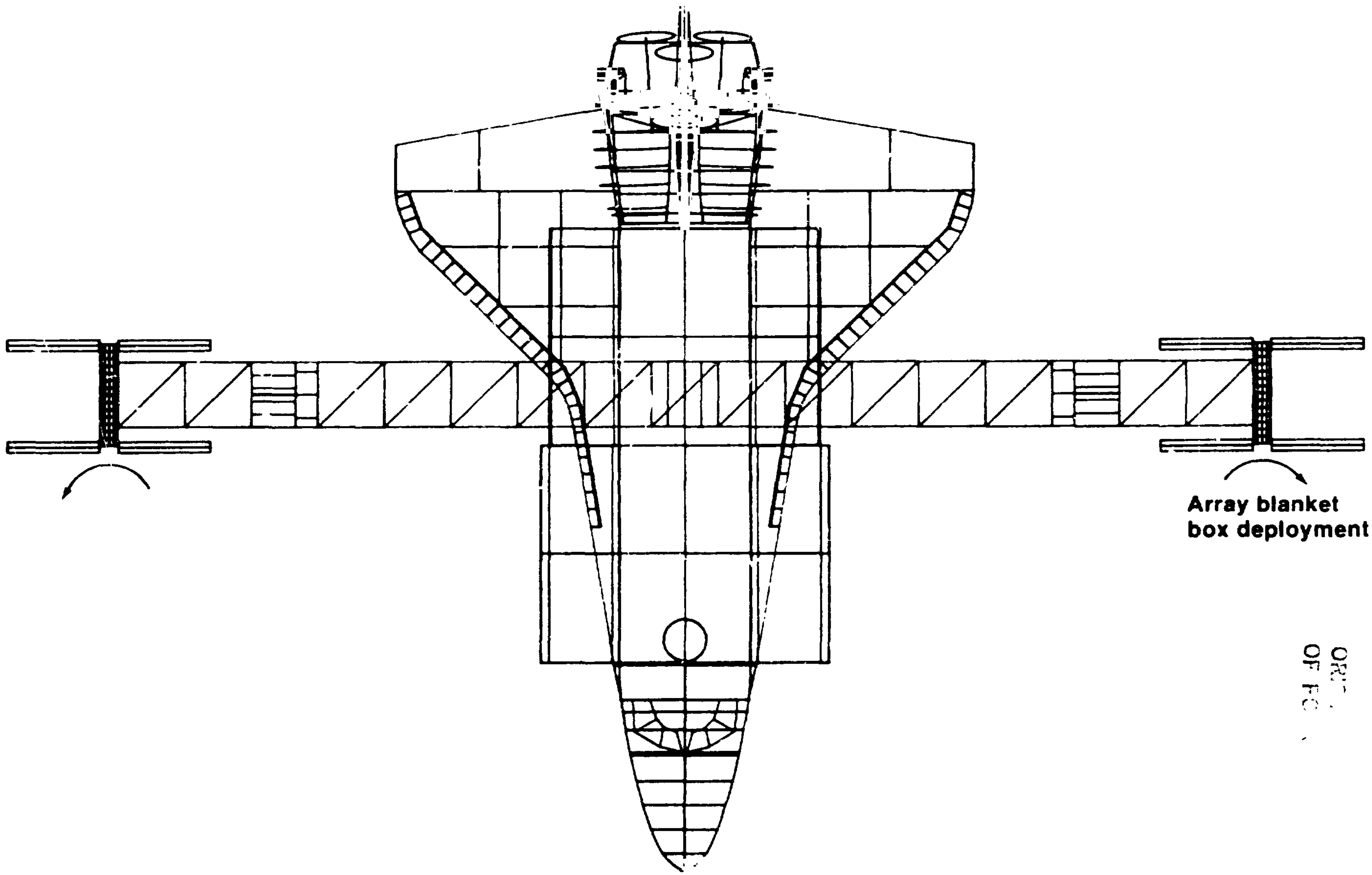


Figure 11. Top half of solar array blanket box rotated into position and ready for blanket deployment.

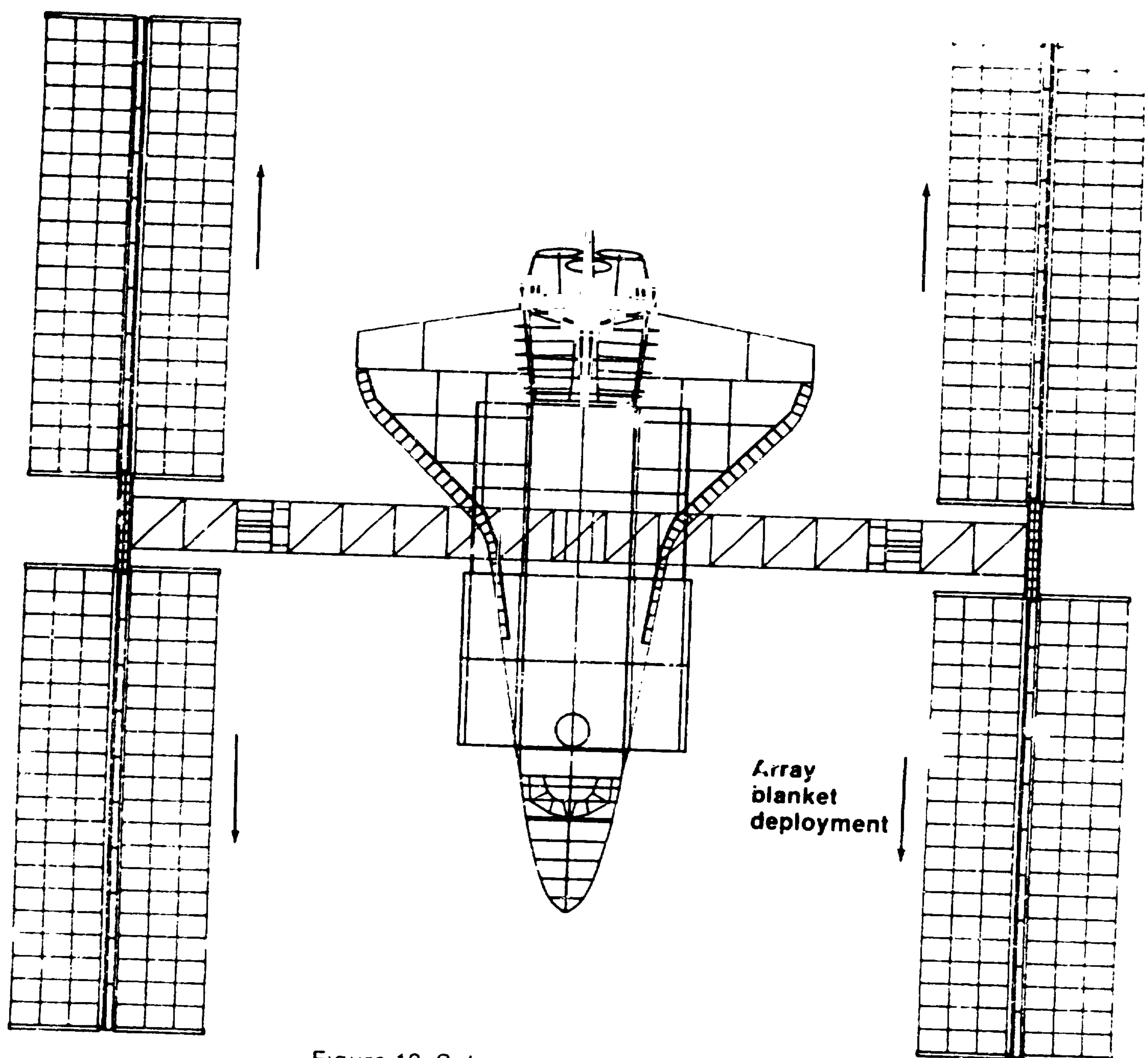


Figure 12. Solar array blankets deployed

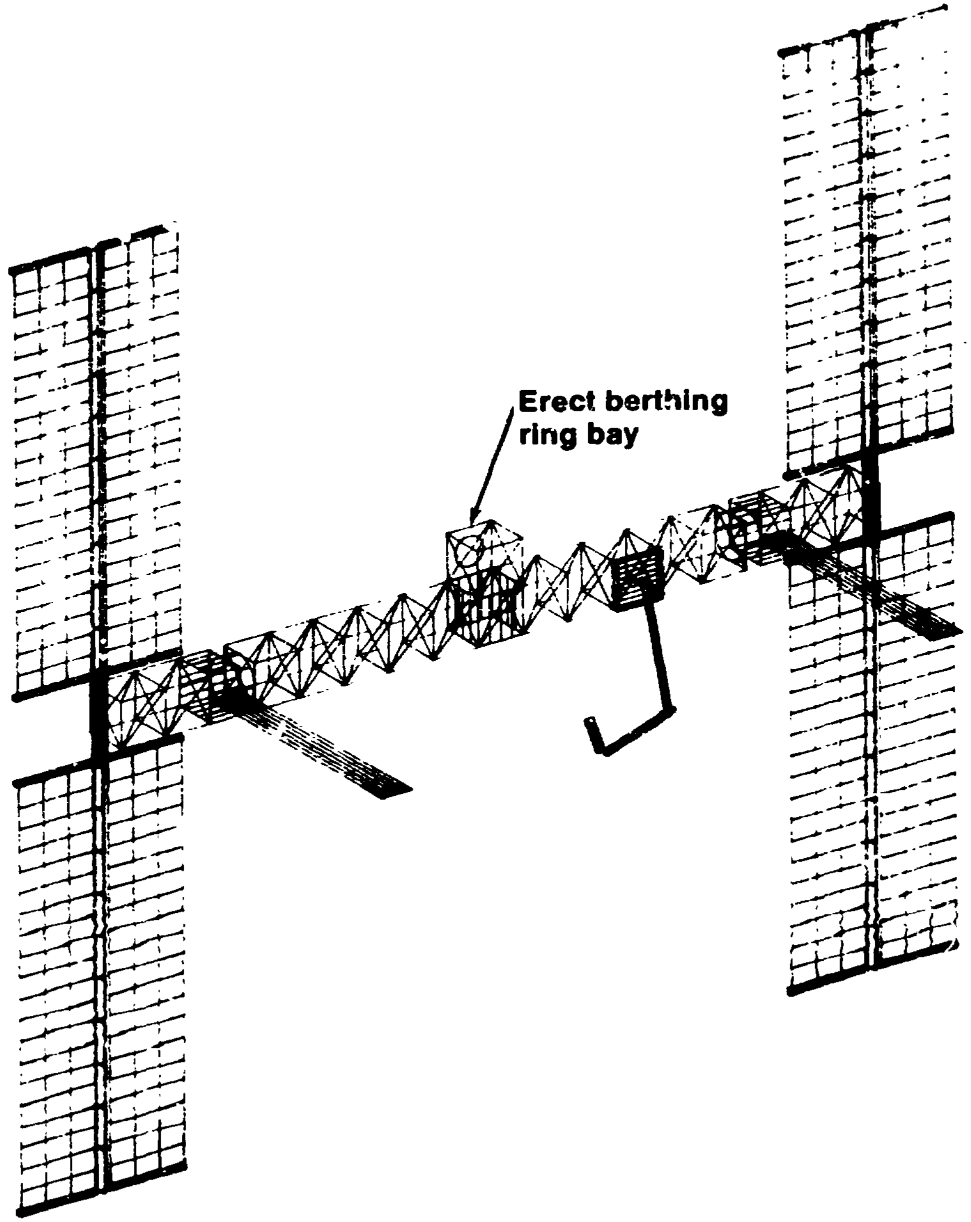


Figure 13. Side bay erected on transverse boom to accommodate a berthing ring for second flight.

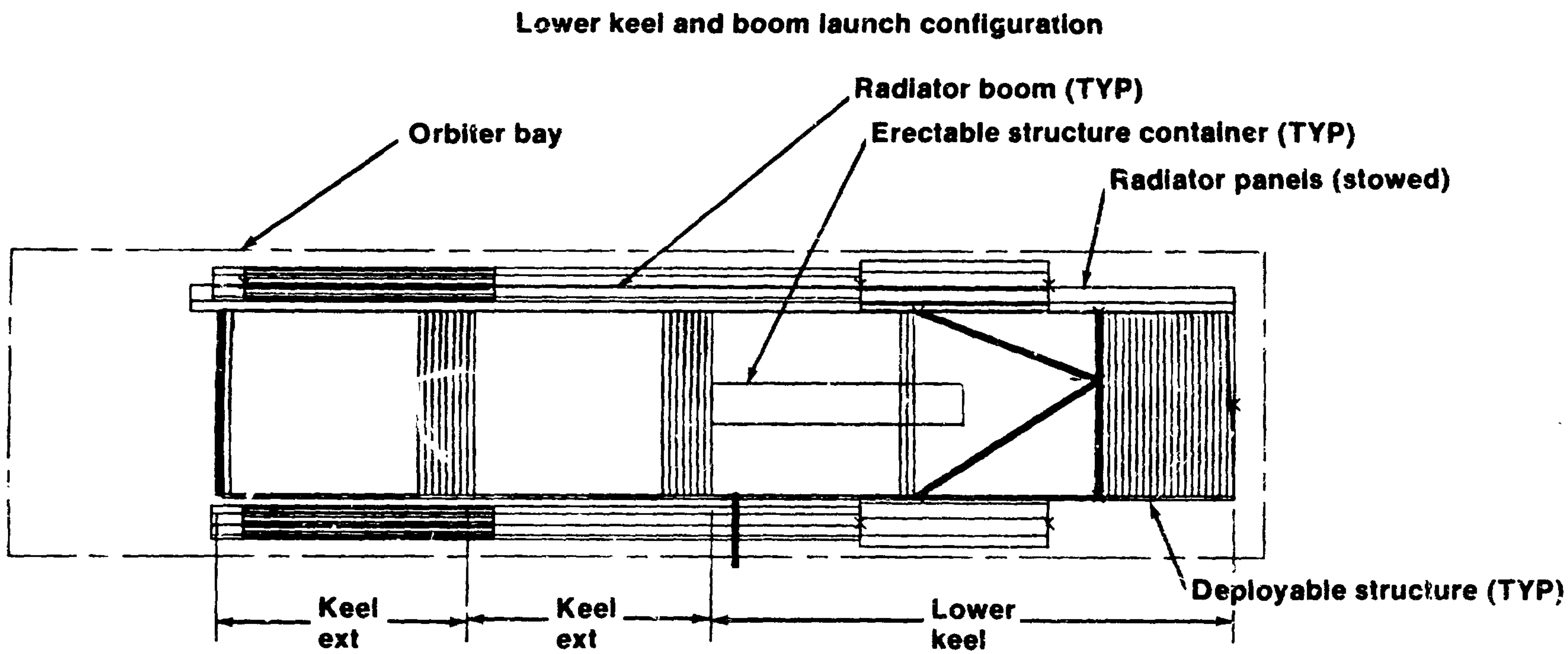


Figure 14. Second launch package.

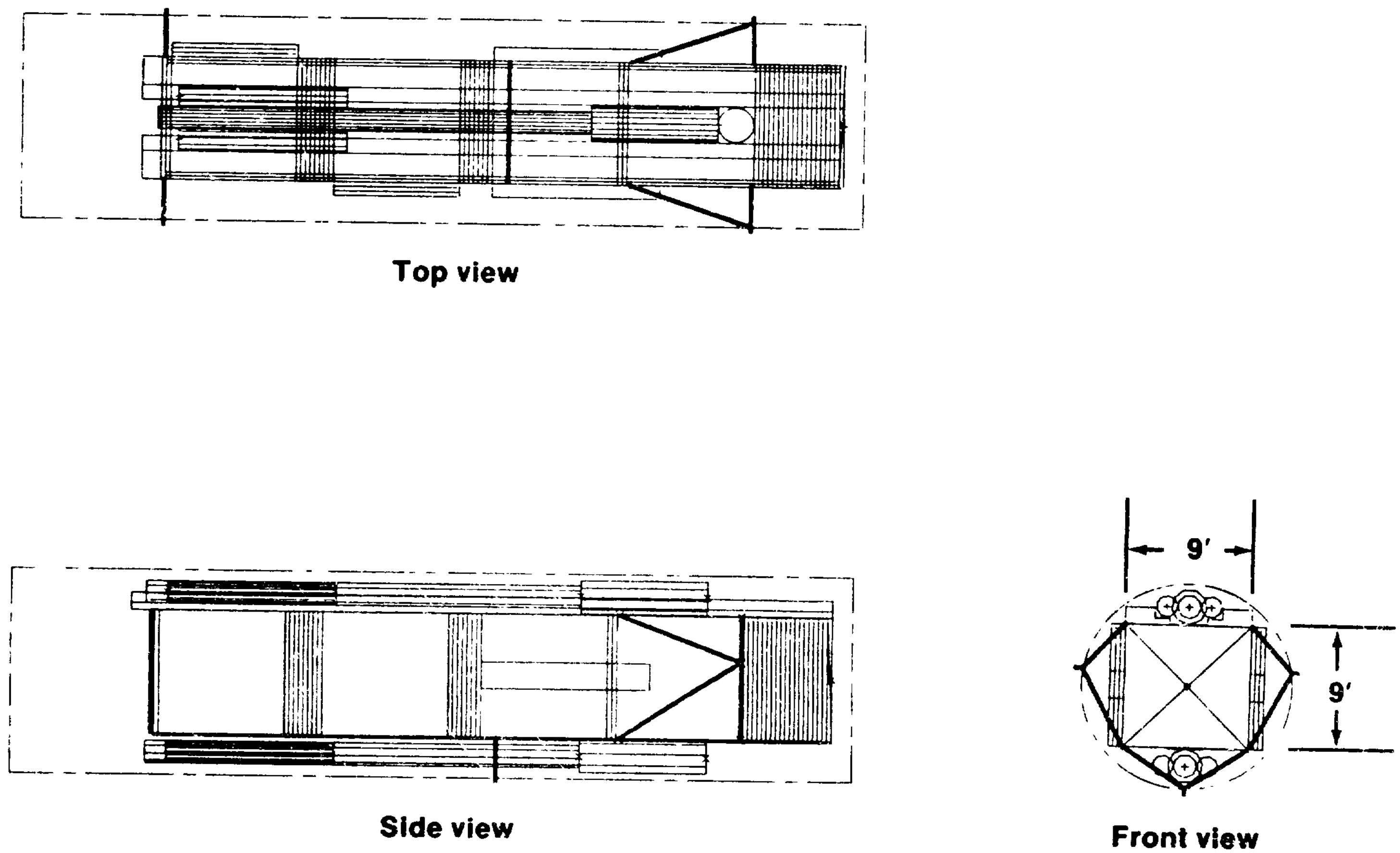


Figure 14 (cont.). Three views of second launch package.

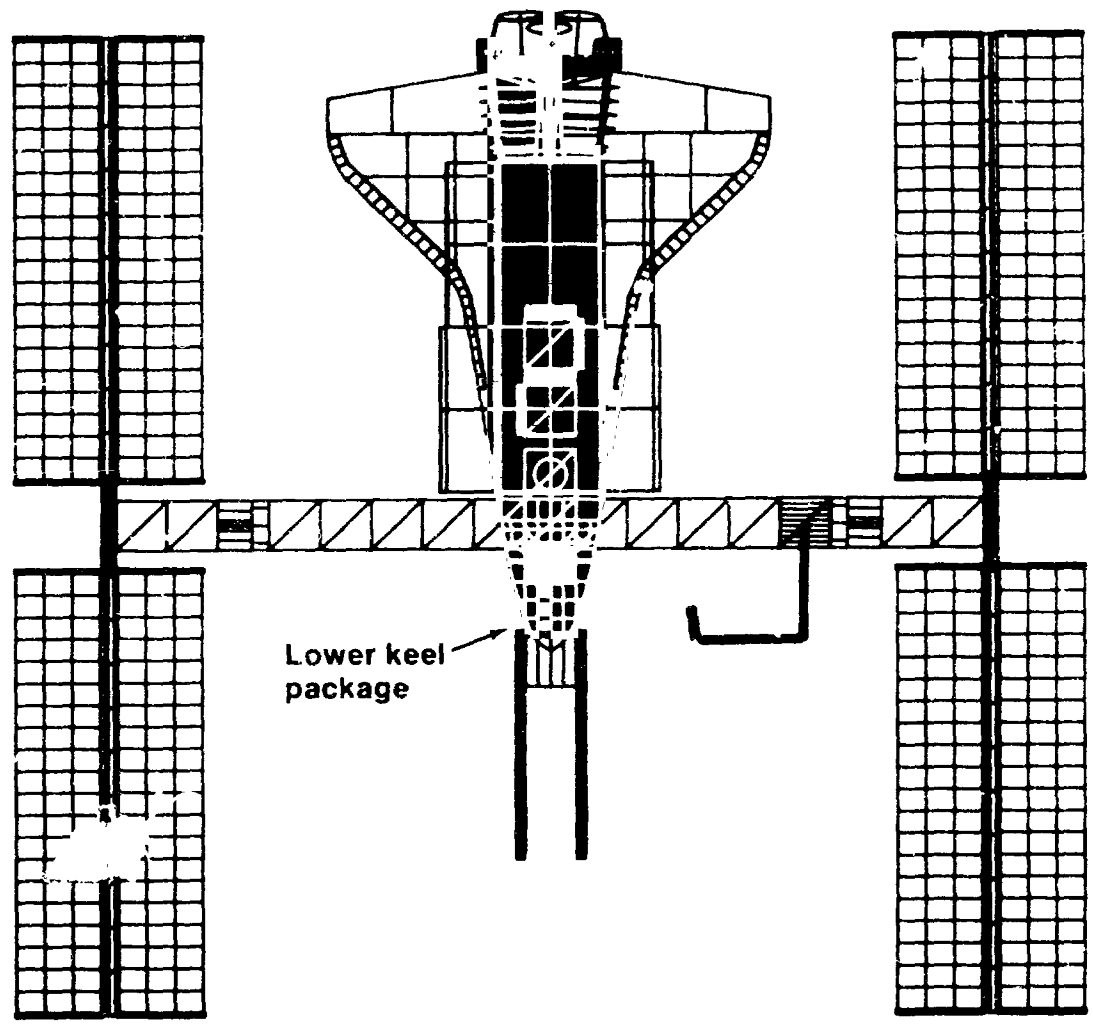


Figure 15. Beginning of second flight build-up. Shuttle shown attached to berthing ring on first flight package. Lower keel package shown removed from cargo bay and attached ready for deployment.

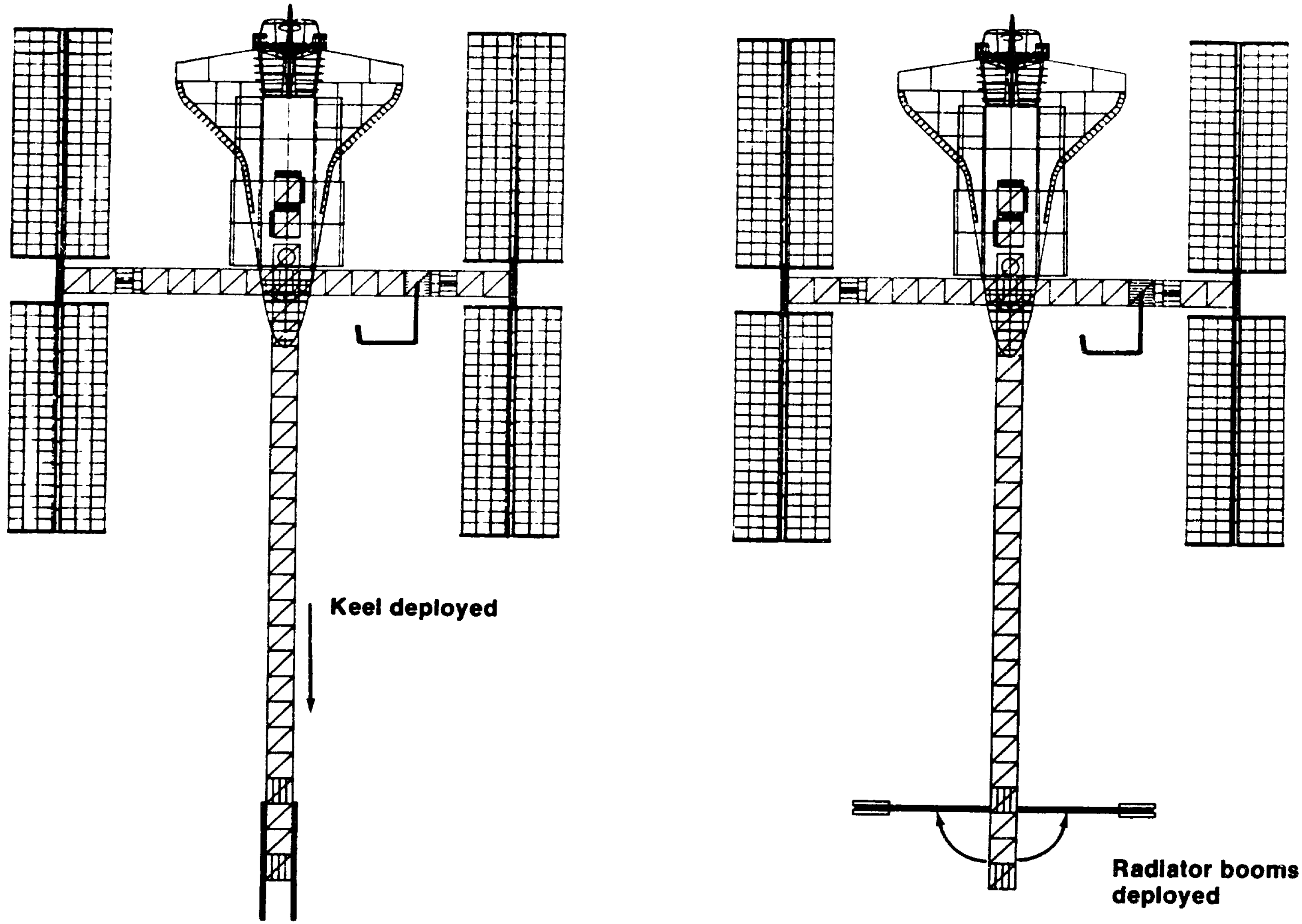


Figure 16. Lower keel structure and radiator boom deployed.

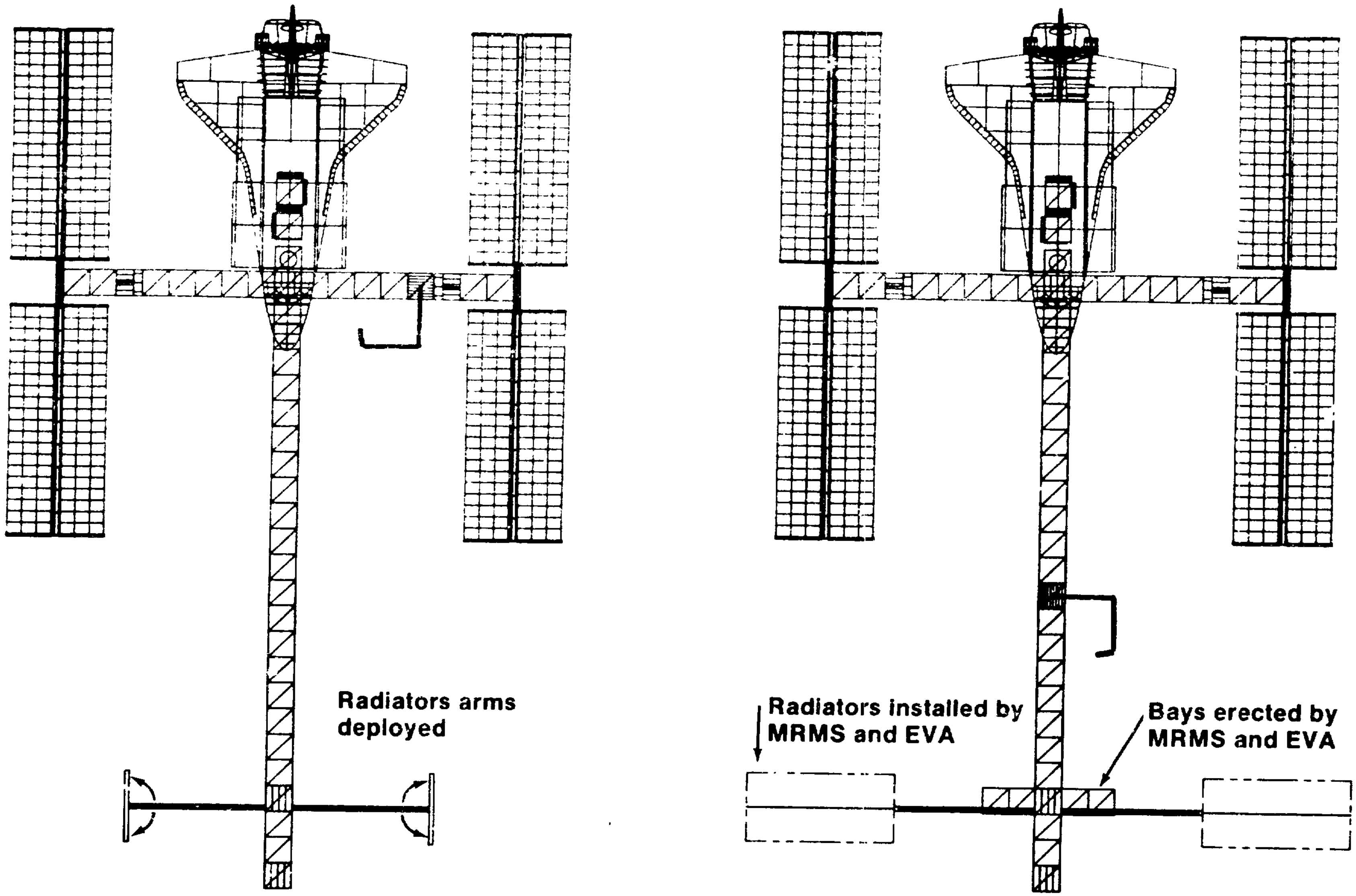


Figure 17. Radiator arms deployed and radiators installed.

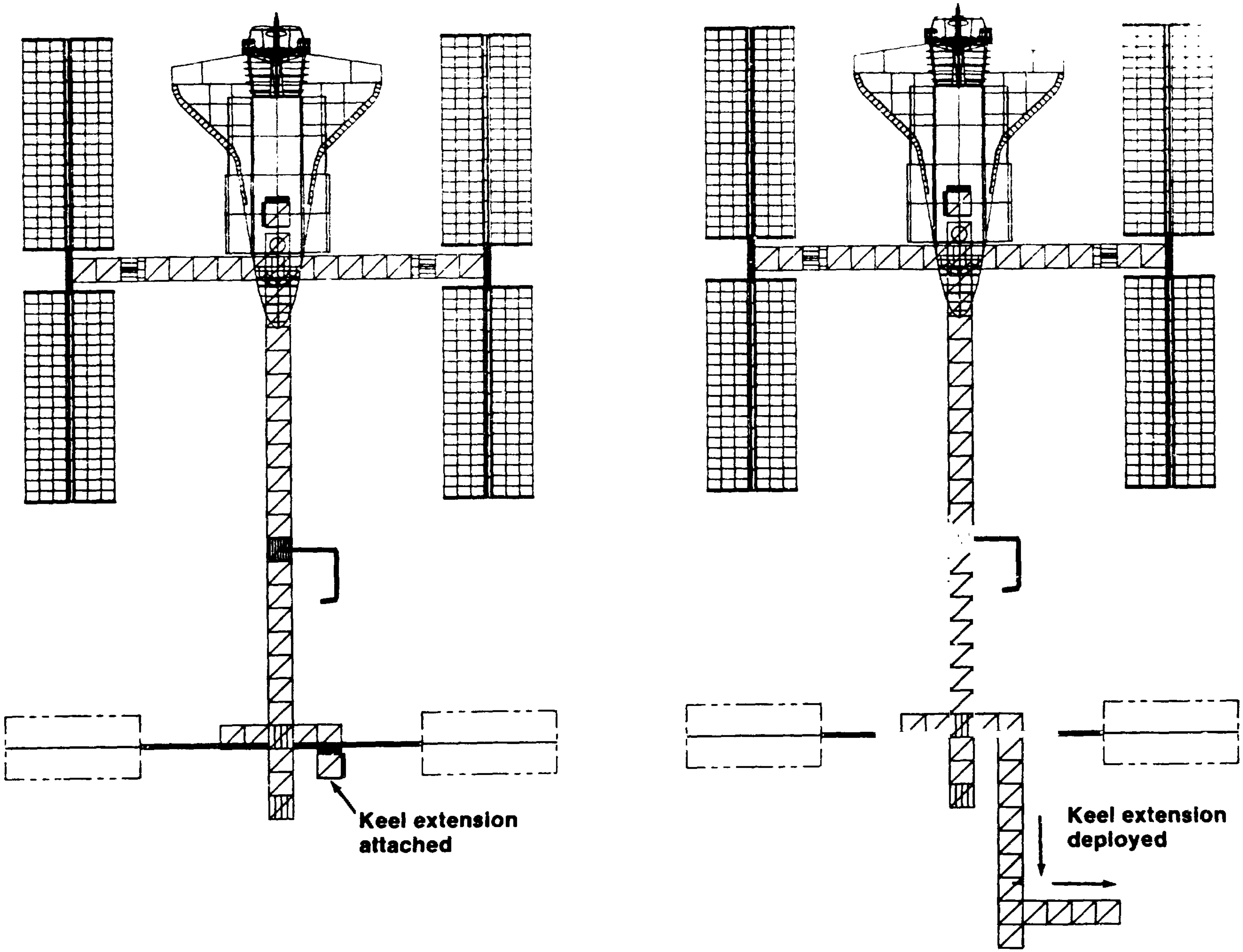


Figure 18. Port keel extension attached and deployed.

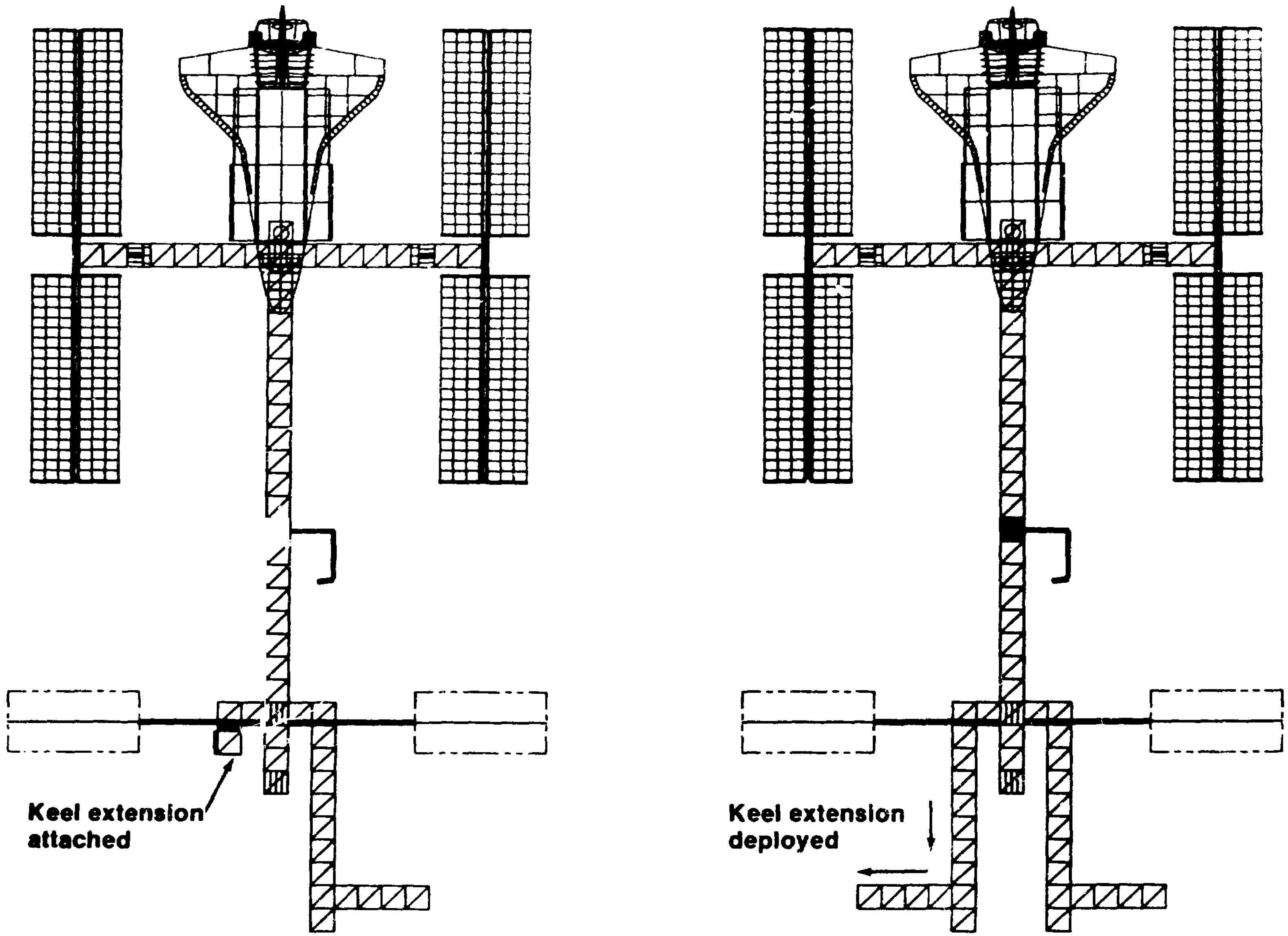


Figure 19. Starboard keel extension attached and deployed.

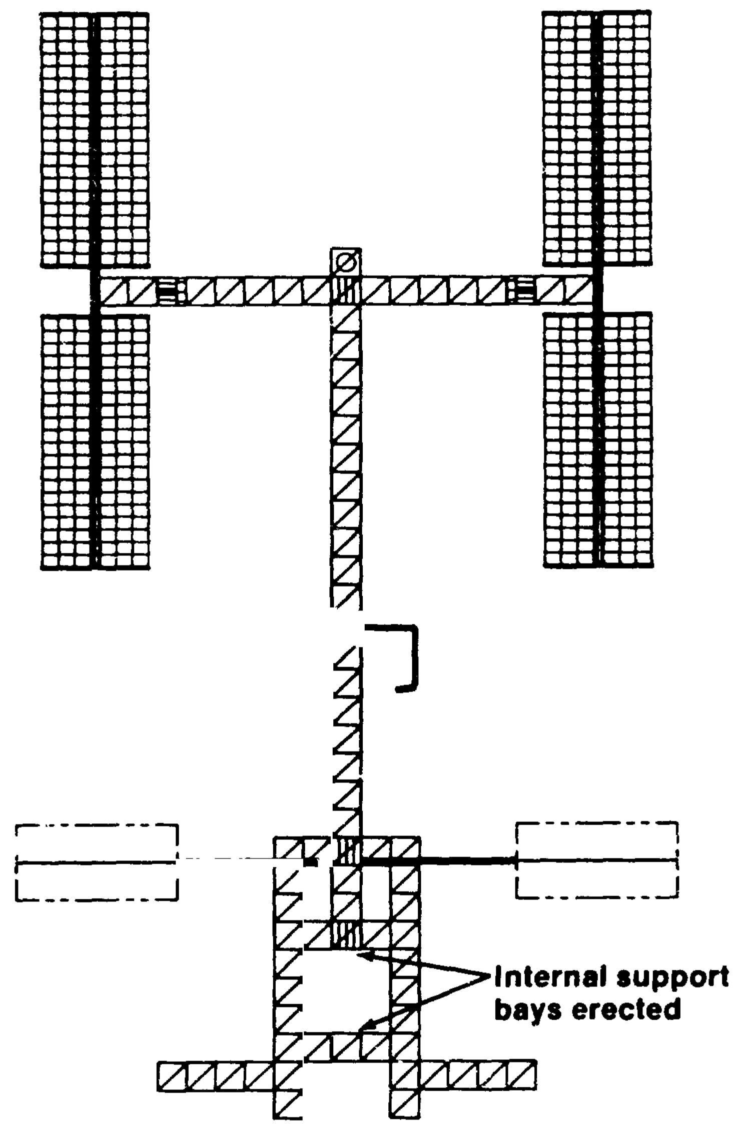


Figure 20. Completed lower keel structure showing support bays erected between the keel extensions.

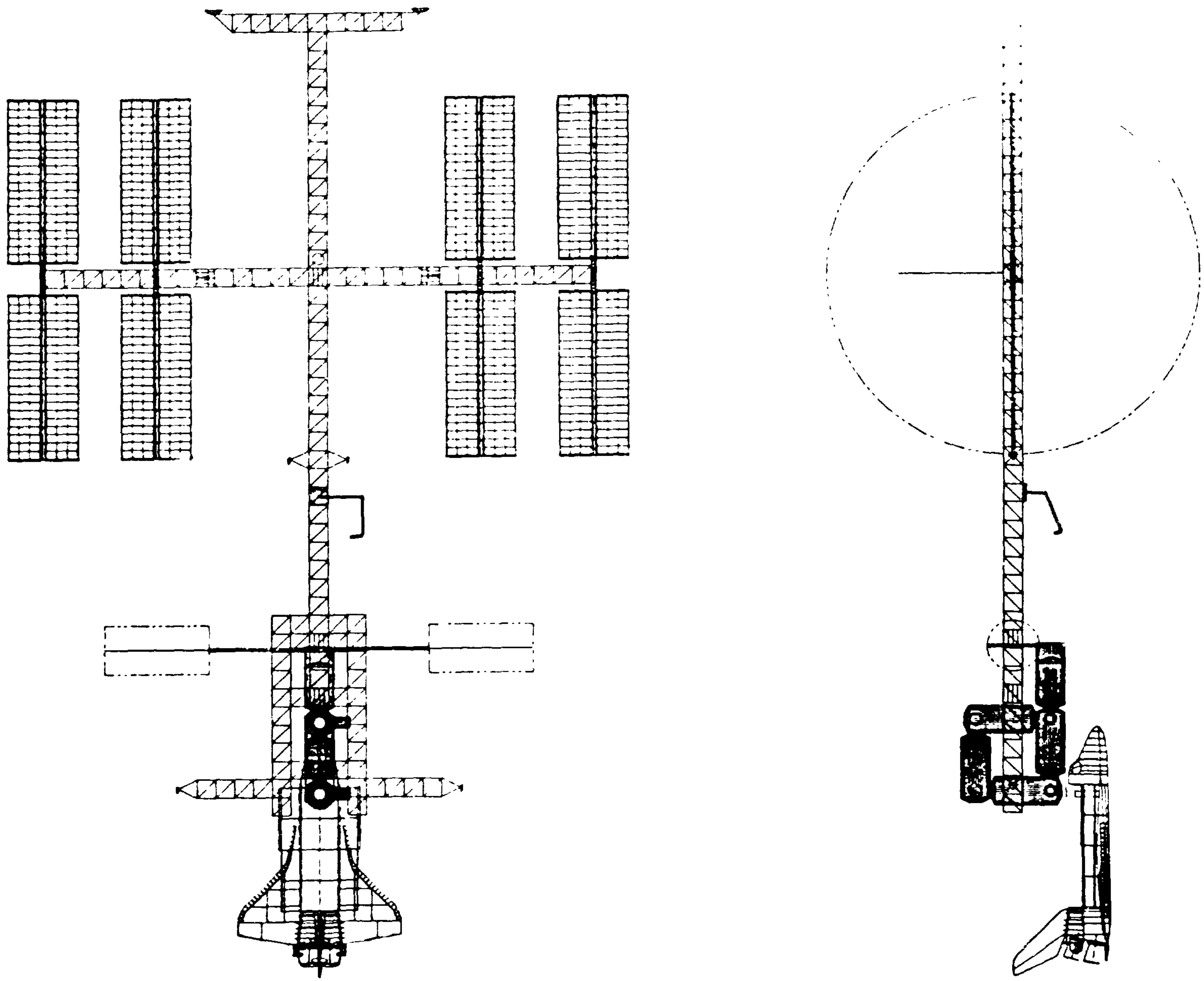


Figure 21. Complete station showing attached race-track module pattern.

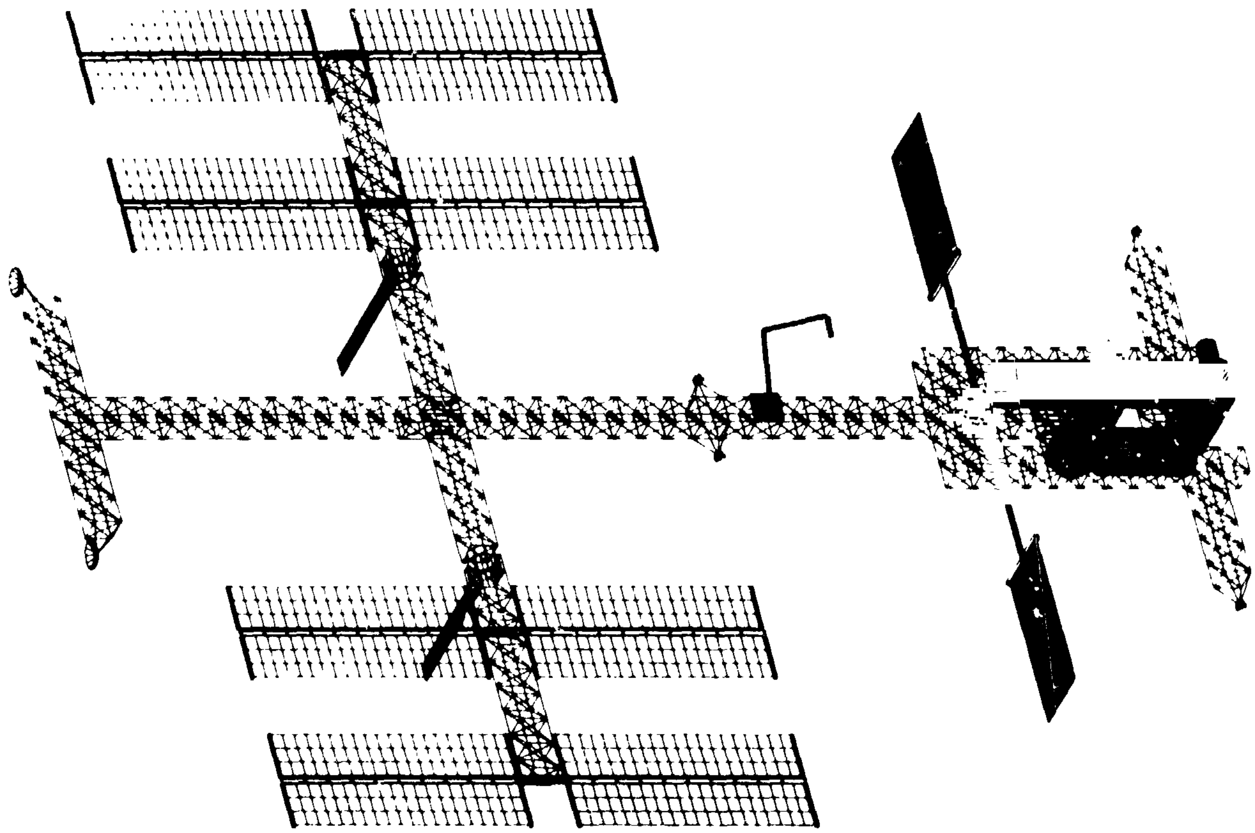


Figure 22. Oblique view of completed space station.

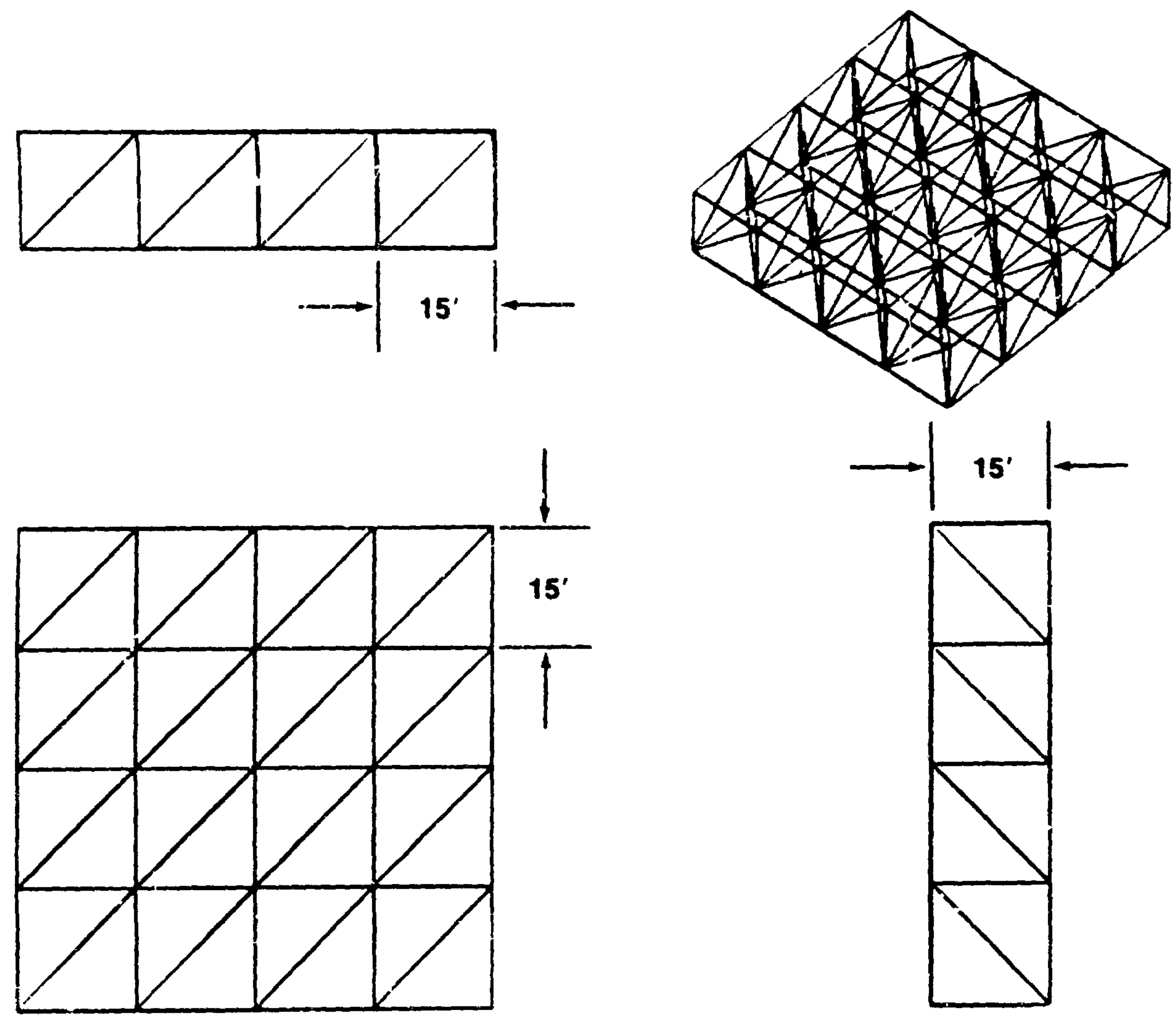


Figure E-1. Geometry of orthogonal tetrahedral truss.

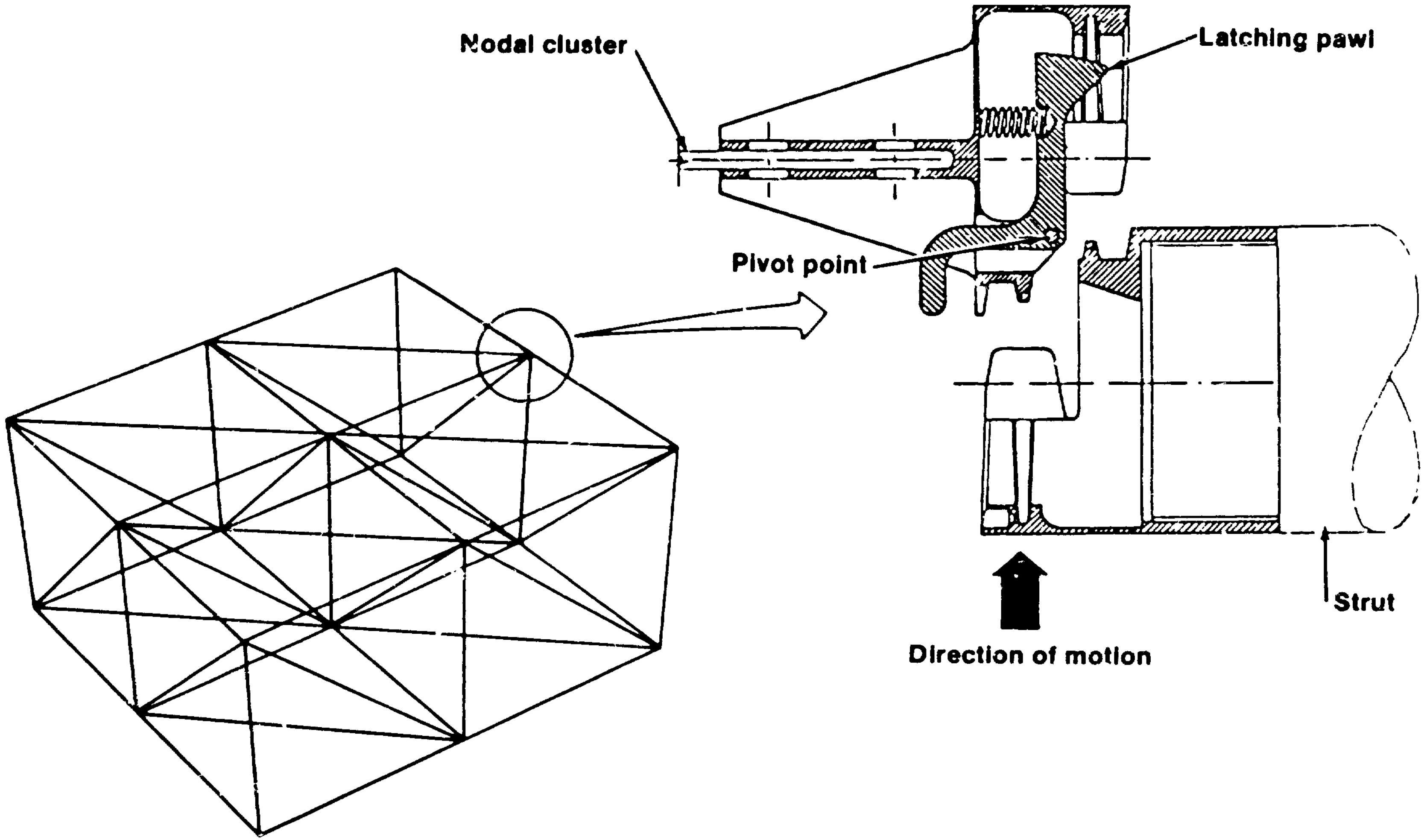


Figure E-2. Erectable strut quick attachment joint.

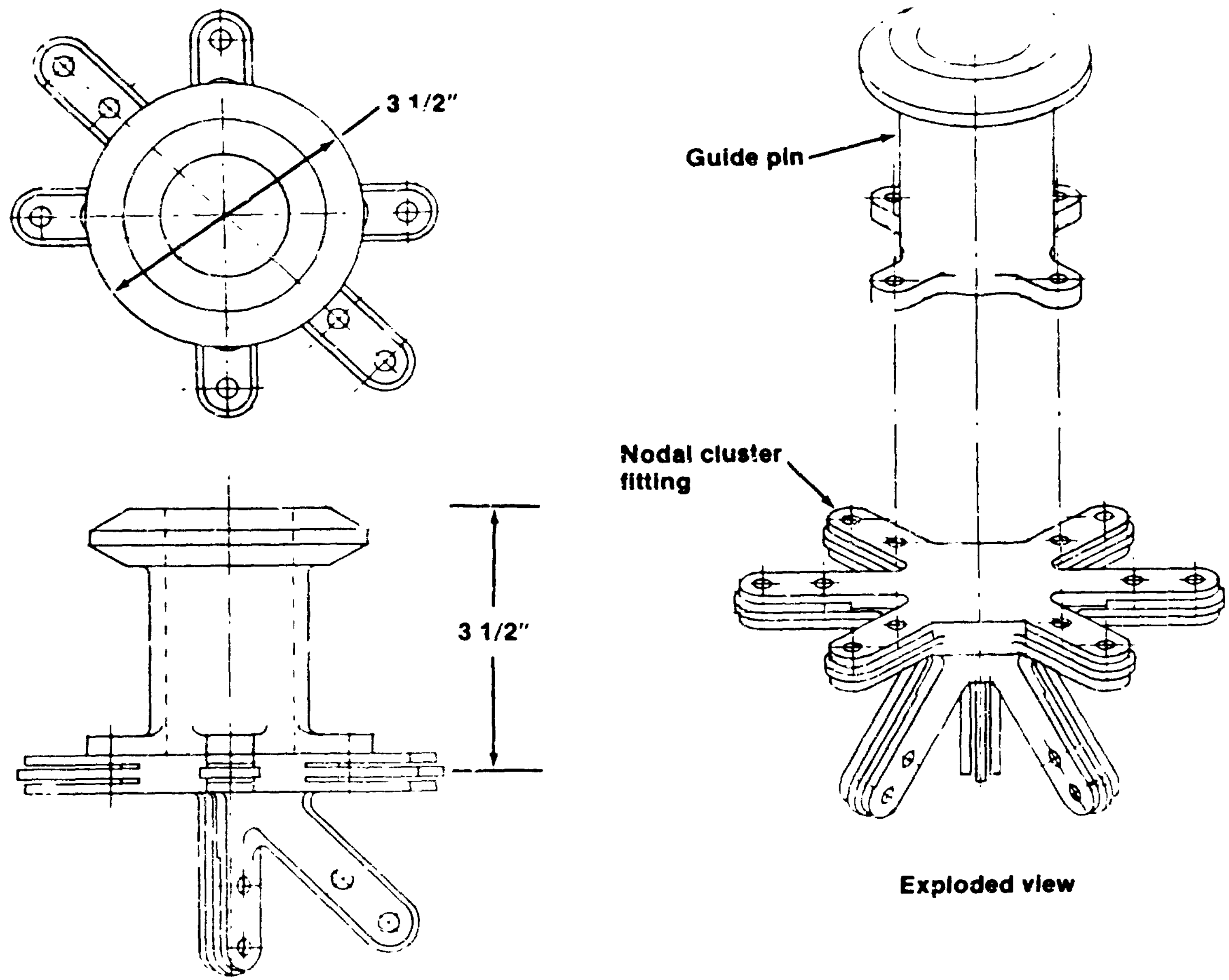


Figure E-3. Nodal cluster fitting and MRMS guide pin.

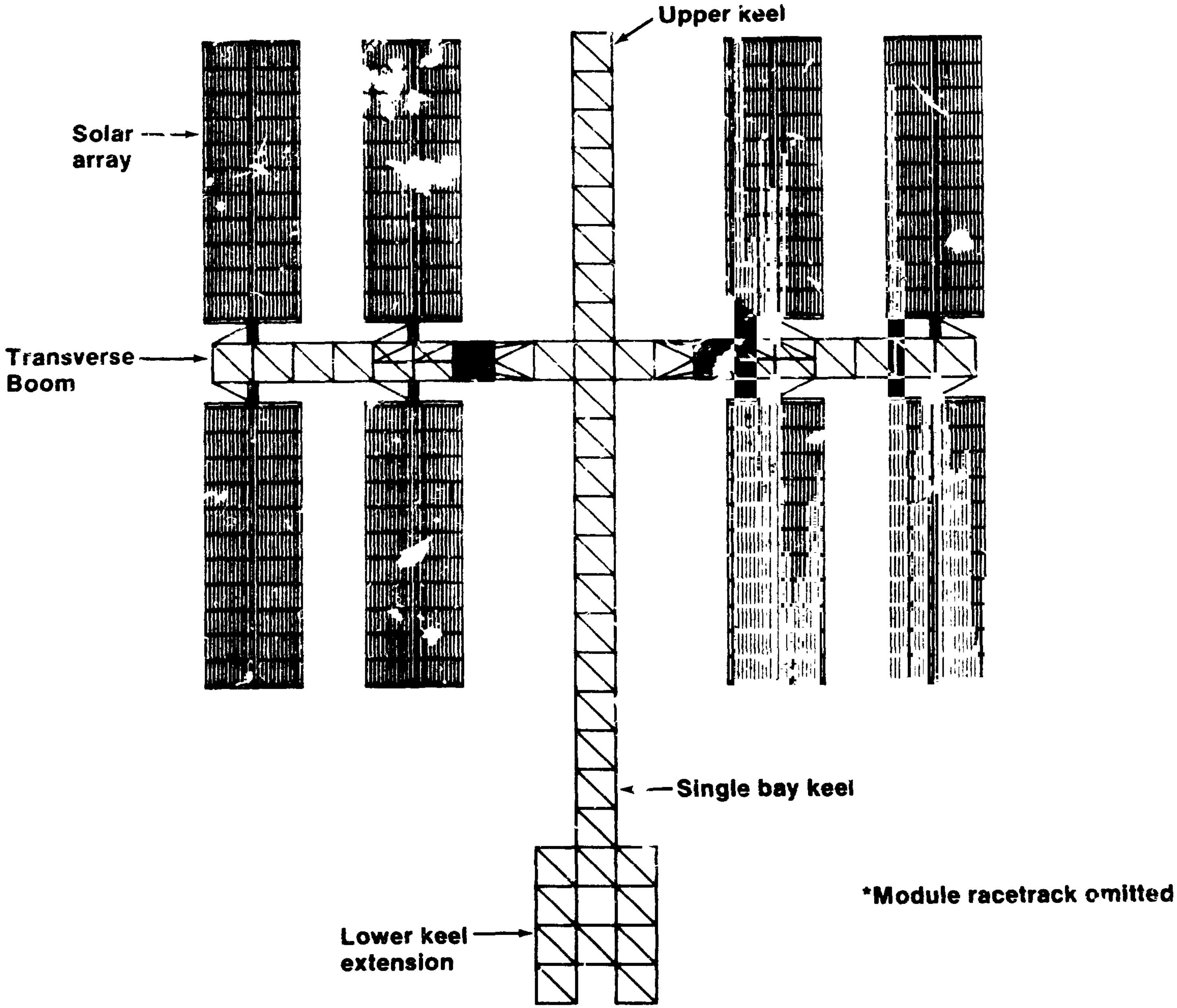


Figure E-4. Space station 15-foot beam structure.

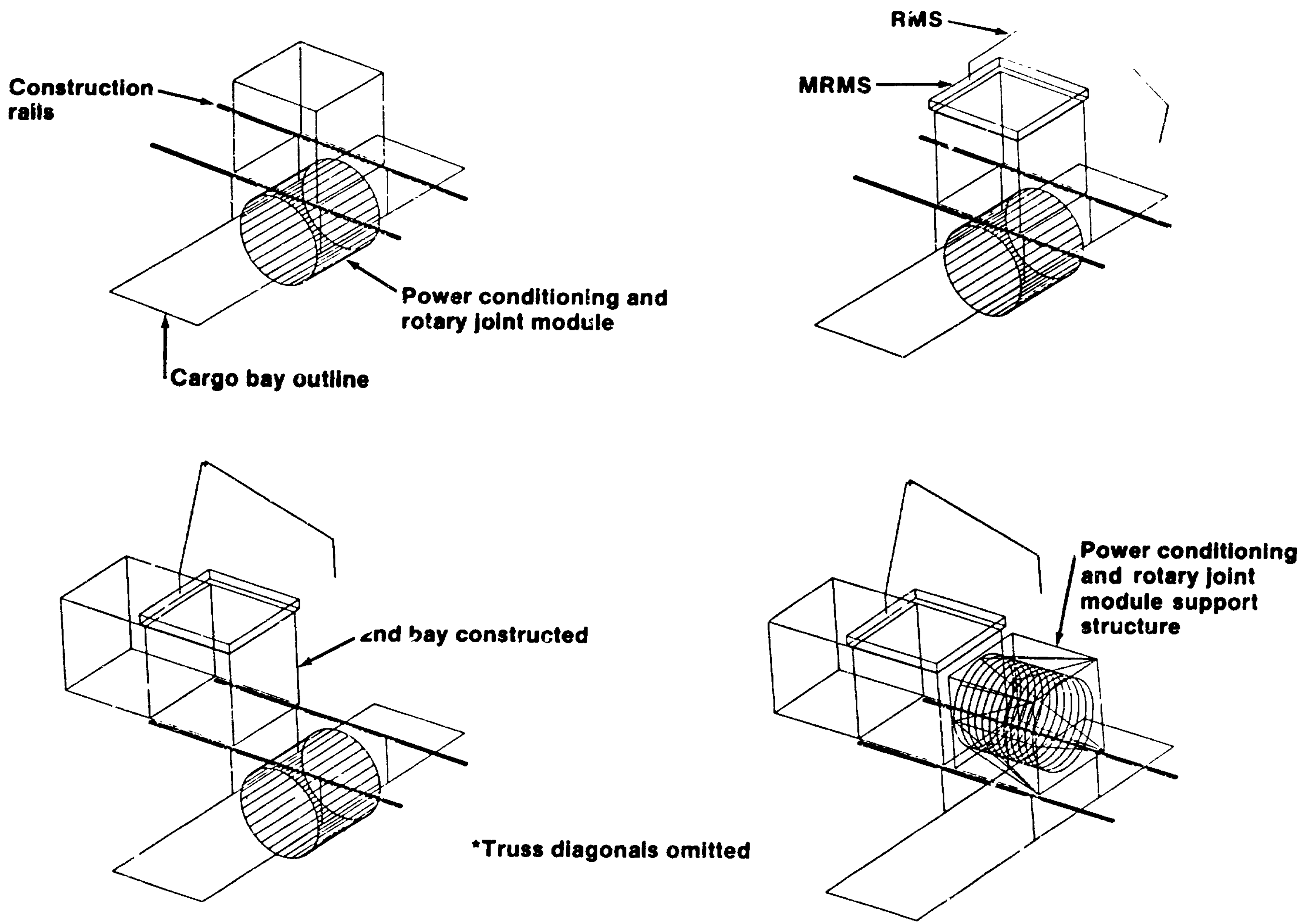
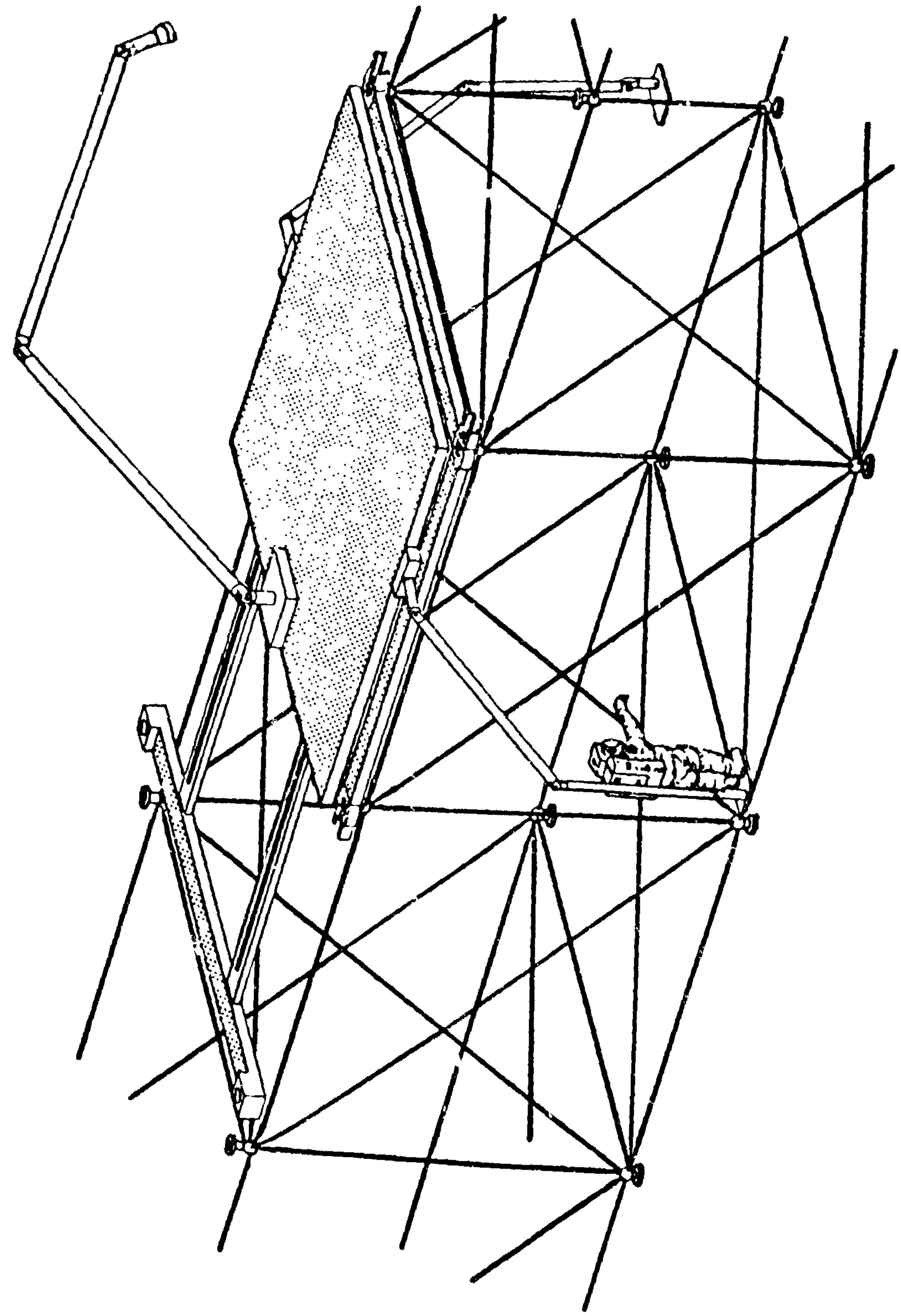


Figure E-5. Initial construction sequence for 15-foot erectable transverse boom.



MOBILE REMOTE MANIPULATOR SYSTEM

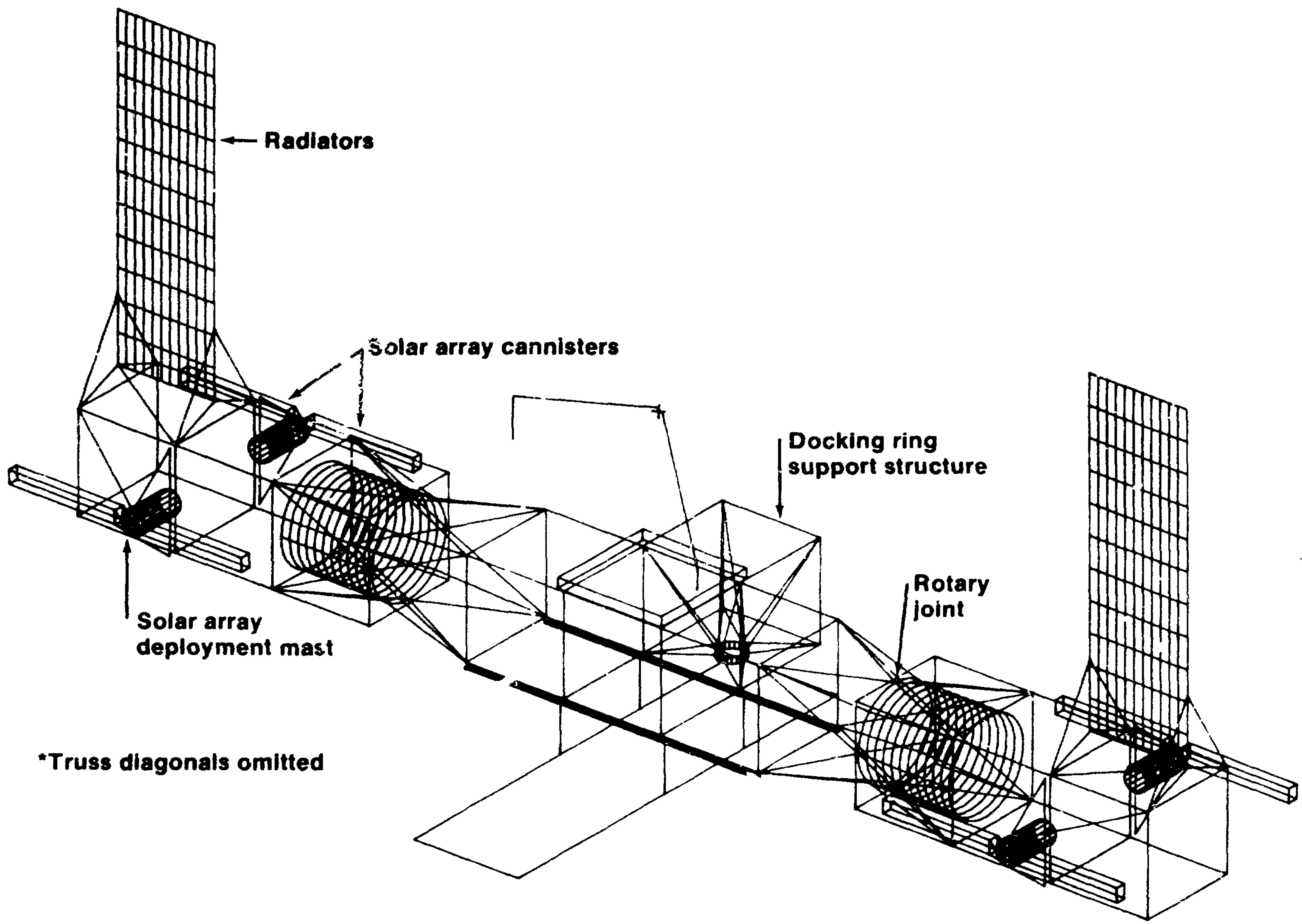


Figure E-6. Completed transverse boom including docking ring support structure.

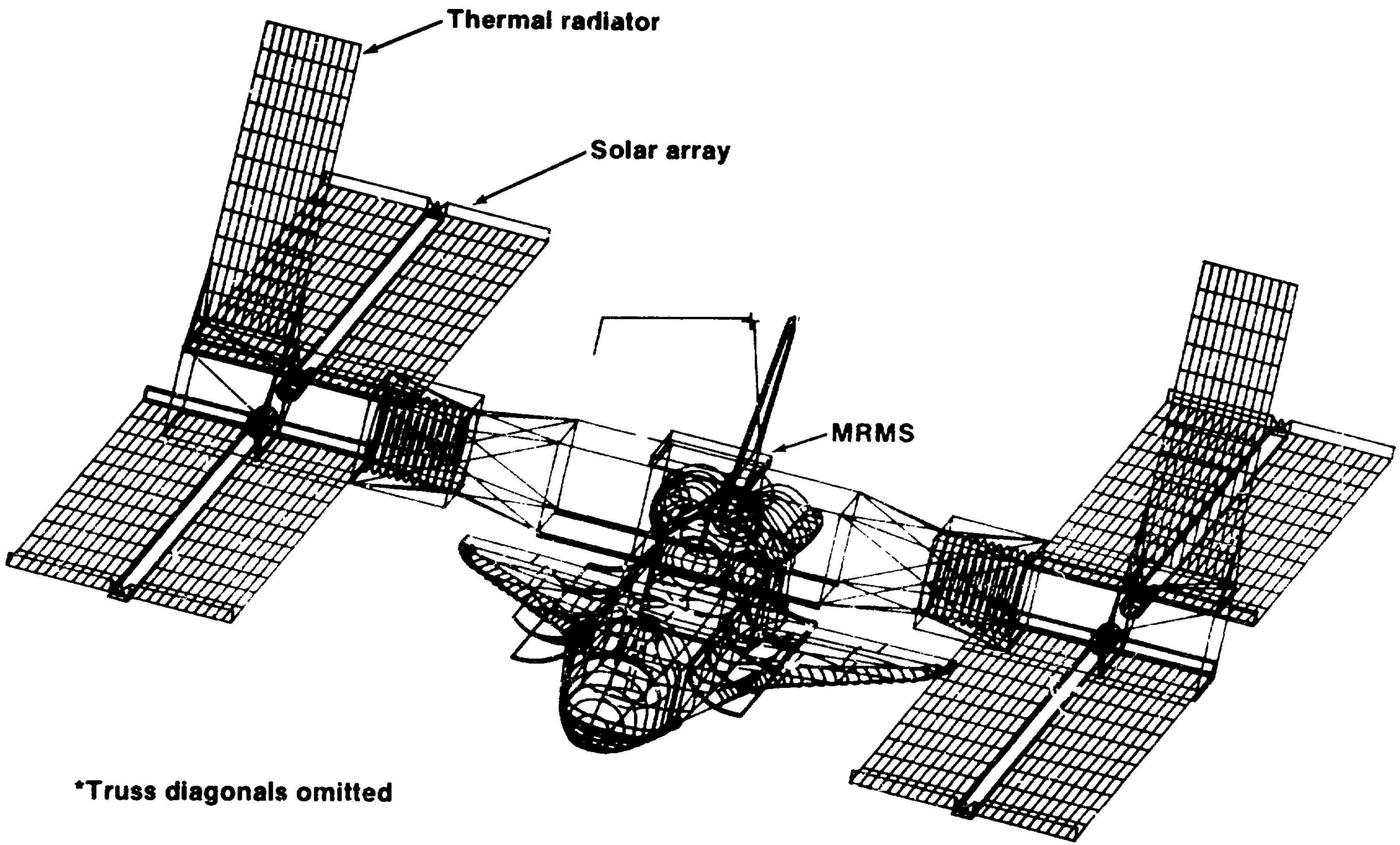


Figure E-7. Solar array deployment and system operational checkout (shuttle attached).

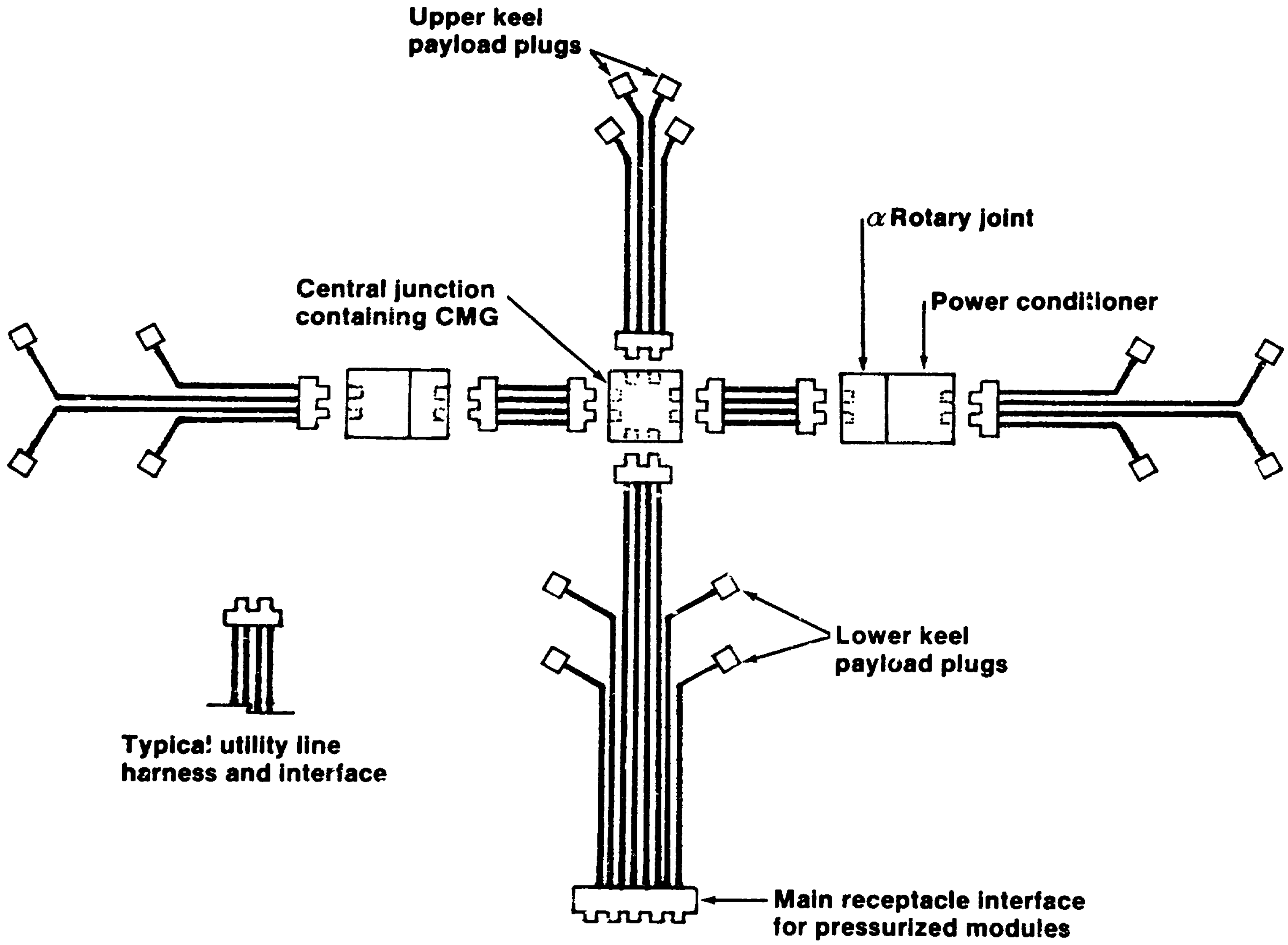


Figure E-8. Gravity gradient stabilized space station utilities harness integration schematic.

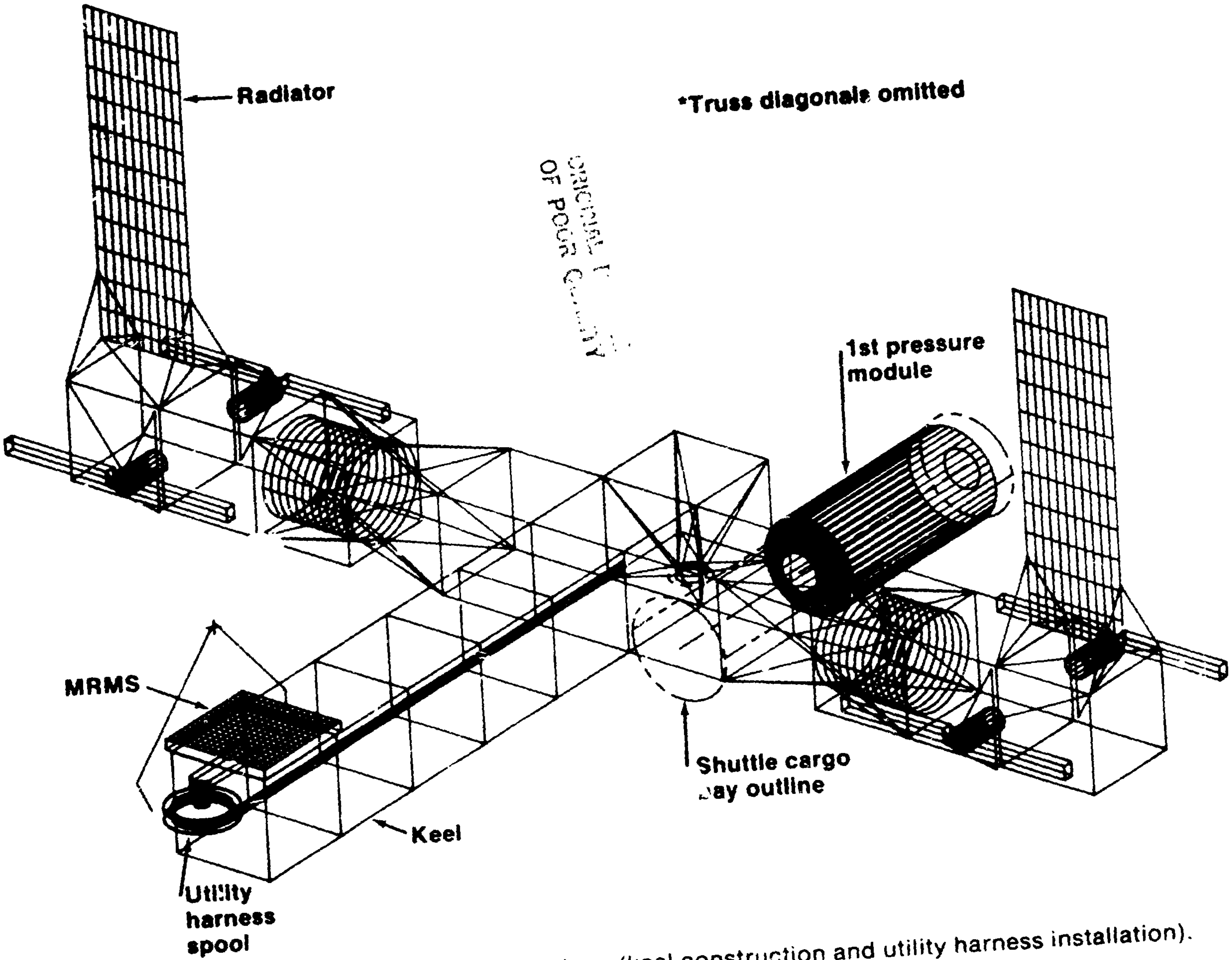


Figure E-9. Second flight operations (keel construction and utility harness installation).

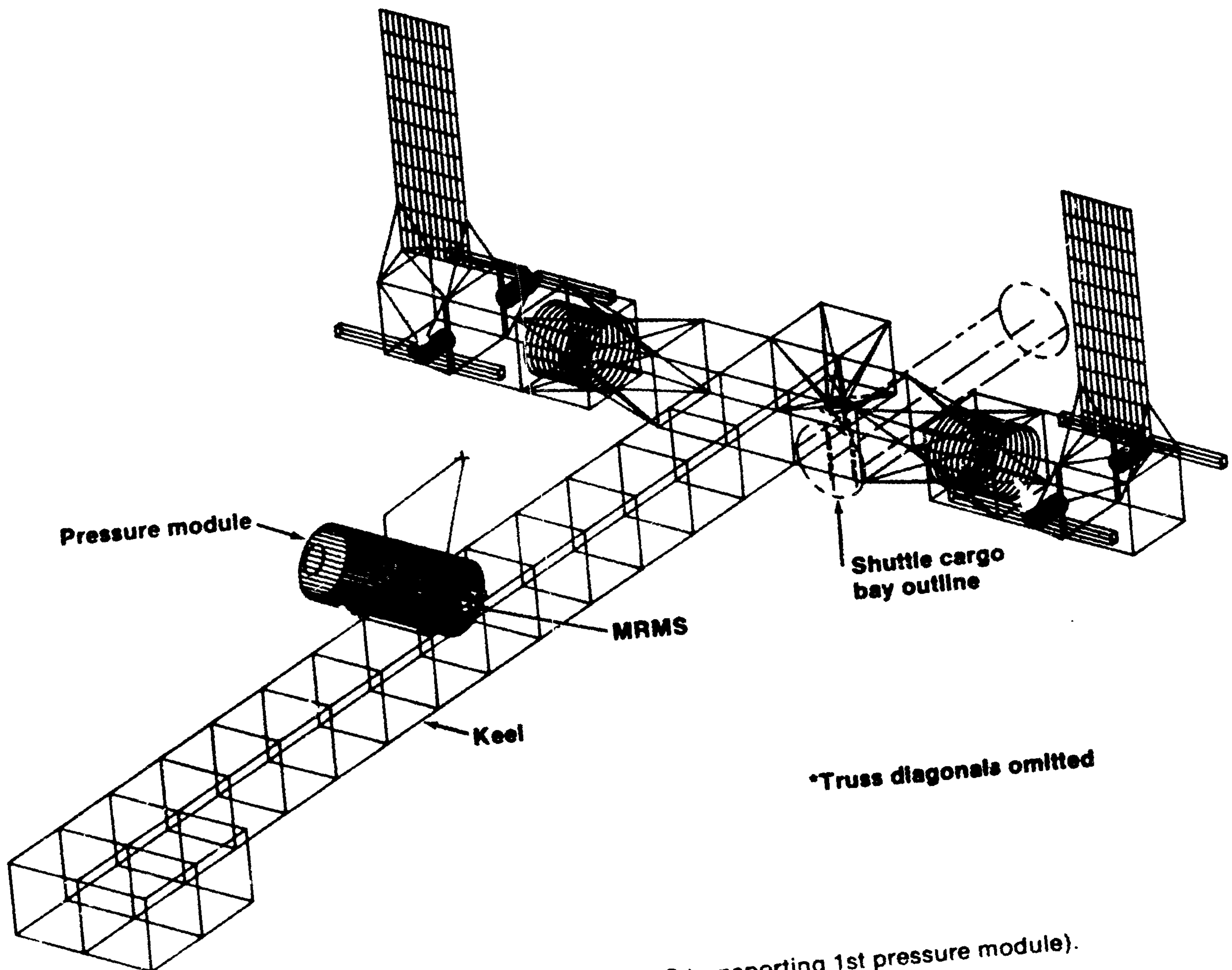


Figure E-10. Second flight operations (MRMS transporting 1st pressure module).

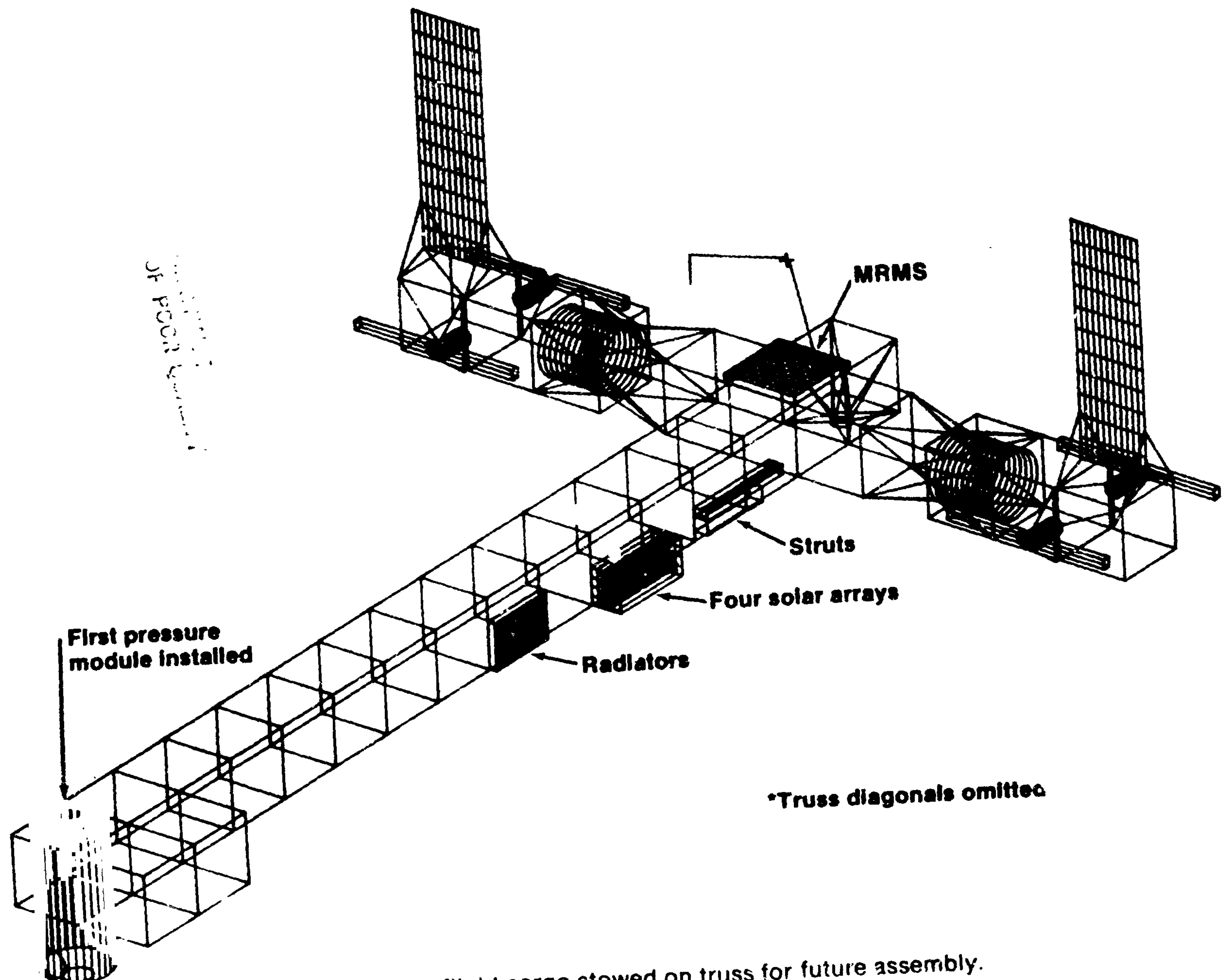


Figure E-11. Second flight cargo stowed on truss for future assembly.

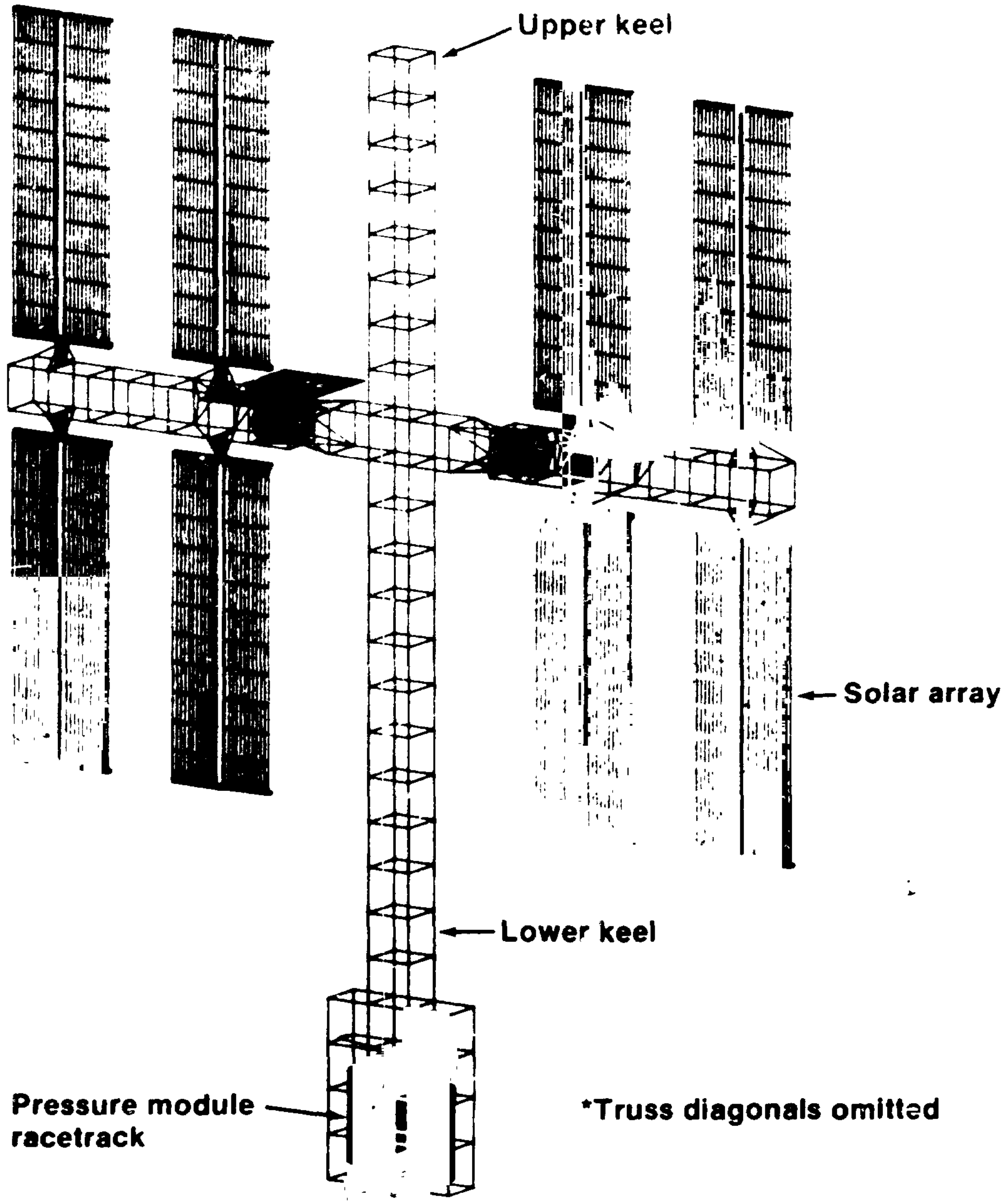


Figure E-12. Completed space station after five flights (minus logistics modules).

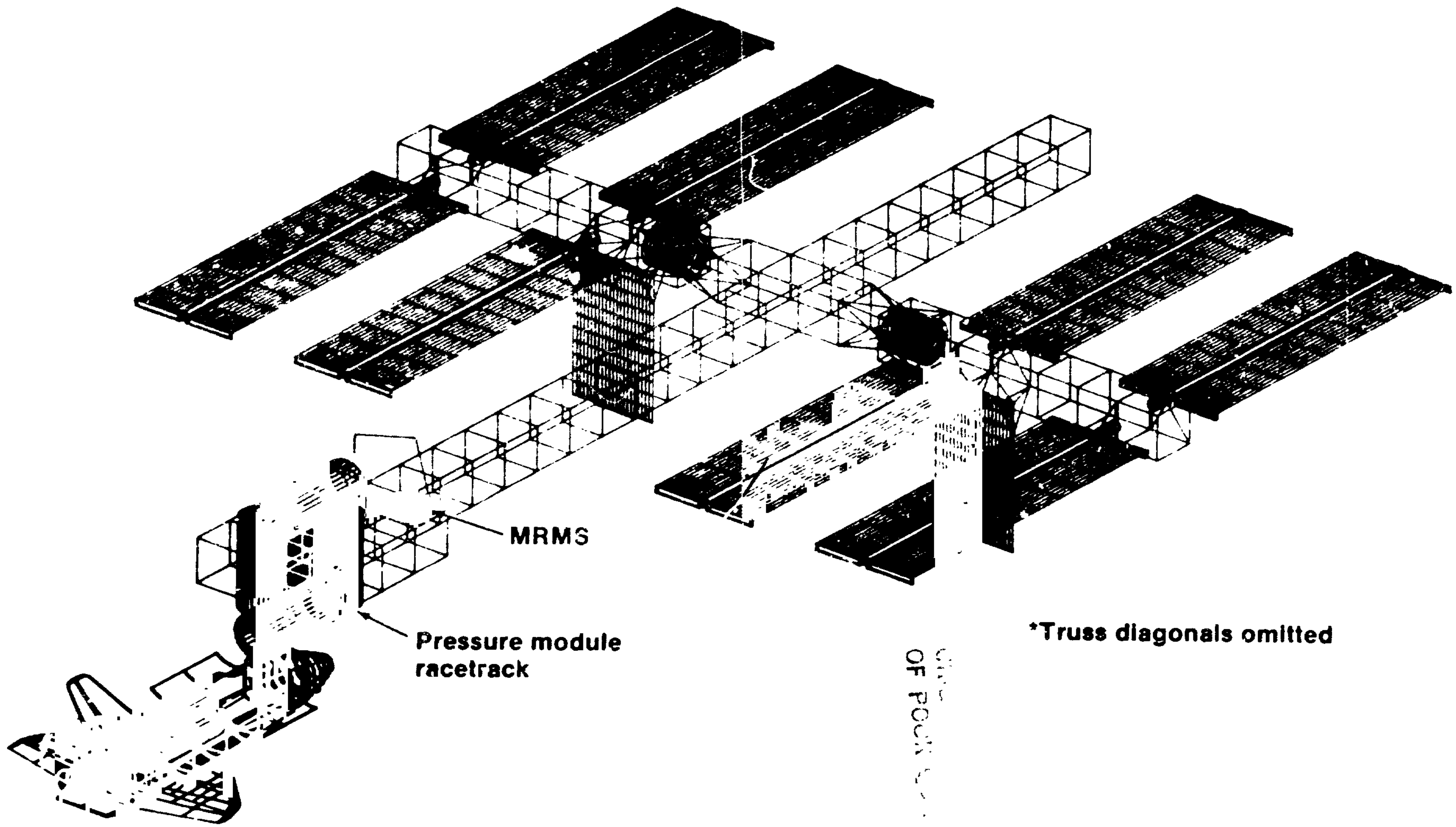


Figure E-13. Sixth flight docking with space station (logistics module shown in cargo bay).

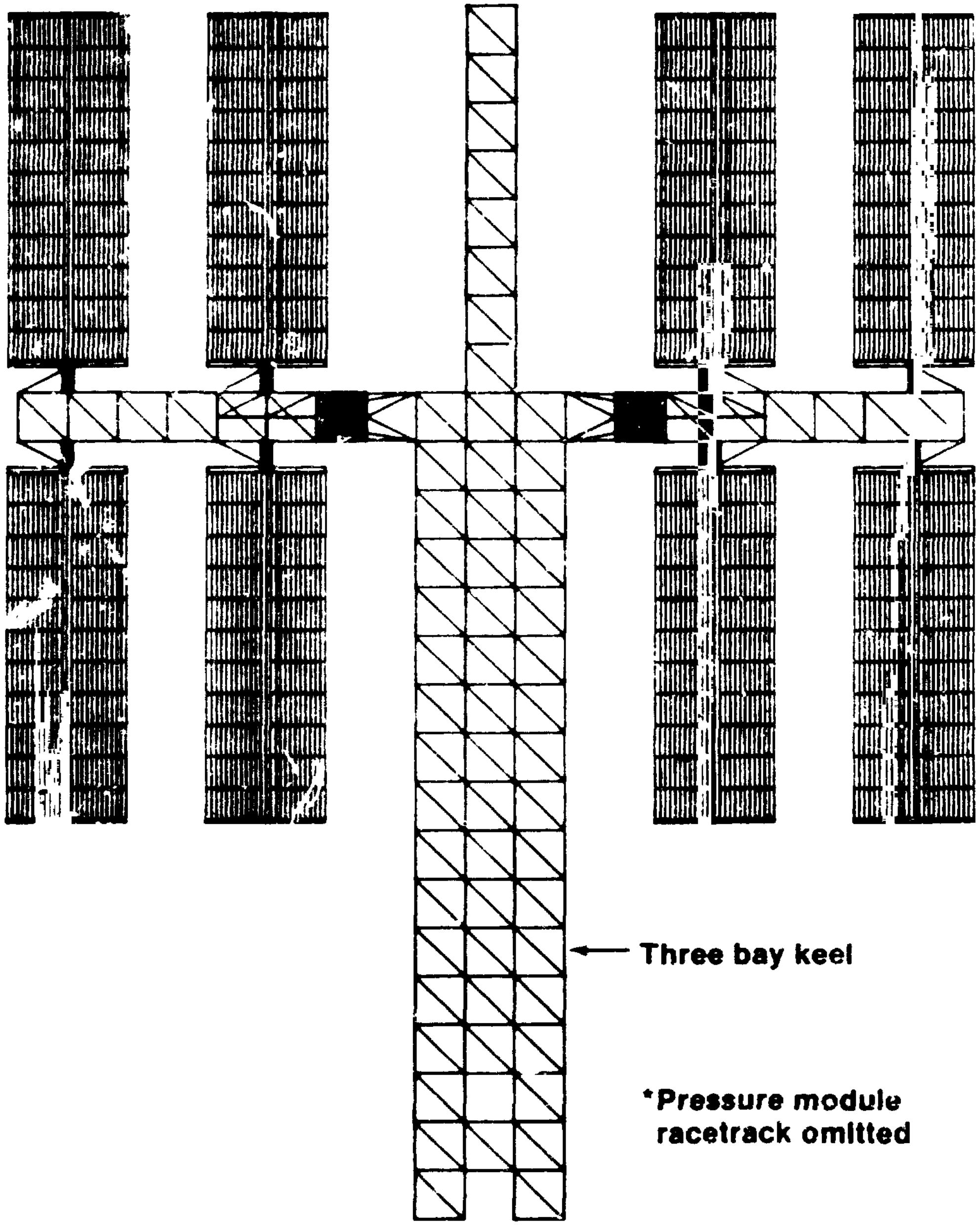


Figure E-14. Growth version of space station (three bay wide erectable keel).

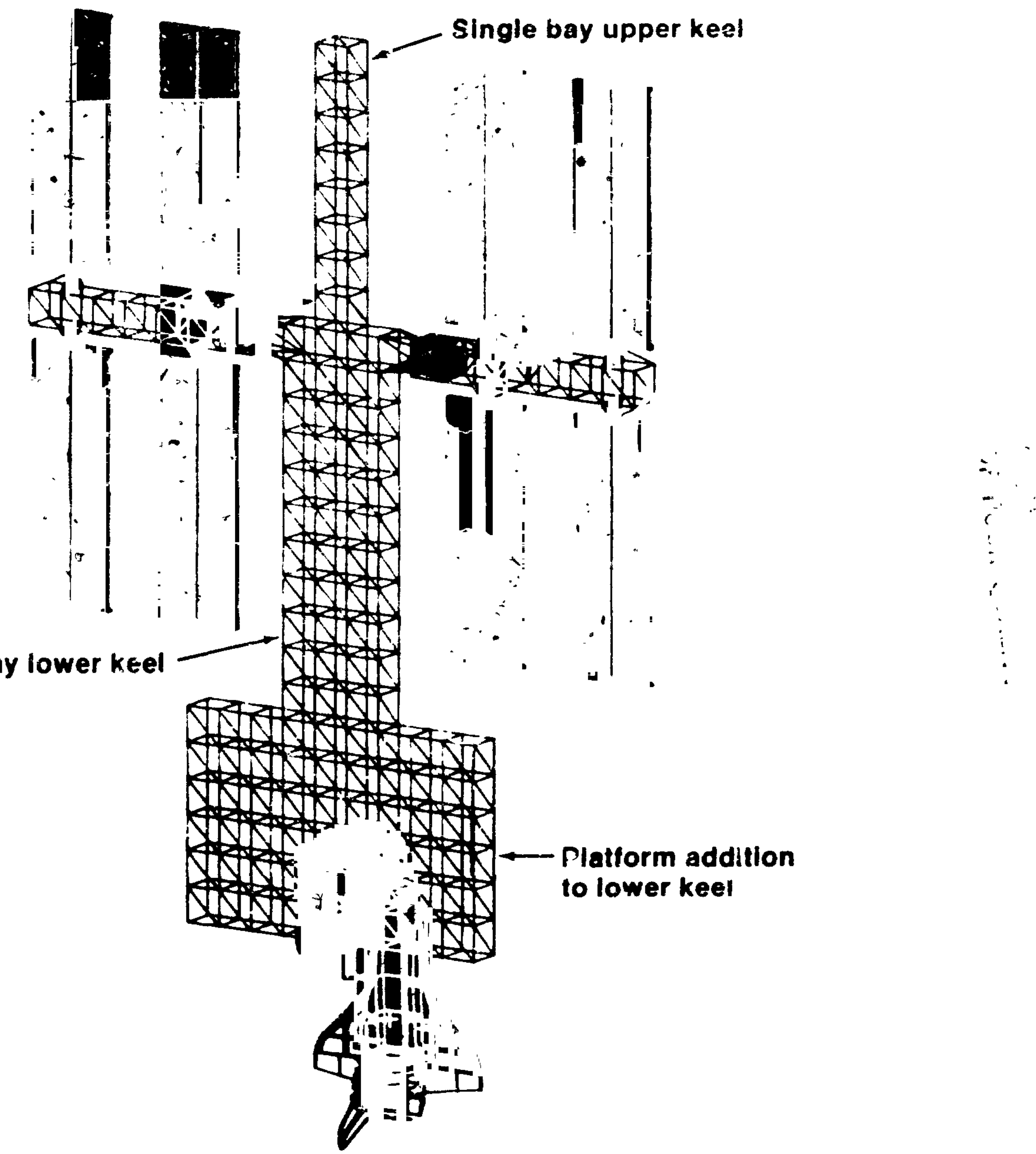


Figure E-15. Growth version of space station showing platform addition (near planform view).

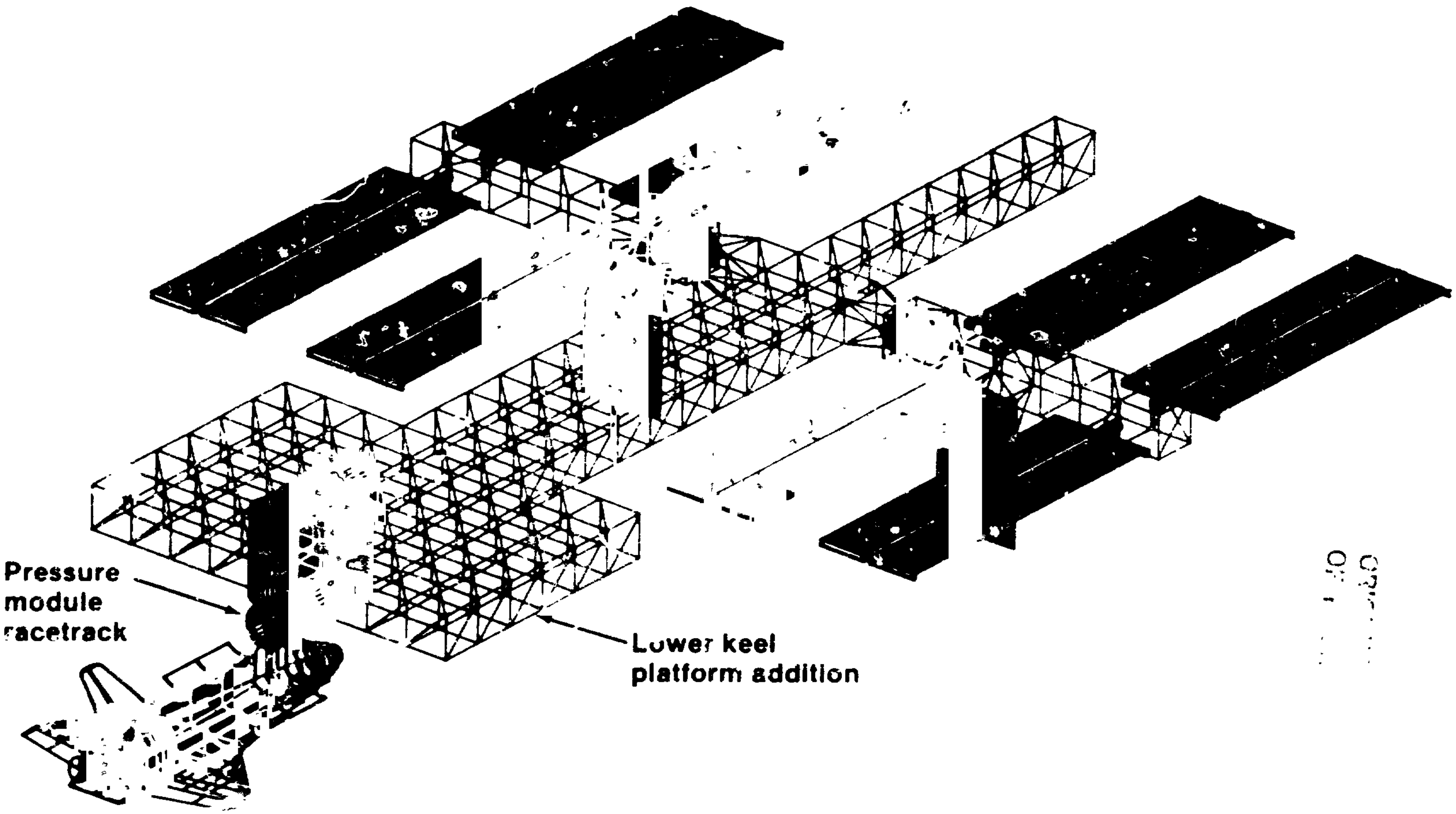


Figure E-16. Growth version of space station showing platform addition (oblique view).

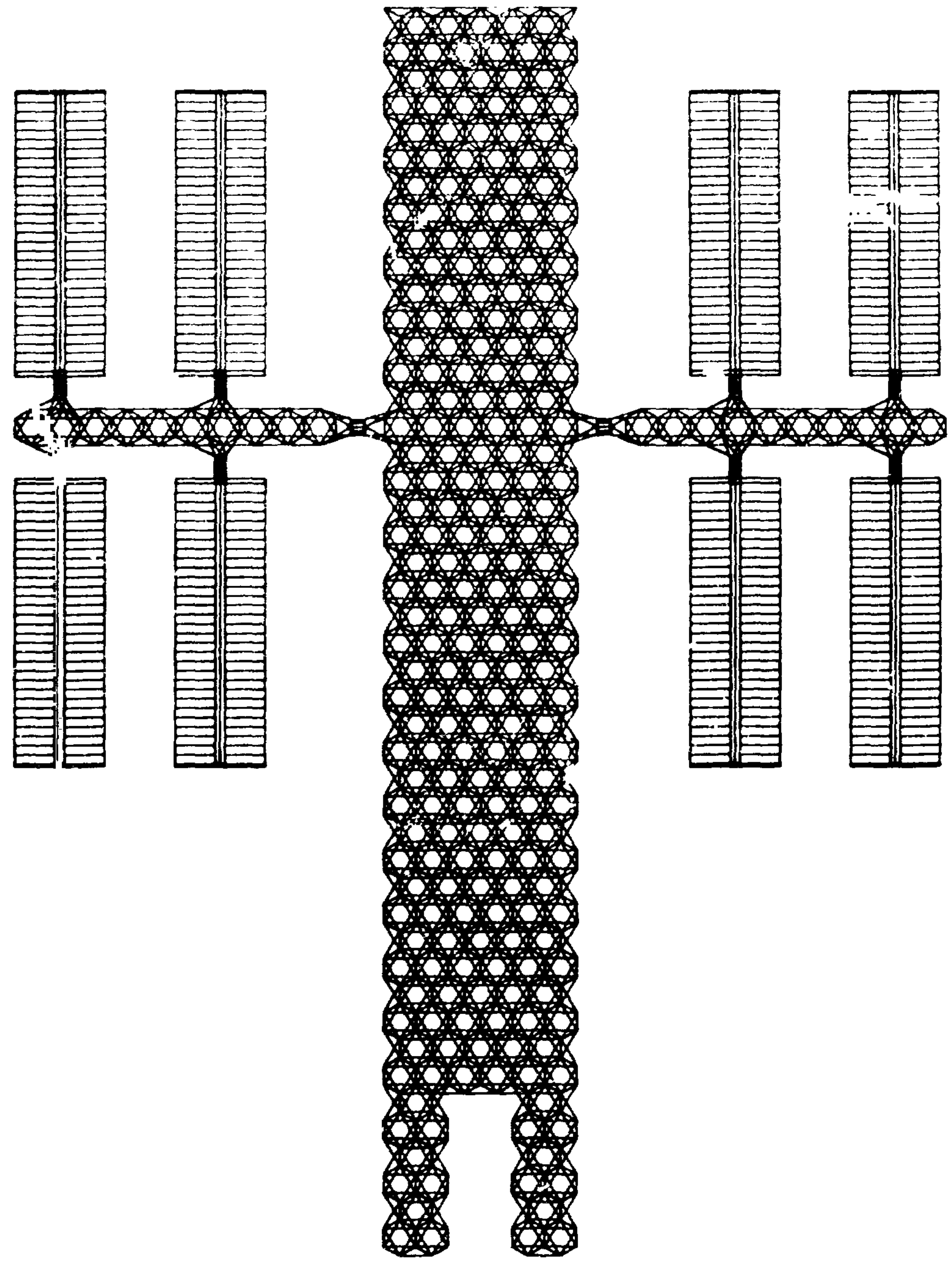


Figure T-1-a. Deployable tetrahedral truss space station.

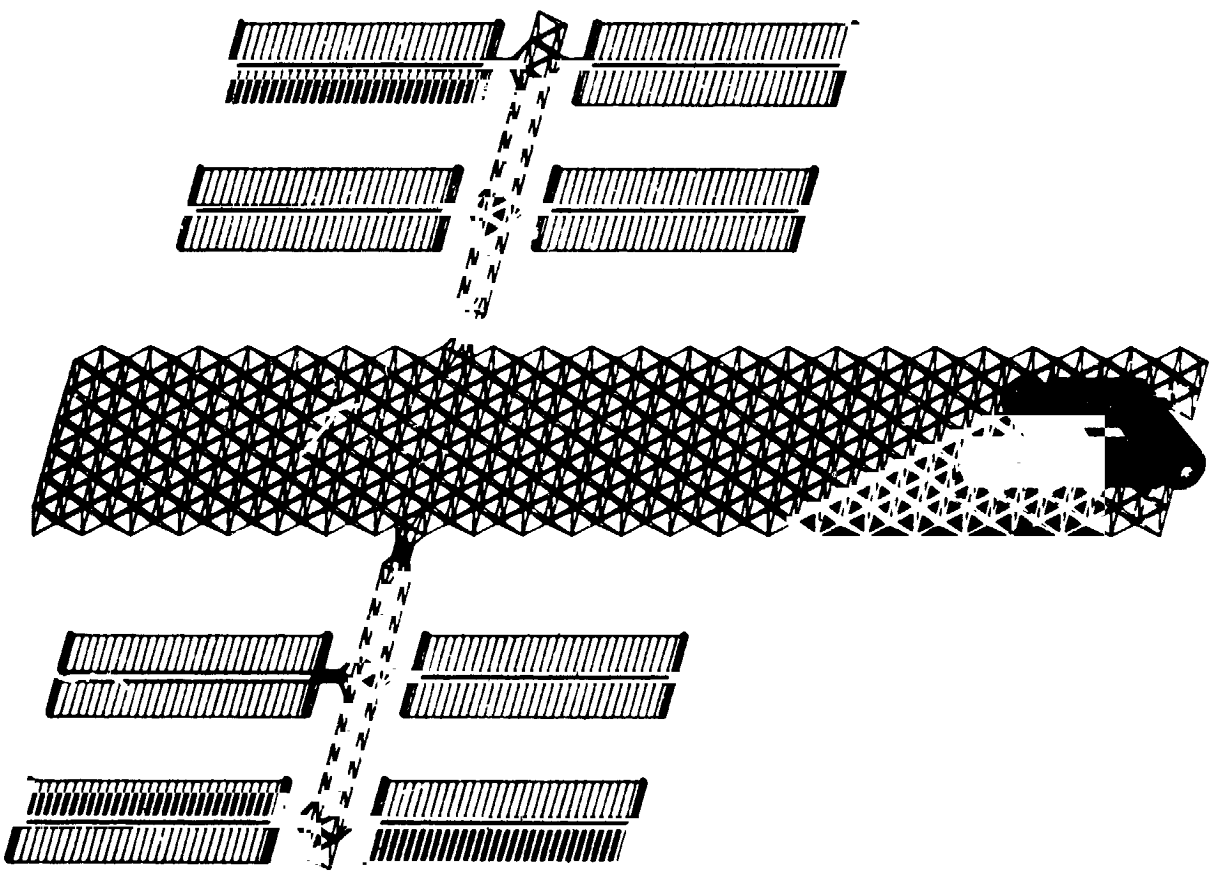


Figure T-1-b. Oblique view showing modules.

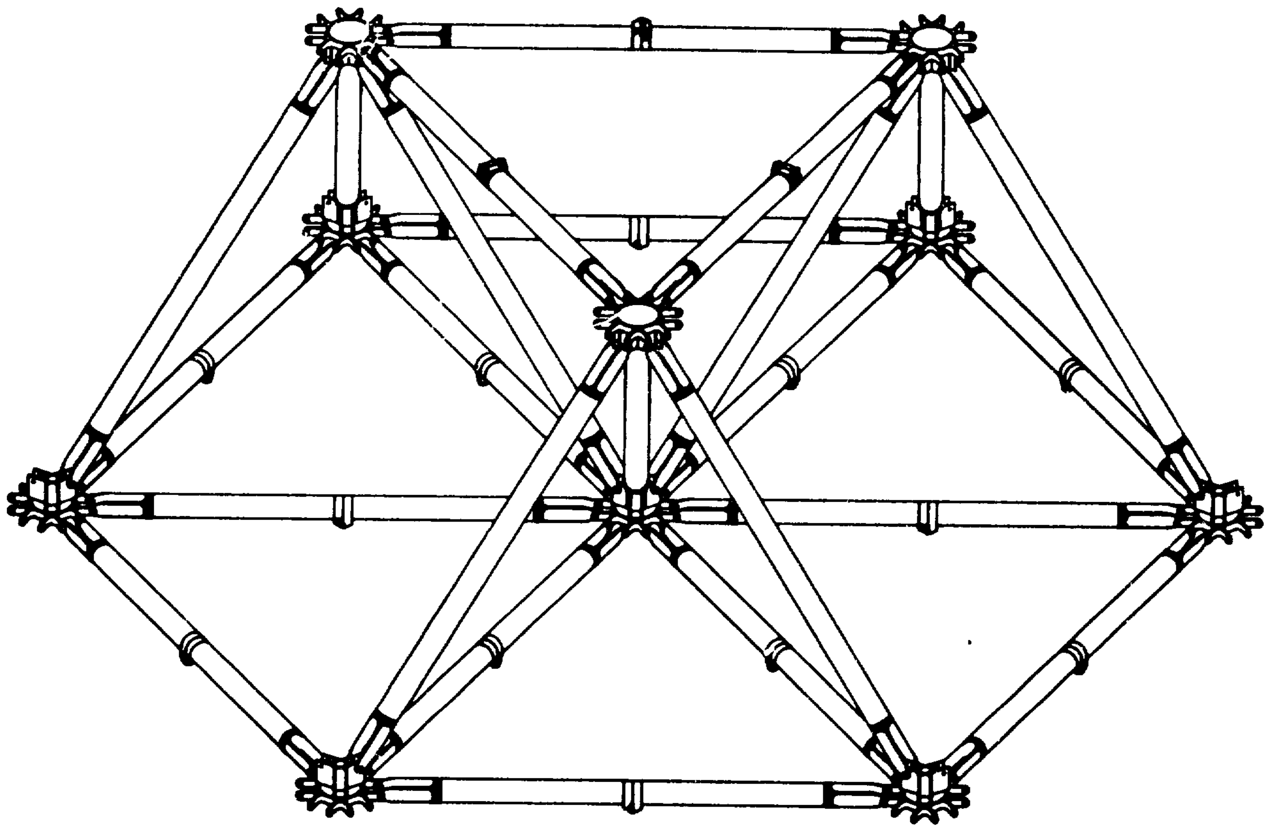


Figure T-2. Typical cell of tetrahedral truss.

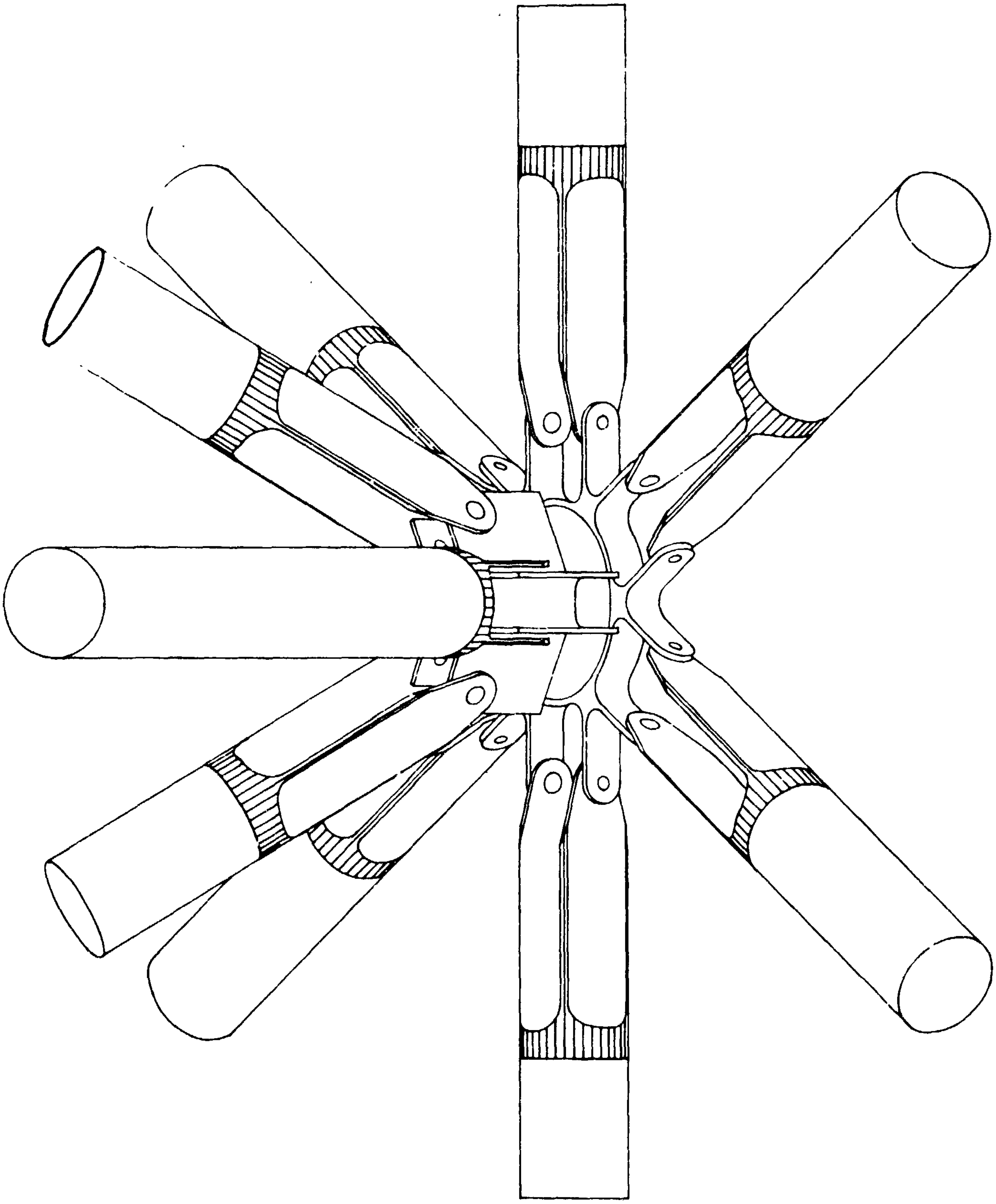


Figure T-3. Close up of nodal fitting.

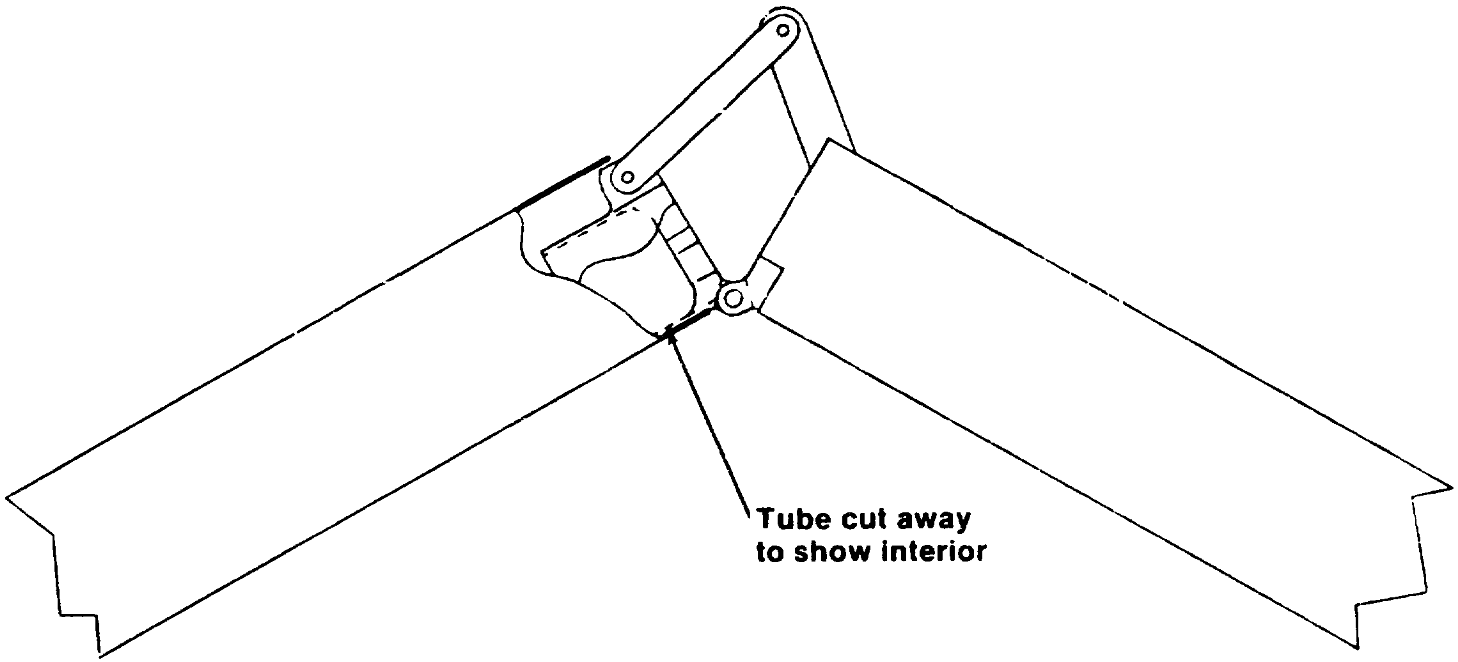


Figure T-4. Over center hinge joint in surface struts.

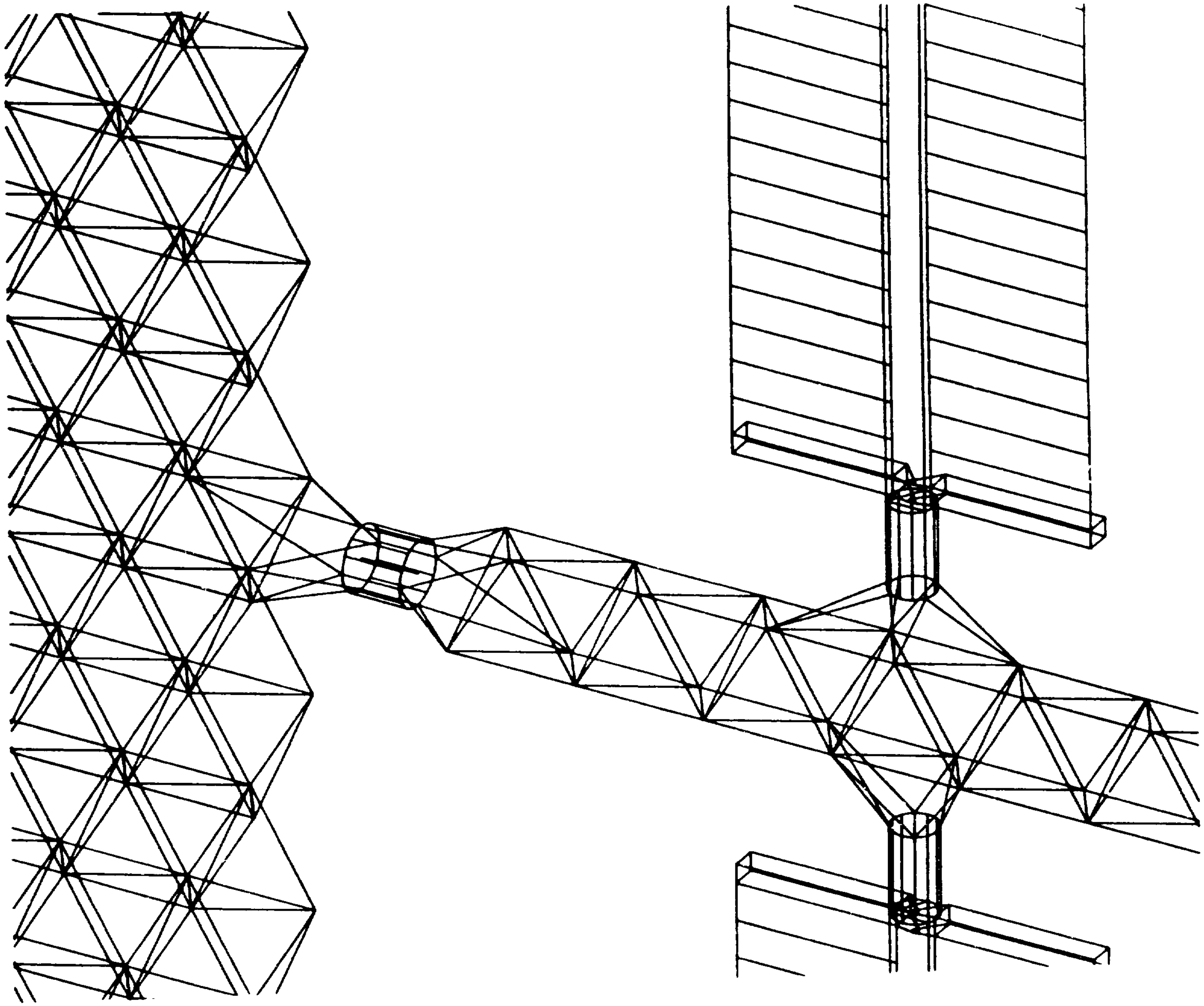


Figure T-5. Close up of erectable attachment struts.

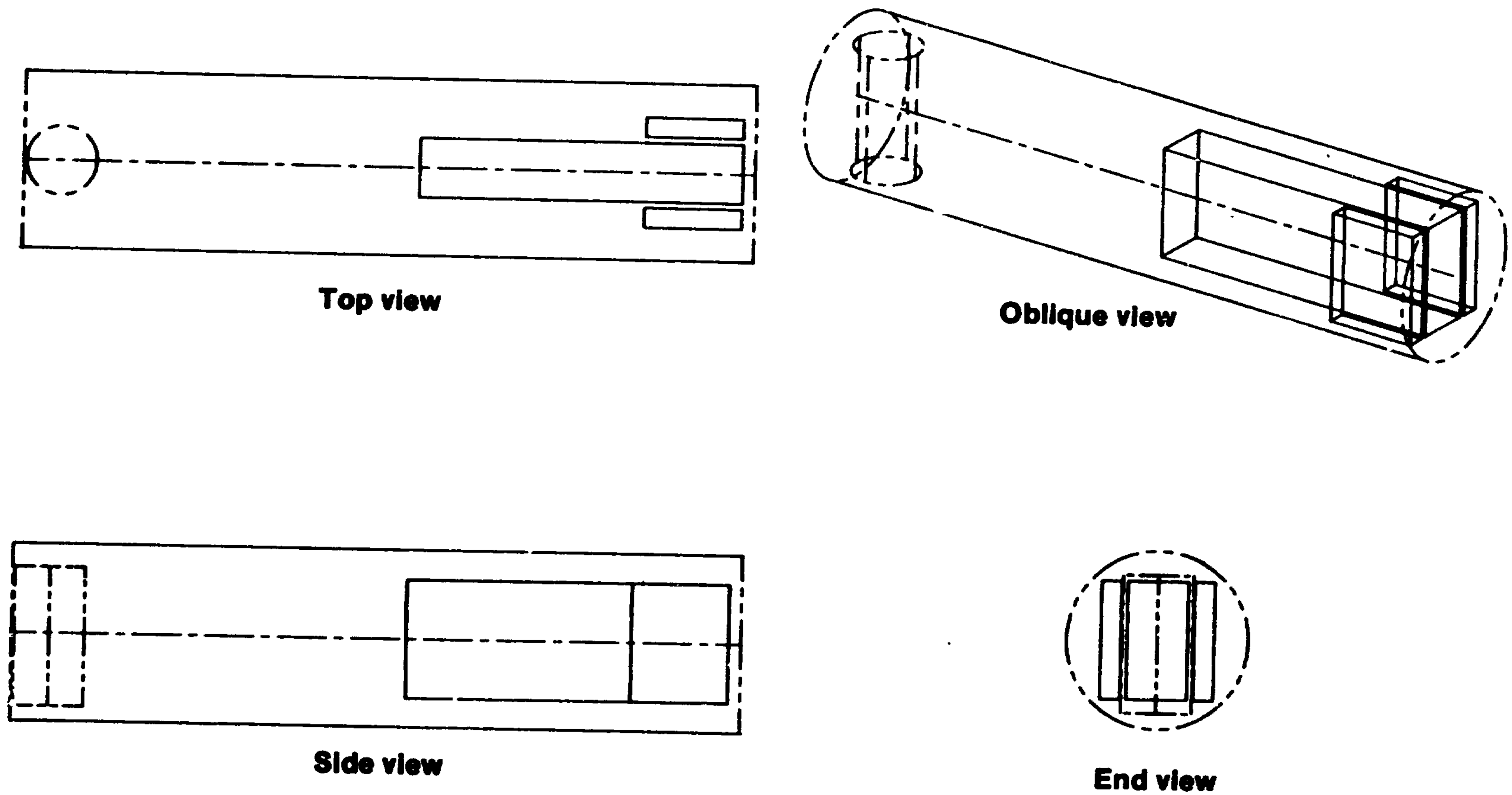


Figure T-6. Packaged tetrahedral station.

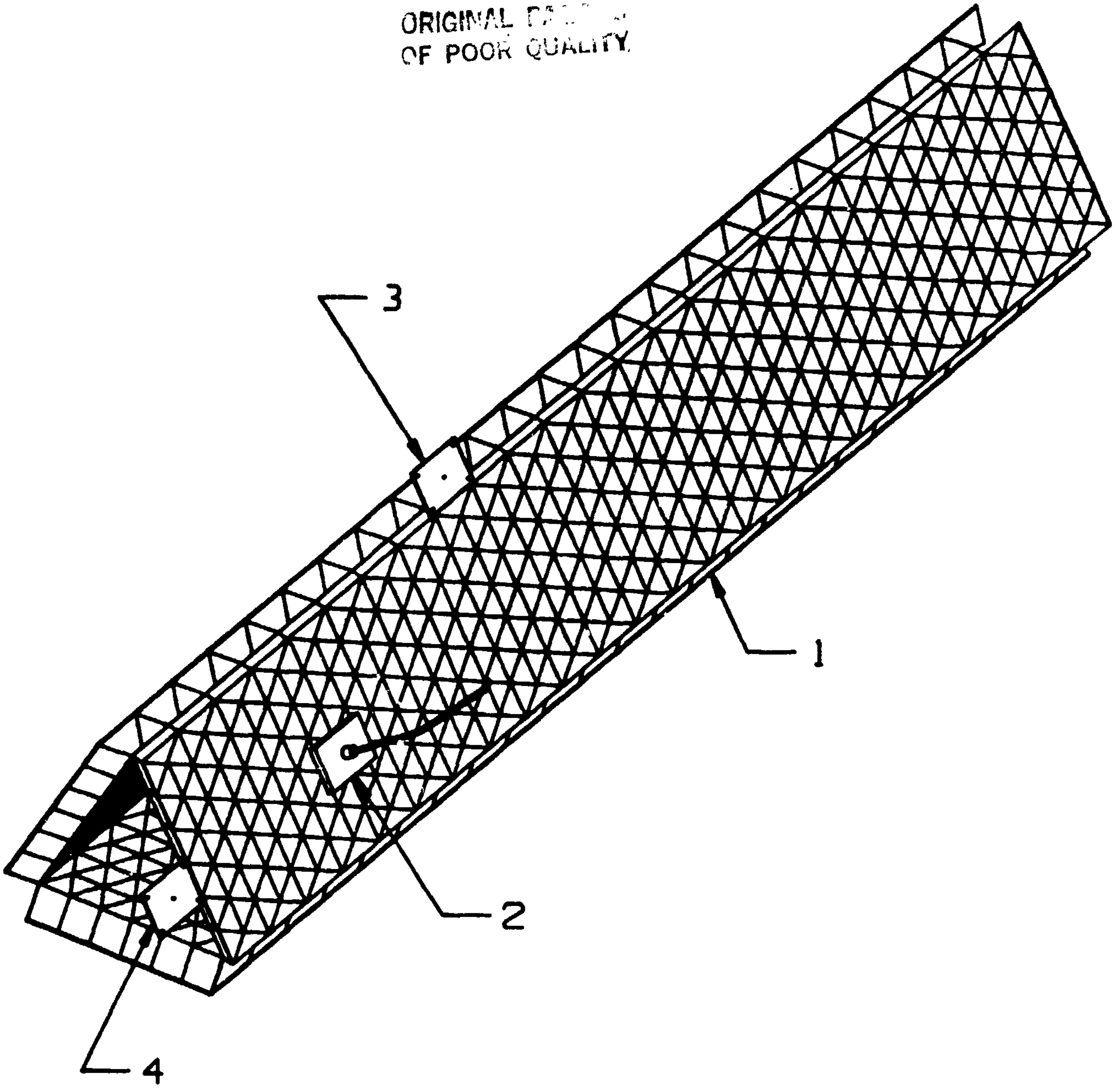


FIGURE A1. MOBILE REMOTE MANIPULATOR SYSTEM SHOWN MOUNTED ON A TETRAHEDRAL PANEL.

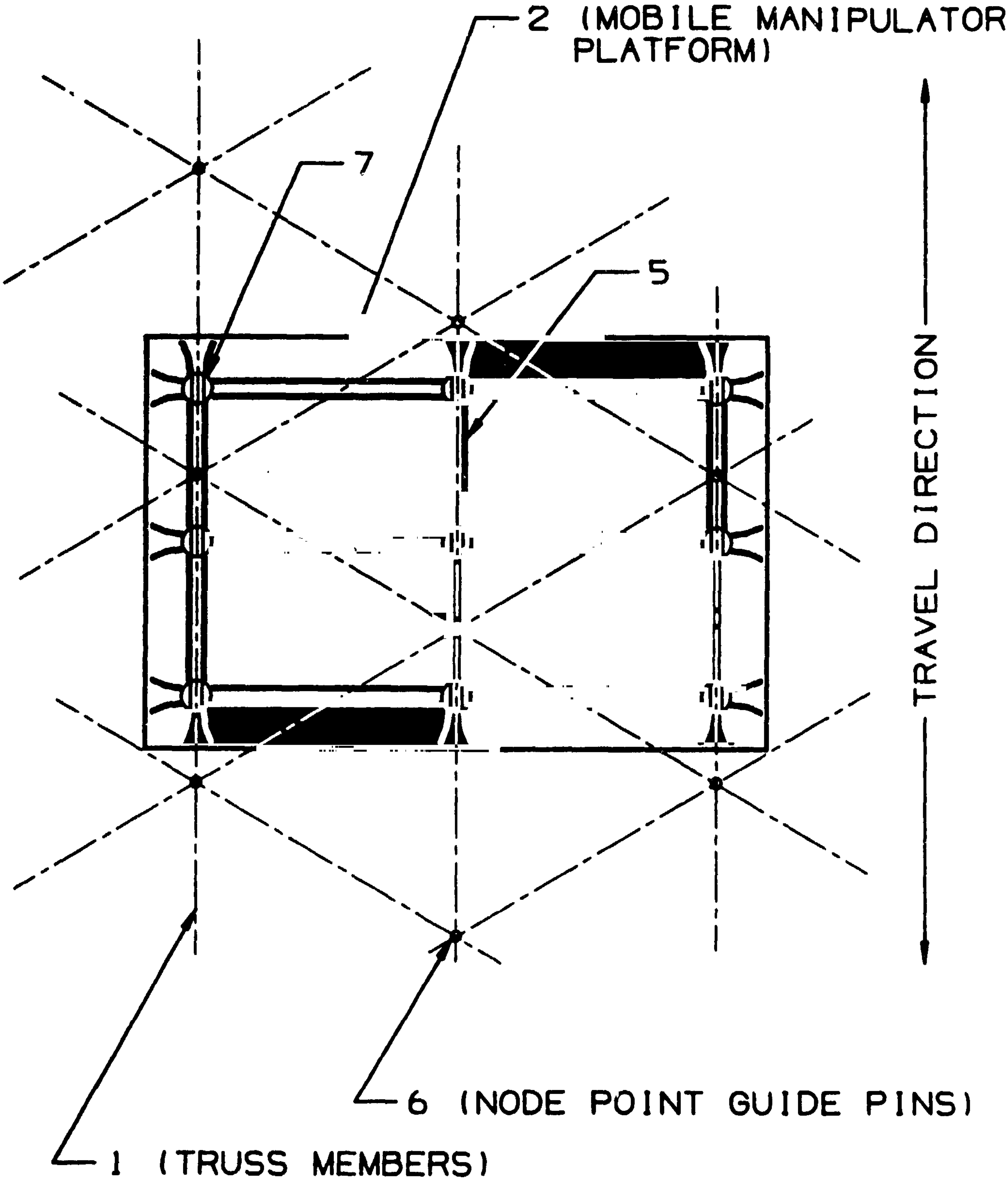


FIGURE A2. SCHEMATIC FOR LONGITUDINAL TRAVEL MODE.

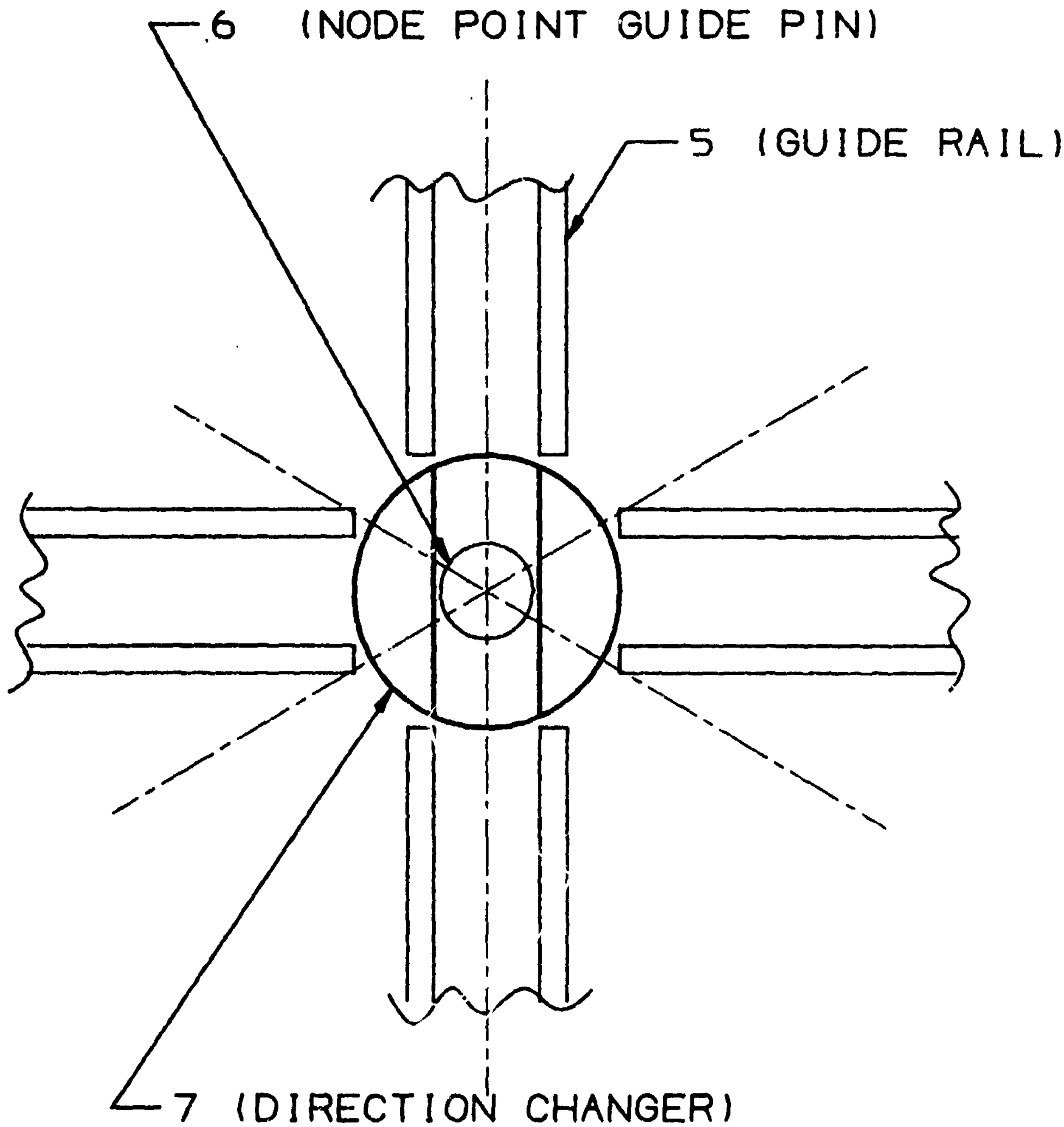


FIGURE A3. SCHEMATIC OF DIRECTION CHANGER.

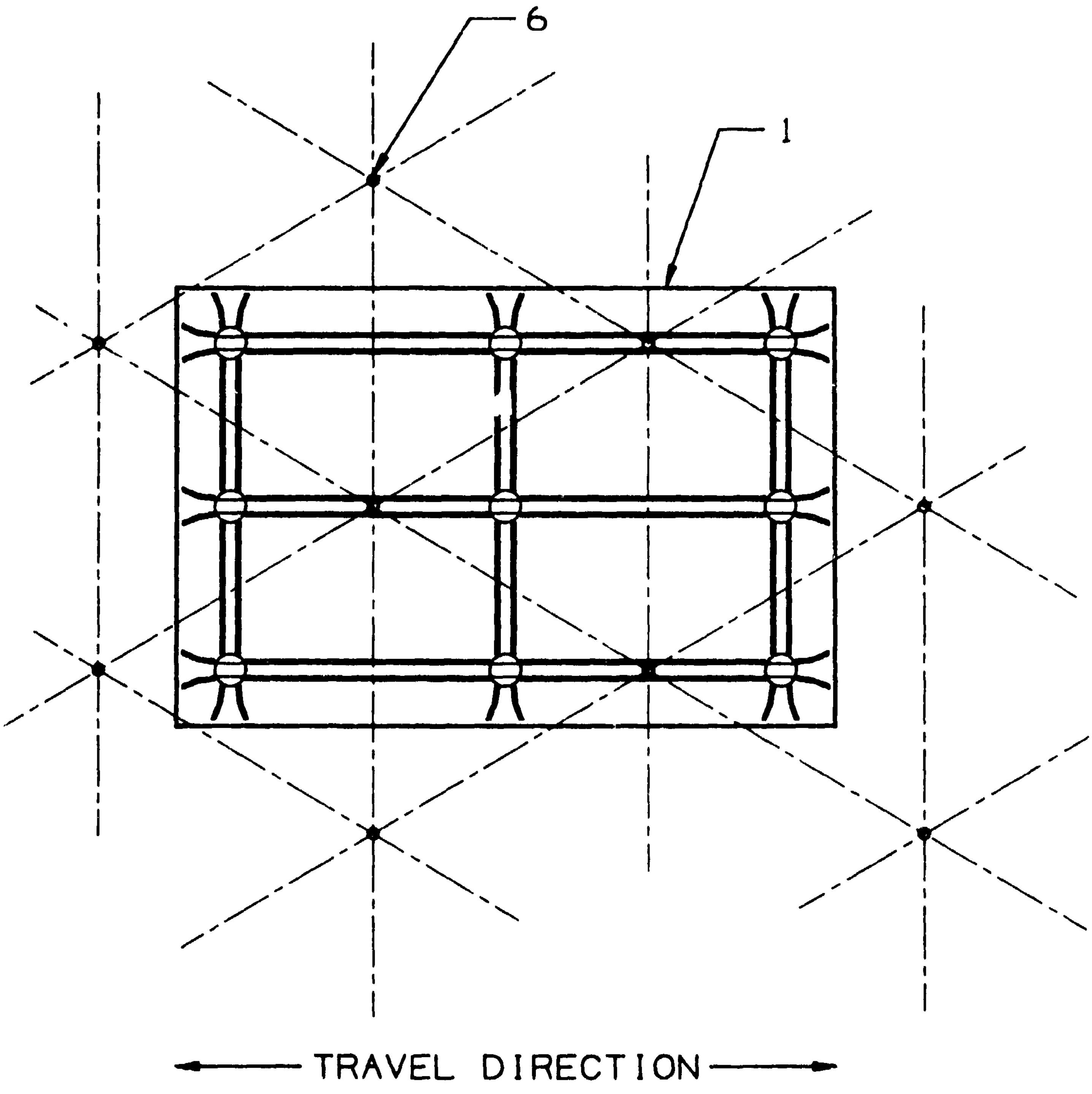


FIGURE A4. SCHEMATIC FOR TRANSVERSE TRAVEL MODE.

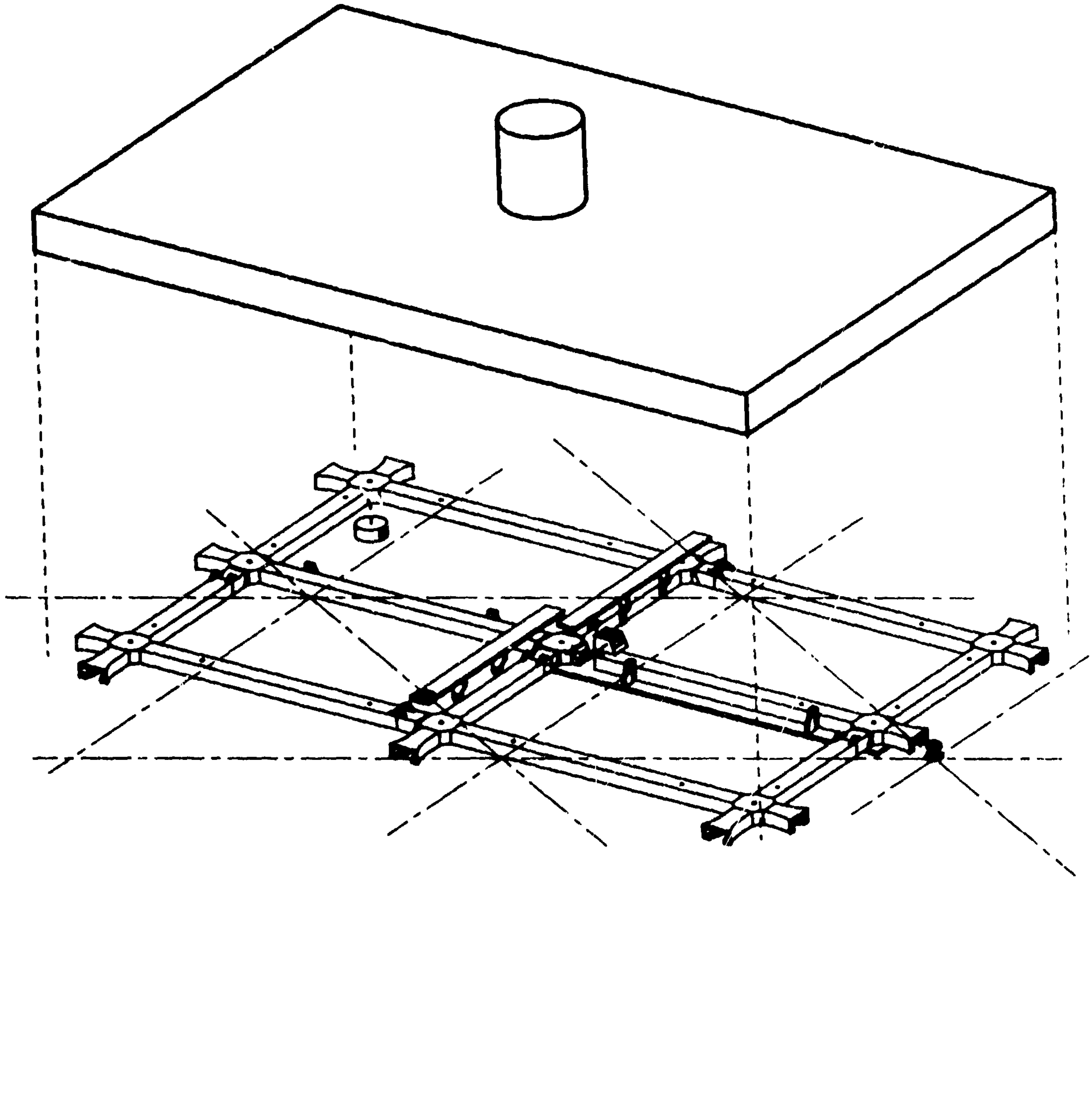


FIGURE A5. PARTIAL EXPLODED VIEW OF MRMS.

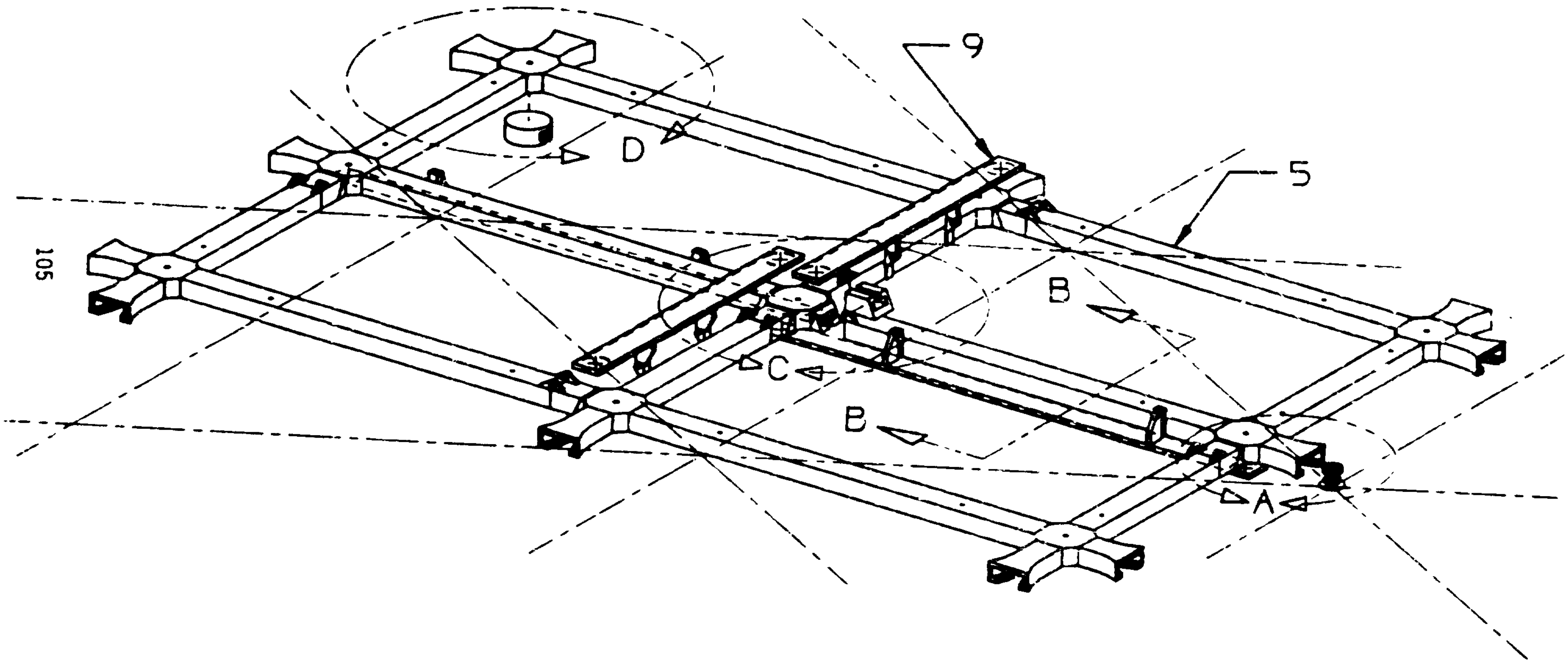
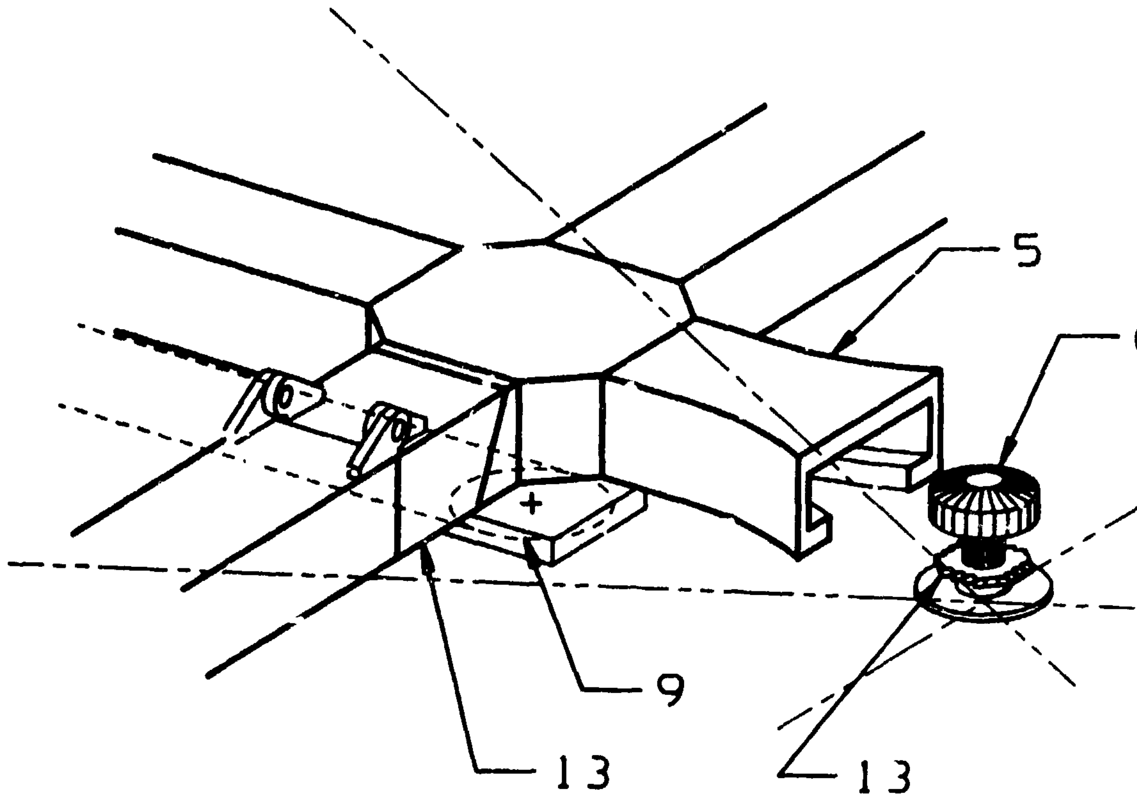
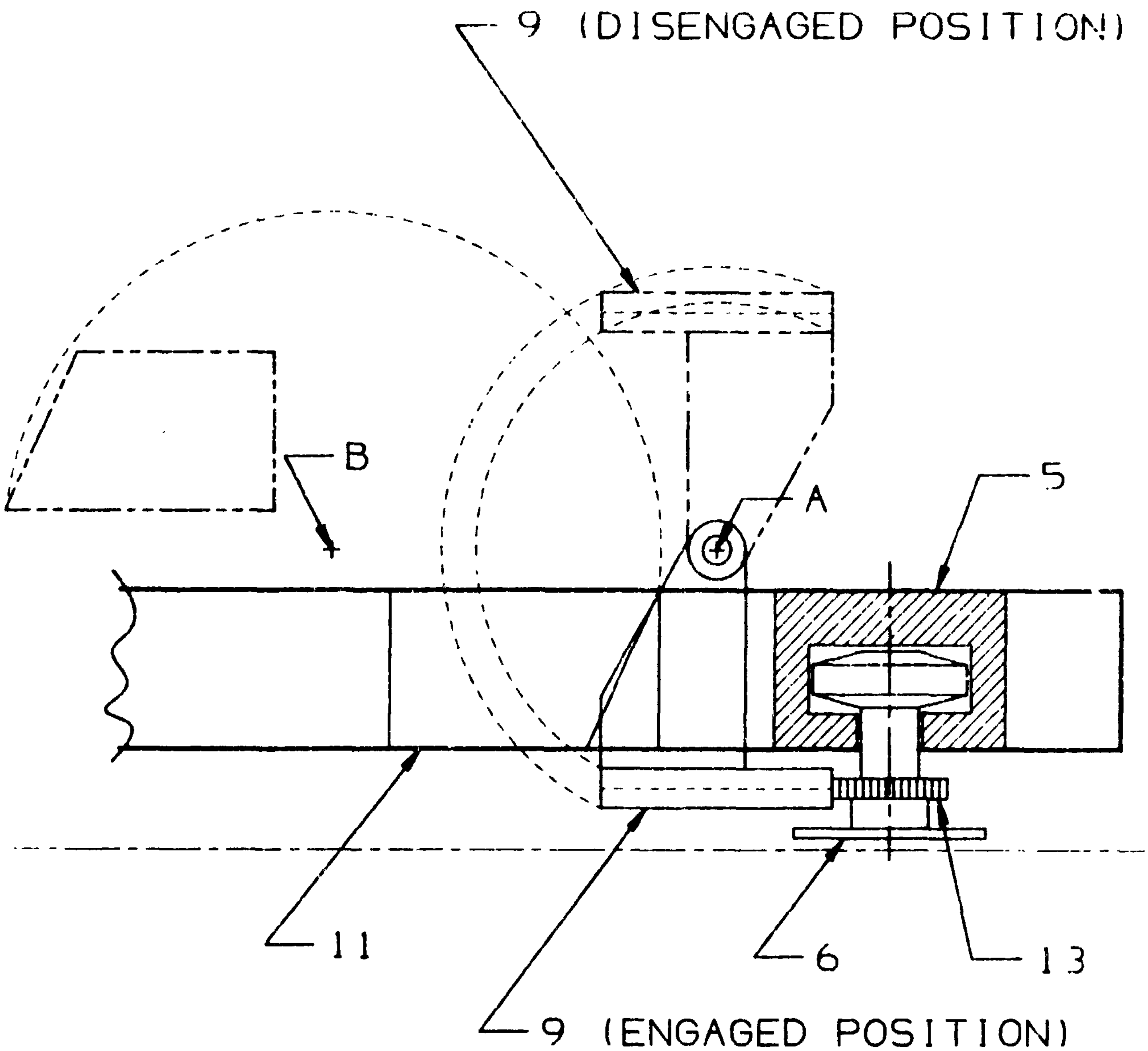


FIGURE A5 (CONT). RAIL AND DRIVE SYSTEM.



VIEW A

FIGURE A6. VIEW SHOWING ENGAGEMENT OF GUIDE PINS INTO RAILS.



SECTION B-B

FIGURE A7. SCHEMATIC FOR CHAIN DRIVE ENGAGEMENT AND DISENGAGEMENT.

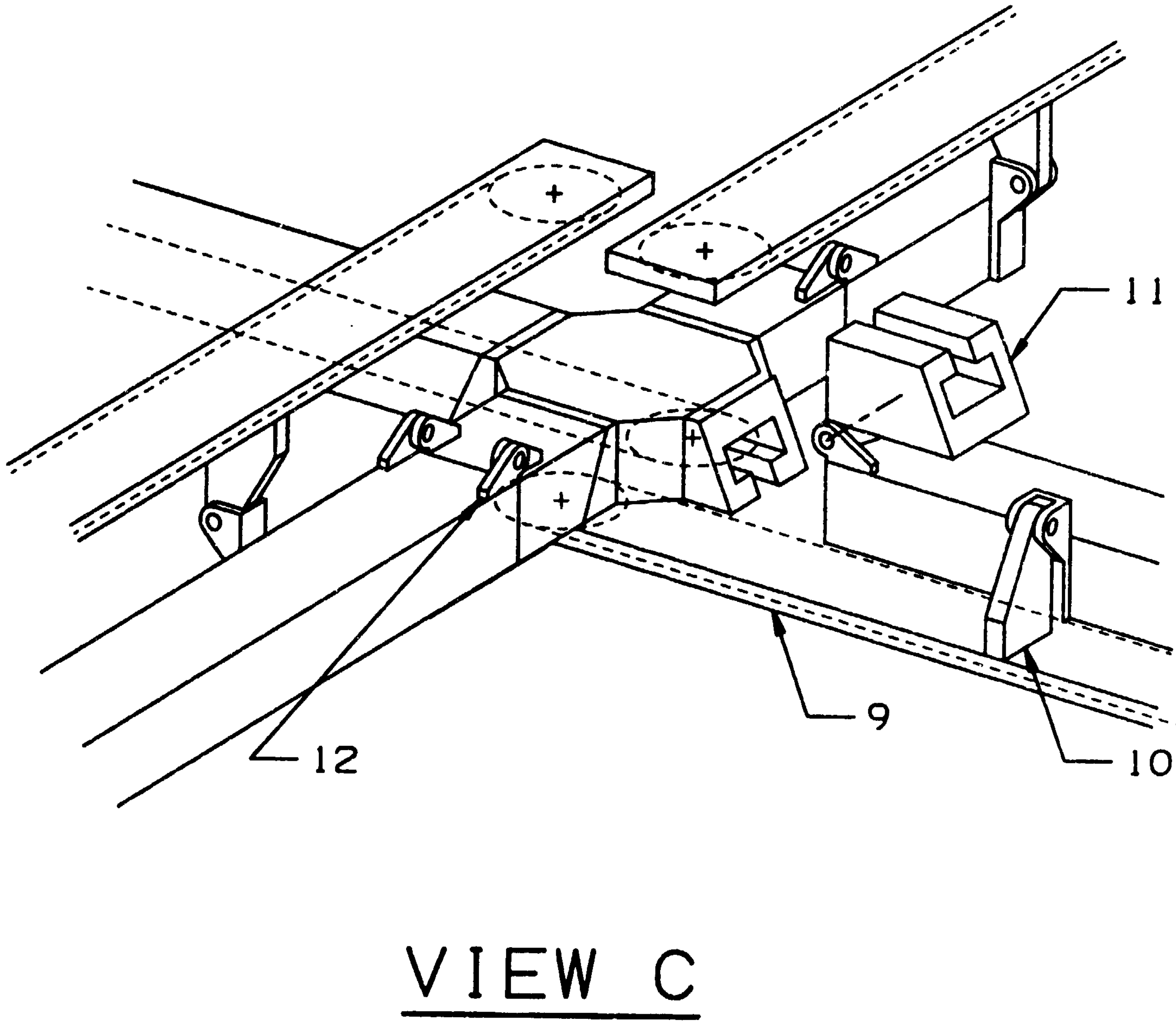
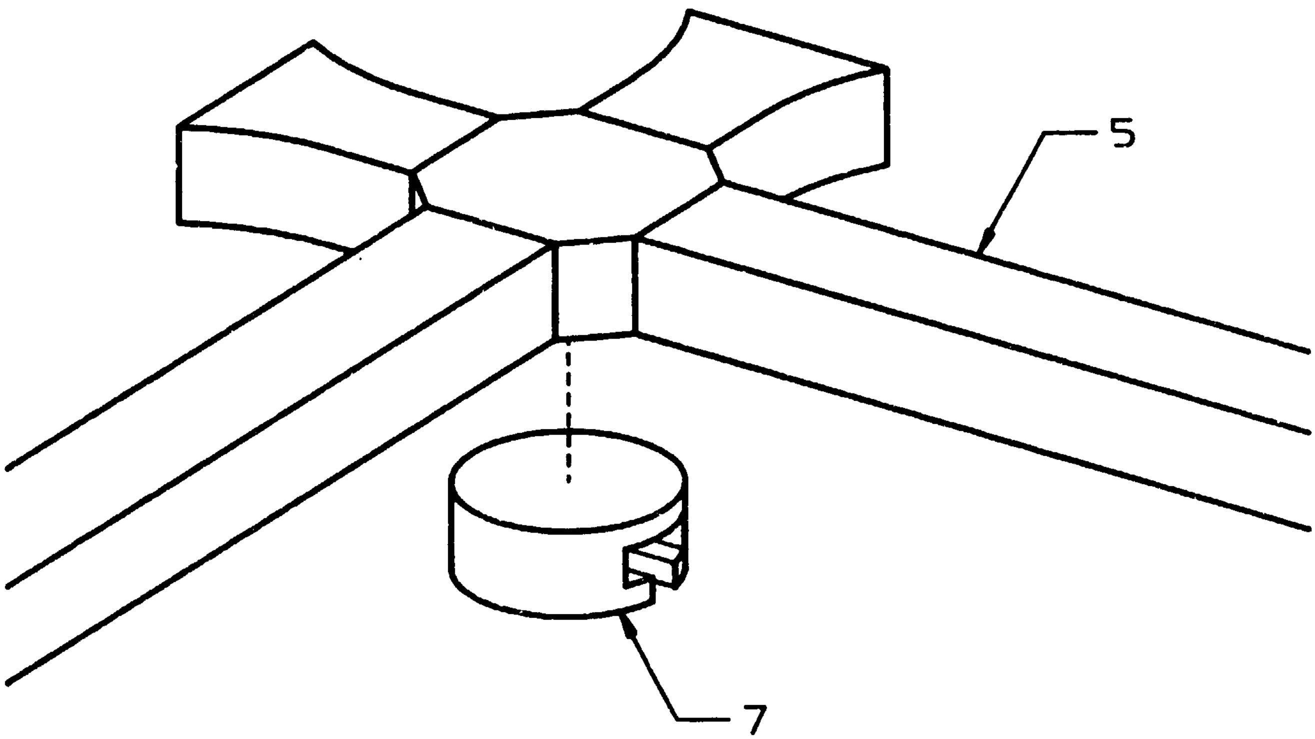


FIGURE A8. VIEW SHOWING RAIL SEGMENT PIVOT.



VIEW D

FIGURE A9. VIEW SHOWING DIRECTION CHANGER.

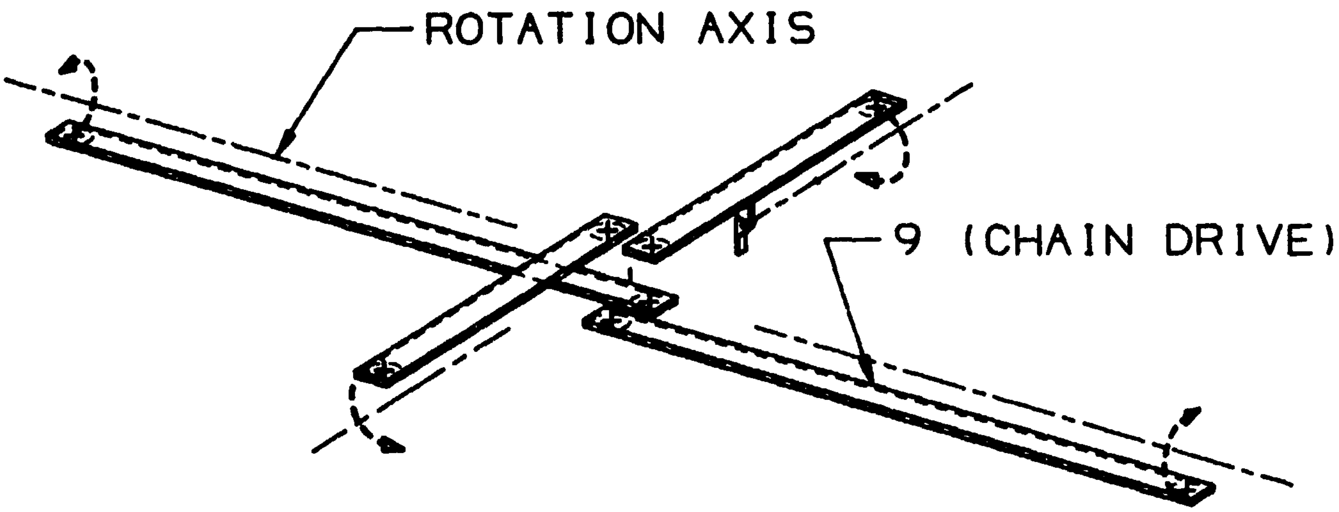


FIGURE A10. SCHEMATIC OF CHAIN DRIVE CONVERSION TO LONGITUDINAL TRAVEL.

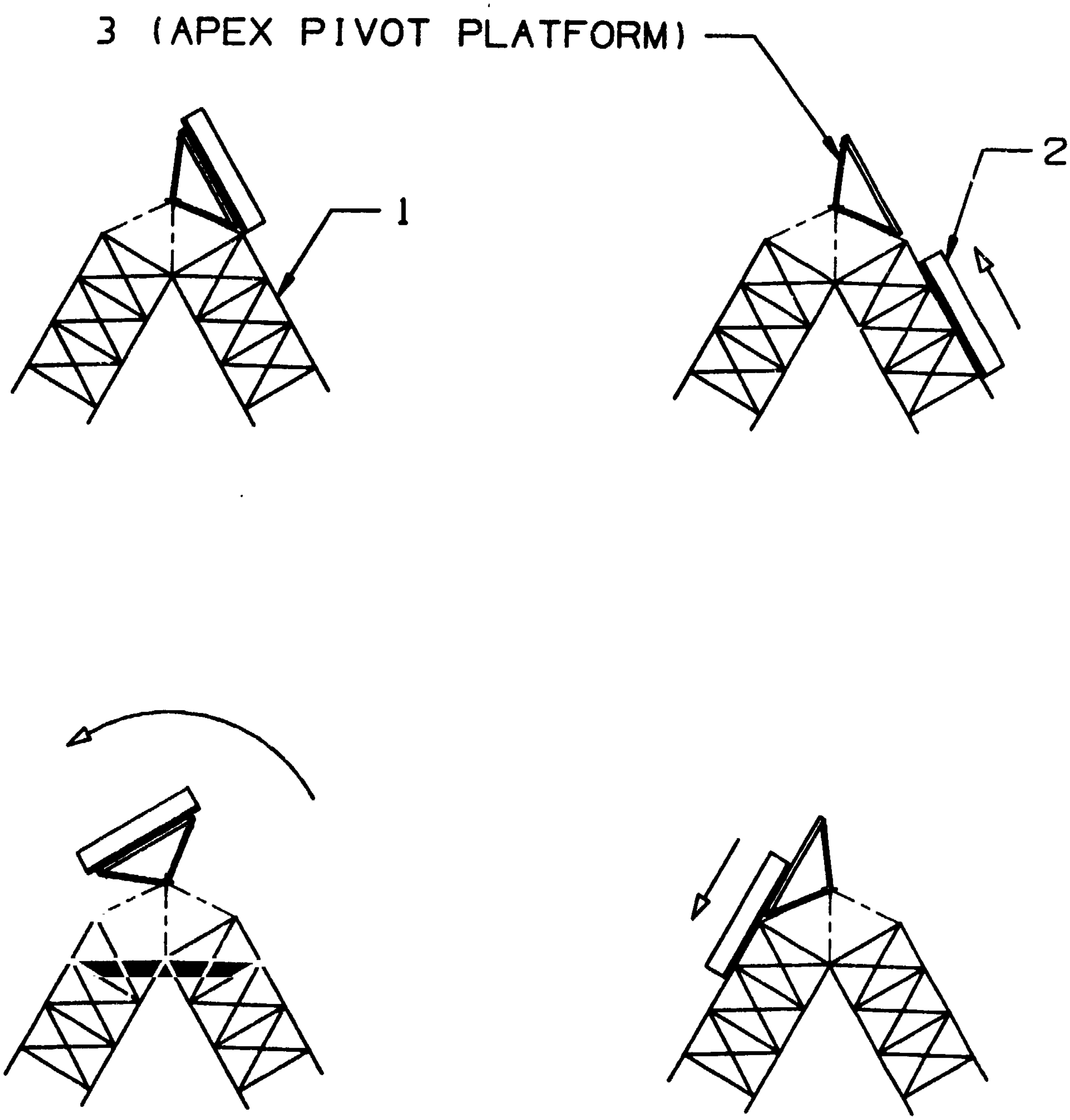


FIGURE A11. SCHEMATIC OF AROUND THE APEX TRANSFER.

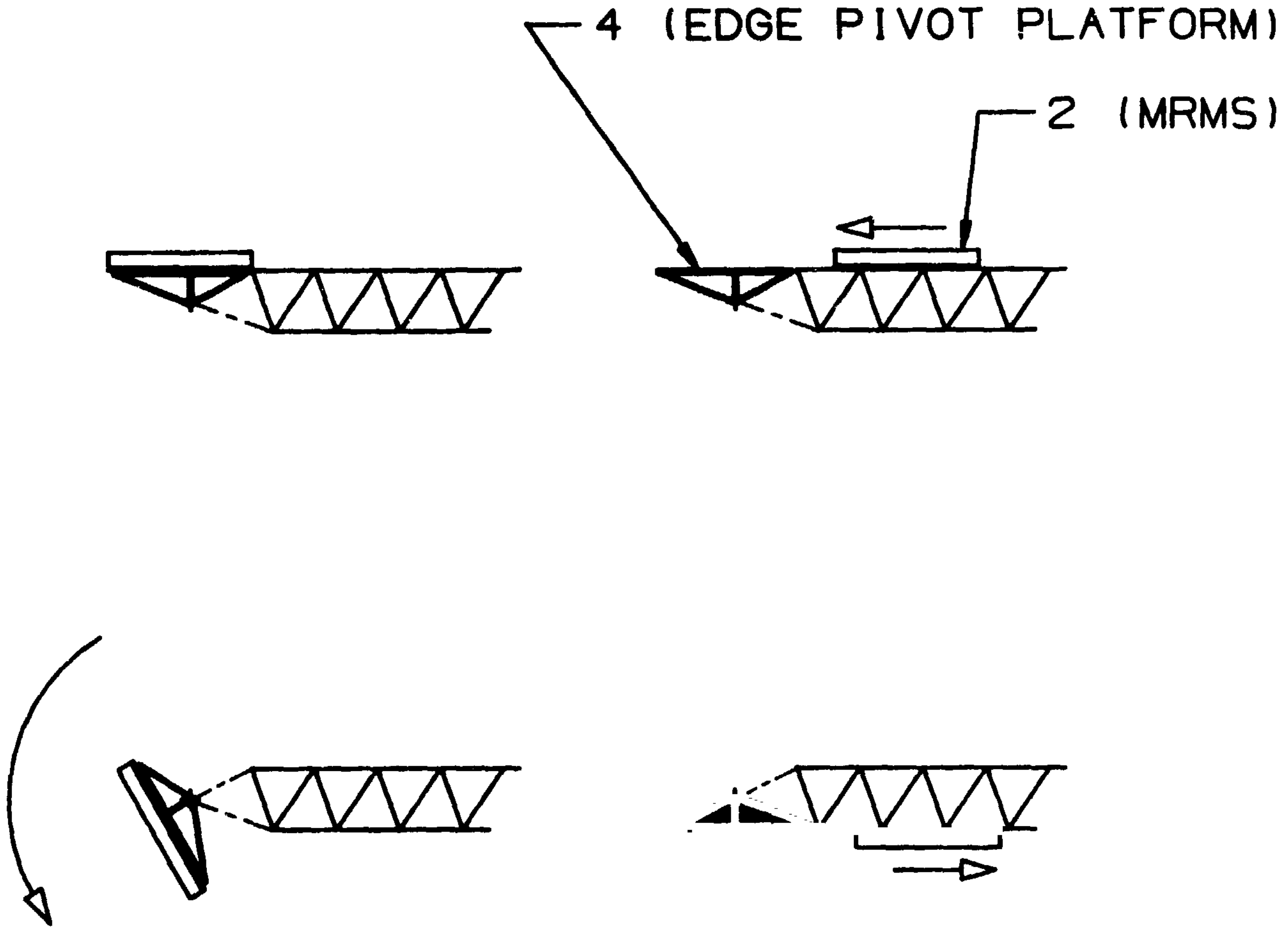


FIGURE A12. SCHEMATIC OF AROUND THE EDGE TRANSFER.

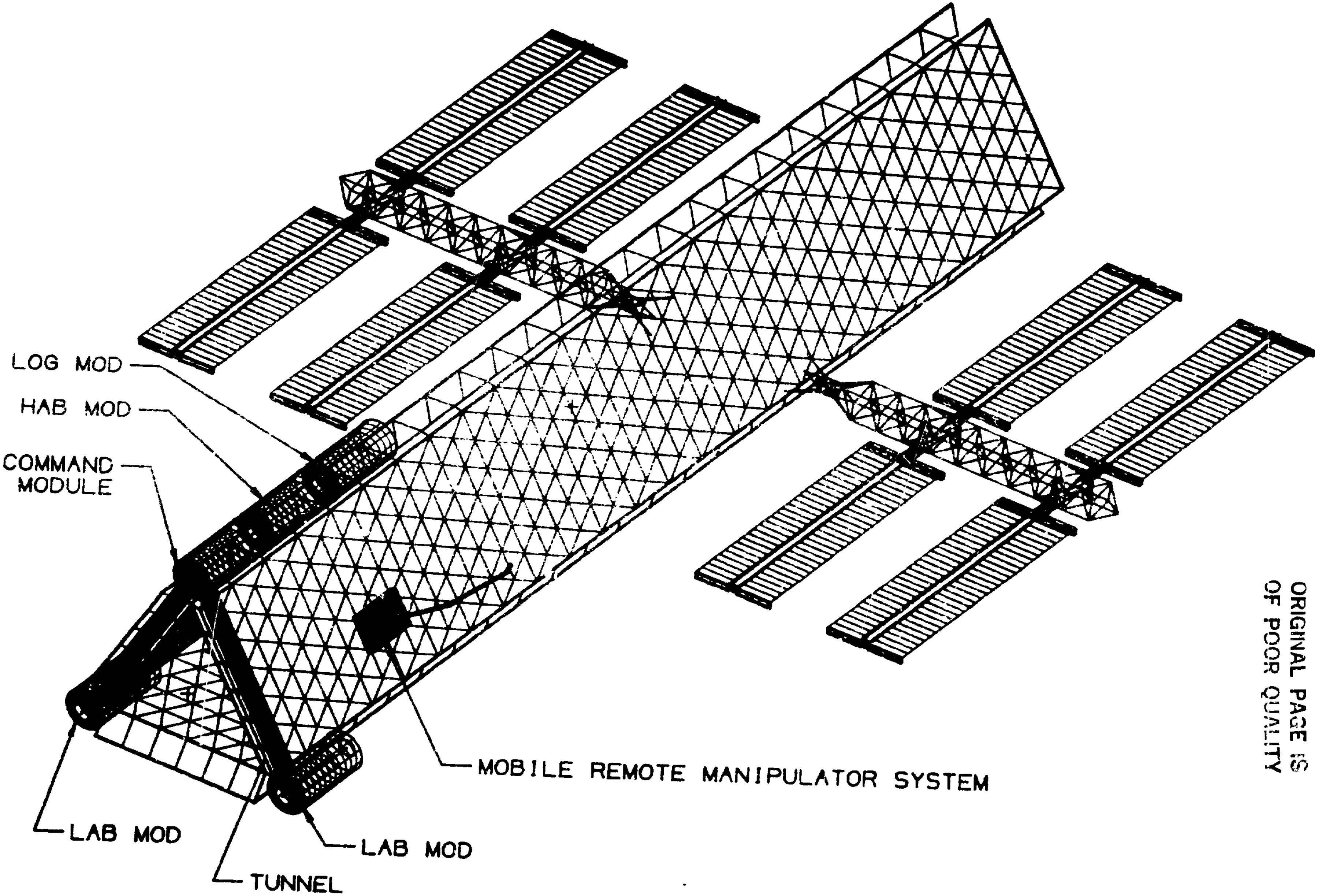


FIGURE B1. Gravity gradient Space Station with delta shaped keel.

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