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Aerobrake Assembly With Minimum Space Station Accommodation

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List of Acronyms

Ao	Solar irradiance, exoatmosphere
AFE	Aeroassist Flight Experiment
ALS	Advanced Launch System
ASAL	Automated Structural Assembly Laboratory
C_D	Drag Coefficient
C_L	Lift Coefficient
CRV	Crew Return Vehicle
CSEI	Controls-Structures-Electromagnetics-Interaction
DMS	Data Management System
EMU	Extravehicular Maneuvering Unit
ETA	External Tank Assembly
ETO	Earth-to-Orbit (Launch System)
EVA	Extravehicular Activity
FRCI	Flexible Refractory Ceramic Insulation
FTS	Flight Telerobotic Servicer
G	Acceleration of Gravity
HLLV	Heavy Lift Launch Vehicle
IMLEO	Initial Mass Low Earth Orbit
IVA	Inner Vehicular Activity
L/D	Lift to Drag Ratio
LEO	Low Earth Orbit
LEV	Lunar Excursion Vehicle
LTV	Lunar Transfer Vehicle
MEV	Mars Excursion Vehicle
MRS	Mobile Remote Servicer
MRSR	Mars Rover Sampler Return
MSC	Mobile Service Center
MT	Mobile Transporter
MTV	Mars Transfer Vehicle
NASP	National Aero-Space Plane
NSTS	National Space Transportation System
ORU	Orbital Replaceable Unit
P/A	Propulsion/Avionics

List of Acronyms

RFP	Request for Proposal
RMS	Remote Manipulator System
RTV	Room Temperature Vulcanized Material
SEI	Space Exploration Initiative
SIP	Stress Isolation Pad
SOW	Statement of Work
SPDM	Special Purpose Dextrous Manipulator
SRB	Solid Rocket Booster
SSF	Space Station Freedom
SSRMS	Space Station Remote Manipulator System
STS	Space Transportation System
TDRSS	Telemetry Data Relay Satellite System
TPS	Thermal Protection System
β, σ, ψ	Orbital Angles Defined In Text

Aerobrake Assembly With Minimum Space Station Accommodation

1.0 Trade Study Synopsis

As part of Langley Research Center's Space Exploration Initiative Office responsibility as Level III agent for Space Exploration Initiative (SEI) Transportation Nodes, a study has been performed to investigate the minimum Space Station Freedom (SSF) accommodations required for the Lunar Aerobrake. This study has encompassed both the initial assembly of the aerobrake as well as its subsequent repair or refurbishment for multiple use. Since various aerobrake concepts are being considered, this study developed representative configurations which captured the major themes in the current spacecraft design efforts. The baseline Space Station Freedom support services, which include the Mobile Remote Servicer, Space Station Remote Manipulator System, Flight Telerobotic Servicer, Special Purpose Dextrous Manipulator, Mobile Transporter, and EVA/IVA, were also assumed to be available. Major options in Earth-to-Orbit (Delta, Atlas, Titan III and IV, Shuttle, Shuttle C and C') were also assumed. The various aerobrake configurations were in turn matched to three structural-mechanical assembly concepts: center-core with petals, orthogonal spars, and tetrahedral truss with panels. Assembly, flight, repair, refurbishment, inspection and reflight scenarios were developed to determine required Space Station Freedom support services and accommodations. Moreover, required but nonexistent or insufficient areas of support or accommodation were identified, such as commonality, sparing, Earth-to-Orbit (ETO) options, and packaging. It was shown in this study that for the aerobrake configurations currently being considered, Space Station Freedom support systems with small modifications can perform the necessary tasks to assemble and refurbish the Lunar Aerobrake. Inspection, on the other hand, will require the development of some specialized sensory hardware, either in the form of end effector tools or stand-alone instruments. Required structural accommodations to Space Station Freedom for just the Lunar Aerobrake will require the addition of three or four 5-meter bays which are standard for Space Station Freedom. In addition, some sort of support mechanism ("lazy susan") will probably be required to rotate the aerobrake during assembly, refurbishment, and inspection. An issue outside the scope of this study is the integration of the aerobrake with the rest of the Lunar Transfer Vehicle (LTV), nevertheless some possible approaches are suggested. Finally, important areas for follow-on study were identified.

2.0 Background and Rationale

2.1 Introduction

It is important to note that for the SEI, the aerobrake has been proposed to be used in several different stages of the Lunar or Mars missions: First, in the precursor Lunar technology and science mission phase, the LTV returns to SSF where it aerobrakes into an orbit properly phased for rendezvous or directly into a descent trajectory for landing. Second, for the proposed manned Mars mission, the Mars Transfer Vehicle (MTV) separates into two vehicles, both of which use aerobrakes larger than those required for the LTV. The Mars Excursion Vehicle (MEV) aerobrakes further into a descent trajectory for landing. After the Mars ascent stage rejoins the MTV, the two begin the flight back to Earth, where the MTV aerobrakes into Earth orbit. Even then, the crew utilizes a Crew Return Vehicle (CRV) to land on Earth via aerobraking. It can readily be seen that only the Mars entry plus Earth return stages, and the Earth return from the Moon into an SSF compatible orbit, represent steps not already well developed in the Mercury, Gemini, and Apollo programs.

Various studies have shown that the use of an aerobrake as part of spacecraft design for both the LTV and MTV offer substantial weight savings over a purely chemical propulsion approach. The savings are particularly significant in the case of the MTV where the weight savings could be as much as fifty percent which reduces the size of the MTV down to the 500-800 tonne mass range. The case for the LTV, while not as dramatic, is still significant. Figures 2.1 and 2.2 are data from McDonnell Douglas studies (ref 1) and are typical of the results which have led to the general consensus on the importance of the aerobrake for the SEI.

As can be seen from the curves done for the LTV, the aerobrake can yield nearly twenty per cent savings in initial mass in low earth orbit (IMLEO). Naturally, the aerobrake cannot represent zero mass, so the savings will be less than the intercept value. Nevertheless, Figure 2.3, which lists the mass budget for the "Single P/A Module" LTV, shows that the aerobrake represents less than twenty per cent of the return weight of the LTV. Such a mass-fraction would realize approximately fifteen per cent savings in IMLEO. Thus, the utilization of an aerobrake would be very desirable.

The utilization of an aerobrake has certain practical problems that tend to mitigate the expected savings. First, even though aerobraking has been used many times before (Mercury, Gemini, Apollo, Viking, and the Shuttle, for example) there still exist the usual concerns over a newly developed configuration. Second, the aerobrake must be transported to Space Station for use on the LTV. Third, because both the LTV and the aerobrake are too large to be brought up *in toto*, the aerobrake must be assembled and mated to the LTV in space. Fourth, the assembled aerobrake must somehow be inspected and proven flight worthy. The system level considerations become more complex if the aerobrake is part of a reusable spacecraft.

The 90-Day Study made the assumption that Space Station Freedom would serve as the in-space location to collect and assemble both the LTV and the MTV. A set of hangers and assembly structures were proposed to be added to the space station to accommodate the LTV and MTV. These structures, illustrated in Figure 2.4, were to provide "strongbacks" for the vehicles being assembled and were to provide large transfer cranes for manipulating the vehicles. Whereas the Space Station Freedom hangar approach is compatible with the capabilities of the space station, the expected cost and complexity of such support systems has given rise to reservations as to whether other approaches, such as direct launch might not be more practical.

It is the purpose of this study to revisit the issue of on orbit assembly, with the purpose of determining what minimum accommodations might be required to build and maintain an aerobrake for the LTV only. By this means, an assessment can be made of how close to baseline SSF the Space Exploration Initiative's earliest needs can be met. The practicality of the aerobrake assembly thus gains strength and credibility from its close association with the SSF design.

2.2 Report Overview

This report is broken into two main parts: First, the elements that will play a role in the aerobrake assembly will be described and in some cases developed. The aerobrake to be assembled is not a settled thing and several types have been proposed. This report discusses the issues related to the aerobrake and postulates an aerobrake configuration subset which captures the main themes in the current concepts under study. There are also several possibilities in the Earth-to-Orbit (ETO) lifting vehicles. These range from already existing expendable launch vehicles such as Deltas, Titans, and Shuttles to proposed heavy lift launch vehicles (HLLV's) such as the Shuttle C Advanced Launch System (ALS) and external tank derived vehicles with IMLEO's somewhat greater than that of a Saturn V. Available SSF support systems will also be presented with some discussion as to what their capabilities are. The ones to be discussed here are the Mobile Remote Servicer (MRS), the Space Station Remote Manipulator System (SSRMS), the Flight Telerobotic Servicer (FTS), the Special Purpose Dextrous Manipulator (SPDM), the Mobile Transporter (MT), and EVA/IVA. These systems are baselined to be part of SSF and are thus potentially available to support the assembly and maintenance of the LTV Aerobrake.

Given the aerobrake configurations, a set of mechanical assembly techniques is described that is compatible with one or more of the aerobrake configurations. These mechanical designs are EVA-teleoperator friendly and the degree to which this is possible is discussed.

The requirements for inspection, both in the initial assembly and in the refurbishment-repair for reuse are presented. The requirements, which are based on current STS practice and plans for the Aeroassist Flight Experiment (AFE), emphasize the thermal protection system (TPS).

With the foregoing elements established, the second part of the study then develops end-to-end scenarios which follow the aerobrake from launch to on-orbit assembly, to inspection, through flight, and return, and then to refurbishment, repair and reuse. Each scenario is exercised to drive out the accommodations and support services required at SSF for the aerobrake. Deficits are noted where a support service is overtaxed, such as requiring two FTS's, where only one exists, or where a system is required but does not exist. Required SSF structural additions are also defined in each scenario. Issues such as micrometeoroid protection and solar radiation heating or exposure to deep-space cold are also considered to identify accommodations arising from these sources. In addition, unresolved issues that do not necessarily relate to SSF accommodations are identified and areas that need further study are suggested.

3.0 Assumptions and Ground Rules

Since the Space Exploration Initiative is in a stage with various options and with early results that will be modified as times goes on, a set of assumptions and ground rules were set to make this study possible. The assumptions and ground rules had to be specific enough to give a solid foundation on which to build a relevant study, while at the same time not be tied to transitory results that make the study outdated before it is completed.

3.1 Baseline Assumptions

For the purpose of this study the following assumptions have been made:

1. Use the 90-Day Study (Ref 1.)
2. Focus on LTV Aerobrake (Defer Mars Aerobrake).
3. Use the LTV Single Propulsion/Avionics (P/A) Module.
4. Use only capabilities in the baseline NSTS/SSF Systems (from RFP's, SOW's, etc.) as of August 1990.
5. Use only already identified aerobrake configurations.
6. Three Phase Activity: feasibility, detailed assessment, flight experiment design.

The first of the assumptions ties this study directly to the mission model of the original "90-Day Study" (Ref 1) with its manifests, payloads, vehicle sizes, schedules, vehicle configurations, and use of Space Station Freedom as a transportation node. The second given condition causes this study to be focused on the earliest required SSF support for SEI. Commonality or evolvability of the aerobrake maintains the linkage to the later Mars Mission. Working the aerobrakes one at a time allows for better visibility into the compatibility of aerobrake assembly,refurbishment, and reuse with SSF. The third assumption maintains consistency with the follow-on work done after conclusion of the 90-Day Study, which continued the concept development of the Lunar Transfer Vehicle. Minimum accommodation is a ground-up exercise to define those capabilities that are not already planned to be available. Thus, this study assumes only the "advertised" capabilities in NSTS and SSF support systems as of August 1990. These planned capabilities are contained in either NSTS standard services (Ref 2) or Requests for Proposals and Statements of Work, for Space Station Freedom e.g., Flight Telerobotic Servicer and the Mobile Remote Servicer. Since a large number of aerobrake concepts have been proposed, including those in the 90-Day Study and many are based on well-developed designs with supporting analysis, it was decided not to create new concepts, but to adapt to those that exist. Last, this study was proposed as a feasibility study to assess required SSF accommodation issues where sufficient information exists and to identify the major unresolved issues that require further detailed study.

3.2 Baseline Space Station and NSTS Support Systems

The current elements of the space station include some support systems whose purpose it is to support the physical operation of the station and its payloads. Generally, these systems operate in conjunction with astronauts in a fashion to support, augment, or supplement EVA activities. In addition, there is some support available from the Shuttle Remote Manipulator System, when the Orbiter is at SSF.

3.2.1 Flight Telerobotic Servicer

Planned, baseline SSF systems include the Flight Telerobotic Servicer, FTS, which is a dual arm, teleoperated remote manipulator. The FTS, illustrated in Figure 3.1, is anthropomorphic in size, being required to fit into an 84 inch by 42 inch by 36 inch volume. The FTS is required to operate independently of SSF power and thermal interfaces for at least two hours as well as with direct SSF support. The FTS has a four-television system with self-contained illumination support. Operation of the FTS is via an SSF workstation with at least two hand controllers, while the vision system can be controlled by a "hands-off" technique that is "to-be-determined " in accordance with Ref 3. The FTS manipulators will be required to have repeatability tolerances of 0.005 inches and 0.05 degrees, with absolute accuracy of better than 1.0 inches in position and 3.0 degrees in orientation. Within the work envelope, the required tip force is 20 lbs and the required tip torque is 20 ft-lbs. Incremental accuracy is to be 0.001 inches and better than 0.01 degrees at the center of the tool plate. The FTS is also required to support power, data, and video through the end effector tool plate on the manipulator.

3.2.2 Mobile Servicing System

The Mobile Servicing System (MSS) consists of ground segments and space segments and is capable of assisting in the on-orbit assembly, inspection, and refurbishment of the Lunar aerobrake. Specifically, the MSS consists of a Mobile Remote Servicer (MRS), a Mobile Transporter (MT), the Space Station Remote Manipulator System (SSRMS), and the Special Purpose Dextrous Manipulator (SPDM). The space segment of the MSS is illustrated in Figure 3.2

The Mobile Servicing Center (MSC), consists of the MT, MRS, and the SSRMS. This rather extensive system is illustrated schematically in Figure 3.3 to clarify the nomenclature.

The MSS/SSRMS has the capabilities illustrated in Figure 3.4 where it should be noted that the SSRMS is baselined to not only handle and transport the full payload capacity of the Orbiter, but is also required to berth the Orbiter which has a mass of 116 tonne. The growth capabilities have since been eliminated from the proposed capabilities.

3.2.2.1 Space Station Remote Manipulator System (SSRMS)

The SSRMS, illustrated in Figure 3.5, is similar to the current NSTS Remote Manipulator System (RMS), with the additional capabilities of attachment or operation from either end and on-orbit maintainability. The SSRMS has two latching end effectors, two arm booms, four roll/yaw joints, and three pitch joints.

The SSRMS is capable of both manual point of resolution or joint control and auto-trajectory, auto-time sequence, or, later, auto-vision-track mode. The SSRMS is 17.6 (57.75 feet) meters long, with a 82 N tip force and handling translation speeds up to 0.37 meters/sec and rotation rates of 4.0 degrees/sec. Tip positioning accuracy is 4.5 cm and 0.7 degrees within a work envelope sphere radius of 14.22 meters.

3.2.2.2 Special Purpose Dextrous Manipulator (SPDM)

An additional Space Station Freedom telerobotic capability is the SPDM illustrated in Figure 3.6. Similar in many respects except size to the FTS, the SPDM has two manipulators each with an arm length of 2 meters at full extension. With the body dimensions and operation on the SSRMS, the SPDM can reach anywhere inside the 5 meter SSF truss bay without repositioning. Accuracies and performance capabilities for the SPDM are summarized in Figure 3.7.

3.2.2.3 Mobile Transporter (MT)

The Mobile Transporter is that part of the Mobile Servicing Center (the space segment of the Canadian Mobile Servicing System) that is to built by the United States. The MT will provide transportation of the MSC along the space station truss, and is able to make plane changes and rotate in 90 degree steps. Translation rates and rotation rates with specified payload masses are shown in Figure 3.8, where it should be noted that the maximum payload corresponds approximately to the STS low earth orbit (LEO) payload capacity.

3.2.3 Extravehicular/Intravehicular Activity (EVA/IVA)

Also available for SSF support are the on-board crew, both inside (IVA) and to some extent outside (EVA). It should be emphasized that the use of EVA, an already heavily subscribed resource, is an area of concern to which this study has been sensitive. On the other hand, IVA, which is in somewhat more abundance, has been tacitly assumed to be available for operation of the MRS, SSRMS, SPDM, and the FTS. Moreover, IVA can be augmented by ground support operations. The primary limitation of FTS and SPDM operation from the ground is the latency of the TDRSS communication link requiring SSF computation support for force-reflection and closed loop control. However, operation of the MRS/MT (excluding SSRMS, SPDM, and FTS) is possible because of the relatively slow operating speeds.

Nevertheless, some EVA will be required. No robotic system can replace the versatility of the human, even a space-suited human, in the area of unstructured operations. Human intervention in on-site operations as well as inspection and observation will certainly be required. A man-machine mix should be able to utilize the best characteristics of both, and if properly done can magnify the effectiveness of both.

3.2.4 STS Remote Manipulator System (RMS)

The Shuttle RMS might be called on to support some phase of the assembly of the aerobrake such as off loading parts to the SSF storage area, however, it is unlikely it would be used for assembly. The performance capabilities of the STS-RMS are nearly the same as the SRMS which are presented in Section 3.2.2.1.

3.3 Earth-To-Orbit Capabilities, Current and Potential

In order to assess the minimum SSF accommodations to support the assembly of an aerobrake, some idea must be developed of the maximum (and minimum) size of parts from which the aerobrake must be assembled. From this size information, structural concepts can be developed to evaluate with respect to SSF support services.
The most obvious extreme is direct launch of the already assembled aerobrake attached in some fashion to a launch vehicle. The "90-Day Study" lunar aerobrake was set at 45 feet (13.7 meters) in diameter, a size far larger than any currently proposed launch vehicle shroud. Studies have been done to consider attaching the aerobrake directly to the outside of an expendable launch vehicle. The tentative conclusion reached in these studies was that the aerodynamic loads would be too severe.

Another issue that requires consideration here is the possible launch vehicles, both already in existence and proposed. The Space Exploration Initiative has added to the push for an alternative to the current STS in view of the large size of the proposed Lunar and Mars transfer vehicles. One proposed heavy lift vehicle development is the Advanced Launch System (ALS) with initial mass in low earth orbit (IMLEO) of approximately 250 metric tons for the largest option. A more modest development with IMLEO's of 60 to 70 metric tons are the so-called Shuttle C and Shuttle C'. These vehicles are developed from the current Shuttle solid rocket boosters (SRB's), external tank, avionics, and propulsion. By making use of already developed STS production facilities, designs, etc., a "bootstrap" vehicle with minimum technology advances could be developed. An unmanned heavy lift launch vehicle (HLLV) would be available in a few years, shortcutting early design cycles and would be consistent with early Lunar mission requirements. Moreover, as mentioned earlier, the direct launch of an aerobrake has been found not to be practical. Thus, some amount of on-orbit assembly of a non-deployable aerobrake must be considered and it becomes an issue of pieces versus bigger pieces with respect to available launch vehicles. Only a conceptual failure in assembling the aerobrake arising from the complexity of the (small) size of the parts compatible with the Shuttle, Shuttle C and C' would necessitate consideration of a larger HLLV. Of course, if other considerations dictated the use and, hence, development of an ALS-sized vehicle, the aerobrake assembly would benefit as well.

With the foregoing in mind, it was decided that the largest HLLV available for assembling the LTV aerobrake would be the Shuttle C and C'. Nevertheless, other ETO logistics support is available. Unmanned launch vehicles include the Delta II, the Atlas and Atlas II, and the Titan IV. Figures 3.9 and 3.10 show schematics of the Delta II, the Atlas, the Titan IV, the Space Shuttle, the Shuttle C, and Shuttle C'. The payload mass and size for each of these launches is presented in Figure 3.11. The Delta II has the smallest payload capacity and the Space Shuttle C' has the largest payload capacity.

The Space Shuttle has a nominal payload mass of 29.5 tonne (65,000 lbs.); however, actual payloads are limited to 18 tonne (40,000 lbs.). The Titan IV has the same diameter as the Space Shuttle, but has a slightly longer bay and can launch a slightly larger payload mass. It should be noted that the mass-to-orbit information presented in Figure 3.11 is dependent on the orbit altitude. As previously stated, none of these launch systems is large enough to hold the assembled 13.7 m diameter aerobrake.

This study tacitly assumes that SSF will have the capability to dock and berth unmanned as well as manned launch vehicles. Whether such a capability actually materializes depends in large measure on developing a rendezvous and proximity operations capability for SSF and at least some unmanned ETO. However, as will be seen later, ETO other than Shuttle is desirable, but not required.

3.4 Thermal Protection System Options

As previously stated, the TPS must be designed so that the structural heat loads are maintained at a low level and the TPS can be refurbished, repaired, and inspected in-orbit. There are three types of TPS which are applicable to the aerobrake: tailorable advanced blanket insulation (TABI), rigid ceramic tiles, and ablators.

The TABI is limited to temperatures below 2000°F and is installed by using gravity to drape over the structure. Installing the TABI on-orbit cannot be performed as easily as on earth; however, it may be possible to use Velcro or similar material on the backside of the TABI. The high aerodynamic loads acting on the aerobrakes will probably compress the TABI and thus reduce the thermal insulation. Another problem is that debris impact might tear or rip the TABI material. Refurbishment of the TABI may not be possible without replacement and will probably require EVA support rather than robotics.

The rigid ceramic tiles are densified flexible reusable ceramic insulation (FRCI) made from high temperature aluminoborosilicate fibers, alumina silicate fibers, and boron oxide silicate fibers. The tiles are limited to temperatures of 2500°F for multimission or 3000°F for a single mission. The ceramic tiles are fabricated with a very thin outer layer (0.012 inches) of reaction cured glass on all the surfaces with a low density fiber interior. If there is a penetration through the thin outer layer, then cracks spread very rapidly. Therefore, if such things as orbital debris penetrates the outer layer, then the tile needs to be repaired or replaced. The tiles can be removed and replaced on an individual basis rather than the whole TPS. The fitting of the tiles to each other and the installation of seam filling material in the assembly and refurbishment processes needs to be further investigated.

One of the concerns of using ceramic tiles for the on-orbit assembled aerobrake is the problem of closure along the seams between two aerobrake structural assembly sections with preinstalled tiles. Arranging the preinstalled tiles on the sections such that gaps are left for installing tiles over the structural seams after assembly will prevent the TPS seams from eroding. Figure 3.12 shows such as arrangement for an aerobrake petal section, one of the construction approaches of this report in section 4.3.1. The TPS closure insert would be installed from the TPS side. It should be noted that for the sphere cone configuration, different shaped TPS closure inserts are required because the radius of curvature of the petal varies with distance along the length. Therefore, each closeout tile must be identified.

The ablative insulation can withstand temperatures up to 5700°F. It can be attached to the structure with mechanical fasteners. Again, like the tiles, there is a problem with seams and how to fill the seams between the assembled parts. The ablators can be designed for multi-use; however, because of the nature of eroding the surface, the more uses, the greater the thickness of the ablator initially. Furthermore, this increased thickness means increased mass of the aerobrake which will decrease with each flight. Another consideration of the ablators is the amount of mass due to the high density of the material. Telltales can be employed to provide inspection of the ablator, however, refurbishment of the ablator may be extensive in that the whole ablator section may require replacement.

The degree of commonality of parts such as the TPS tiles is dependent on the aerobrake geometry. The spherical or Apollo shape has spherical symmetry and thus offers the highest degree of TPS and structural commonality. The sphere cone and biconic have an axis of symmetry and thus have a limited degree of parts interchangeability. The Aeroassist Flight Experiment (AFE) shape has a plane of symmetry and hence not even the TPS elements are interchangeable. This has a major impact on both the number of spare parts, storage locations, and required mass to orbit.

Four techniques were considered for the refurbishment of the ceramic tiles. The first method consists of removing and replacing the tile in situ. The methodology for doing this needs to be developed since removing the tile is not easily accomplished and replacing the tile needs to be done in space where the glue setting agents of air and water are not readily available. The second method involves removing and replacing an entire structural assembly section with the tiles already installed with a spare assembly section using EVA or robotics. The damaged tile on the removed assembly section still needs to be repaired or replaced. A third method involves using small airlock compatible preintegrated panel/tile sections which can be removed and refurbished inside the laboratory in the presence of atmosphere. With this method, pull tests could be employed to evaluate the tile bond strength. The fourth method is to remove and replace a preintegrated panel-tile ORU section with a spare ORU section using EVA or robotics.

For the LTV aerobrake, the ceramic tile was selected for the TPS primarily because it can be readily handled by EVA or robotics, it has demonstrated manrating performance, it has good performance capability, and it has low mass properties to provide the necessary thermal insulation in the high aerodynamics load environment. Also the tiles have an extensive refurbishment and performance database and can be installed and/or refurbished with minimum impact on Space Station accommodations. Also with the tiles there are procedures available for in-flight refurbishment during the LTV mission using the STS ablator repair tool.

3.5 Inspection Requirements

For the on-orbit assembly of an aerobrake, inspection separates into two major categories: Inspection of the mechanical structure and inspection of the Thermal Protection System (TPS). Both types of inspection occur at both initial assembly and at reuse.

A consideration of the mechanical structure leads to the conclusion that assembly (including disassembly-reassembly) and post-flight inspection will require that the structure be checked for structural integrity. The information would be used to ensure that a mechanical joint was properly made or unmade, that no parts of the structure were broken or cracked, and that there was no mission-endangering hidden damage.

To perform the required mechanical structure inspection, the available resources include EVA visual inspection, imbedded structural sensors (fiber optic), computer enhanced imaging, and non-imaging sensors such as X-Ray (non-contact) and Acoustic (contact.) The above listed sensory techniques are already well-developed and the number of structural support elements for the aerobrake are rather small. Therefore, it is assumed that EVA inspection or RMS, FTS, or SPDM mounted television (particularly with zoom) is sufficient to perform the superficial checks on ensuring that a joint is made. It should be noted that the latter assumes that any structural elements would have telltales embedded in a fashion similar to what is already being considered for SSF struts. Internal structural integrity would be checked through use of the embedded sensors.

The aerobrake TPS, because of the large surface area, requires most of the inspection function. Not only do the TPS "interconnects" require verification, but also the entire surface of the aerobrake must be proven free of defects. In the case of the STS Orbiter, two sorts of TPS tile requirements are encountered. The most stringent are for areas around the nose, tail, etc., and reflect the desire to minimize heating and sensitivity to turbulence due to tile roughness and inter-tile "steps and gaps." The fact that the Orbiter encounters both rarefied and dense atmosphere causes requirements for "step and gap" to be very stringent in some areas and less so in others. The Aeroassist Flight Experiment (AFE) will not be required to come completely through the atmosphere, therefore, while the AFE will use the same tiles as the Orbiter, less stringent Orbiter requirements are expected to be used. For the Orbiter, these less stringent requirements for "step and gap" are that the gap between tiles must be +0.045", -0.02" with steps of +0.0", -0.03". This accuracy requirement must hold at the midpoint of the side of each tile. It should be noted that the more stringent requirement has the same accuracies, but the requirement must hold at the corners of the tiles, each corner to all neighbors.

In addition, there are requirements for the filler in between the tiles. The desire to avoid surface roughness and at the same time avoid penetration of hot gas into the region between the tiles dictates a "recession" requirement. The gap filler must be recessed into the area between the tiles to a minimum depth of 0.060 inches (1.5 mm) and a maximum depth of 0.200 inches (5.0 mm).

To develop a requirement for TPS surface quality inspection, an appeal must be made to Shuttle practice. The glass-like outer tile surface is approximately 0.012 inches (0.3 mm) deep. If, through some cause, this layer is penetrated, the surface layer crazes around the hole to a minimum diameter of approximately 0.25 inches. If it is assumed that penetration of the "glass" tile surface can lead to loss of the tile during re-entry, an inspection requirement can be set, at least for the purposes of this study. It will be assumed that inspection of the TPS for the Lunar Aerobrake will be required to detect a 0.012 inch deep hole whose diameter is 0.25 inches.

4.0 Analysis

4.1 The Aerobrake

An aerobrake is a structure that utilizes the drag of a body to reduce the speed of the vehicle as it moves through an atmosphere. However, "aerobrake" is a misnomer in the sense that a body normally generates lift as well as drag. In practice, the lift generated can play a very important role in the use of the aerobrake. Direction of flight can be changed by use of the lift and, hence, modulation of the drag can be accomplished, final landing location can be affected, or orbital parameters can be changed. In the Space Exploration Initiative, all other things aside, some minimum vehicle set operates in a round trip mode: from Earth-to-Moon-to-Earth or from Earth-to-Mars-to-Earth. On entry to Moon or Mars or return from Moon or Mars to Earth, a vehicle must be decelerated from the high cruise velocity to be captured properly into orbit or effect direct entry. To reduce the interplanetary speeds, the kinetic energy of the incoming vehicle must be exchanged or dissipated. Exchange is accomplished by a propellent burn which slows the vehicle. Dissipation is accomplished by allowing the vehicle to intercept and use the planetary atmosphere to convert the vehicle kinetic energy into heat. Using a propulsive burn requires propellent to be carried both out and back on the interplanetary trip and represents an overhead. Using an aerobrake also requires some overhead in the aerobrake mass, although less than propellent. Moreover, the aerobrake must be capable of absorbing and dissipating a great deal of heat, requiring specialized materials. Aerobraking offers limited control, even utilizing lift, and is generally restricted to one pass through the atmosphere. With too large an entry angle, vehicle penetration is too deep and the vehicle burns up, and too small an entry angle allows it to skip out of the atmosphere before the required amount of kinetic energy is dissipated. Entry accuracy is obviously critical and, because there may be no second chance, there are major points of concern.

For propulsive entry, the required deceleration burns are also critical, requiring the operation of an engine which may have been used several times and has been idle over a considerable time, giving rise to concerns over reliability among other major concerns.

As part of the early development of the Space Exploration Initiative, several potential aerobrake configurations were put forward. While the "90 Day Study" selected some aerobrake concepts, they were meant to serve the purpose of a technically reasonable approach or reference and not to imply any final selection. In order to justify the selection of the representative aerobrake concepts used in this study it is useful to review a few of the characteristics which drive the design of an aerobrake both as a technology and as a system.

The function of the aerobrake is to provide controlled dissipation of kinetic energy which permits a vehicle to have a lower energy trajectory. This function can apply to changing an interplanetary trajectory to an orbit around some destination planet, such as in the SEI mission to Mars or from Mars to the Earth, or for re-entry into the Earth's atmosphere for landing.

In order to investigate the accommodation requirements for an aerobrake at SSF, it is necessary to develop the structural requirements the aerobrake must meet. With the structural requirements in hand, the mechanical designs can be developed. Structural loads developed during aerocapture set the forces the support structure must withstand. The aerocapture velocities and forces set the thermal loads which drive the thermal protection system selection, while wake impingement stability requirements impact the size of the aerobrake.

The curves generated by the Vehicle Analysis Branch of Langley Research Center's Space Systems Division are representative of the conditions to be found in an actual Lunar return. The vehicle assumed for this analysis includes an aerobrake with a 13.7 m diameter and a mass of 2.15 metric tons, which is equal to 15 percent of the vehicle mass which is 14.3 metric tons. The aerobrake has an assumed lift-to-drag (L/D) ratio of 0.2, resulting from a coefficient of drag (C_D) of 1.45 and a lift coefficient (C_L) of 0.29. The resultant ballistic coefficient is 66.7 kg/m^2. Figure 4.1 shows the altitude vs. velocity profile, while Figure 4.2 shows the deceleration rate in G's as a function of time. The trajectory has been chosen to keep the peak G-load (human factor requirement) approximately 5 G's. The free-stream dynamic pressure for these altitude-velocity profiles is shown in Figure 4.3. It is the latter which, when taken with the aerobrake geometry, allows the calculation of the actual pressure on the structure. The calculations performed in this study, results of which will be presented later, assumed Newtonian impact analysis to give a good idea of the required strength, and hence, size and weight of the aerobrake mechanical support structure.

The physical shape of an aerobrake is important since the aerobrake generates lift as well as drag. It is not the purpose of this study to address the issues related to the utilization of lift to provide control or reduce G-forces, etc. It is sufficient to note that certain expected requirements for the Mars robotic and manned missions likely will result in the use of at least some lift capability. Figure 4.4 shows lift can result from asymmetric design at zero angle of attack, or can come from angle-of-attack induced asymmetry. An important point to note, therefore, is that one aerobrake design can be used in several applications by varying orientation or angle of attack. With the foregoing in mind, it is not surprising at this stage in the SEI that several distinctive aerobrake configurations have emerged. Figure 4.5 illustrates the plethora of possible aerobrake configurations and points to the first effort of this study: selecting a workable subset of aerobrake options.

Utilizing the assumptions and ground rules (section 3.0) and the second level performance parameters shown in Figure 4.1 through 4.3, the model aerobrake design parameters used in this study are shown in Figure 4.6. Here we note an assumption of a total vehicle mass of 21.6 tonne, including aerobrake mass. This increased mass comes from the LTV modified from the "90-Day Study" called the "Single P/A Module" introduced earlier. (Note also that the increased mass impacts the trajectory curves introduced earlier.) The Single P/A Module is proposed to have five reuses and the aerobrake will then be expected to be maintainable to meet this requirement. Human factor concerns limit peak deceleration to approximately 5 G's. Ballistic coefficient and heating concerns indicate a nominal 13.7 meter diameter for the aerobrake, while guidance capabilities for Earth return are sufficient that a very low L/D is acceptable. No upper limit on L/D is noted, so that other considerations could be accommodated, if necessary. Finally, to be compatible with the model trajectory needs, a C_D near 1.5 is required.

In trying to winnow down the many aerobrake configurations for SSF accommodation assessment, four major evaluation criteria were identified: First, noting that the major payoff for an aerobrake is in the Mars mission part of the SEI, an aerobrake concept which is evolvable from the LTV to the MTV is desirable. Second, since the aerobrakes are to be used for manned application as well as cargo, any aerobrake option that can benefit from current or expected flight experience is desirable. Third, an aerobrake configuration that offers the possibility of major commonality, and, hence, minimizes sparing and assembly complexity is desirable. Fourth, any aerobrake which can alleviate other major systems concerns, such as guidance-navigation, wake impingement, launch vehicle compatibility, etc., is also considered desirable.

Mars evolvability requires larger diameter aerobrakes because the Mars vehicles are larger and the atmosphere is thinner. Also, studies such as Reference 4, have shown that the low L/D applicable to Lunar return is insufficient for Mars vehicles, and that L/D's below 0.3 cause a major constraint on available launch opportunities. On the other hand, L/D's above 1.0 appear to gain very little. Note from Figure 4.4 that varying the angle of attack can increase the L/D, while adding a built-in asymmetry can accomplish the same thing. As developed in the "90-Day Study", the conceptual Mars aerobrake represents the latter approach, yielding a reasonable L/D at zero angle of attack. Thus, Mars evolvability not only requires the ability to grow in size, but also requires higher L/D's.

After careful consideration, three aerobrake configurations were selected which were believed to effectively capture the characteristics desirable for an SEI lunar aerobrake. The first of these is actually a set and is dubbed the axisymmetric set as shown in Figure 4.7. The second configuration is the AFE-shape, an asymmetric design with skirt as shown in Figure 4.8. The third configuration is called a "biconic" since it is constructed from a cone of one slope matched to the frustum of another cone of a different slope and is presented in Figure 4.9.

The axisymmetric shapes consisted originally of three: a section of a hyperboloid, a section of a sphere similar to the Apollo heat shield-aerobrake, and a sphere-cone, which has a 70 degree angle axisymmetric cone and spherical nose-cap for thermal protection. These configurations offer maximum opportunities for commonality in both mechanical structure and thermal protection system elements. The experience of Mercury, Gemini, and Apollo in the manned Earth-entry application, as well as the Viking aeroshell, and Mars-entry missions provide a solid base for development. Evolvability in the case of the axisymmetric set is straight forward in the sense that the larger Mars aerobrake can be developed by simply increasing the skirt to the required size, and can even involve an asymmetric skirt with L/D > 0.3 at a zero degree angle of attack.

It was determined that evaluating the hyperboloid shape separately was unnecessary because the hyperboloid aerodynamic performance and ballistic coefficient, etc. are virtually indistinguishable from other axisymmetric shapes such as the sphere. Consequently, the hyperboloid was absorbed into the spheroid.

The second shape selected was the AFE-shape, named after the Aeroassist Flight Experiment (AFE) design. The highly symmetric AFE-shape has lift at zero angle of attack. Roll modulated lift control maneuvers can be performed, giving the ability to control entry G-forces or correct for guidance errors, and allowing also for a limited amount of orbital plane change. This latter is important because proper phasing of a SSF rendezvous in a Lunar return happens far less frequently without plane change capability.

The most important attribute of the AFE-shape is that it will benefit from a planned flight experiment. Considerable experience will be gained in use of the AFE-shape long before the design of the Lunar aerobrake is finalized. The Lunar mission will in turn yield valuable information for application to the Mars missions of SEI. This expected progression of experience in the development of a data base resulted in the early inclusion of the AFE-shape.

The final shape, illustrated in Figure 4.9, considered as representative of the selection criteria was the "High L/D Biconic." As mentioned earlier, the "pull" of the Mars mission may be stronger than the "push" from the Lunar mission. This "push versus pull" is most evident in the biconic. As illustrated in Figure 4.10, the biconics have inherently high L/D's which exceed the minimum requirement of 0.3 and cluster around the desirable levels of 1.0. Moreover, Figure 4.11 indicates that the biconics are capable of making plane changes at low angles of attack. For Mars this is important both for cross-range trajectories and for compensating for uncertainties in entry angle due to guidance uncertainties. For the Lunar return case, it has already been noted that low L/D's are satisfactory and that L/D's around 1.0 are unnecessary. Higher L/D's, however, can offer more frequent Lunar return rendezvous with SSF, an issue important in contingency situations. It is also self-evident that the biconic is much more immune to wake impingement effects than either the axisymmetric or AFE-shapes.

4.2 Design and Assembly Considerations

The 13.7 meter diameter aerobrake has too large a cross section to fit in one piece in a current or near term planned earth-to-orbit vehicle. Therefore, the aerobrake must be transported in parts and assembled or be folded and then deployed. Thus, on-orbit assembly or deployment must be incorporated into the design of the aerobrake. There are three aspects to the design and assembly criteria. First, there are the structural design considerations, second, the space station accommodation considerations, and third, the logistics considerations.

The structural design considerations include the structural integrity, mass, thermal protection system integrity, the testing and verification of the assembled parts, post-flight inspection, and the simplicity of refurbishment on-orbit. The structural integrity involves designing the structure so that it can be easily assembled on-orbit and support the aerodynamics and acoustic loads at the structural operating temperatures. The aerobrake mass needs to be minimized to maximize the benefit to the LTV. The thermal protection system must be designed so that the heat load into the structure is adequately low and so that it can be easily refurbished, repaired, and inspected on-orbit. The testing and verification of the structural assembly require that a methodology must be developed for evaluating the reliability of the assembly process. Post-flight inspection is primarily concerned with the damage to the TPS although the structural assembly also needs to be inspected. The simplicity of refurbishment involves designing the aerobrake such that the TPS and the structural components can be repaired or replaced on-orbit with minimum space station support.

The space station accommodation considerations include accommodation requirements such as storage of parts and location for assembling the aerobrake, the robotic or EVA system requirements, and the commonality of parts. The accommodation requirements also include additional hardware and power for assembly. The robotic requirements may include use of the SSRMS, the FTS, and the SPDM during both the assembly process and during the inspection and refurbishment processes. The commonality of parts impacts the number of parts to be stored and the time to select the correct part, either with EVA or robotics. The logistic considerations include designing the aerobrake so that it can be packaged in an existing or near-term planned Earth-to-orbit vehicle.

4.3 Construction Approaches

To evaluate the Space Station Freedom accommodation requirements, it is necessary to define methods for constructing and assembling the aerobrake which can then be used to evaluate the accommodation requirements. Three construction approaches were selected as worthy of further consideration in this report and include (1) the center-core with petals, (2) the orthogonal spars, and (3) the tetrahedral truss with panels. The center-core with petals and the orthogonal spars are adaptations from the "90-Day Study" and the tetrahedral truss with panels is based on the aerobrake structural concept developed by Dorsey and Mikulas (Ref 5). These three approaches are shown in Figure 4.12. The figure shows the construction approaches as applied to the sphere-cone aerobrake configuration, although these construction approaches are applicable to the sphere, the biconic, and aeroassist flight experiment configurations.

4.3.1 Center-Core with Petals

The center-core with petals, hereafter referred to as "core-petal", configuration consists of eleven (11) major sections, a circular core and ten (10) interchangeable petals which are sections of a truncated cone. This configuration allows the aerobrake and the LTV crew module to be a structural entity. The core is attached at its periphery to the forward end of the LTV crew module with a monocoque cone. The aft end of the crew module has an interface that allows struts to support the petals near midspan. Figure 4.13 shows how the aerobrake is attached to the crew module of the LTV. These struts allow the aerodynamic loads acting on the aerobrake to be transmitted to the Lunar Excursion Vehicle. The petals are fastened to the core using interlocking hinge devices which are held in place by aligning the holes in the hinges and then inserting expandable diameter fasteners to make a firm fit. The petals are attached to each other by a series of overcenter latches along the seam which latch the edge longerons of adjacent petals together.

4.3.1.1 Assembly Component Design

The assembly components include the center core and the petals. The center core should be designed as a pressure vessel with external pressure being applied. It also has a stiff outer ring that reacts the pressure vessel loads and the petal shear loads as shown in the free body diagram in Figure 4.13. It is planned to attach the petals to the core with expandable diameter fasteners which are described in the orthogonal spar fastener section 4.3.2.2. When all the petals are installed and secured, the center core interface will be secured and the structural assembly will be an integral unit.

The petals, like the center core, are designed as cone frustrum sections of a pressure vessel with the pressure acting on the outside of the cone. The petal structure will probably be skin stringer although isogrid or honeycomb could also be used. The petal structure must be designed to transmit the loads to the reaction points as shown in the petal free-body diagram in Figure 4.13. If the structure is designed correctly the moments and consequently the edge rotations will be small. This can be accomplished by making the stringers continuous members which extend from the center-core interface to the petal and ring as shown in Figure 4.14. The strut ring, which connects the petal to the crew module structure, would sit on top of the stringers allowing the struts to be connected in a manner similar to the Space Station truss system joints. Intercostals would provide lateral "Z" stringer support to minimize edge rotation. In order to fasten adjacent panels, it will be necessary for the edge stringers to be stiff longerons with rectangular shear panels that use overcenter latches to attach to the adjacent "Z" stringer. Although the longerons could be machined in place if the skin is isogrid during ground fabrication, it is more practical to machine the longerons and rivet them in place.

4.3.1.2 Fasteners

As previously mentioned, the "core petal" construction approach employs two types of fasteners. The hinges with the expandable diameter fasteners used to attach the petals to the center core are discussed in detail in the orthogonal spar fastener section (Section 4.3.2.2). The overcenter latch type fasteners used to connect adjacent petals together are discussed here. The latch concept which is shown in Figure 4.15 is based on a similar unit being used on the Crew and Equipment Translation Aid (CETA) project. That design used a 0.5 inch "Tee" bolt that was designed and tested for a 3,000 pound load. The aerobrake would probably employ "Tee" bolts that are 0.312 inches in diameter, because the load requirements are considerably less than 3,000 pounds. The actual load requirements are controlled by the depth of the longerons as well as the spacing between the latches. Figure 4.14 shows the petal with 17 overcenter latches. It is planned to have a drive system so that all the latches can be gang operated by a single actuator.

The latch works by having the latch arm rotated from the stowed position to the latch position where it is loosely held in place by a door lock device. After all the petals are installed and loosely latched, the latches are rotated into the lock position. The process is run in reverse to unlock and open the latch. As previously stated a drive system would be installed to allow gang actuation of all the latches along one edge. Furthermore, this drive system will probably be designed so that the latches nearest the cone apex are activated first so that the petal being installed is properly aligned. The latch drive system will be removed after all latching is completed. As an alternative to the latch drive system, the continuously rotating wrist of FTS could be employed to rotate the latches.

4.3.1.3 ETO Packaging

The "core petal" configuration presented in Figure 4.12 consists of a center core and 10 petals which are sized to fit in the bay of the Space Shuttle. The center core diameter was set at 4.4 m and the petal lengths were set at 5.06 m with a cross section length of 4.23 m at the bottom of the skirt and 1.36 m at the top of the skirt. The petal together with the installed TPS was assumed to have a thickness of 0.2 m. The center core diameter of 4.4 m easily fits in the 4.6 m diameter shuttle bay. Figure 4.16 shows a picture of the center core and one petal. The petals were sized to fit in the shuttle bay by stacking them in a box which fits in the lower or upper half of the shuttle bay as shown in Figure 4.17. The figure shows a method for packaging six (6) petals in the lower half of the shuttle bay. A similar type package would be stacked in the upper half of the shuttle bay, thus allowing 12 petals and 2 center cores to be transported to orbit in the shuttle bay. This provides for 2 spare petal sections and a spare center core.

4.3.1.4 On-Orbit Assembly

The on-orbit assembly of the "core petal" construction approach employs a number of space station accommodations including a powered "lazy susan", four additional space station truss bays, a ramp with support guide rails for installing the petals in place, the mobile transporter with the SSRMS and the FTS or SPDM. The first step in assembly is to fasten the center core to the "lazy susan". The next step is to align the "lazy susan" so that the first petal can be translated along the guide rails and then loosely fastened to the center core. The petal is now loosely held in position by the center core. It is tucked under the center core ring and held against the guide to reduce undesirable movement. The guide rails are then retracted to the down position and the "lazy susan" with the petal and center core is rotated 36°.

The guide rails are rotated to the up position and the second petal is selected from the parts box and placed in position along the guide rails by the SSRMS. The SSRMS then pushes the petal inward and down along the guide rails until it comes in contact with the center core. The adjacent longerons of each petal also have an alignment type boss and recess to provide alignment of the petal in the radial direction. It is then fine adjusted until the center core hinges and the petal hinges interweave and expandable diameter fasteners are loosely slipped in position through the hinges using the FTS or SPDM. Next, the side of the second petal is adjusted using the SSRMS such that the edge longerons of the two adjacent petals are in contact with each other. The FTS or SPDM is then used to gang actuate the over center latches to the latch position. As the latches are actuated, the petals are pulled together. The latches are not put into the lock position until all the petals are installed. The rail guides are rotated to the down position and the "lazy susan" is rotated 36° so the next petal is installed. This process is repeated until the last petal is installed. Figures 4.18 and 4.19 show the side and front views of the aerobrake assembly including the "lazy susan", the rail guides, the FTS or SPDM, and SSRMS. By installing the ramp at a 45° angle as shown on Figure 4.20, there is sufficient room for the SSRMS to maneuver the next petal into position.

The last petal is installed (Figure 4.19), however, it is adjusted so that the edge longerons on each side are in contact with the edge longerons of the two adjacent panels. This may require actuating some of the latches to the lock position of the other panels. Then the latches on the last panel are actuated into the latch position on each side of the panel, all petal latches are actuated to the lock position, and then the center core expandable diameter fasteners are tightened. As the the petal latches are tightened, the petal leaves are drawn inward towards the core and thus downward to a smaller cone radius and the whole assembly becomes a unified structure. The actual sequence for installing the last panel and tightening the expandable fasteners and latches needs to be refined and verified experimentally. The results of this experiment should provide valuable insight into how to design the guide rails, which right now exist as a concept only. However, it should be noted that the guide rails need to be mounted on a four bar linkage structure which can be moved to allow the guide rails to retract from the plane of the the aerobrake so that the "lazy susan" with the aerobrake on board can be rotated without the petal structure interfering with the rail guides during this rotation. It is anticipated that the assembly of the "core petal" aerobrake can be accomplished entirely with robotics either preprogrammed and/or telerobotics.

4.3.2 Orthogonal Spars

The orthogonal spars consists of five (5) major sections which include a center section, upper and lower midsections, and upper and lower end sections as shown in Figure 4.21. The orthogonal spar configuration presented in the the 90 day study consists of four sections, however, by using five sections there is no seam across the nose of the sphere cone which is where the heating rate and the pressure loads are maximized. The use of five sections eliminates any TPS seam from being parallel to the flow. The five orthogonal spar sections are fastened together using the interlocking hinges with expandable fasteners. These hinges allow shear loads to be transmitted from one section to another thus providing for a unified integrated structure. Like the "core petal", the LTV crew module is attached to the aerobrake by a series of struts which transmit the aerodynamic loads to the LEV. Because the exact aerobrake loads are not known, the actual position and loading of the strut interfaces has not been determined. However, because of the nature of the orthogonal spar truss work, the strut attachment points are not limited to particular places on the aerobrake.

4.3.2.1 Assembly Component Design

The assembly components include the center section, the two mid sections, and the two end sections. The 13.7 m diameter aerobrake is divided into five equal section widths of 2.74 m. The mid sections and the center section each have two longerons which run along the length of the section along the outside edges, and a third longeron which runs the length of each section down the middle. Thus the longerons on each of these sections are 1.37 m apart. The end sections each have a longeron which runs the length of the section along the straight edge and another longeron which runs parallel to the first edge and is 1.37 m from the edge. The outside edges of each of the sections have a stiff outer ring which reacts to the aeroshell pressure loads. The outside rings of adjoining sections are fastened together with over center latches which were employed in the center-core petal construction approach and are described in section 4.3.1.2. Between the longerons or between the longerons and outer ring secondary spars, cross spars are installed to provide lateral support. The longerons, secondary spars and outer ring structure is shown schematically in Figure 4.21. Figure 4.22 shows the center section with the longerons, the cross spars, and the outer ring members. Figures 4.23 and 4.24 show the stick models of the midsection and end section pieces, which are constructed in the same manner as the center section. The entire upper surface of the aerobrake acts like a pressure vessel and the loads are transmitted through the skin to the orthogonal truss structure to the struts which are mounted to the LEV. The skin structure can be plate or thin honeycomb with the TPS tiles installed during ground assembly.

4.3.2.2 Fasteners

The orthogonal spars construction approach primarily employs the expandable diameter fasteners although the overcenter latch type fasteners may be used on the outer ring. The longeron spars contain a set of interlocking fingers like a door hinge which allows shear load reaction. The small head of an expandable diameter pin or blind bolt is then dropped through the hole into a socket so that the bolt will not rotate. Tightening a "quick acting" nut on the top side or twisting the pin with a "quick acting" cam allows the diameter to expand and tighten radially against the walls of the hole thus aligning the two parts and providing for high shear load reaction. Figure 4.25 shows the application of the expandable diameter fastener for joining the orthogonal spar sections. It should be noted that these fasteners are removed easily by rotating the pin or bolt in the opposite direction so that the diameter contracts, allowing the pin to be easily removed.

4.3.2.3 ETO Packaging

The orthogonal spar configuration shown in Figure 4.21 through 4.24 consists of five sections each of which has a width of 2.74 m and lengths varying from 13.7 m to 10.96 m and heights varying from 2.5 m to 1.2 m. Thus with these widths and heights it may be possible to stack several pieces into the cargo bay of the current space shuttle by overlapping lengthwise and stacking the parts similar to the way the petals were stacked. The exact details for stowing the five sections in the 4.6 m diameter by 18.6 m long cargo bay of the current shuttle have not been worked out . In any case it appears that the three spare sections cannot be loaded on the same launch as the initial five sections. Thus if a spare section is required, there would be a delay. The alternative is to break the aerobrake into smaller sections which could be more easily packaged into the current shuttle. However, more sections requires more longerons and more fasteners and thus more mass. Thus, there is a tradeoff for this configuration of section size for ETO versus aerobrake mass.

4.3.2.4 On-Orbit Assembly

The on-orbit assembly of the orthogonal spars construction approach requires several space station accommodations including either a powered "lazy susan" or an unpowered support mount, three additional space station truss bays, a guide rail support, the mobile transporter with the SSRMS and the FTS or SPDM. With the powered "lazy susan", the first step is to attach the center section (section 1) to the "lazy susan". Next, one of the midsections (section 2) is picked up with the SSRMS and aligned with the center section using the guide rails and the locater pins. It is then pushed into position with the SSRMS until the attach fingers are aligned and then the expandable diameter fasteners are inserted into the attach finger holes starting with each end first using the FTS or SPDM. The fasteners are not tightened until all the attach finger expandable fasteners are installed. Then the FTS or SPDM goes back and tightens the "quick acting" expandable fasteners which completes the final alignment of the center section and midsection. Next, the end section (section 3) is installed onto the midsection in the same manner. The "lazy susan" is then rotated 180 degrees and the remaining midsection (section 4) is installed to the center section as shown in Figure 4.26. The figure does not show the rail guides or the FTS or SPDM and SSRMS. The process is repeated until all five sections are connected together. Figure 4.27a shows the installation sequence.

Using the unpowered support mount to assemble the orthogonal spars involves a set of guide rails, the SSRMS, and the FTS or SPDM as shown in Figure 4.28. The end section (section 1) is installed on the support mount and then the first mid-section (section 2) is picked up with the SSRMS, transported and aligned with the end section using the guide rails and location pins. This section is then pushed into final position, the attach fingers are aligned, and the expandable diameter fasteners are installed and tightened with the FTS or SPDM. The next step is to remove this assembly from the support mount and move it vertically so that the newly installed mid-section is now mounted to the support mount. The center section (section 3) is then installed to the mid-section in the same manner that the mid-section was installed. Again, the assembled pieces are removed from the support mount and moved vertically so that the center section can be mounted to the support mount. The mid-section (section 4) is then installed and the assembly is moved one more time vertically so that the end section (section 5) can be installed. Figure 4.27b shows this sequence. The disadvantage of this method is that the TPS inspection process cannot be accomplished by rotating sections through a prescribed inspection area, instead the whole surface must be inspected with the stationary aerobrake.

4.3.3 Tetrahedral Truss with Panels

This section of the report is based on data from the Automated Structures Assembly Laboratory (ASAL) at NASA Langley Research Center (Figure 4.29). Among the advantages of the tetrahedral truss structure are small part size and high degree of commonalty between parts which significantly reduces the number of spares required. Because the support structure is not integrated into the TPS system, each may be designed to better perform its respective function. Use of a truss network for the support structure appears to result in lowest total mass of the three configurations studied. While the part count for the tetrahedral truss structure is higher than the other options studied, the number of ETO options is significantly increased. In fact, with proper design, the potential exists to transport all required material to SSF without utilizing the Space Shuttle at all. It will be shown in this study that Atlas-type vehicles are capable of carrying the components. Extension to an aerobrake capable of supporting a Mars vehicle can be accomplished with minimum design and assembly changes and the experience gained from the Lunar aerobrake can be directly applied to the aerobrake for a Mars vehicle.

4.3.3.1 Assembly Component Design

The basic building blocks of the tetrahedral truss with panels are struts, scars, nodes (Figure 4.30) and panels which take the thermal and aerodynamic loads. Structural strength is obtained from a tetrahedral support structure built from truss members with preattached nodes. Struts are the truss members that provide a structural framework for the aerobrake. Struts are connected in the proper orientation by a combination of nodes and scars. Connection actually occurs between the scars and struts. The scars act as both a receptacle and passive guidance fixture during the connection procedure. The strut contains the mechanism that moves to secure the joint (Figure 4.31). Scars provide the added advantage of moving the connection point outward radially from the node, thus increasing the work area around the connection point. Nodes are spherical components used to provide the tetrahedral geometry by fixing the orientation between scars and thus the struts. The scars are preintegrated on the nodes. Finally, hexagonal panels are placed over the strut framework as rings are completed.

The completed aerobrake has a serrated edge (Figure 4.32) which has the potential of complicating the aerodynamics. If a more even edge geometry is required at least two possible solutions exist. Both trade improved edge geometry for increased part count. The first solution is to place small wedge shaped sections in the serrations (Figure 4.33a). This will improve the edge geometry to a certain extent, but corners will still exist. The second solution is to have unique panels for the outer ring. These special panels can be shaped to provide a smooth edge without corners (Figure 4.33b). The wedge approach has the advantage of smaller unique parts, therefore smaller spares at the expense of some edge irregularity.

The major problem foreseen with this approach for constructing the aerobrake is TPS close-out. The large number of independent TPS panels results in a larger total seam length than the other options studied. TPS close-out has not been an area of research focus, however, as shown in Figure 4.34 panels may be fitted with male and female joints to provide an interlocking arrangement. Thus there exist possible engineering solutions to this problem leading to the conclusion that this area needs detailed study. Extension of this approach to larger aerobrakes, such as those required for Mars missions, is straight forward; simply add additional rings of truss support structure and panels

4.3.3.2 ETO Packaging

By decreasing the size of the panels or the support structure or both, any ETO option can be supported. Assuming the panel is supported at 3 points (Figure 4.35 Concept A), a panel with diagonal length 2.743 m will easily fit in an Atlas II launch vehicle. The resulting strut length is 2.376 m assuming the above support arrangement. Appendix D includes the geometry of a generic panel along with the part counts and sizes of the aerobrake options studied.

4.3.3.3 On-Orbit Assembly

The assembly technique requires additional space station hardware: This includes a "lazy susan" to provide a fixture and positioning device for the aerobrake, and three standard SSF bays assembled as a vertical boom to provide a work area. With the strut and panel canisters properly positioned along the vertical boom, the SPDM or FTS is used to assemble the aerobrake.

Assembly starts after the "lazy susan" has been located at the end of the vertical boom and its operation verified. Canisters containing required struts with pre-attached nodes and canister of panels are located along the vertical boom. These canisters have been stored along the vertical boom as shown in Figure 4.36.

The "lazy susan" is used to position and support the aerobrake during assembly. As a section of the aerobrake is completed the aerobrake is rotated by the "lazy susan" to bring an uncompleted section within the work envelope of the robot. The first strut, with its preattached node, is placed in the fixture on the "lazy susan", the "lazy susan" is rotated 120 degrees and the second strut, with two nodes, is placed in the fixture. The final strut is then placed completing the base of the first tetrahedron. Struts are then placed to form the rest of the tetrahedron. When the inner tetrahedron is complete, construction of the first ring begins. Struts are placed according to rules based on structural integrity, reduction of required motion, reduction of end-effector changes, and access for latter operations. The assembly of the inner ring leaves corridors for robot entry to place the panels. After panels have been placed the final struts are installed to complete the ring, and construction of the next ring begins. Figure 4.36 shows the assembled aerobrake.

The approach taken by ASAL is to develop an assembly technique that may be completely automated. Apply the robot to repetitive assembly and verification and use the operator to determine solutions to unexpected situations. This requires an extremely robot friendly design in which the structural components are designed to reduce the operations required by the robot. Current ASAL structure assembly requires human intervention only during error handling. To achieve the necessary confidence in the completed structure all operations are verified. If an error occurs a software error handler is activated to attempt to eliminate the source of the error. If the error handler is unable to eliminate the error, then the operator is notified and the current operation suspended until the error is resolved.

The support structure is based on a tetrahedral truss network which has significant advantages including high strength to weight, simple load analysis, and easy integration of attachment points. The high component packing efficiency is due primarily to the small component size which has the added advantage of increasing the ETO options. The percentage of unique parts is small, reducing spare weight and volume. The primary disadvantage to large part counts is a longer assembly time, but because only supervision is required, large space station crews are not dedicated to the assembly operation. In fact the supervision could potentially be performed by ground based personnel.

Assembly starts at the center and moves outward as discussed above. After a ring is completed the robot moves outward radially with respect to the aerobrake to begin construction of the next ring, thus radial translation is required. This motion can be provided by either the MT or a dedicated device attached to the vertical boom.

4.3.3.4 Experience

Experience gained from ASAL has led to the following design goals:

A. All actions must be capable of independent preferably redundant verification,
    - when a gripper is commanded to close a sensor must be available to verify that the gripper closed.

- note that for redundancy to be useful there must be at least three independent methods for sensing the variable. For example, if a signal is returned from a single sensor that a gripper did not close, it is unknown whether the gripper or the sensor has failed. If two sensors are available, one indicating closed and the other indicating open, then we know that a sensor is bad, but not which one, and we have not gained any additional information about the operation. If three sensors are available, then the two that agree are accepted, the third is assumed bad, flagged for maintenance, and ignored until maintenance has been performed.

B. When mating parts, slow operations are preferred because fast operations do not allow small misalignments to adjust via the inherent compliance of the parts,

C. The increased flexibility gained from proportional control of end-effector mechanisms justifies the increased complexity of the controlling software and hardware,

D. All parts should include passive alignment characteristics to offset part dimensional inconsistency and inaccuracies in the control systems perception of the environment,

E. All parts must contain clear unique identification markings to aid human operators and support vision systems,

F. All systems must be capable of operator override.

G. All actions must be reversible
  - if an operation fails, it is usually necessary to reverse the current operation before planning a work around. For example if one end of a strut can not be secured, it is necessary to free the other end, and return the strut to its storage location before trying a spare.

H. To increase reliability and speed of operation, parts must be maintained in know positions via fixturing. This has the added advantage of localizing damage in the event of unexpected collisions.

Current designs have focused on attaching panels experiencing small to no aerodynamic loads. This work is in support of solar panel or heat transfer devices where it is desirable to allow the panels to expand and contract without significantly loading the support structure. On the other hand, an aerobrake is exposed to a significantly different environment and loading condition. At this time neither closeout between panels, nor attachment of the panels to the truss frame work has been defined for an aerobrake. Current research is based on construction of structures with planar surfaces. Extension of these principles to structures with curved surfaces, such as the aerobrake or a space-based reflector, will be necessary to fully compare this technique with the previous two construction approaches.

4.4 Assembly and Refurbishment Scenarios

In order to define the required Space Station accommodations for the on-orbit assembly and refurbishment of the LTV Aerobrake, it is necessary to define the step-by-step procedure. The end-to-end assembly and refurbishment procedures for each of the three construction approaches is presented in this section.

4.4.1 Center-Core With Petals

As described in the construction approach, the "core petal" required hardware includes four extra space station truss bays, a powered "lazy susan" support, and a rail guide support ramp. Also required are the assembly and inspection end effectors for the robotic tools which include the mobile transporter with the RMS and the FTS or SPDM. These parts must be collected at the earth launch site and transported to the Space Station and assembled prior to transporting the aerobrake equipment. Similarly the aerobrake parts must be assembled at the launch site. These include the center core, the petals, the fasteners, the TPS close out sections, and the gap filler material along with spares for each of these parts. After collecting the aerobrake assembly support equipment, the aerobrake parts can be launched and stored on Space Station. The next step is to get the mobile transporter with the SSRMS and either the FTS or SPDM and start unpacking and assembling the aerobrake. First the center core is mounted to the "lazy susan" with the TPS side facing outwards. Then the first petal is installed using the rail guide. This process is continued until all the petals are loosely docked in place. Then the latches are tightened and the petals are drawn downward and inward to a smaller radius and the expandable fasteners are tightened making the petals and center core become a unified structure. After making the proper checks, the TPS closure panels are unpacked and installed along the panel joints. These panels are bolted down from the truss side of the aerobrake. Next, the TPS side is inspected to ensure that tiles are in place and not damaged and that the gap filler is properly installed in all the seams. All necessary repairs are made and the assembled aerobrake is removed from the "lazy susan" and installed on the LTV, where it is launched, flown and then returned to Space Station. Following the return, the aerobrake is removed from the LEV and mounted on the "lazy susan" for post flight inspection and refurbishment. Appendix A to this report presents a step-by-step scenario for the on-orbit assembly and refurbishment of the center-core with petals aerobrake.

4.4.2 Orthogonal Spars

The required assembly hardware for the orthogonal spars includes three extra Space Station truss bays, a set of guide rails, and a support mount for the aerobrake. This support mount could be a powered "lazy susan" but this is not absolutely required. Also required are the assembly and inspection end effectors for the robotic tools which include the mobile transporter with the RMS and the FTS or the SPDM. Again, these assembly support parts must be collected at the earth launch site and transported to Space Station and assembled prior to transporting the aerobrake equipment. The aerobrake parts include one center section, two midsections and two end sections, the

TPS closeout sections, the fasteners, and the gap filler material along with the spares for each of these parts. After assembling the aerobrake support parts, the aerobrake parts are launched and stored on Space Station. Next the aerobrake parts are unpacked and the assembly is started using the mobile transporter with the RMS and either the FTS or the SPDM. If the powered "lazy susan" is used, then the center section is mounted to the "lazy susan" such that its lengthwise axis is perpendicular to the assembly accommodation vertical truss as shown in Figure 4.26. Next, one of the midsections is attached to the center section on the underside (side nearest the Space Station truss) using the guide pins and guide rails for positioning. The expandable diameter fasteners are attached and locked, then the end section is installed to the midsection in the same manner. With the "lazy susan" mount the aerobrake is rotated 180° and the other midsection and end sections are attached and fastened as shown in Figure 4.2. Next, the TPS closure panels are unpacked and installed along the section seams. The TPS side is then inspected to ensure that the tiles are in place and not damaged and that the gap filler is properly installed. The necessary repairs are made and the assembled aerobrake is removed from the the "lazy susan" and installed on the LTV where it is launched and returned to Space Station, similar to the "core petal" construction approach. Upon return, the aerobrake is disassembled from the LEV and mounted on the "lazy susan" for post flight inspection and refurbishment. Part 1 of Appendix B to this report presents a step-by-step scenario for the on-orbit assembly and refurbishment of the orthogonal spars aerobrake, with the "lazy susan."

The orthogonal spars can also be assembled using an unpowered mounting plate rather than a powered "lazy susan". This is accomplished by first mounting the midsection to the mounting plate, then installing the end section to the midsection using the guide rails and guide pins, then the fasteners are installed. The center section is then installed to the midsection using the guide rails and the guide pins and fastened in place. The partial aerobrake assembly is removed from the mounting plate using the RMS and shifted upward away from the Space Station main truss network and the newly installed center section is attached to the mounting plate. The remaining midsection is installed in the same manner. Again, the partially assembled aerobrake is removed from the mounting plate and shifted upward and the midsection is attached to the mounting plate and the remaining end section is installed. Because there is no "lazy susan" in this approach, inspection of the TPS side requires that the robotic arm with the inspection end effector be able to reach over the entire aerobrake area which has a diameter of 13.7 m (45 ft). Part 2 of Appendix B to this report presents the step by step scenario for assembling the orthogonal spar aerobrake without a powered "lazy susan".

4.4.3 Tetrahedral Truss With Panels

The assembly technique developed in ASAL requires additional space station hardware. This includes a "lazy susan" to provide a fixture and positioning device for the aerobrake, and three space station bays assembled as a vertical boom to provide a work area. This hardware along with the aerobrake hardware must be collected at the earth launch site and transported to the Space Station.

At Space Station, the vertical boom is assembled followed by "lazy susan" installation and checkout. As the aerobrake hardware arrives at Space Station, it is stored in its launch canisters along the vertical boom. The assembly process can begin at any time after all required hardware has reached SSF.

With the strut and panel canisters properly positioned along the vertical boom, the SPDM or FTS is used to assemble the aerobrake. Assembly starts at the center and moves outward as discussed earlier. After a ring is completed, the robot moves outward radially relative to the aerobrake to begin construction of the next ring, thus radial translation is required. This motion can be provided by either the MTS or a dedicated device affixed to the vertical boom. The assembly technique does require lighting, however the required lighting is extremely localized and can be provided by the end-effector. Thus, the assembly may take place independent of the sun angle. Before the ring is completed, the TPS panels covering that ring are installed. After the TPS panels are installed, the final struts are placed, completing the ring, and the construction of the next ring begins. During the assembly all connections are verified, the TPS is inspected, and TPS closeout is verified. If problems are encountered, then the defective parts are replaced with spares after the defective part has been replaced in the launch canister and flagged for repair.

After the aerobrake has been completed, the entire TPS surface is scanned to verify that it meets "set and gap" requirements discussed in section 3.5. After all necessary repairs are made, the assembled aerobrake is removed from the "lazy susan" and installed on the LTV.

Upon return of the LTV from the moon, the aerobrake is reinstalled on the "lazy susan" for post-flight inspection and refurbishment.

Appendix C to this report presents a step-by-step procedure for the on-orbit assembly and refurbishment of the aerobrake based on the tetrahedral truss with panels.

4.4.4 Construction Approach and Commonality Evaluation

Each of the three construction approaches can be evaluated with respect to the design and assembly considerations presented in Section 4.2. Table 4.1 summarizes these evaluations. From the Table 4.1, it can be seen that the tetrahedral truss with panels is the simplest design, does not require a designated Shuttle or Titan IV for ETO, has high parts interchangeability, and requires the minimum EVA support. However, this approach does have the most parts, has an extensive number of TPS closure seams, requires the most extensive on-orbit checkout, and may require considerable disassembly for refurbishment.

The center-core with petals approach has some design complexity, all petals are interchangeable so that a minimum number of spare parts are required, and it can be assembled with minimum EVA support. All the parts and spares can be shipped at one time on the current Space Shuttle or Titan IV. This construction approach requires four additional space station bays rather than the three required by the other approaches. The additional bay provides attachment points for the guide rail support structure. Also, it has many TPS closure seams and requires considerable assembly checkout.

The orthogonal spars approach has some design complexity and requires spares for the center section, the midsection, and the end section. The large orthogonal spar sections will fit in the Space Shuttle or the Titan IV, however, the spares must be shipped separately. Also, with the orthogonal spars there are few TPS closure seams and the assembly checkout involves large pieces. The rail guide assembly is rather large and the orthogonal spars can be assembled with minimum EVA support, however, the SSRMS must handle large pieces.

The Apollo-like aerobrake configuration is the simplest to assemble. The "lazy susan" approach takes extensive advantage of angular and radial symmetry, which is inherent in a spheroid. The high degree of symmetry significantly reduces the number of unique parts required. Not only does this reduce the number of spares required, but it significantly reduces the complexity of the software required to support assembly and reduces the required operator training by reducing the number of system configurations that must be studied.

The sphere cone maintains the angular symmetry, but lacks radial symmetry, thus the panels further from the center have a different curvature than those near the core. This implies that the panel surface and support structure curvatures vary with distance from the symmetry axis, assuming uniform panel thickness. Note that a spherical support structure can still be used at the expense of additional weight. As shown in Figure 4.37, the panels near the edge and center of the aerobrake would be thicker than those half way up a side. This added thickness increases the unit weight of these panels. The trade off is smaller part count, simpler assembly, with larger, heavier panels versus higher part count, more complex assembly, and smaller, lighter panels. A detailed study may show that with the correct selection of sphere radius, the additional mass incurred by increased panel thickness is offset by the reduction in the mass and number of spare parts.

The AFE shape has mirror symmetry about its longitudinal axis. This shape has no radial or angular symmetry and thus significantly impacts ETO weight and volume due to the large numbers of spares required. Assembly of an AFE-like aerobrake could potentially be more difficult than the other two configurations because of the lack of a repetitive procedure. As discussed above a spherical support structure may still be imposed on the aerobrake, however the weight/volume penalties are believed to be significantly higher.

All these construction approaches are feasible and will provide a basis for further study and evaluation of a lunar aerobrake. The selection of a "best" construction approach will require more analysis to develop equivalent levels of trade parameters for each construction approach. Furthermore, the man-rating issues have not yet been developed or assessed.

4.5 Required Space Station Accommodations

The on-orbit assembly of the aerobrake requires certain space station accommodations depending on the structural assembly approach. Some of these are common to all the construction approaches, whereas others are unique to the specific construction approach. Those that are common to all three construction approaches (Section 4.3) include the addition of a Space Station Freedom truss structure consisting of three standard 5-meter bays, a powered "lazy susan", a location for parts and spares storage, specialized end effectors, and a system to support inspection.

4.5.1 Addition of Truss Structure to Space Station

Previous designs for Space Station Freedom (SSF) included a dual keel which provided for construction and assembly of both the Lunar Transfer Vehicle (LTV) and the Mars Transfer Vehicle. One of the goals of this study is to define the minimum space station accommodations for constructing an aerobrake for the LTV. The analyses presented in this report show that a 13.7 m diameter aerobrake can be assembled on-orbit at SSF with the addition of a vertical truss consisting of three to four SSF bays. This will provide adequate space for assembling and inspecting the aerobrake. The vertical addition is presented schematically in Figures 4.18, 4.26, and 4.36. The vertical truss is to be positioned as close to the SSF center-of-gravity as possible so that it will have minimum impact on the microgravity experiments. Furthermore, it needs to be positioned near the Shuttle docking site so that the parts do not have to be transported over a long distance, and it needs to be attached to a Space Station truss bay where power is available or accessible. Another consideration is that the vertical bay must be located such that the aerobrake construction will not interfere with the line-of-sight of a Space Station operation or experiment.

4.5.2 Powered "Lazy Susan"

To facilitate construction, inspection, and refurbishment of the aerobrake, it is desirable to have a rotatable mounting platform. This "lazy susan" device will require power to rotate a 5 tonne aerobrake and it will also have to have the capability for angular positioning which will vary depending on the construction approach. The "lazy susan" will be anchored to the vertical truss and extend outward parallel to the main SSF structure, such that the aerobrake is mounted parallel to the velocity direction of SSF. The "lazy susan" is illustrated in Figures 4.18, 4.26, and 4.36.

4.5.3 Parts Storage

Prior to assembling the aerobrake, it is necessary to stow all the parts near the assembly area. In the case of the center core with petals and the orthogonal spars, the parts include the main sections, the main section spares, the fasteners, the TPS closeout sections, and the close out section fasteners. The mass of the stowed parts will be considerably greater than the mass of the aerobrake because of the number of spare parts and the packaging mass. For the center core with petals and the orthogonal spars, it is proposed that the parts be stowed along the main truss of Space Station Freedom in the vicinity of the aerobrake assembly location as shown in Figures 4.18. The parts storage will require SSF to have some sort of container holding equipment. Furthermore, the position and orientation of the parts in the parts storage area is critical so that the assembly can be done in an orderly fashion with a minimum amount of EVA support.

For the tetrahedral truss with panels construction approach, all the parts do not have to be transported to SSF from earth at the same time. Also, there are no large pieces which need to be stored. The struts, scars, nodes, and panels can be stored in their respective containers along the additional vertical truss bays as shown in Figure 4.36. Again, there will be some sort of attachment device to hold the containers in place. Because many of the parts are similar in style but may have different dimensions, each part must be identified by a unique marking to ensure that it is the correct part.

4.5.4 Inspection Support

Inspection of the aerobrake naturally divides into two broad categories, sensory interrogation and inferential assessments. Sensory interrogation of internal structural conditions include such techniques as embedded sensors, bulk property tests, or externally applied stimuli, etc. Inferential assessments involve visual or quantitative remote sensing systems.

As far as internal assessment techniques are concerned, many options are available. For the aerobrake support structure, embedded fiber optics, acoustic techniques, X-ray imaging, nuclear particle probes, thermal probes, and mechanical telltales are just some of the many tools to draw from.

As far as the thermal protection system is concerned, many of the above techniques are applicable, but they are dependent on the type of TPS material. Table 4.2 lists the sensor approaches for various type of TPS. Selecting which set of internal inspection techniques depends not only on the TPS materials, but also on operation, orbital and cosmic debris, solar radiation, atomic oxygen, etc. Man-rating of the aerobrake will entail specifications on the degree of verification required. Nevertheless, the techniques suggested here encompass the great majority of applied methods for the non-destructive evaluation of the TPS and structural integrity. It should be noted that many of these techniques have capabilities beyond those used in current STS practice. On the other hand, the difficult assembly environment of the aerobrake will require that a great deal of man-enhancing capability be brought to bear.

SSF accommodations for the internal structural inspection techniques will require information systems support and perhaps some sensor end effector hardware. Interrogation or assessment of sensor information will take the form of data systems umbilicals on the SSF support structure being connected to the appropriate connectors on the aerobrake. Data from the umbilicals might be of a reasonably high rate, a few megahertz, and require either on-board data systems support, or linking to the ground through TDRSS. If the SSF high rate communication patch panel is available, it will be used, if not, then either an on-board data system or a separate link to TDRSS will be required. Portability of the interrogation system, if required, would be in the form of specialized end effectors for the SSRMS. Mass for such systems, based on modern microcircuit technology, would be minimal.

The more difficult inspection problem, that of verifying the surface integrity and TPS element-to-element spacing on the aerobrake, could draw on a combination of human visual (including computer-enhanced television) inspection and electro-optical techniques. As was noted earlier the required surface quality of the aerobrake was postulated to be closer to AFE than to the full STS requirements. The justification for this relaxation from the STS requirements is based on the argument that aerobraking for AFE occurs only in a rarefied atmosphere, while entry for the Shuttle includes flight through dense atmosphere with considerable turbulent flow. It should be noted that the two specifications related to TPS are quite similar, however, as noted earlier,the STS tiles require more extensive measurements.

The most severe (postulated) requirement on surface measurement comes from what is essentially an empirical result from the Shuttle. The smallest damage seen on a tile is typically a hole in the ceramic tile surface about 0.5 cm across and about 0.3 mm deep. Detecting such a damaged area is what has been assumed for this study., Although plausible, the relationship to the exact Shuttle requirement has not been established. Nevertheless, damage below such dimensions, particularly in respect to depth, would not penetrate the surface coating of the tile. Moreover, reasoning from a kinetic point of view, a damaging impact sufficiently powerful to completely penetrate the surface would be expected to generate a crater of some minimum size. Thus, the inspection specification for this study (Section 3.5) permits the determination of the sampling grid required to inspect the TPS surface. Moreover, full inspection of the TPS surface integrity has, implicit in the generated data, the information necessary to address the "Step and Gap" requirement (at least for ceramic tiles.)

In concert with this strategy of extracting from the TPS inspection data the information on "Step and Gap," it will be assumed that the inspection hardware is capable of oversampling in the areas around the TPS tile-to-tile interfaces.

Thus, the inspection requirement can be summarized as: a complete survey of the aerobrake TPS surface with a 0.25 cm by 0.25 cm grid at 0.3 mm detectable accuracy. At boundary and interface areas, the sampling interval reduces to 0.1 mm. Shown in Figure 4.38 are estimates of surface areas and perimeters of the aerobrake configurations studied in this report. The number of samples across each aerobrake will range from 2.5 X 10^7 to 3.2 X 10^7, each with a minimum resolvable depth of 0.3 mm.

Whether such measurements are possible in reasonable times is an issue of considerable importance. Systems are available that can measure very small surface irregularities, but have very limited depth of range. Other systems are available that can measure range over considerable distance (laser-based range finders) at a sufficiently small position resolution. However, these systems are slow or insufficiently accurate. An in-house study in 1987 (Ref. 8) assessed the requirements and capabilities to do non-contact absolute range measurements ("optical metrology.") The major subject of the study was the "15 Meter Hoop Column Antenna" of the Controls-Structures-Electromagnetics-Interaction (CSEI) experiment. Of particular interest to this study is the fact that the 15 Meter Antenna is similar in size to the aerobrake for the LTV and that the measurements on the antenna were to be made from the center support mast over the entire surface. Although only 888 points were to be actually sensed, they were to be scanned at least 10 times per second. Shown in Figure 4.39 are the requirements for the CSEI experiment with large dots showing the capabilities of representative remote ranging systems. Attention should be directed to the point that the accuracy for the range measurements (minimum detectable change in range) is higher than for the aerobrake. Thus, the techniques capable of satisfying the 15 Meter Antenna requirements are also prime candidates to solve the 13.7 Meter aerobrake inspection requirements. To more fully make this point, Figure 4.40 shows the predicted performance of a Position Sensitive Detector ranging system at a range of several meters. Positional accuracy (calibratable to absolute) is seen to be considerably better than required, even at very high sampling rates. It should be noted that the 888 points on the 15 Meter Antenna were cooperative retroreflectors. However, the scan rates are sufficient and the laser power such that both could be traded for a less friendly aerobrake surface reflectance.

Perimeter and interface areas where recession and "step and gap" requirements must be met would be handled by oversampling. "Step and gap" would use the raw samples and lower accuracy while averaging for higher accuracy would give surface quality mapping. Absolute accuracy in position on the aerobrake would only be needed to a fairly coarse grid sufficient to ensure EVA ease of location unless verification of the surface geometry is desired.

To support the remote scanning of the aerobrake surface, the following items would be required: (1) A mounting point on the structure no farther than a few meters but not so close as to miss a view as far as the aerobrake's center, (2) a triangulation range sensor mounted on the support structure with a baseline on the order of a couple meters, (3) a scanning system (mirror or other means) integral to the sensor capable of covering at least a few degrees, (4) a "lazy susan" to provide rotation of the aerobrake over angles within the field of view of the range sensor, and (5) data system support within the sensor and interfaced to the SSF Data Management System (DMS) or direct linkage to the ground for detailed assessment of the sensor data. A very useful addition to the triangulation system would be a television camera with zoom capability to be able to provide remote images of areas being scanned for coordinated imagery and range maps.

In the event that the "lazy susan" is not a possible option, inspection would be carried out by means of a range sensor mounted either on the SSRMS or on a scanning structural mechanism. For this study, it is assumed that the necessary range accuracy can be achieved by means of the structure-mounted sensor. Nevertheless, the possibility of adding a special sensor end effector is such a simple option and allows so many more sensor options that it should be kept in mind as a very real possibility. Moreover, it may be desirable to use the SSRMS to provide detailed sensor assessment of anomalies found by the structure mounted rangefinder.

4.5.5 Solar Shielding

Whether or not solar shielding is required must be part of the larger question of what is the required thermal environment for aerobrake assembly. A detailed thermal analysis of the aerobrake structural concepts during assembly must be performed to completely assess required SSF accommodations. However, it is possible to evaluate the effects of intermittent solar heating on the aerobrake. Assuming that the aerobrake is mounted on SSF so that it lies mostly in the SSF orbit plane, then the solar radiant flux on the surface of the aerobrake is proportional to

$$A_0 \mathrm{Sin}(\sigma)\mathrm{Sin}(\psi)$$

Where A_0 represents the exoatmospheric solar irradiance

While the solar flux on the edge of the aerobrake varies as:

$$A_0\ [\mathrm{Cos}(\beta)\mathrm{Cos}(\psi) + \mathrm{Sin}(\beta)\mathrm{Cos}(\sigma)\mathrm{Sin}(\psi)]$$

SSF's orbit precesses at a rate of about 7.5 degrees per day to yield Ψ. The angle σ represents the 28.5 degree tilt of SSF's orbit, while β represents its orbital angle around the earth. The maximum orbital day-time solar flux varies from zero to a maximum of:

$$A_0 \mathrm{Sin}(\sigma)$$

On the other hand, the edge of the aerobrake receives solar flux that varies constantly during the orbital period. Because the edge of the aerobrake is fairly narrow and has a small surface area, the heat load is relatively small compared to that on the front or back. The overall effect of solar radiation on the aerobrake edge during assembly must await a specific mechanical design and the associated thermal analysis. Nevertheless, if solar radiant flux on the edge is a problem, then a small reflective shield along the edge of the aerobrake should be adequate to reduce the edge heat load. It should be noted that the thermal environment might be such that the aerobrake requires some form of thermal control during assembly, including heating. Again, only some reasonably specific designs with the associated orbital environment driven thermal analysis can effectively determine the accommodation requirements.

4.5.6 Center-Core with Petals Unique Accommodations

The only accommodations which are unique to the center-core with petals are an additional support bay and a set of rail guides which provide support for matching the edge longerons of the adjacent petals so that the overcenter latches can be easily operated. The extra truss support bay is necessary to provide a fixed end support for the guide rails structural support. The rail guides must be able to be retracted so that when the petals are rotated on the "lazy susan", they do not interfere with the support rails. This can be accomplished by mounting the rails on a four bar linkage support system which can be rotated into place by the FTS or SPDM, so that the rail guides would not require power. The addition of an extra SSF support bay, mounted at 90 degrees relative to the extra three bay vertical support truss described earlier, allows the rail guides to be supported by a diagonal strut as shown in Figure 4.20.

4.5.7 Orthogonal Spars Unique Accommodations

The orthogonal spars construction approach requires a guide device to help locate the large sections as they are installed in place. The installation guide will act as a support which allows the section being installed to only be maneuvered in two directions rather than three. The guide combined with the section locator pins should simplify the assembly process. This guide needs to be relatively large as shown in Figure 4.28. The SSRMS can then pick up a section, maneuver it into position against the guide, and then slide it along the guide until the section locator pins from each section are aligned. The section being installed is then pushed into final position using the guide and the locator pins for alignment until the holes in the fastener hinges are aligned, and the expandable diameter fasteners are installed using the FTS or SPDM.

4.5.8 Tetrahedral Truss With Panels

This study has identified no unique accommodations associated with the tetrahedral truss and panels.

4.6 Unresolved Accommodations

In addition to the SSF accommodation requirements presented in Section 4.5, there are several unresolved accommodations which are beyond the scope of this report. The unresolved accommodations include the installation of the aerobrake on the Lunar Transfer Vehicle, the stationing of the LTV at SSF , the detailed definition of the refurbishment support systems for the TPS, and effect of increases in aerobrake size.

4.6.1 Installation of Aerobrake on the LTV

Although this study is limited to the on-orbit assembly of the LTV aerobrake, assembly is just one of the many steps involved in the on-orbit assembly of the LTV. The results of the assembly and refurbishment scenarios presented in Sections 4.4 imply that the assembled aerobrake would then be picked up and installed on the LTV. The relocation of this 5 tonne aerobrake could be expected to have some effect on the stability characteristics of the SSF. The exact locations of the assembled aerobrake and the LTV would have to be optimized. Furthermore, it is very possible that the aerobrake would be assembled on the LTV which would, itself, be mounted to the "lazy susan". The "core petals" or the orthogonal spar construction approach could also be modified to allow the aerobrake to be assembled directly to the LTV. The direct assembly of the aerobrake to the LTV on SSF would probably involve additional accommodations such as more SSF truss bays and a more massive "lazy susan" support structure. The effect of the LTV mass with the aerobrake on the SSF stability also has to evaluated.

4.6.2 LTV Stationing at SSF

An issue that was outside the scope of this study relates to the transport and integration of the aerobrake with the LTV. More broadly viewed, the issue is one of integration and stationing of the entire LTV. As noted earlier in this study, the "Single P/A Module" represents an empty weight of approximately 21.6 tonne when it is without the external tank assembly (ETA) assembly. This mass includes the aerobrake and represents the entire lunar return vehicle configuration without cargo. It should be noted that the empty LTV mass is well within the handling capability of the MT, MRS, and SSRMS and, at least as far as mass is concerned, within STS capabilities.

The natural inclination is to suggest that the LTV could be assembled and based at SSF. With the "lazy susan" properly designed to handle the load, total vehicle integration could be supported. The LTV would be assembled piece-by-piece with the aerobrake done first or last. Length of the LTV without ETA is only a little over two SSF bays.

The reason for introducing this issue here is to note that not only can the aerobrake be assembled at SSF, but also that important SSF support services are capable of handling the entire LTV. In addition, the LTV, once assembled can be undocked, much like the Orbiter and, with its own RCS thrusters, can fly itself away to the co-orbiting ETA for final preflight integration.

No attempt has been made to develop the detail on the actual accommodations and operations required to support the LTV assembly. However, no gross "show stoppers" have been identified that would eliminate the possibility, while the large potential benefits virtually dictate study in this area.

4.6.3 On-Orbit TPS Repair Techniques

The on-orbit refurbishment and replacement of the ceramic tile insulation is not a simple process. The tiles are removed from the Shuttle using a hot wire tool inserted under the tile which causes the room temperature vulcanized material (RTV) to loosen and then the tile can be easily removed. Heating the underside of the tile in orbit with a hot wire will probably cause out-gassing from the RTV and possibly from the tile itself. The possibility of out-gassing must be considered in view of the effect that condensation of the out-gassed material might have on SSF or other surfaces. Similarly installing a ceramic tile on the strain isolation pad (SIP) is currently accomplished on the Shuttle with RTV. The curing of the RTV occurs in conjunction with both air and water taken from the earth's atmosphere. In space the bonding material will have to consist of some type of two part bonding material, since neither air nor water are available to participate in the curing process. Similarly, checking the bond is difficult because of the absence of atmosphere. The bonding of the ceramic tiles to the SIP on the Shuttle is checked by creating a suction force with a plunger locked onto the tile. Force is then exerted by pulling on the tile to determine the adequacy of the RTV bond strength. This same type of test could be performed with IVA where there is an atmosphere. Out in space, the pull test cannot be done for obvious reasons.

Another concern associated with repairing or refurbishing the TPS is the sealing between the tiles with gap filler. The gap filler needs to be pressed down in between the edges of the ceramic tiles. Furthermore, the gluing of the gap filler to the tiles with RTV encounters the problems alluded to above. It may be possible to use a two part gluing material similar to RTV which would set in a vacuum, with one part the polymer resin and the other being the curing agent or hardener. However, a readily available source of this type of material has not been identified. Furthermore, when this type of material sets there is probably out-gassing, the effects of which would have to be determined.

4.6.4 Aerobrake Size

The 13.7 m diameter aerobrake is based on the results of the "90-Day Study" (Ref. 1) which assumed a 14.3 tonne mass returning to earth. Recent updates indicate that the mass has increased to 21.6 tonne without any change in the aerobrake size. Thus at a deceleration rate of 5 G's, the aerobrake loading increased from 4757 N/m^2 to 7185 N/m^2. To maintain the same loading, the aerobrake size should be increased 23 percent to 16.8 m diameter. In addition to the loading considerations, there are also the problems of stability and control at angle of attack as well as wake impingement on the afterbody which are affected by the size. Additional studies are required to better define the aerobrake size since increased size could affect the aerobrake construction methodology as well as the required space station accommodations.

4.7 Unresolved Issues

Several issues were identified during the study that were not directly related to the question of on-orbit SSF accommodation, or were insufficiently defined with respect to SSF accommodation to warrant their enumeration.

4.7.1 Wake Impingement

An area of considerable importance, but outside the scope of this study, is the issue of wake closure behind the aerobrake. The low pressure behind the aerobrake causes the hypersonic flow over the aerobrake to turn inward and impinge on the LTV payload behind the aerobrake. This turning is much greater on the high pressure windward side than the leeward side. The rate at which this very hot flow converges governs the heating that the payload experiences. The studies that have been done so far have generally assumed there is a defineable "wake angle" and that vehicle packaging need only avoid intruding into that "zone of exclusion." Unfortunately, there is no fixed angle for the wake closure, instead there is a gradation of hot gas regions behind the aerobrake. Making the aerobrake size larger can alleviate hot gas impingement problems, but at the same time the accommodation and ETO requirements become more difficult. Thus, the wake impingement issue can be expected to impact vehicle design through the packaging versus aerobrake diameter versus TPS selection, and finally impacting the on-orbit accommodations.

4.7.2 Man-Rating

Another issue with undoubtedly major impacts on overall system design and development, and in particular, the on-orbit aerobrake subsystem is the question of flight qualification for man-rated use. Both in initial flight and in refurbishment and reuse the aerobrake will be subject to stringent inspection conditions. The inspection requirements postulated in this study were designed to capture the major aspects of Shuttle tile usage with a minor modification for the more restricted regime of the LTV aerobrake. Nevertheless, the actual inspections will most certainly be a very complex issue. This study was designed to identify issues which went to the heart of the feasibility issue and has focused on the tiles because of their prominence in STS concerns. The number and degree of built-in-test and external inspections are expected to be more extensive than presented here. However, the built-in-test and inspection is nowhere expected to be as severe as in the aerobrake surface inspection. Moreover, development in TPS materials has continued since STS design and the operating regime is less severe for the LTV than for STS. Consequently, there is hope for less stringent requirements than for STS and consequently propagation of relaxed requirements down the subsystem chains. The issue of man-rating and its impacts on SSF accommodation still remain areas which will quite likely dominate aerobrake design and SSF accommodation as the SEI develops.

4.7.3 Flight Stability

A second issue which surfaced was the impact of aerobrake guidance and control on the size of the aerobrake including the location of the payload center of gravity and aerobrake center of pressure. In fact the issue of concern was a little broader in that a cursory look at the "stage and one half" and "the single P/A module" indicated a concern that the configuration was potentially unstable. The packaging for the vehicle and return payload may be very difficult to achieve in any case, and may require a larger aerobrake than that used in this study. (Also see section 4.6.4.)

4.7.4 Debris Protection

As part of this study, a cursory look was given into the danger from orbital debris and what might be needed to protect against potential damage. A study of orbital debris (Ref. 9) provided data giving probability of collision for various orbital inclinations and spacecraft sizes which are shown in Figure 4.41. The first entry in Table 2 of that figure corresponds to a Space Station Freedom-sized vehicle and gives a comparison of collision probabilities in 1970 and 1989. It should be noted that careful examination of the results in this paper revealed an order of magnitude error in the collision probabilities. The values should be ten times higher. The time intervals over which these calculations hold are a one year in-orbit period. The assumed size of the SSF-like vehicle was 200 M^2. With the aerobrake of this study on the same order of magnitude in size, the same collision probability would be expected to hold. Moreover, the orientation of the aerobrake plane in the orbital plane of SSF would reduce the collision probability significantly. Assembly and refurbishment of an aerobrake will require much smaller time periods than the one year period assumed in the referenced paper, further reducing the probability of a major hit. It would seem from this study that the probability of an aerobrake collision with orbital debris of any size is very small (on the order of one in a million.) Consequently, while there is a danger of debris collision, it appears not to be significant enough to require a shield. This conclusion is one, however, that requires in-depth study and future confirmation as the aerobrake concept development proceeds.

4.7.5 SSF Control Impacts

The focus of this study has been to determine the minimum SSF accommodations to support the assembly of the LTV aerobrake. The converse to this study is to determine the impacts on SSF of assembling an aerobrake in orbit. The NASA Langley Space Station Freedom Office executed a study to assess the impacts for mounting an aerobrake. The two major issues addressed were the impact on SSF controllability and the consequent impacts on static microgravity at the materials laboratories. The impact on the controllability is best seen in the increased amount of pitch which SSF experiences. For purposes of the analysis some plausible values were chosen for the support and accommodation system masses, as shown in Figure 4.42. As a result of the aerobrake accommodation, the normal pitch of 7.5 degrees is increased to around 10.0 degrees (Table 4.3), an increase of 2.5 degrees.

The impact on the microgravity environment is seen in Figure 4.43. At the center of the U.S. microgravity laboratory, the equivalent acceleration is increased from 1.1 to 1.3 micro-G's. This value is a static value and ignores the stopping and starting of the various mechanical systems. In defense of the aerobrake accommodation, it should be noted that with or without the aerobrake at SSF, the support systems would still be generating disturbances.

4.7.6 Acoustic Loading

Experience with hypersonic transportation systems including the Space Shuttle and the National Aero-Space Plane (NASP) technology program indicates that at very high velocities in the continuous flow regime, the acoustic loads are very significant. For example, on the Space Shuttle the acoustic loads caused the TPS tiles to fail by either cracking or breaking loose from the structure. On the NASP, it is anticipated that the wing surfaces would experience acoustic pressures as great as 160 dB. Thus for the aerobrake, both the TPS and the structure must be designed to withstand the high unsteady aeroacoustic loads which will be experienced while operating in the earth's atmosphere. The first step in this process is to conduct an analysis to define the intensity and distribution of the acoustic loading on the aerobrake surface. These loads would then be incorporated into the TPS and structural designs.

5.0 Conclusions and Recommendations

This study has attempted to extract from the various Lunar aerobrake concepts a representative set which capture the main Space Exploration Initiative aerobraking concepts. From that set this study has identified the fundamental, minimum Space Station Freedom support requirements to perform on-orbit assembly and refurbishment of the Lunar aerobrake. Moreover, this study also attempted to identify auxiliary support such as Earth-to-Orbit launch and logistics support, as well as ground and other support needed.

The study was based on "advertised" capabilities of NSTS and SSF support systems and three feasible assembly techniques. This study applied a scenario approach to identify the required support systems with the objective of assessing feasibility. The results of the study have been summarized in Table 5.1. Each of the structural assembly approaches serves as the horizontal entry in the matrix, while accommodation entries form the column labels.

It was determined that the assembly of just the Lunar aerobrake can be accommodated at SSF with the addition of only 3-4 standard SSF 5 meter truss bays and the use of the standard support services: SSRMS plus either the FTS or the SPDM with some EVA participation. Without regard for the Mars aerobrake, the assembly of the Lunar aerobrake is independent of the shape selected, but not, as can be seen in Table 5.1, of the structural assembly approach. The development of timelines to estimate the total assembly time of the three structural approaches was not done. Nevertheless, it is anticipated that none of the assembly approaches would take more than a few 24 hour periods. This should not be interpreted to mean the complete turnaround of the aerobrake would take place in so short a time. Inspection and checkout would be expected to consume a considerable amount of time, primarily through human confirmation of various items to meet quality assurance and man-rating requirements.

Support hardware specifically related to the aerobrake, supplied outside SSF baseline services, includes three or four standard SSF 5-meter truss bays, a "lazy susan," a truss mounted or SSRMS/FTS/SPDM mounted (or both) inspection sensor, augmented information systems support, TPS repair tooling, container holders, specialized end effectors, and possibly rail guides.

Issues which were identified as subjects to receive more definition were: TPS closeout, thermal environment, debris environment, wake impingement , flight stability, and acoustic loading. These latter two affect the aerobrake size, and hence, accommodation. Moreover, installation of the aerobrake on the LTV was outside the scope of this study, but would obviously require some support hardware or strategy.

A few areas were also identified that represent potential high-impact areas for follow-on study: First, a detailed look at the types of TPS that would be suitable for the Lunar mission. Issues such as wake impingement and thermal loads can affect the type of TPS selected or the distribution of such materials over the aerobrake surface. Other issues in the TPS area that should be looked into include debris, mechanical, and thermal damage effects, and ease of repairability and refurbishment. Second, it is essential to develop some criteria for man-rating the on-orbit assembled, repaired, or refurbished aerobrake with respect to the various feasible TPS materials to permit better definition of the level of required inspection, among other things. Third, there exists the apparent possibility of stationing, or assembling, handling, and verifying the "dry" LTV at SSF. A true minimum accommodation would occur if the entire LTV (excluding ETA) could be processed on the baseline SSF without a Lunar Vehicle Processing Facility. An investigation into this area would be of obvious benefit.

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APPENDIX A

Center-Core With Petals

Assembly Scenario

1. Collect assembly equipment at launch site
   - Space Station vertical truss bays
   - Lazy susan and supporting mounts
   - Petal assembly rail guide and support mounts (RAMP)
   - Assembly and inspection end effectors for SSRMS.
   - Inspection computer hardware and associated software.
   - Parts storage devices.

2. Collect aerobrake equipment at launch site.
   - Center-core + spare
   - 10 petals + 2 spares
   - fastener bolts for petal to center core assembly
   - thermal close-out panels and spares
   - tile gap filler material
   - fasteners for thermal close out sections
   - (over center latches are already installed on panels)

3. Load and launch assembly equipment.

4. Unload and store assembly equipment.

5. Assemble vertical bays on space station.

6. Mount and install lazy susan onto vertical bay and verify operation.

7. Mount and install petal guide rails onto vertical bay.

8. Load and launch aerobrake parts.

9. Unload and store aerobrake parts.

10. Get mobile transporter with RMS and FTS or SPDM.

11. Attach end effectors to RMS and FTS or SPDM.

12. Unpack aerobrake center core and inspect for defects.

13. Install center core onto lazy susan.

APPENDIX A

Center-Core With Petals

Assembly Scenario (Continued)

14. Rotate lazy susan to position for first petal and rotate rail assembly into position.

15. Unpack first petal and inspect for defects.

16. Install first petal by moving and guiding along rails into position and draw into center core and install expandable diameter fasteners.

17. Check installation and retract guide rails.

Repeat Steps 18 thru 22 for 2nd thru 10th panels.

18. Rotate lazy susan and rotate guide rails into position.

19. Unpack next petal and inspect for defects.

20. Install next petal by moving and guiding along rails into position and draw into center core and install expandable diameter fasteners.

21. Loosely lock panel edges together with latch.

22. Check installation and retract guide rails.

23. Finish tightening panel edge locks to that panels fit together snugly.

24. Check and inspect all latches and bolts to ensurer aerobrake assembly is serviced.

25. Unpack thermal protection system closure panels and inspect for defects.

26. Install thermal protection system closure panels by aligning tapered shafts with holes in aerobrakes structures. (These are installed on TPS side of aerobrake)

27. Tighten TPS closure panels by bolting down on truss side of aerobrake.

28. Inspect all TPS closure panel bolts to ensure panels are secure.

Repeat Steps 29 thru 35 for each flight.

APPENDIX A

Center-Core With Petals

Assembly Scenario (Continued)

29. Inspect TPS side of assembled aerobrake checking all seams to ensure gap filler material is properly installed.

30. Inspect TPS tiles for, defects including material damaged during shipment, assembly and/or micrometeroid impact.

31. Repair gap filler as required.

32. Move assembled aerobrake from lazy susan and install on Lunar Transfer Vehicle. (The methodology for this step is beyond the scope of this report).

33. Fly LTV and return to Space Station.

34. Disassemble aerobrake from Lunar Excursion Vehicle as required.

35. Post flight inspection of TPS

APPENDIX B

Orthogonal Spars

Assembly Scenario

Part 1 -- with "lazy susan"

1. Collect assembly equipment at launch site
    - Space Station vertical truss bays
    - Lazy susan and supporting mounts
    - Orthogonal Spar rail guide and support mounts
    - Assembly and inspection end effectors for SSRMS and SPDM or FTS.
    - Inspection computer hardware and associated software.
    - Parts storage devices.
2. Collect aerobrake equipment at launch site.
    - Center section & spare
    - 2 midsections & spare
    - 2 end sections & spare
    - expandable diameter fasteners
    - thermal close-out panels and spares
    - (over center latches are already installed on panels)
    - tile gap filler material
    - fasteners for thermal close out sections
3. Load and launch assembly equipment.
4. Unload and store assembly equipment.
5. Assemble vertical bays on space station.
6. Mount and install lazy susan onto vertical bay and verify operation.
7. Mount and install petal guide rails onto vertical bay.
8. Load and launch aerobrake parts.
9. Unload and store aerobrake parts.
10. Get mobile transporter with RMS and FTS or SPDM.
11. Attach end effectors to RMS and FTS or SPDM.
12. Unpack aerobrake center section and inspect for defects.

APPENDIX B

Orthogonal Spars

Assembly Scenario

Part 1 -- with "lazy susan" (Continued)

13. Install center section onto lazy susan.

14. Unpack wide section and inspect for defects.

15. Install midsection by moving and guiding along rails into position and align locator pins.

16. Push midsection into final position using locator pins and rail guides align holes in fastener fingers, and install expandable diameter fasteners.

17. Check installation.

18. Unpack end section and inspect for defects.

19. Install end section in same manner as first midsection (steps 15 and 16).

20. Check installation .

21. Rotate lazy susan 180 degrees.

22. Repeat steps 14 thru 20 for second midsection and second end section.

23. Unpack thermal protection system closure panels and inspect for defects.

24. Install thermal protection system closure panels by aligning tapered shafts with holes in aerobrakes structures. (These are installed on TPS side of aerobrake)

25. Tighten TPS closure panels by bolting down on truss side of aerobrake.

26. Inspect all TPS closure panel bolts to ensure panels are secure.

Repeat Steps 29 thru 35 for each flight.

27. Inspect TPS side of assembled aerobrake checking all seams to ensure gap filler material is properly installed.

APPENDIX B

Orthogonal Spars

Assembly Scenario

Part 1 -- with "lazy susan" (Continued)

28. Inspect TPS tiles for, defects including material damaged during shipment, assembly and/or micrometeroid impact.

29. Repair gap filler as required.

30. Move assembled aerobrake from lazy susan and install on Lunar Transfer Vehicle. (The methodology for this step is beyond the scope of this report).

31. Fly LTV and return to Space Station.

32. Disassemble aerobrake from Lunar Excursion Vehicle as required.

33. Post flight inspection of TPS

Orthogonal Spars

Assembly Scenario

Part 2 -- without "lazy susan"

1. Collect assembly equipment at launch site
    - Space Station vertical truss bays
    - Lazy susan and supporting mounts
    - Orthogonal Spar rail guide and support mounts
    - Assembly and inspection end effectors for SSRMS and SPDM or FTS.
    - Inspection computer hardware and associated software.
    - Parts storage devices.
2. Collect aerobrake equipment at launch site.
    - Center section & spare
    - 2 midsections & spare
    - 2 end sections & spare
    - expandable diameter fasteners
    - thermal close-out panels and spares
    - (over center latches are already installed on panels)
    - tile gap filler material
    - fasteners for thermal close out sections
3. Load and launch assembly equipment.
4. Unload and store assembly equipment.
5. Assemble vertical bays on space station.
6. Mount and install lazy susan onto vertical bay and verify operation.
7. Mount and install petal guide rails onto vertical bay.
8. Load and launch aerobrake parts.
9. Unload and store aerobrake parts.
10. Get mobile transporter with RMS and FTS or SPDM.
11. Attach end effectors to RMS and FTS or SPDM.
12. Unpack aerobrake end section and inspect for defects.
13. Install end section onto lazy susan.

Orthogonal Spars

Assembly Scenario

Part 2 -- without "lazy susan" (Continued)

14. Unpack mid section and inspect for defects.
15. Install midsection by moving and guiding along rails into position and align locator pins.
16. Push midsection into final position using locator pins and rail guides, align holes in fastener fingers, and install expandable diameter fasteners.
17. Check installation.
18. Unpack thermal protection system closure panels and inspect for defects.
19. Install TPS closure panels by aligning tapered shafts with holes in aerobrake structures (these are installed on TPS side of aerobrakes).
20. Tighten TPS closure panels by bolting down on truss side of aerobrake.
21. Inspect all TPS closure panel bolts to ensure panels are secure.
22. Unpack and install center section in same manner as midsection (steps 14-21).
23. Remove partially assembled aerobrake from support mount and move aerobrake upward away from SSF main truss so that center section can be mounted on support mount.
24. Mount center section to support mount with partly assembled aerobrake above support mount.
25. Unpack and install midsection to center section in same manner as previous sections were installed (steps 15 thru 21).
26. Unpack and install end section to midsection in same manner as other sections were installed (steps 15-21)
27. Inspect TPS side of assembled aerobrake checking all seams to ensure gap filler material is properly installed.
28. Inspect TPS tiles for, defects including material damaged during shipment, assembly and/or micrometeroid impact.

Orthogonal Spars

Assembly Scenario

Part 2 -- without "lazy susan" (Continued)

29. Repair gap filler as required.
30. Move assembled aerobrake from lazy susan and install on Lunar Transfer Vehicle. (The methodology for this step is beyond the scope of this report).
31. Fly LTV and return to Space Station.
32. Disassemble aerobrake from Lunar Excursion Vehicle as required.
33. Post flight inspection of TPS

Appendix C

Tetrahedral Truss With Panels

Assembly Scenario

1. Collect assembly equipment at launch site
    - Space station vertical truss bays,
    - Lazy susan
    - Assembly and inspection end-effectors for SSRMS and FTS/SPDM
    - Inspection computer hardware and associated software.

2. Collect aerobrake equipment at launch site
    - Struts with pre-attached nodes,
    - Panels and spares(one of each type min),
    - Tile gap filler material, and
    - Fastener for thermal close out of panels.

3. Load and launch assembly equipment
4. Unload an store assembly equipment
5. Assemble three vertical bays on space station.
6. Mount and install lazy susan onto vertical bay and verify operation.
7. Load and launch aerobrake parts.
8. Unload and store aerobrake parts directly on vertical truss.
9. Get mobile transporter with FTS/SPDM.
10. Attach end-effector to FTS/SPDM.
11. Load MTS with struts.
12. Assemble struts to form ring.
13. Unload strut canister, load MTS with panels.
14. Install panels.
15. Install gap filler as required.

Repeat steps 11-15 until desired number of rings have been completed.

Note preliminary inspection/verification is done while assembling.

16. Inspect TPS side of assembled aerobrake checking all seams to ensure gap filler material meets specs.
17. Inspect TPS tiles for defects including material damaged during shipment, assembly, and/or from micrometeorite impact.
18. Repair as required.
19. Move assembled aerobrake from lazy susan to Lunar Transfer Vehicle docking location.
20. Dock with Lunar Transfer Vehicle. (The methodology for these 2 steps are beyond the scope of this report.)
21. Fly LTV and return to Space Station.
22. Disassemble aerobrake form Lunar Excursion Vehicle as required.
23. Post flight inspection of TPS.

Repeat steps 11-15.

Appendix D

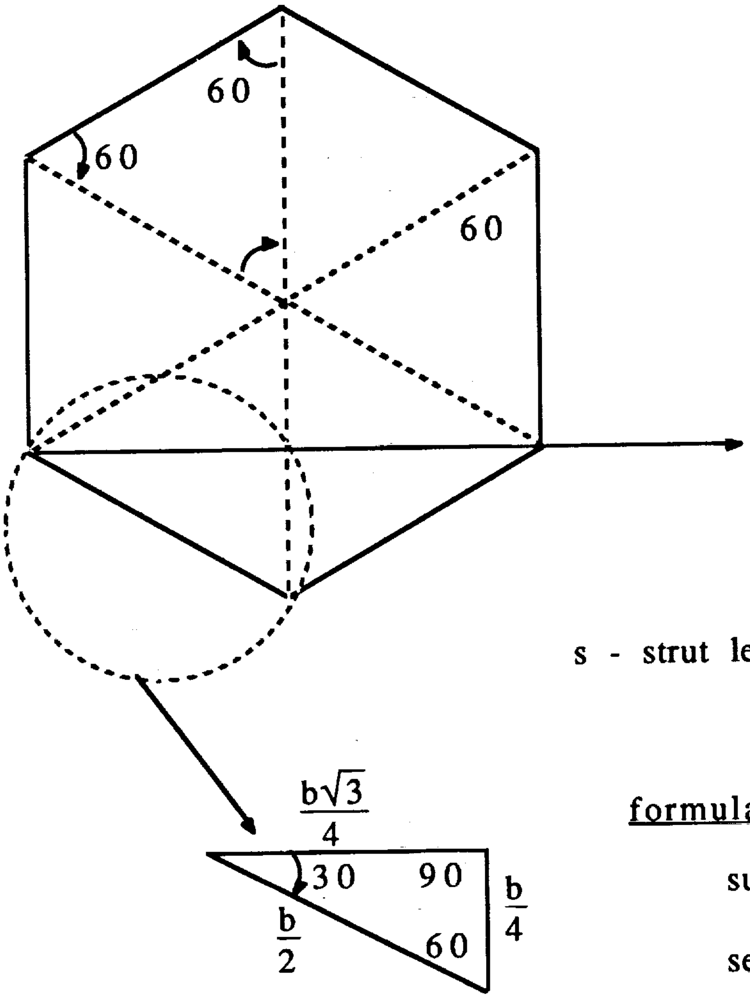
Supporting Data for Sizing Tetrahedral Truss with Panels

Aerobrake

based on

TETRAHEDRAL TRUSS with PANELS

(45' or 13.716m diameter)

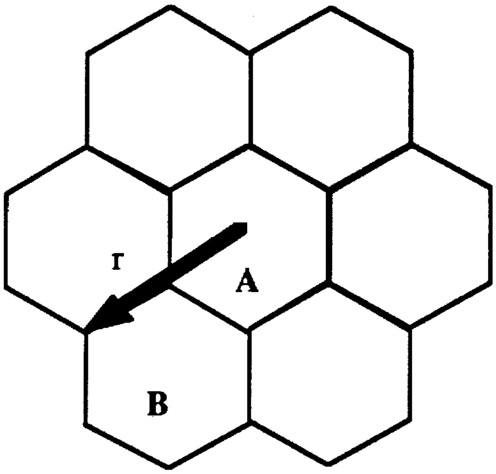


Panels are hexagons.
3 sector truss config.

s - strut length

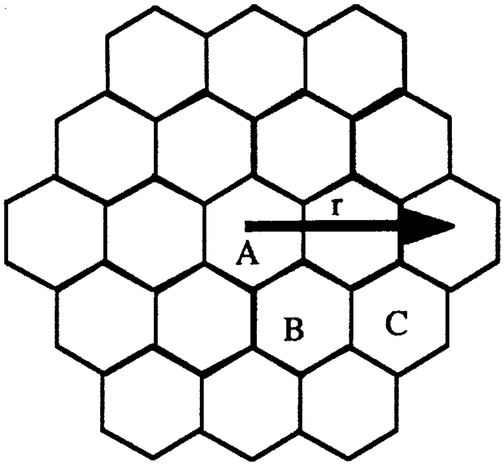
formulas

surface area of panel	$\frac{b^2 3\sqrt{3}}{8}$
seam length per side	$\frac{b}{2}$
panel diagonal length	b



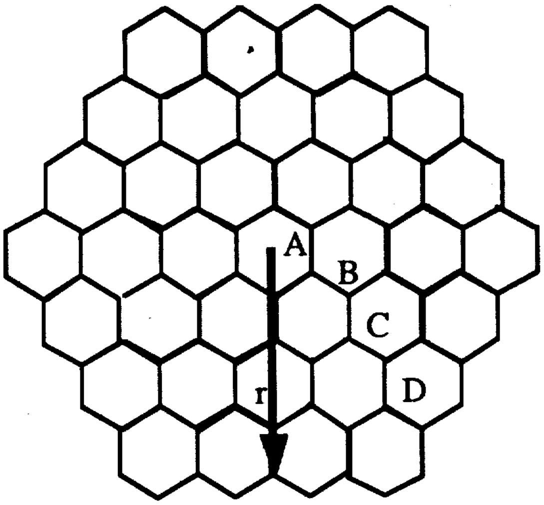
I) 1 ring

strut length		5.939m
panel diag		6.858m
counts		
panels		
	A	1
	B	6
	total	7
struts		51
nodes		18
seams		12
ETO		
panels		C'
struts		atlas 11'



II) 2 ring

strut length		3.429m
panel diag		3.959m
counts		
panels		
	A	1
	B	6
	C	12
	total	19
struts		156
nodes		45
seams		42
ETO		
panels		Titan IV
struts		Atlas 11'

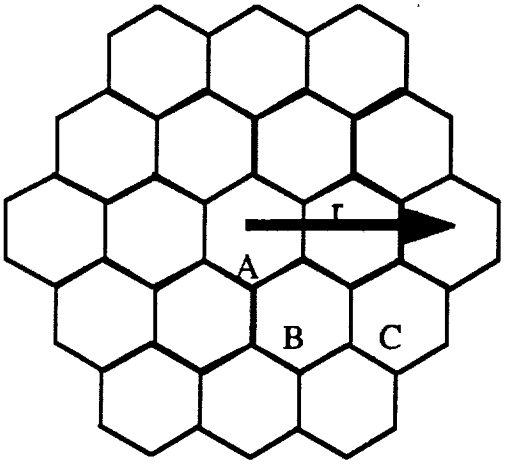


III) 3 ring

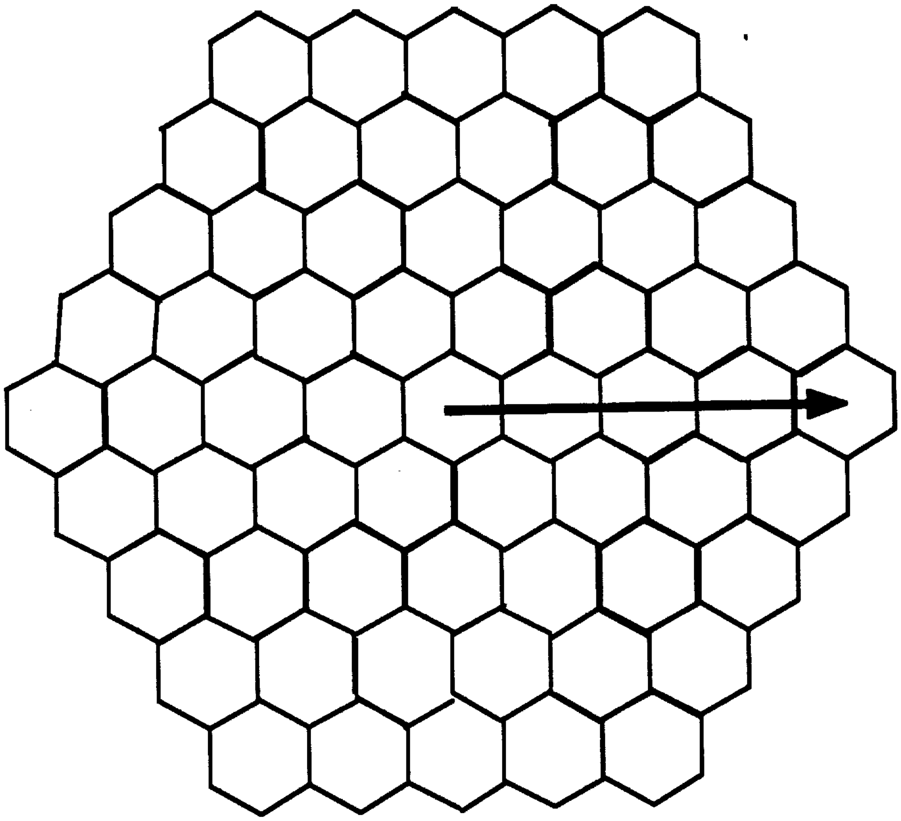
strut length	2.376m
panel diag	2.743m
counts	
panels	
A	1
B	18
C	6
D	12
total	37
struts	315
nodes	84
seams	89
ETO	
panels	Atlas 11'
struts	Atlas 11'

5 meter struts

20m diameter(65.2 feet)
aerobrake



2 ring				
	strut length			5 m
	panel diag			5.7735m
	counts			
		panels		
			A	1
			B	6
			C	12
			total	19
		struts		156
		nodes		45
		seams		42
	ETO			
		panels		Titan IV
		struts		Atlas 11'



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Tables

LEV AEROBRAKE ASSEMBLY CRITERIA

CRITERIA	STRUCTURAL CONCEPT		
	CENTER CORE WITH PETALS	ORTHOGONAL SPAR	TETRAHEDRAL W/PANELS
Structural Integrity Design	Some Design Complexity	Some Design Complexity	Simple
TPS Integrity	Many Joints	Few Seams	Extensive Number of Seams
ETO Packaging	Titan IV or Space Shuttle	Titan IV or Space Shuttle	Efficient (Any ETO)
Space Station Accommodations	Lazy Susan 4 Extra Bays SSRMS and SPDM/FTS Rail Guide	Lazy Susan 3 Extra Bays SSRMS and SPDM/FTS Rail Guide	3 Extra Bays SSRMS and SPDM/FTS Lazy Susan
Commonality of Parts	Interchangeable Leaves	Interchangeable Mid Sections and End Sections	Limited Interchangeable Panels
Robotic System Req'ts	Handle Medium Size Pieces	Handle Large Pieces Pieces	Most Extensive
EVA System Req'ts	Minimal	Some	Minimal
Testing of Assembly Amenable To Automation	Many Checkouts	Limited Large Piece Checkout	Extensive Checkouts
Post Flight Inspection	Robotics	Robotics	Robotics
Ease of Refurbishment	Disassembly of Large Pieces	May Require Extensive Work	May Require Considerable Disassembly

Table 4.1-Aerobrake Assembly Criteria.

LUNAR EXCURSION VEHICLE AEROBRAKE
INSPECTION METHODS OF THERMAL PROTECTION SYSTEM

THERMAL PROTECTION SYSTEM CHARACTERISTIC TO BE INSPECTED	INSPECTION TECHNIQUE EVA VISUAL INSPECTION	COMPUTER OPTICAL RANGING	COMPUTER MECHANICAL RANGING	MECHANICAL TELLTALES	ACOUSTIC IMAGING	OTHER* REQUIRED
TAILORABLE ABLATIVE BLANKET INSULATION						
SURFACE CHARRING	X	X				
SURFACE TEARS/HOLES	X	X				
BONDING TO SURFACE						X (1)
ABLATOR						
DEGREE OF ABLATION	X	X	X	X		
BROKEN PIECES	X	X	X			
SURFACE INTEGRITY	X	X	X	X		
FASTENER INTEGRITY					X	
CERAMIC TILES						
TILE DEFECTS						
TILE EROSION	X	X	X		X	
SURFACE INTEGRITY	X	X	X		X	
HAIRLINE CRACK					X	
BROKEN TILE	X	X			X	
DELAMINATION OF FIBERS					X	
TILE SUPPORT DEFFECTS						
BOND BETWEEN TILE AND SIP					X	X(2)
BOND BETWEEN SIP AND PLATE					X	X(2)
SIP INTEGRITY					X	X(2)
TILE JOINT BONDING					X	X(2)

*** OTHER INCLUDES: X-RAYS, ELECTROMAGNETIC IMAGING, NUCLEAR PARTICLES, MAGNETIC RESONANCE IMAGING, AND THERMAL GRAPHIC IMAGING.**

(1) INSPECTION OF TABI BOND REQUIRES SOME SORT OF SENSOR SYSTEM ON BACKSIDE OF FABRIC TO EVALUATE BOND STRENGTH BETWEEN FABRIC AND PLATE OR A METHOD FOR PULLING ON TABI.

(2) TILE BONDING COULD BE CHECKED BY APPLYING A LOAD AND PULLING ON TILES.

Table 4.2-A Potential List of TPS Inspection Sensors.

NASA — FREEDOM

Assembly Complete (AC) Comparison

	AC	AC with Aerobrake
Total Mass	265000 kg	272700 kg
Center of Mass (x,y,z)	-1.2, 0.2, 3.5 m	-1.2, 0.3, 3.3 m
Average Drag Area	2300 m^2 (2340)	2380 m^2 (2430)
Average Ballistic Coefficient	50.1 kg-m^2 (49.3)	49.8 kg-m^2 (48.8)
Average Flight Attitude from LVLH (Φ, Θ, Ψ)	0.36, -7.5, 0.24 deg (0.24, -11.3, 0.36)	-0.09, -10.0, 0.22 deg (0.01, -18.4, 0.22)
Micro-g Level at Center of U.S. Lab	1.1 μg (1.5)	1.3 μg (2.0)
90 Days Reboost Fuel	2960 lbm (6642)	3130 lbm (7023)
Reboost Altitude	231 nmi (245)	231 nmi (245)
Orbital Lifetime to 220 nmi	204 days (81)	207 days (80)

Atmospheric Assumptions :
- Flux = 121.20 (243.00)
- AP = 22.60 (19.60)
- Alt. = 220 nmi (220)

LaRC SSFO

Table 4.3-Summary of Aerobrake Accommodation Impacts on Space Station Freedom.

Space Station Freedom Accommodation Summary

		Solid Core with Petals	Orthogonal Spars		Tetrahedral Truss/Panels	Comments
			A	B		
SSF	Structure	4 Bays	3 Bays	3 Bays	3 Bays	
	FTS/SPDM EVA	Yes	Yes	Yes	Yes	Any mix or match
	SSRMS (Log)	One	One	One/No		STS RMS or EVA for Truss-Panels
	SSRMS (Ops)	One	One	One		
	MSC/MRS	Yes	Yes	No	Yes	Tractor Drive for Orth. Spars B
	Dedicated Storage	Medium	Large	Large	Nominal	
Non SSF	Lazy Susan	Yes	Yes	No	Yes	Continuous Drive Best, Stepper O.K.
	Inspection Sensor					Truss, Special Boom or RMS Mount
	Special Hardware	Limited	Limited	Same	None	Rails + Tractor for Orth. Spars
	Information System Support	Yes	Yes	Yes	Yes	
	Shielding					Solar No DebrisTBD

Table 5.1-Summary of minimum accommodations required to assemble the Lunar mission aerobrake.

NASA

Lunar Mission Aeroassist Advantage

NASA Option 5

LOX/LH_2 Aeroassist vs. LOX/LH_2 only
27 MT Payload Delivered/1 MT Payload Returned

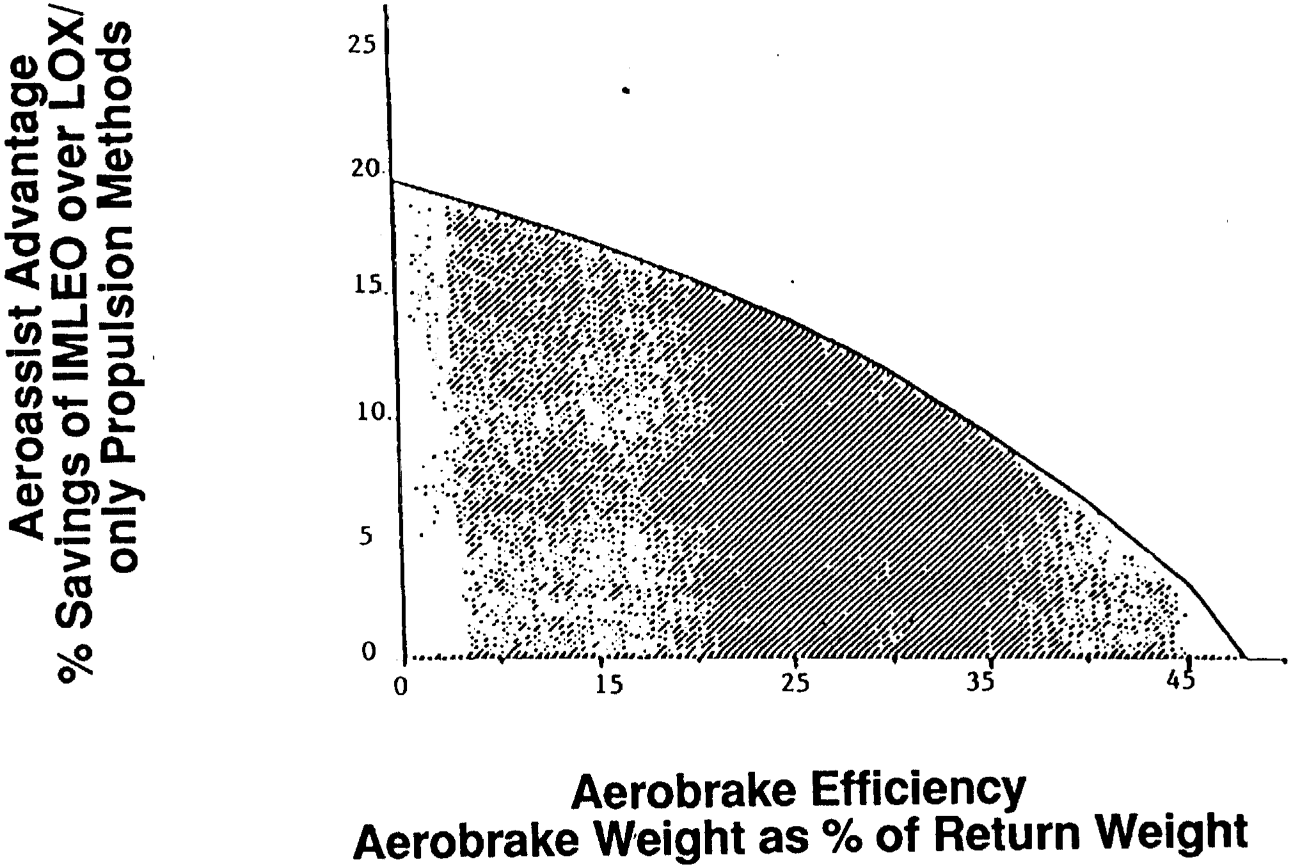

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Figure 2.1 - Illustration of Lunar Mission propellant savings by use of an aerobrake as a function of aerobrake mass fraction (Reference 1.)

Mars Mission Aeroassist Advantage

NASA Option 5
LOX/LH_2 Aeroassist vs. LOX/LH_2 only
25 MT Payload Delivered/1 MT Payload Returned

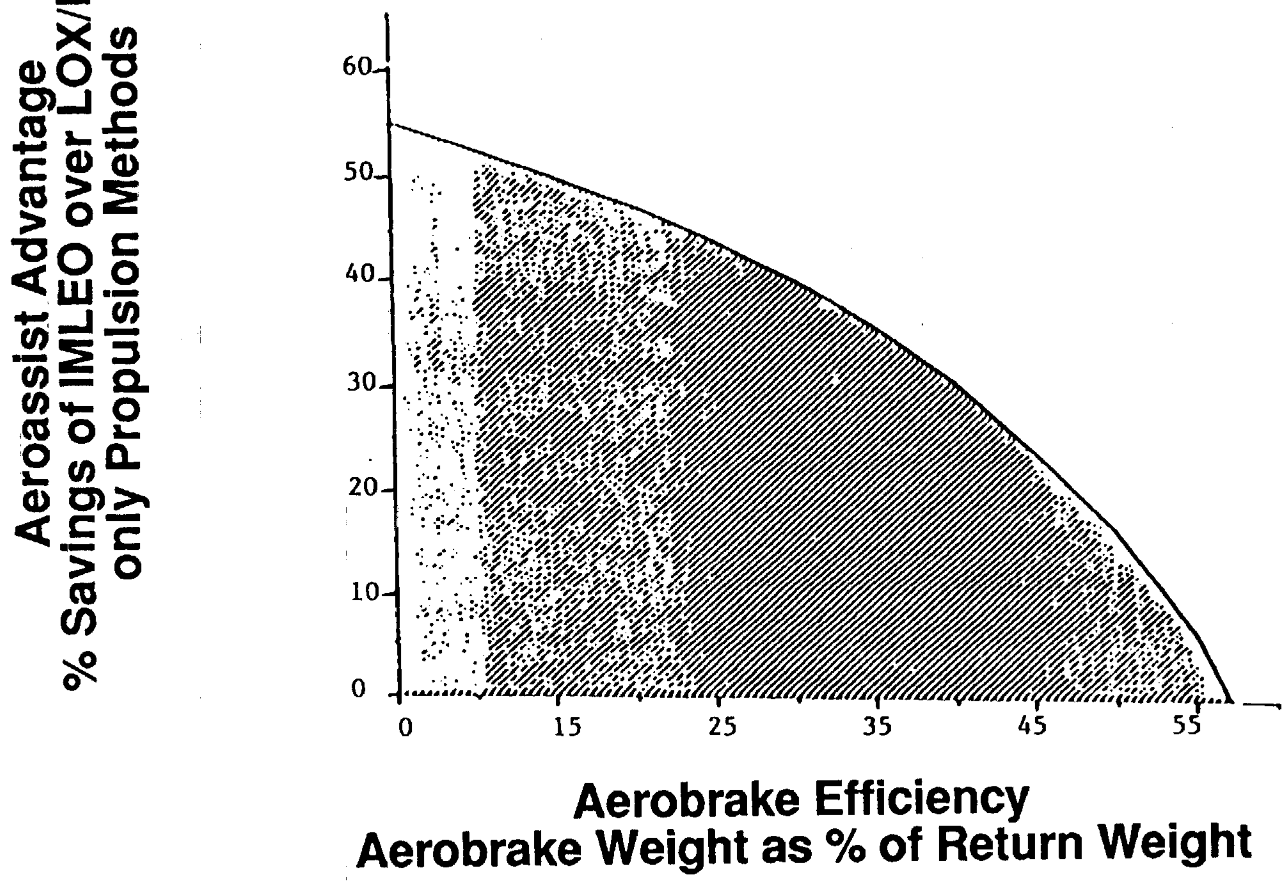


Figure 2.2 - Illustration of Mars Mission propellant savings by use of an aerobrake (from Reference 1.) Note the larger savings than in the Lunar Mission case.

Single P/A (Propulsion/Avionics) Module

Mass Statement P/A Module Configuration

	LTC	ETA
Crew Module	0235	---
Structures	2780	465
Tanks	1214	2877
Micro-Shield	350	645
Engine & Feed Sys.	1523	100
RCS System	171	206
Thermal Control	344	962
Power	379	30
C&D11	868	10
GN&C	339	20
Aerobrake	4196	---
Contingency (15%)	1195	825
Dry Weight (kg)	21595	6324
Propellant Capacity (kg)	31360	112524

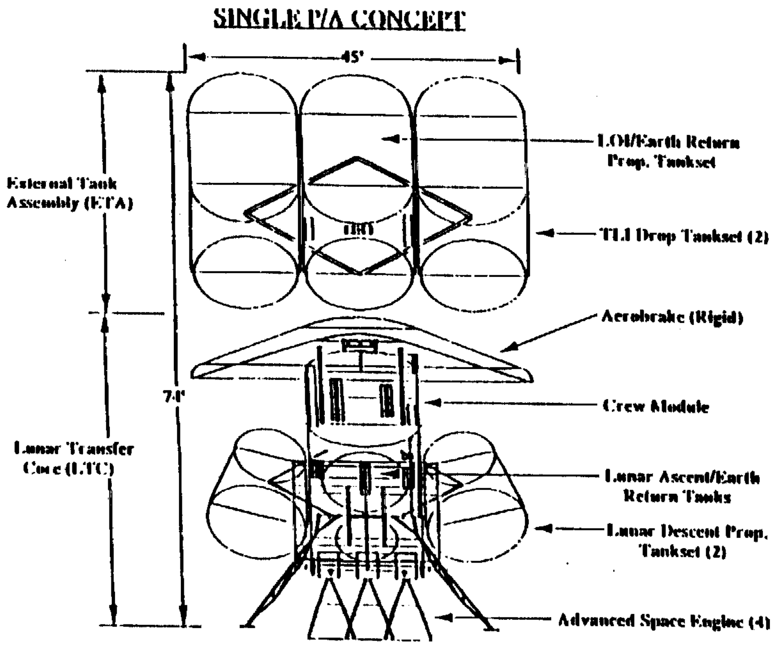


Figure 2.3 - The "Single P/A Module", a more developed version of the Lunar Transfer Vehicle than that used in the "90-Day Study" (Reference 1.)

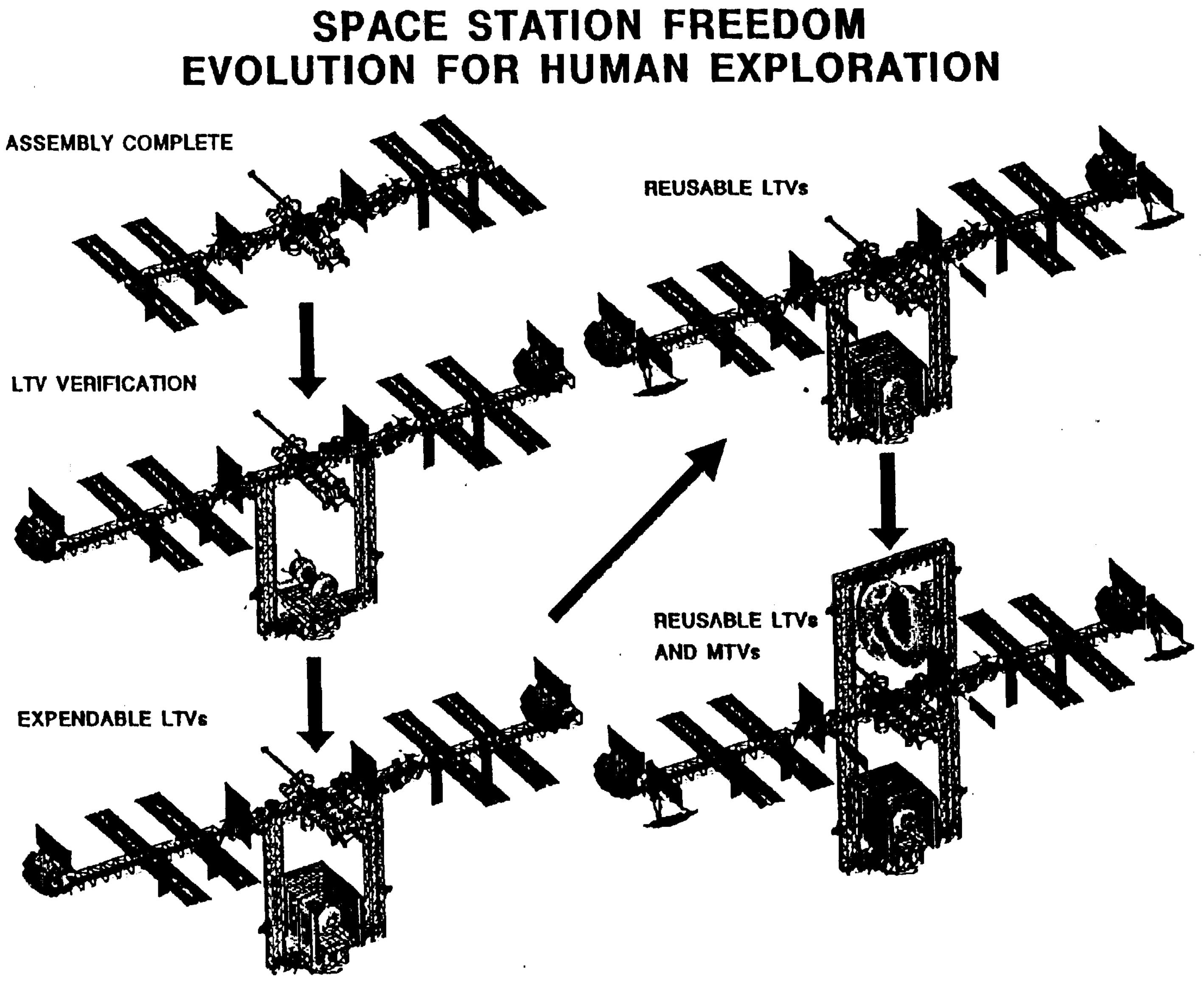


Figure 2.4-Space Station Freedom evolution to support the full Lunar and Mars Missions. It is the "Reusable LTV's" stage which is being assessed for minimum accommodation in this study.

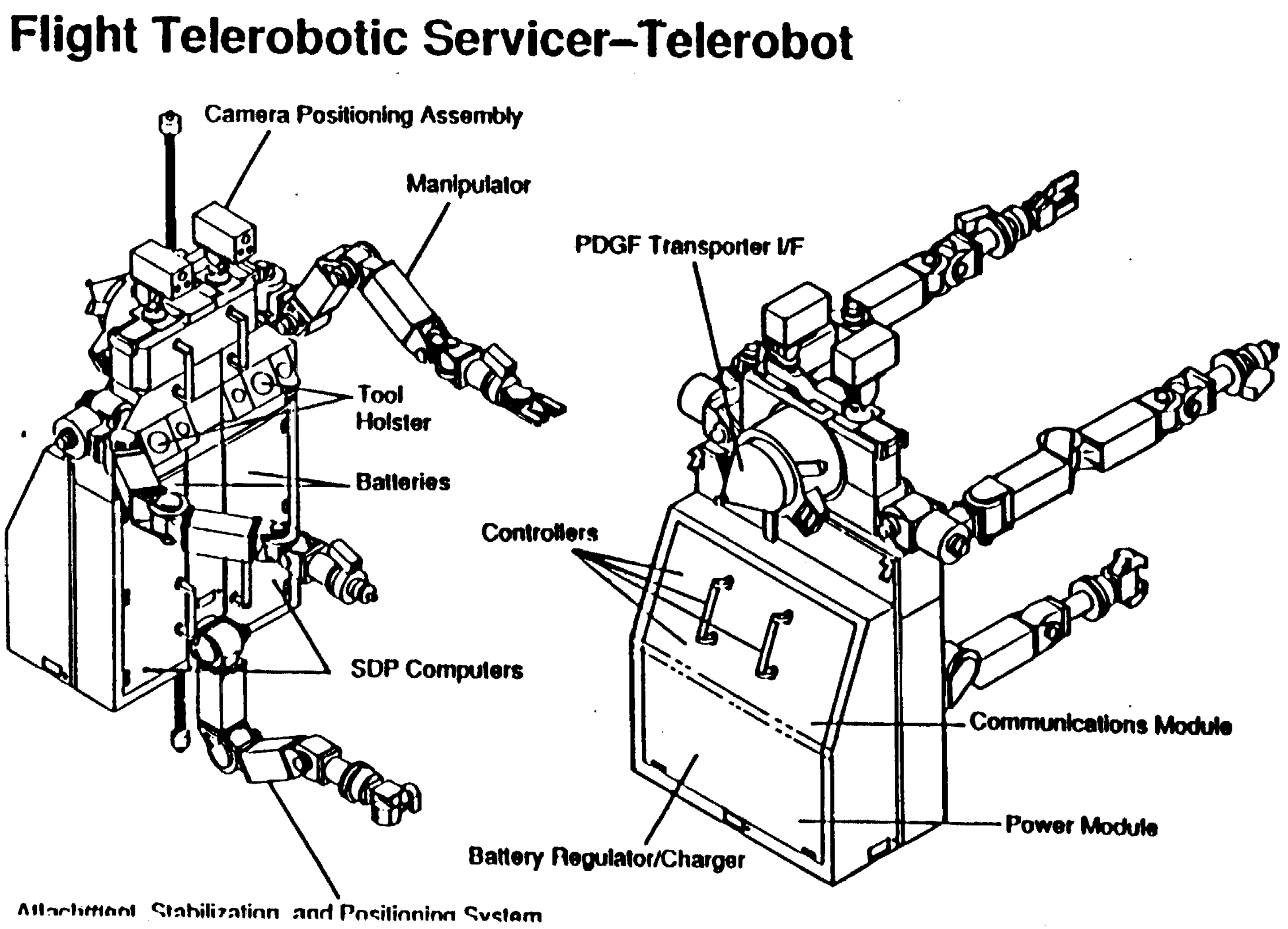


Figure 3.1-Illustration of the Flight Telerobotic Servicer, FTS, one of Space Station Freedom's baseline support services.

Mobile Servicing Centre (MSC)

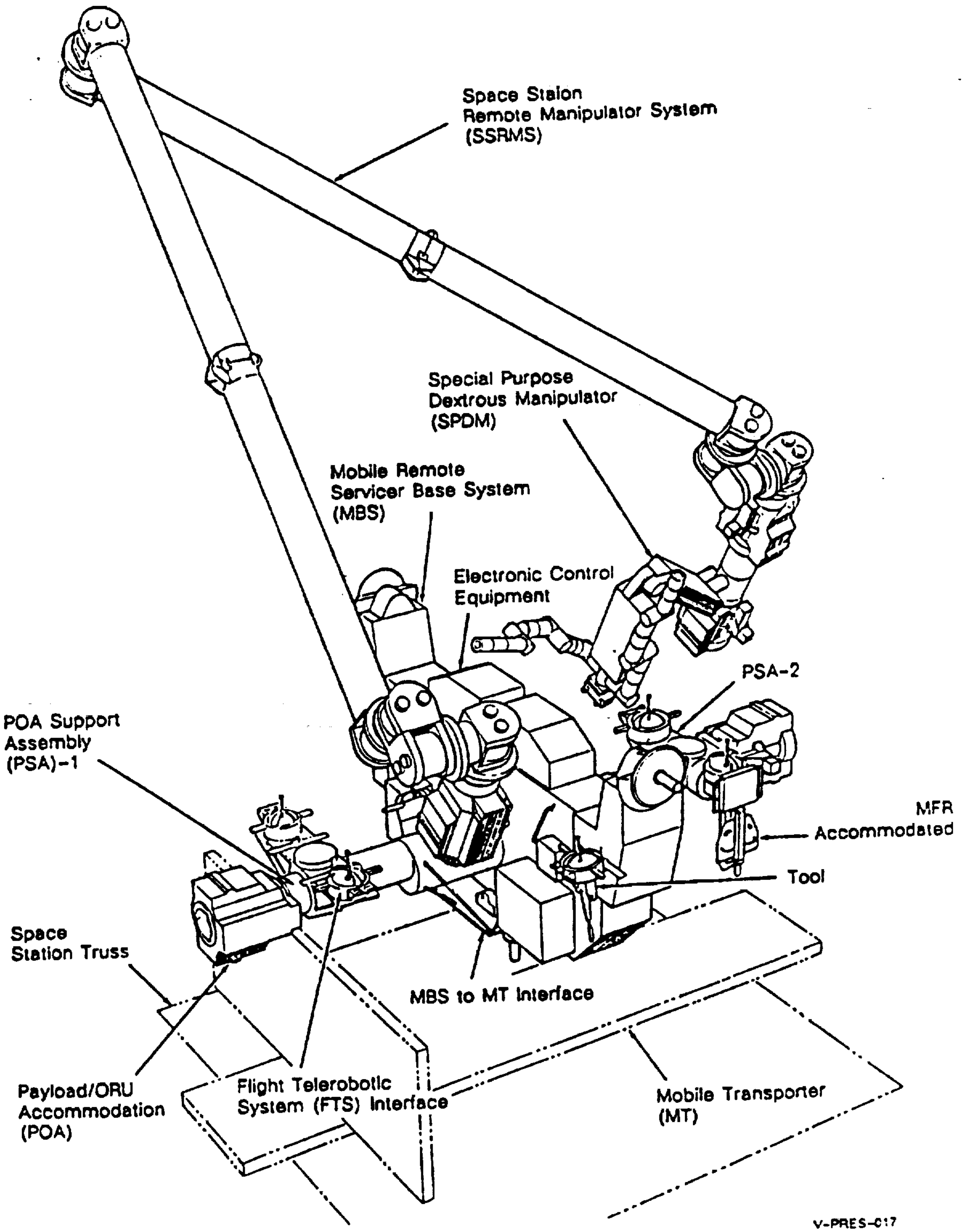
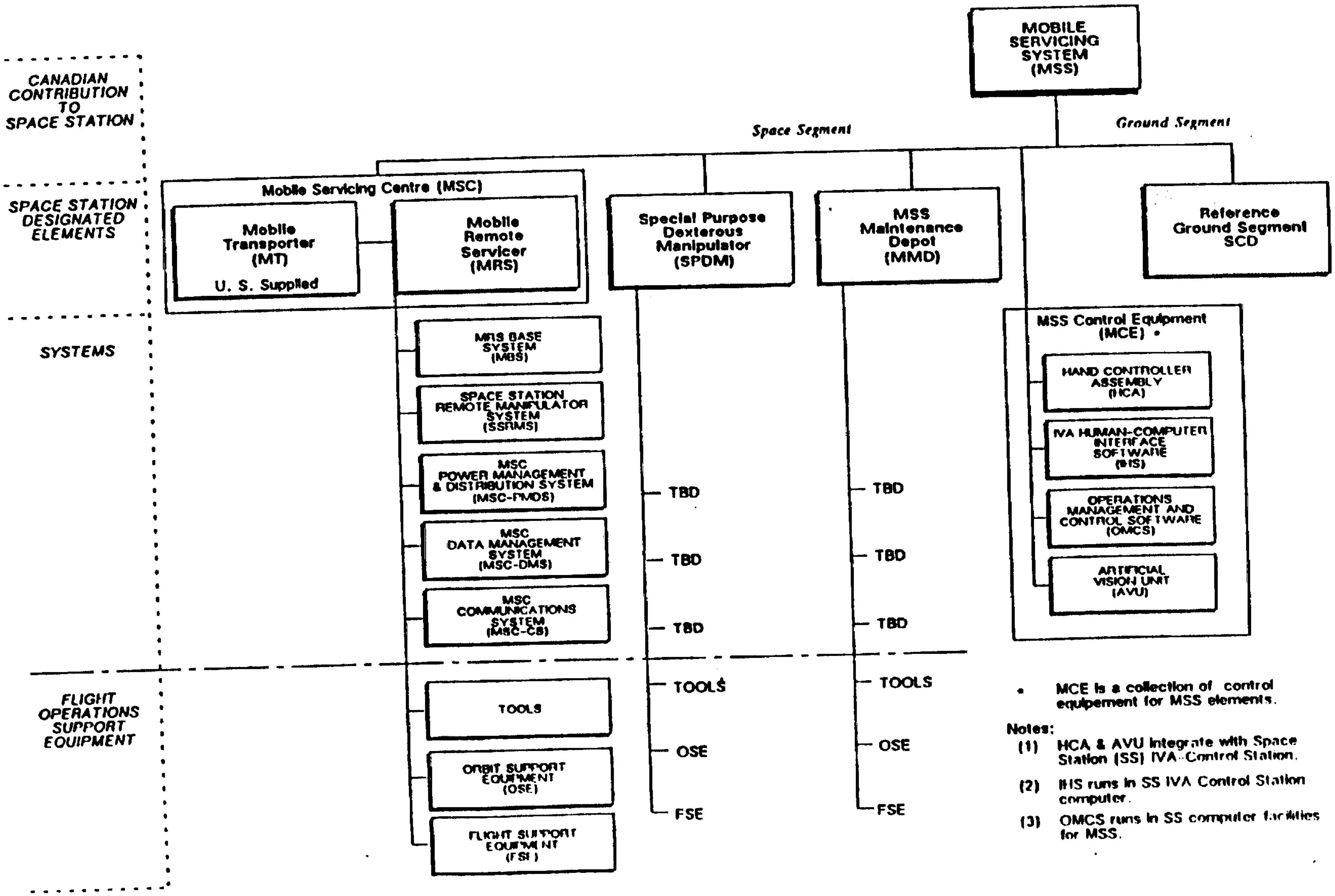


Figure 3.2-Illustration of the Mobile Servicing Center, MSC, a Canadian-supplied SSF baseline support service.

Mobile Servicing System (Space Segment) Hierarchy

SPAR



- MCE is a collection of control equipement for MSS elements.

Notes:

(1) HCA & AVU integrate with Space Station (SS) IVA Control Station.

(2) IHS runs in SS IVA Control Station computer.

(3) OMCS runs in SS computer facilities for MSS.

Figure 3.3-A system schematic of the Canadian Mobile Servicing System to illustrate interrelationships of the flight segments.

MSS / SSRMS Capabilities

SPAR

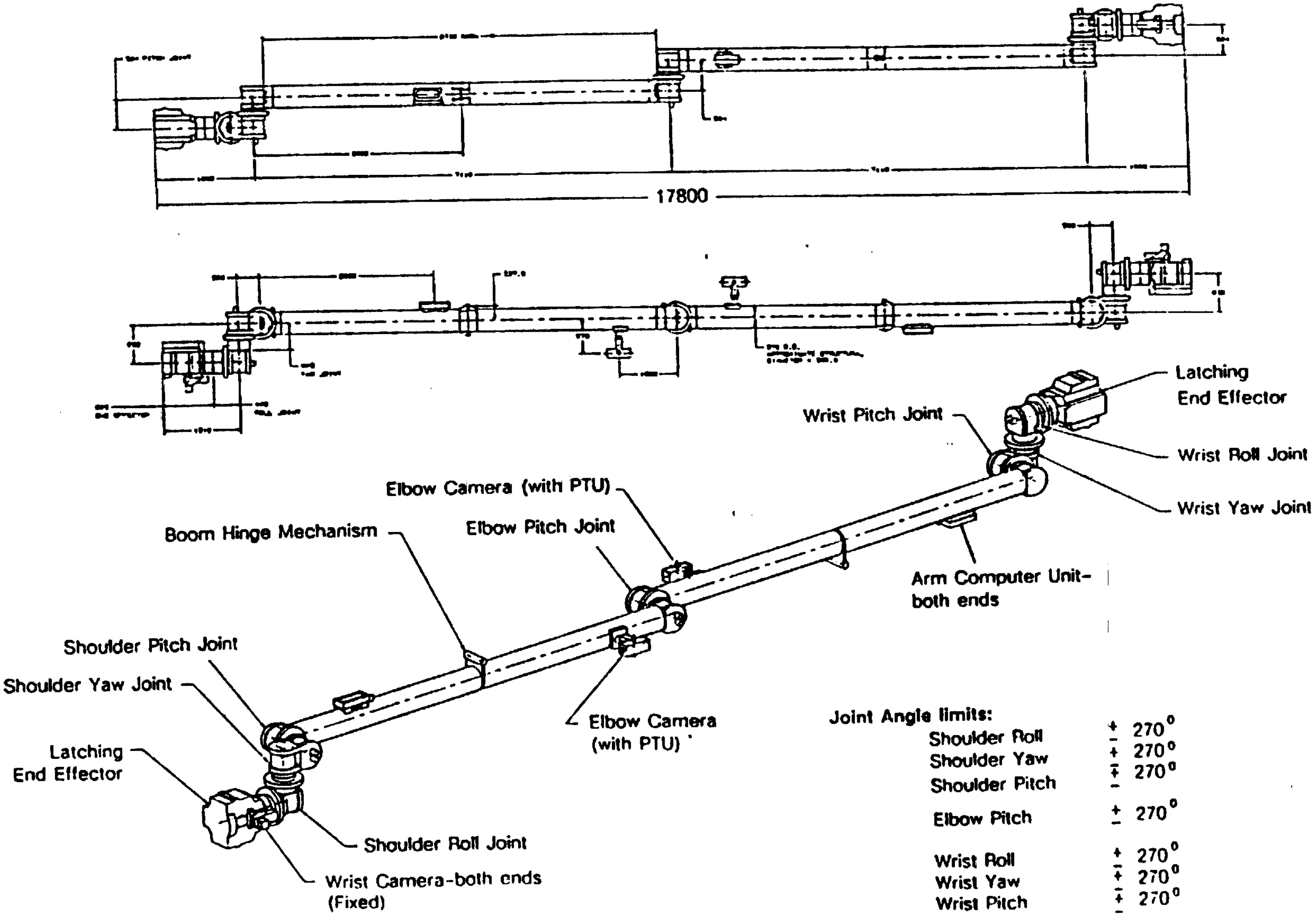
■ Handling:	Baseline	Orbiter	Growth
☐ Maximum Payload Mass	20,900Kg	116,000Kg	128,000Kg
☐ Maximum Payload Size	4.5m Diameter	24.1m Diameter	13.4m Diameter
	17m Length	34.3m Length	44.7m Length

■ Transportation:	Baseline	Growth
☐ Maximum Payload Mass	20,900Kg	128,000Kg
☐ Maximum Payload Size	4.5m Diameter	13.4m Diameter
	17m length	44.7m Length

Figure 3.4-Capabilities of the Space Station Remote Manipulator System, SSRMS, a part of the Mobile Servicing Center.

SSRMS Configuration

SPAR



Joint Angle limits:

Shoulder Roll	± 270°
Shoulder Yaw	± 270°
Shoulder Pitch	± 270°
Elbow Pitch	± 270°
Wrist Roll	± 270°
Wrist Yaw	± 270°
Wrist Pitch	± 270°

Figure 3.5-Schematic drawing of the SSRMS with dimensions.

SPDM Configuration

SPAR

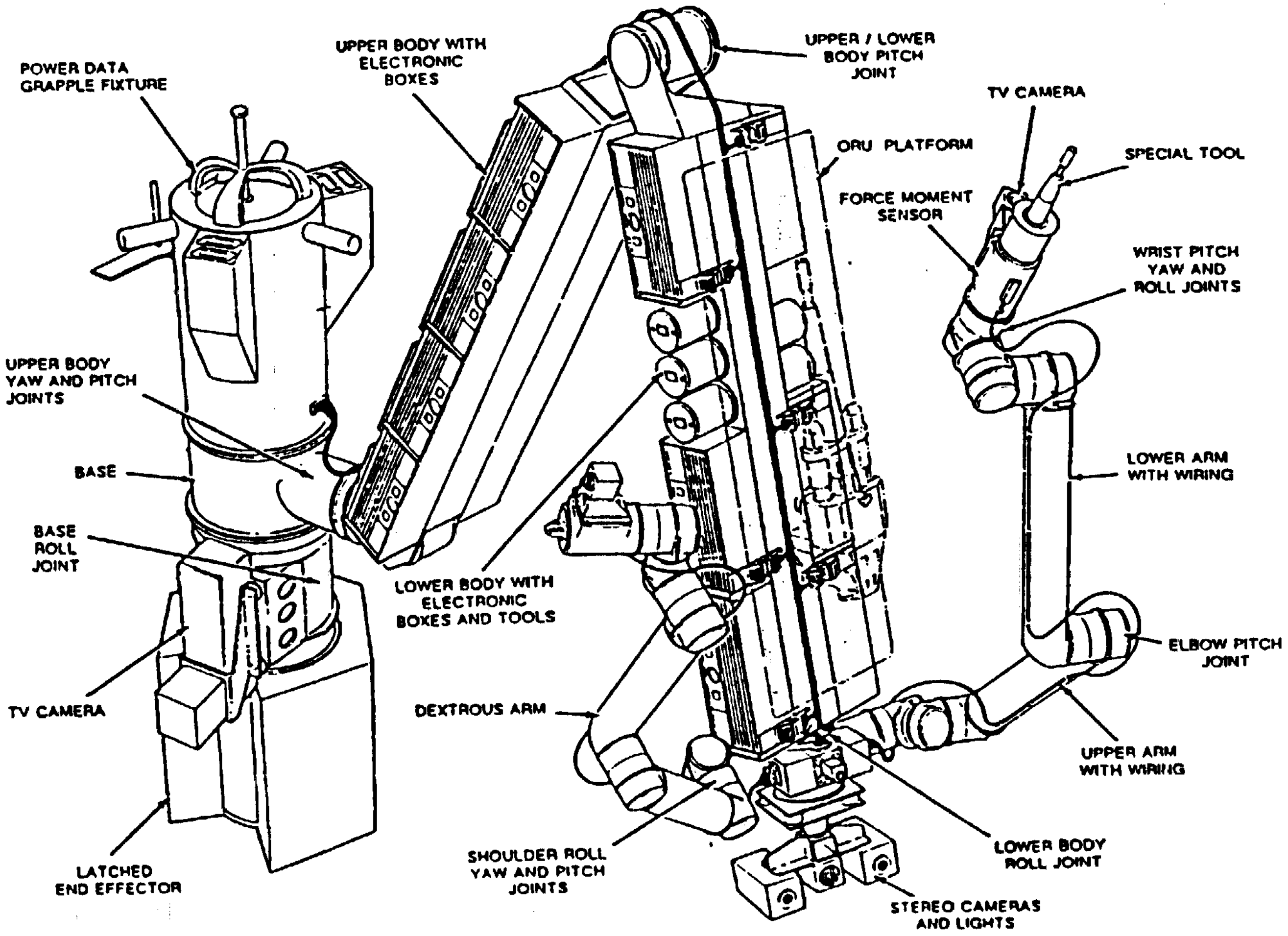


Figure 3.6-Schematic drawing of the Special Purpose Dextrous Manipulator, SPDM, part of the Canadian supplied MSC. The SPDM is a telerobot somewhat like the FTS.

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Performance Requirements / Capabilities

SPAR

- Maximum size ORU to be handled =TBD (600kg)
- Tip force capability : 25lbs (111N)
- Tip positioning accuracy during positioning and attachment/detachment of ORU's:
  - ☐ Without vision system: TBD (0.6 cm)
TBD (1 degree)
  - ☐ With vision system: TBD (0.125 cm)
TBD (0.5 degree)
- Tip positioning accuracy = 0.050 in (0.125 cm) (with vision system)
- Maximum stopping distance = 2 in. (5.0 cm)
- Weight = 1800 lbs. (815 kg)
- Standard interface for handling ORU's and tools
- A standard set of tools to be provided with SPDM

Figure 3.7-Expected performance characteristics of SPDM.

MOBILE TRANSPORTER ELEMENT
MOBILE TRANSPORTER

- Key design parameters
  - Payload Capacity: 59,000 lb. nominal (MRS + 50,000 lb)
  - Strength: 18,000 ft-lb bending moment
    7,420 ft-lb torsional moment
  - Velocity:

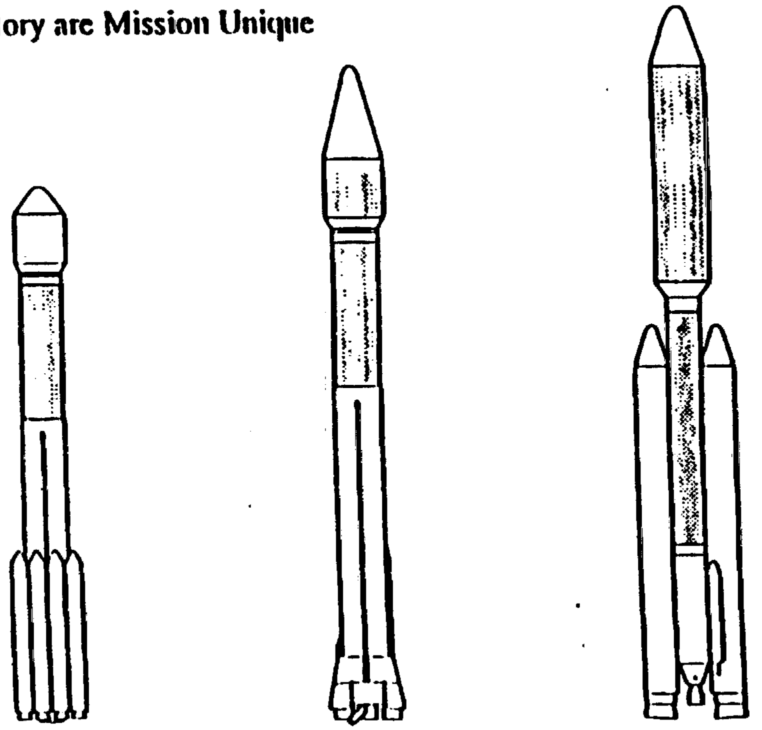
	No payload	59,000 lb payload
1 Bay translation	185 sec.	8.3 min.
90 deg. rotation	64 sec.	45 min.

Figure 3.8-Characteristics of the U.S. Mobile Transporter that is generally used with the MSC.

NASA *Exploration Initiat*

Launch Vehicles for Robotic Missions

- **Requirements**
  - **Earth Orbit, Lunar, Mars and Solar Satellites**
  - **Payload Size and Trajectory are Mission Unique**



ELV Family	**Delta II**	**Atlas**	**Titan IV ***
LEO Payload	**3.9-5.0 t**	**6.7-8.8 t**	**17.7-22.3 t**

*** Current Limit on Launch Rate Must Be Assessed.**

Technical Study Group

Figure 3.9-Illustration of the available earth-to-orbit transportation to bring up aerobrake parts and support hardware.

Shuttle Derived ETO Lunar Vehicle

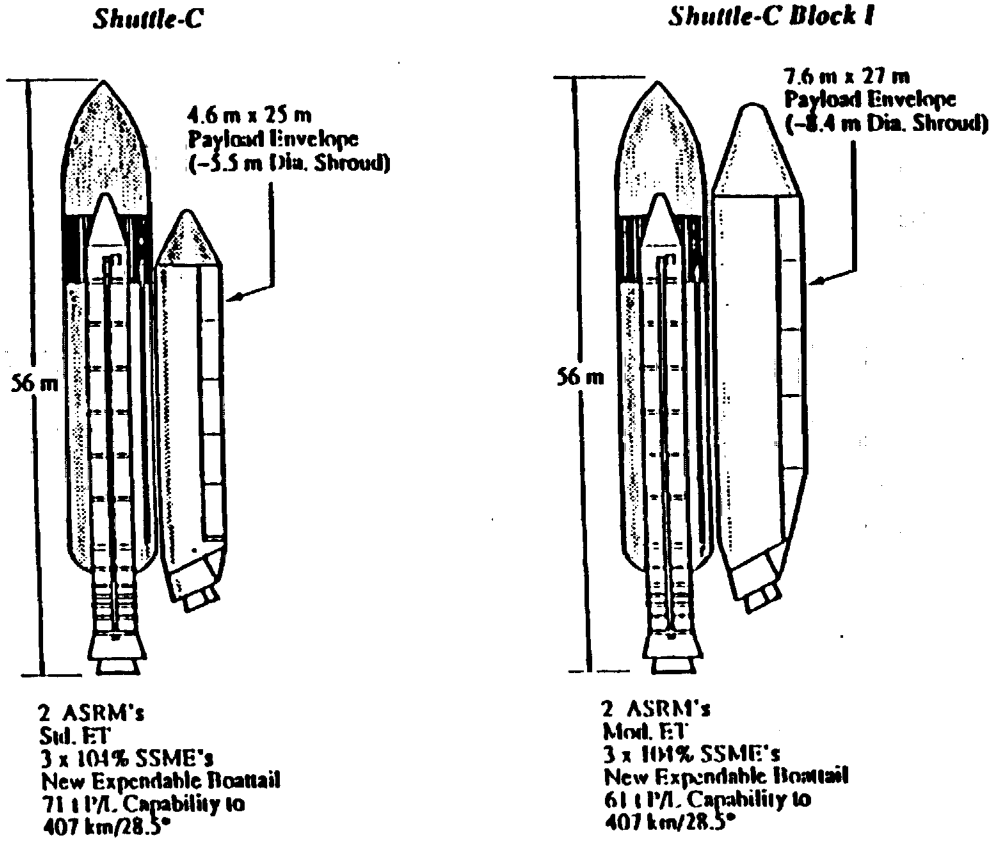


Figure 3.10-Illustration of the proposed Shuttle C and Shuttle C', expected to be ready to participate in the Lunar Mission phase of the Space Exploration Initiative.

EARTH - TO - ORBIT SYSTEMS

LAUNCH VEHICLE	PAYLOAD SIZE
DELTA II	5 t
ATLAS	8 t 3.7m by 9.3m
TITAN IV	20 t 4.6m by 20.1m
SHUTTLE	20 t 4.6m by 18.3m
SHUTTLE	18 t 4.6 m by 18.3 m
SHUTTLE C	71 t 4.6m by 25m
SHUTTLE C'	61 t 7.6m by 27m

Note: Aerobrake Diameter larger than any of launch Vehicle Payload Diameters. Therefore, some Space Station Assembly required.

Figure 3.11-Initial Mass in Low Earth Orbit, IMLEO, capabilities of the various launch vehicles selected for this study.

petal thermal protection closure

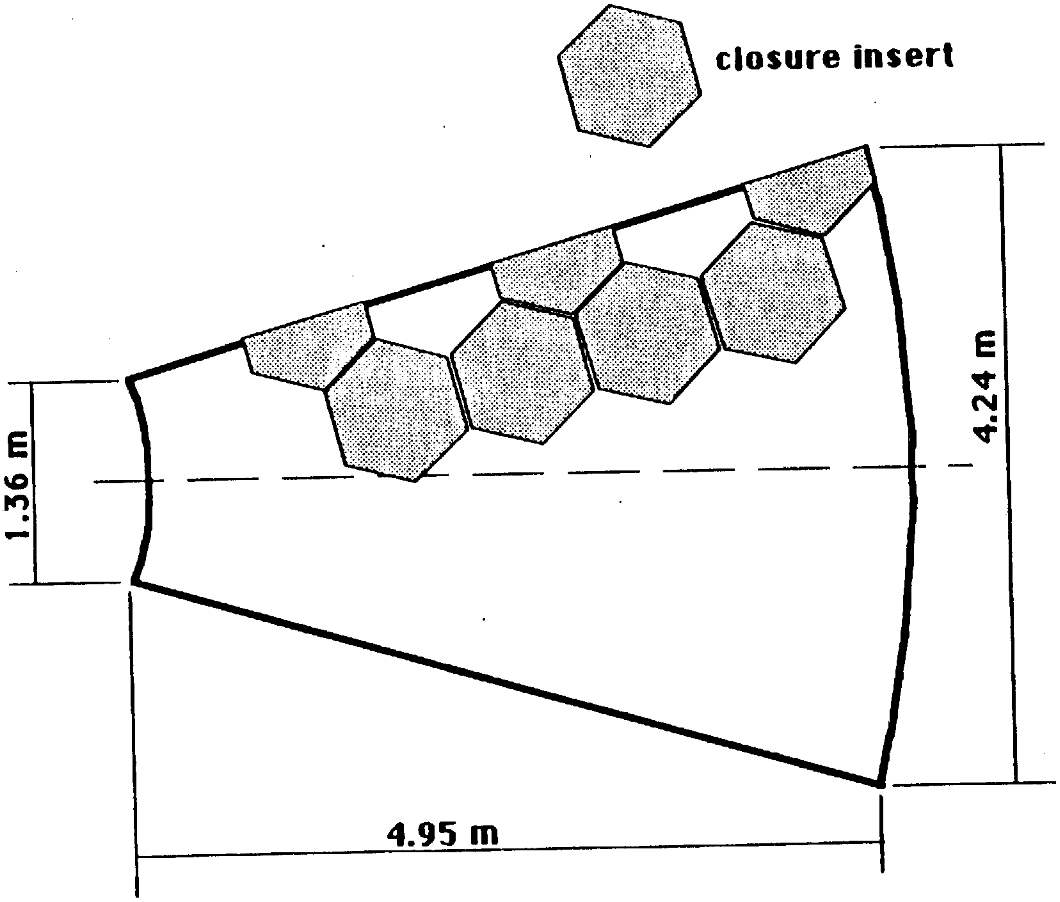


Figure 3.12-Technique for eliminating flow of hot gas down mechanical joints on aerobrake structure.

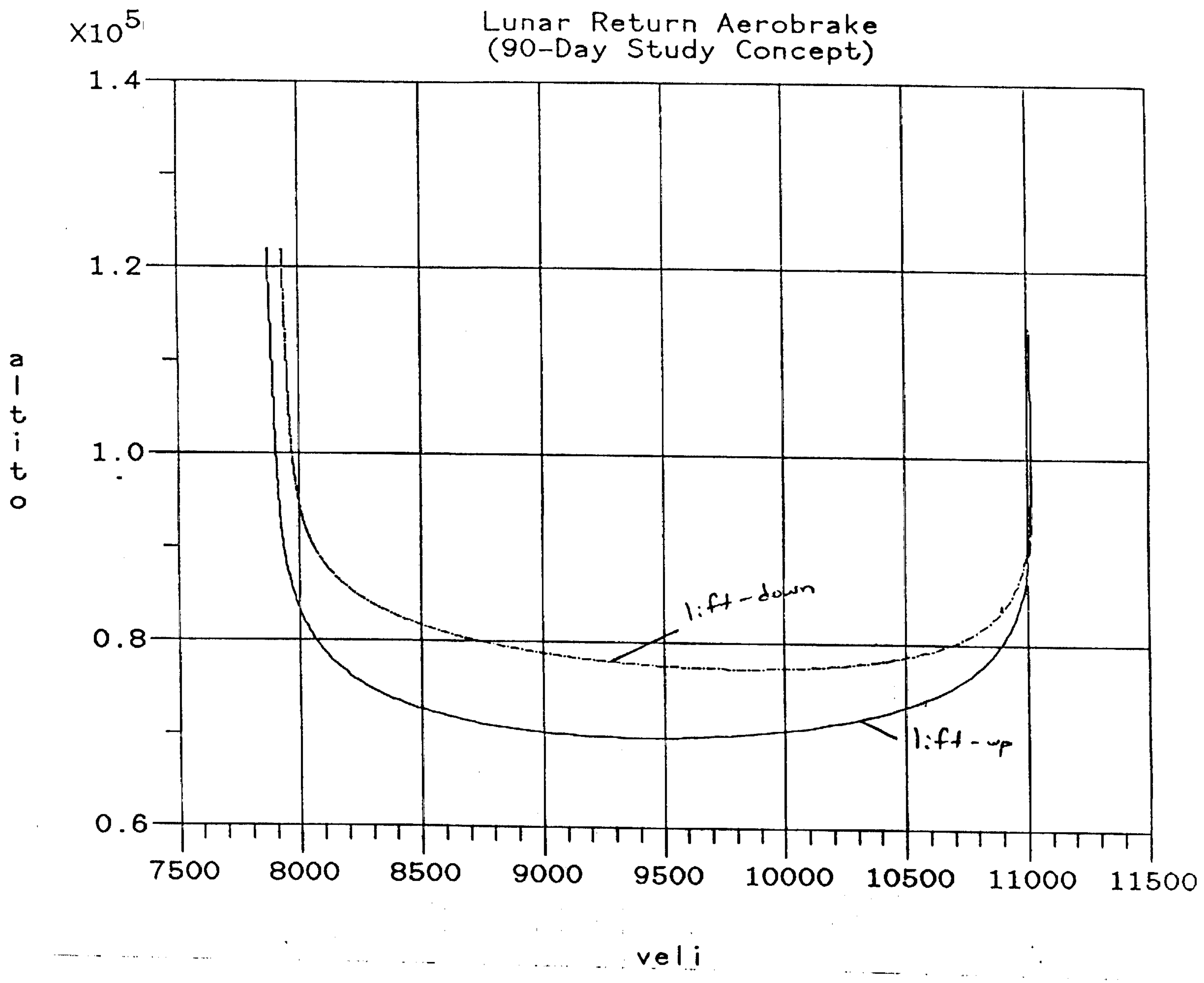


Figure 4.1-Model Lunar return mission. Abscissa represents vehicle speed in meters per second, while the ordinate represents altitude in meters.

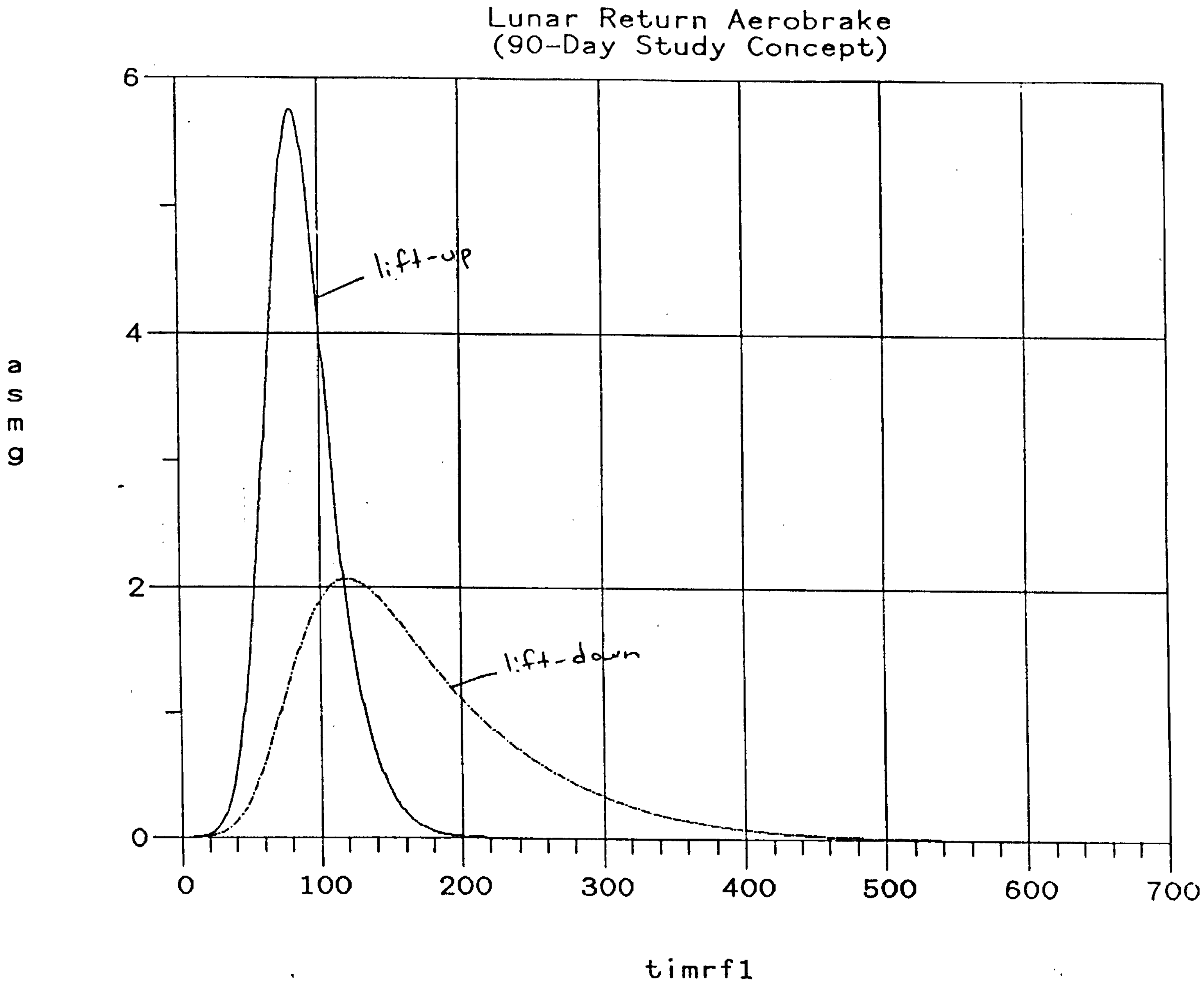


Figure 4.2-Deceleration scaled to the acceleration of gravity (G's) experienced during the model Lunar return mission of Figure 4.1.

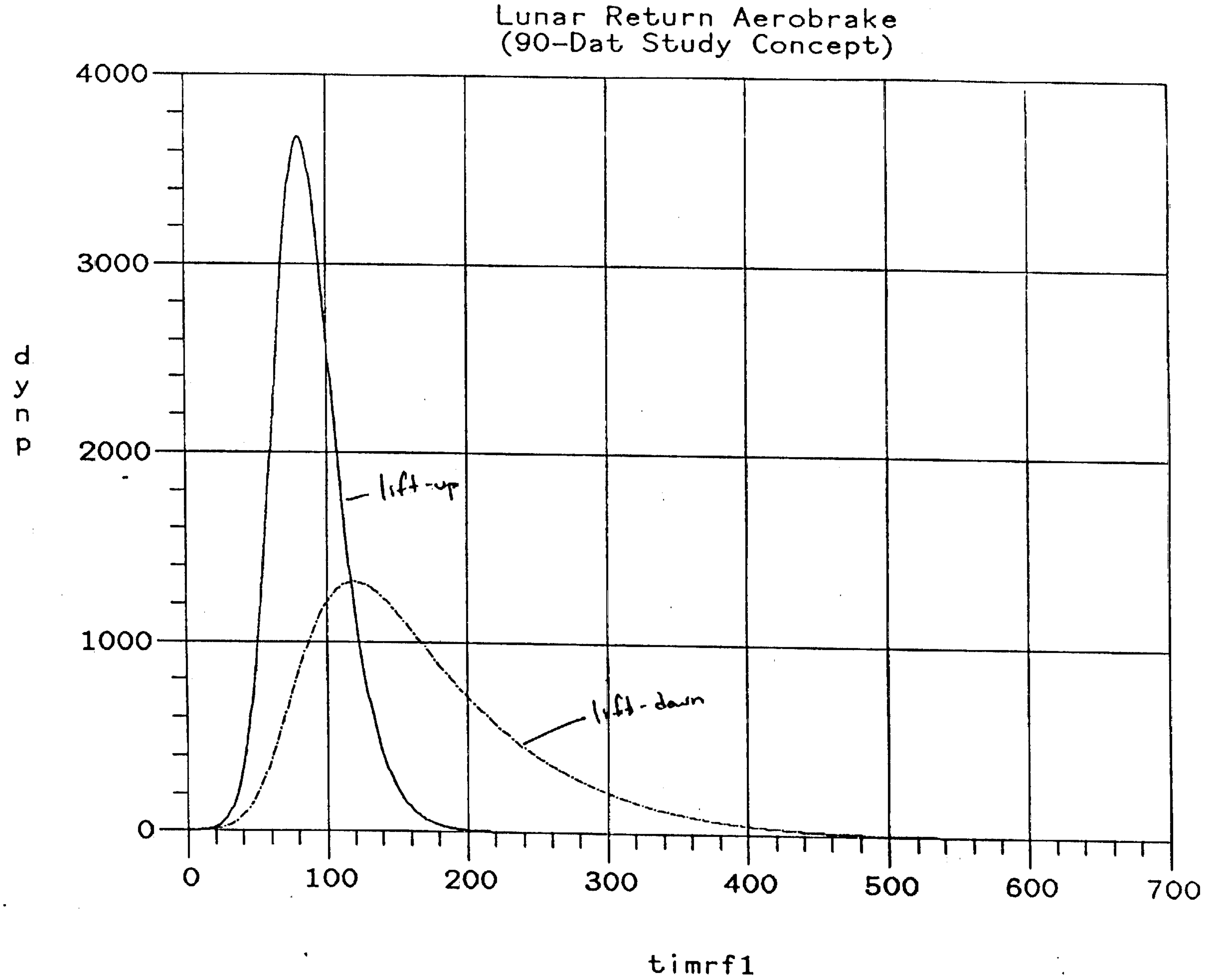


Figure 4.3-Free stream dynamic pressure experienced by the aerobrake during the model Lunar return mission of Figure 4.1.

Aerobrake hape Effects & Protected Area Estimates

90 Day Study

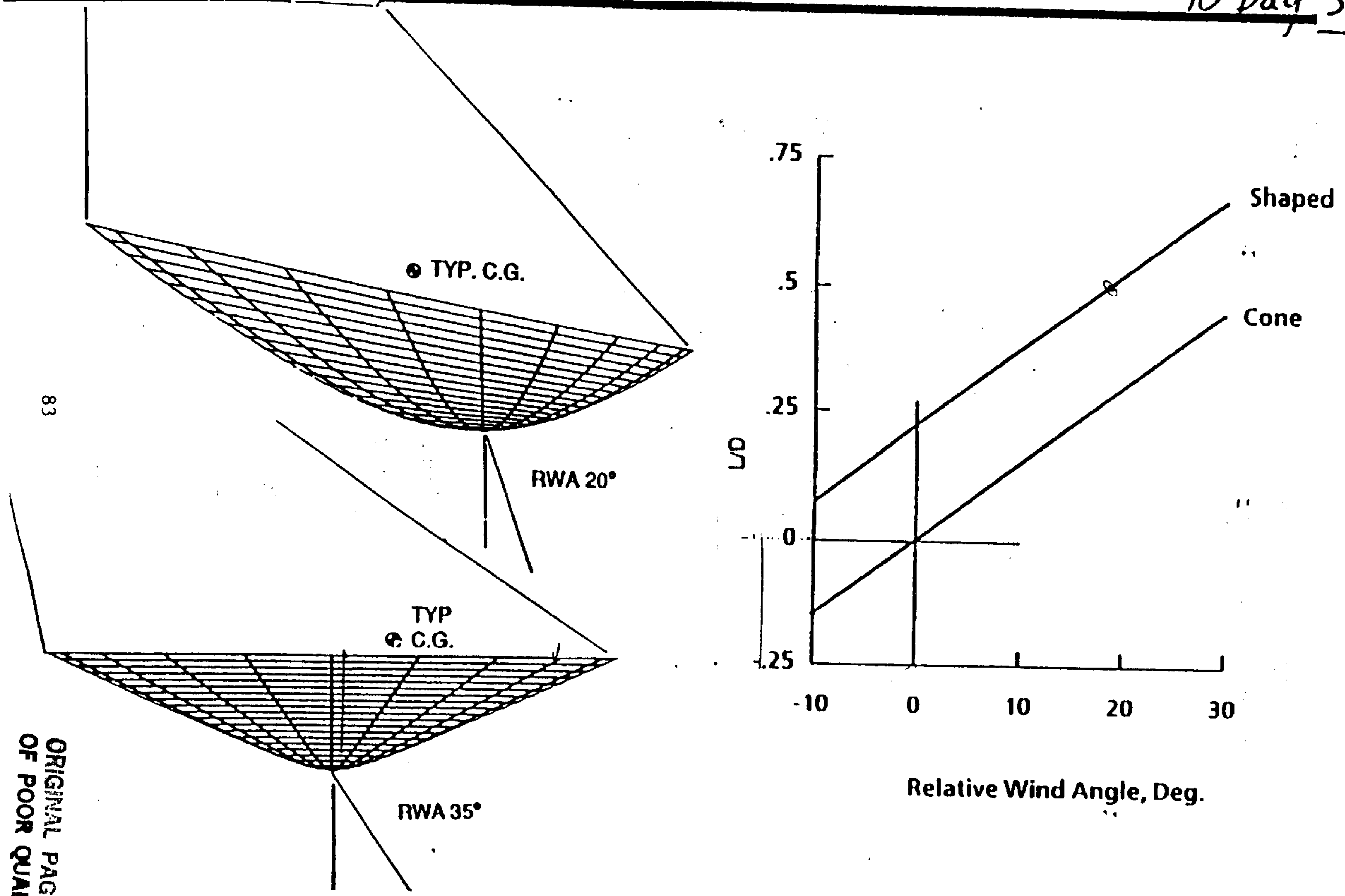


Figure 4.4-Illustration of the variation of L/D versus angle of attack for a symmetric and asymmetric aerobrake. Asymmetric shape experiences lift at zero angle of attack.

Aerobrake Vehicles and Concepts

BOEING

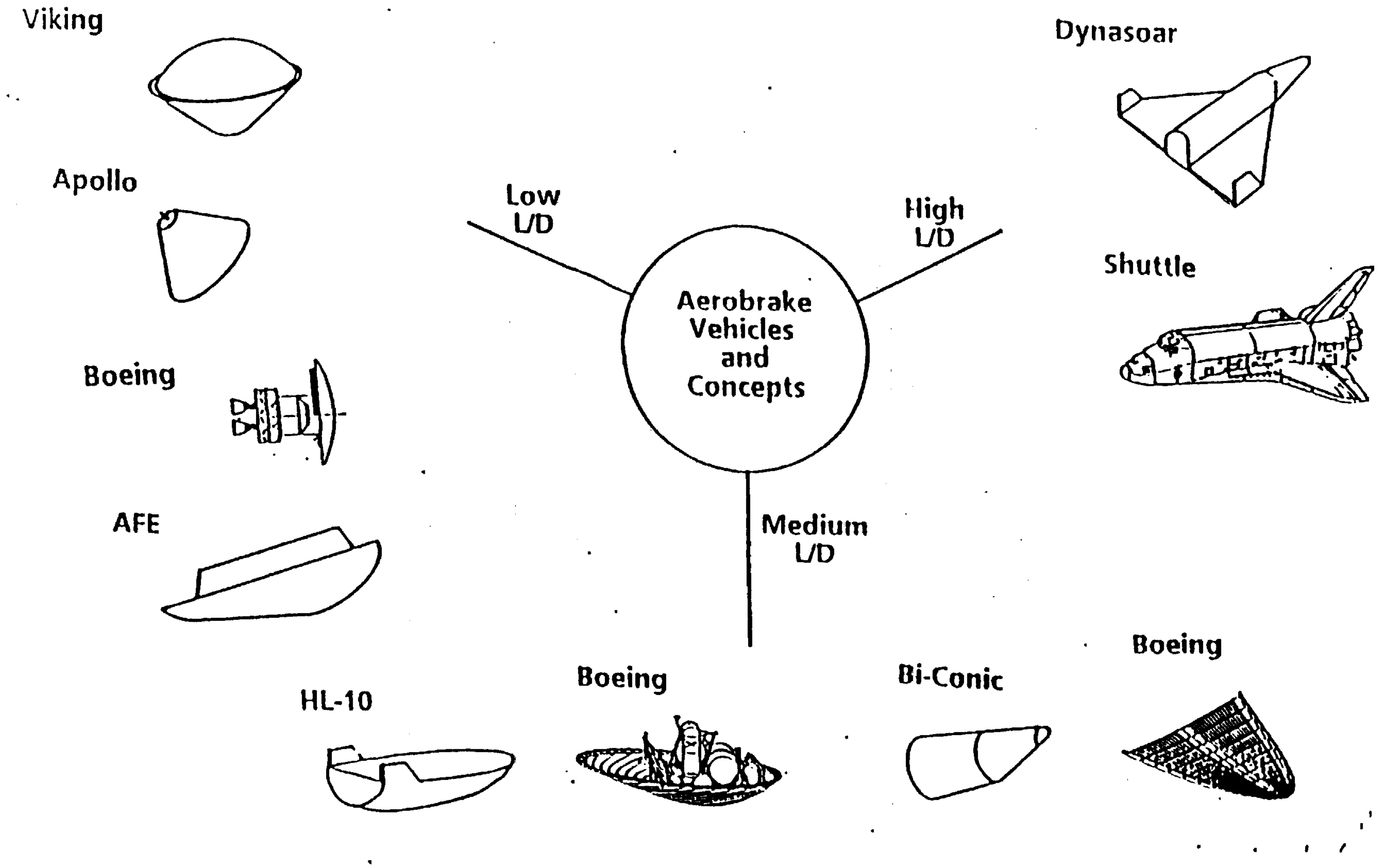


Figure 4.5-Illustration of some of the many aerobrake shapes and concepts that abound.

THE MODEL AEROBRAKE FOR THIS STUDY

- Total Vehicle Mass: 21.6 MT (Includes Aerobrake)
- Number of Reuses: 5
- Maximum Decleraton: 5 G's
- Nominal 13.7 meter diameter
- Low L/D acceptable: 0.1
- Cd on order of 1.5

Figure 4.6-Characteristics of an aerobrake required to function as part of the "Single P/A Module" Lunar mission vehicle of this study.

AXISYMMETRIC EVOLVABLE

- o LUNAR SYMMETRIC
- o SURFACE OF REVOLUTION
  - HYPERBOLOID
  - SPHEROID (APOLLO)
  - SPHERE-CONE
- o SKIRT GIVES L/D OF > 0.3
  - FOR MARS APPLICATION
- o DIRECTLY EVOLVABLE TO MARS

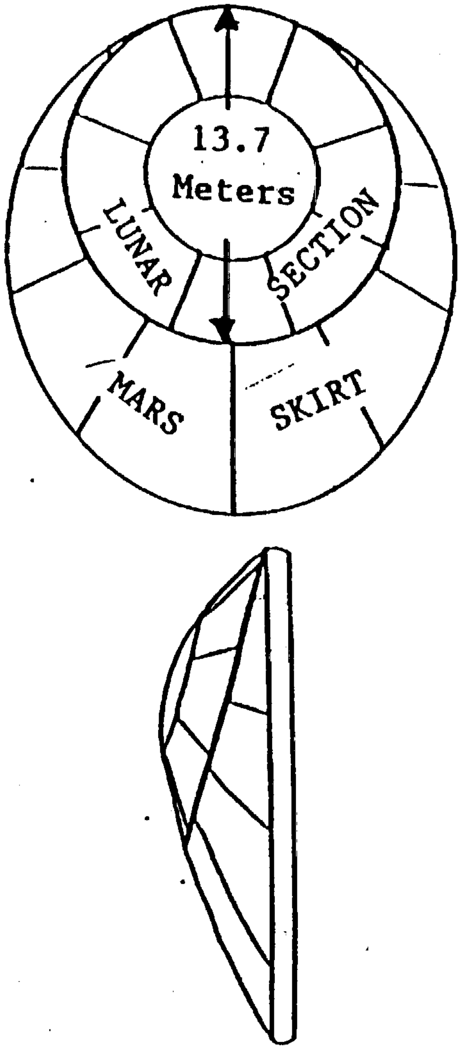


Figure 4.7-One of the three aerobrake configurations selected for this study. The axisymmetric aerobrake captures the evolvability, previous flight history, and commonality attributes.

AFE-SHAPE LUNAR AEROBRAKE

- ASYMMETRIC WITH SKIRT
- SCALES FROM AFE TO 13.7M
- REQUIRES SCALING FOR MARS
- BUILDS ON AFE EXPERIENCE (MAN-RATING IMPACT)

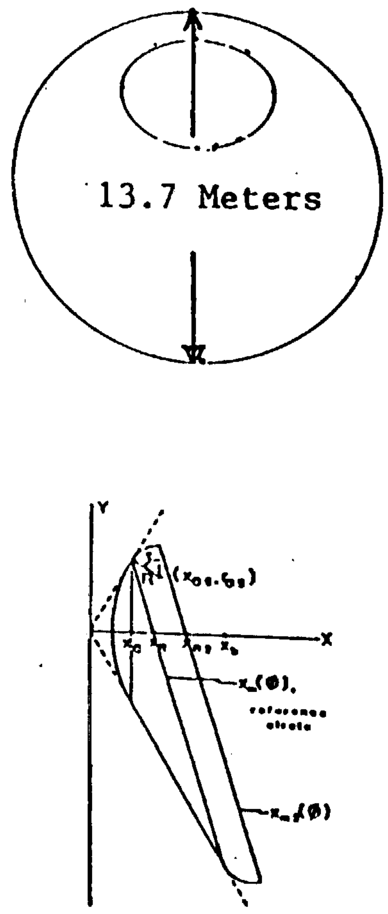
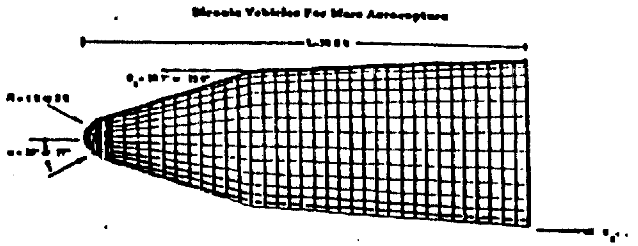


Figure 4.8-The AFE-shape, one of the three aerobrake configureations selected for this study. Flight experience will be gained by this shape, leading to its inclusion here.

HIGH L/D BI-CONIC



- WIDE ENTRY CORRIDOR
- POTENTIAL PLANE CHANGES LUNAR/MARS
- MINIMUM WAKE IMPINGEMENT
- LARGE HLLV COMPATIBLE
- LARGER RANGE OF L/D'S WITH α

Figure 4.9-The high L/D-biconic shape, one of the shapes selected for this study. Experience during Mars sample return missions, the capability to do plane changes, and freedom from hot wake impingement led to inclusion.

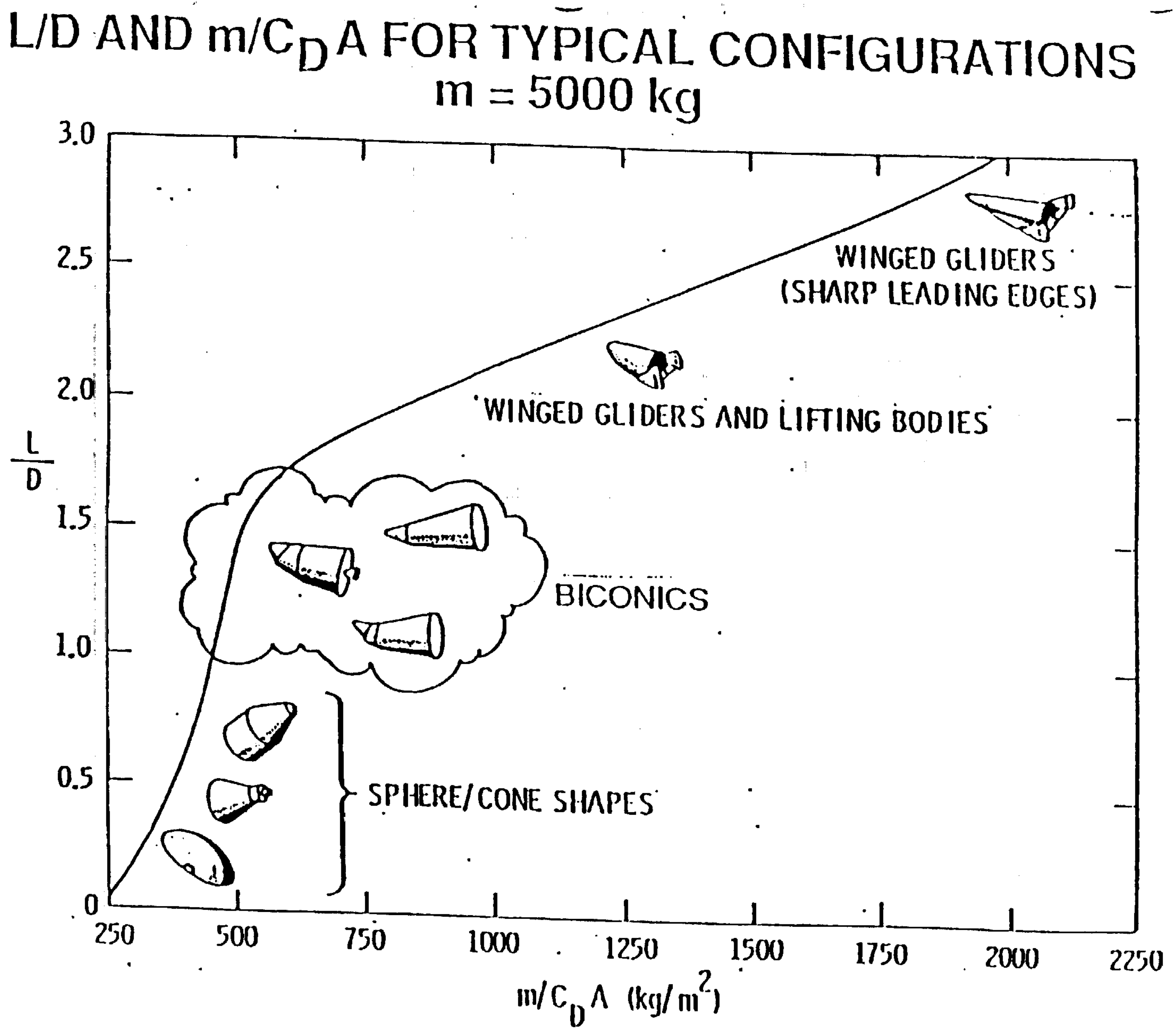


Figure 4.10-Illustration of the broad range of shapes and their affect on L/D.

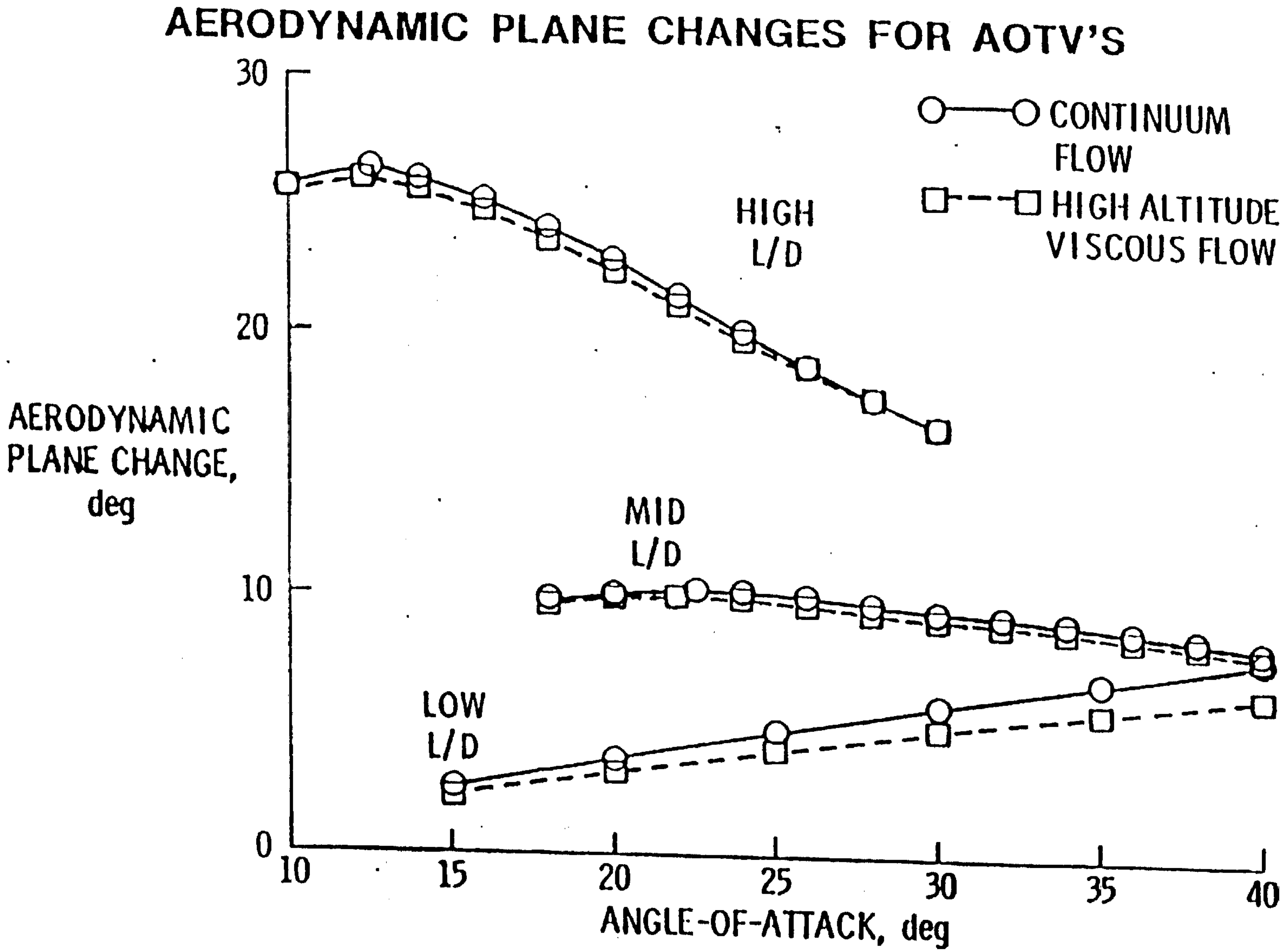
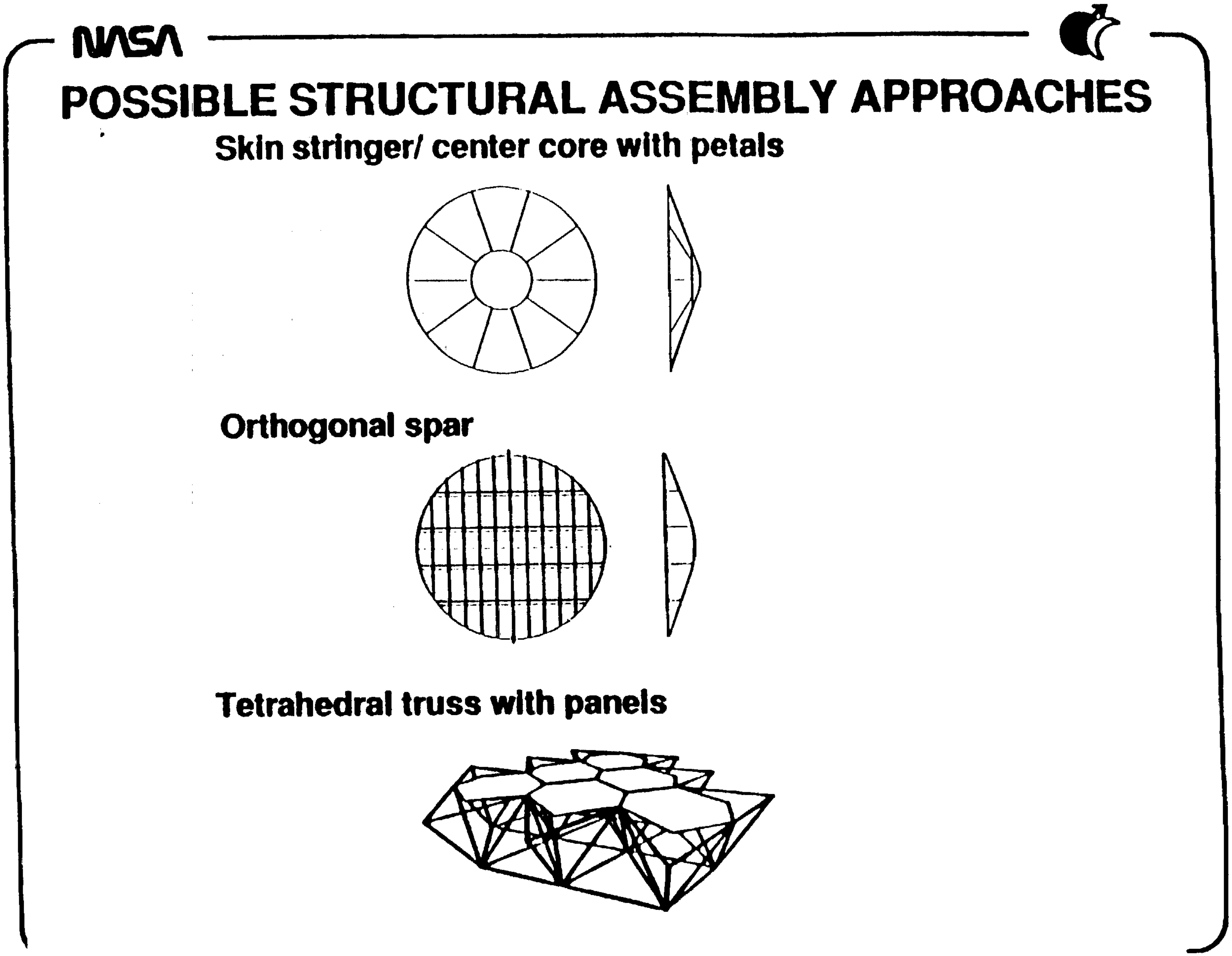


Figure 4.11-Typical results showing amount of orbital plane change possible with angle of attack and L/D.



NASA

POSSIBLE STRUCTURAL ASSEMBLY APPROACHES

Skin stringer/ center core with petals

Orthogonal spar

Tetrahedral truss with panels

Figure 4.12-The three structural assembly approaches used in this study. The top two are adaptations from some suggested in the "90-Day Study" while the bottom is one under development at Langley Reasearch Center.

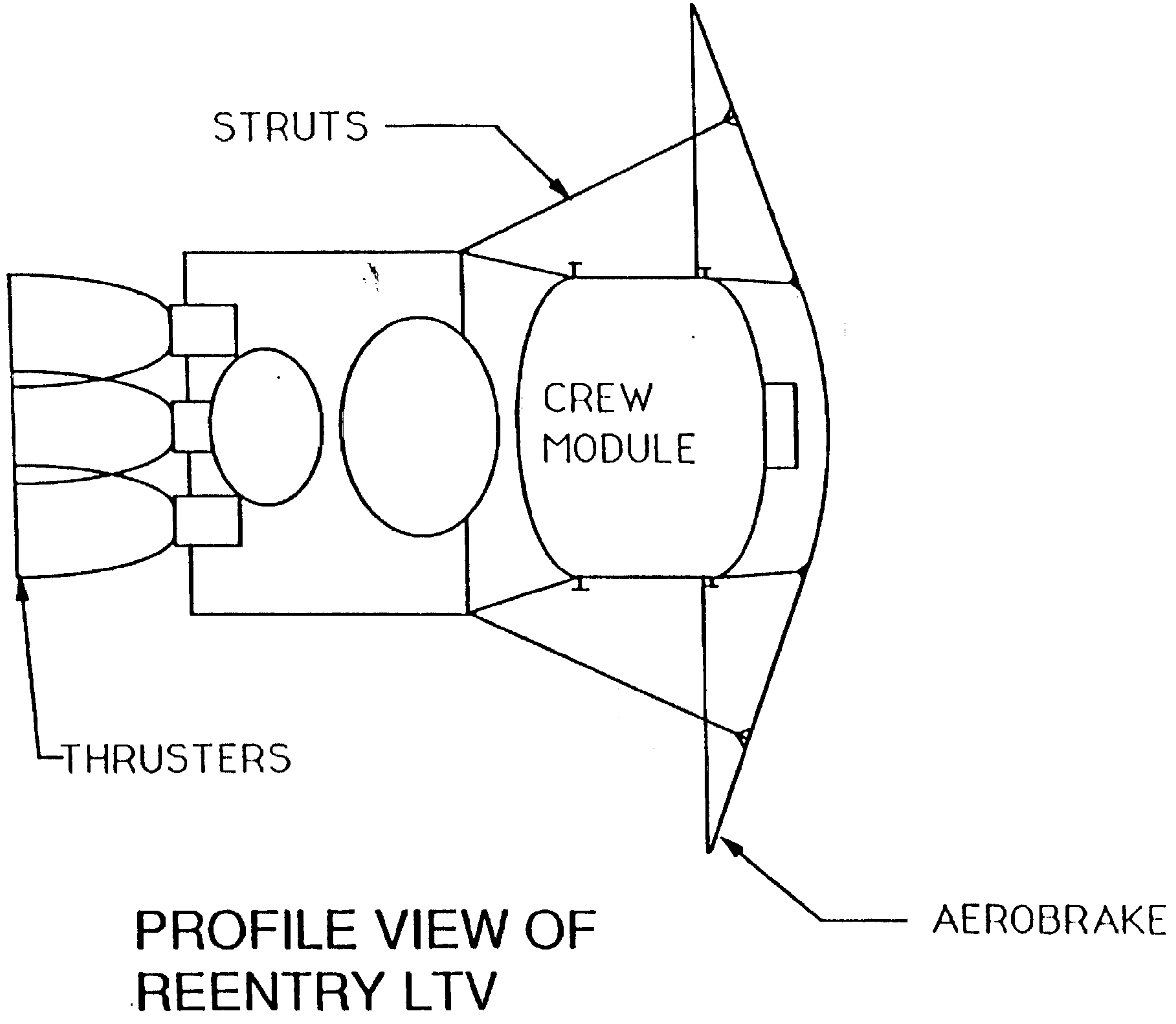
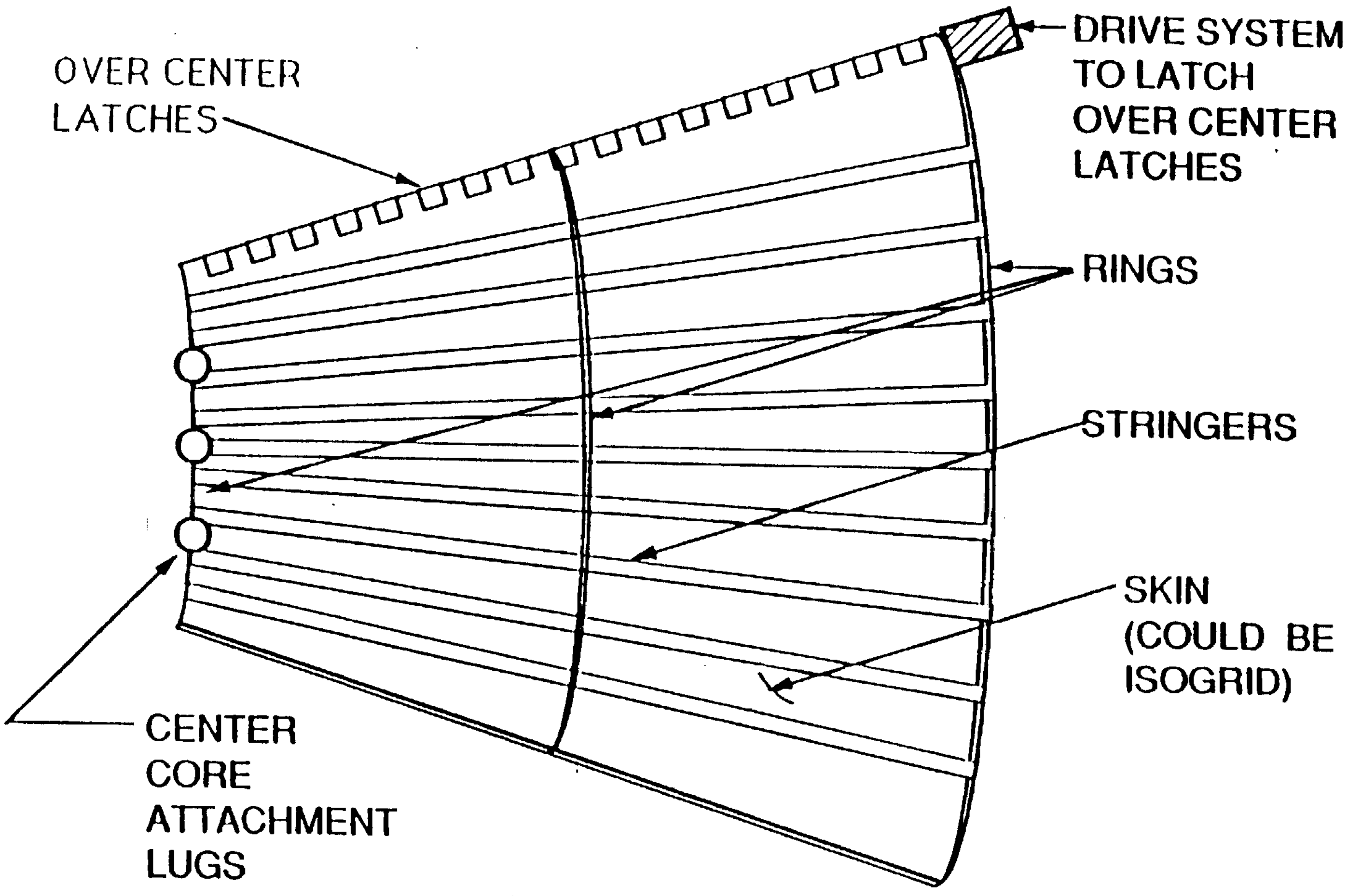


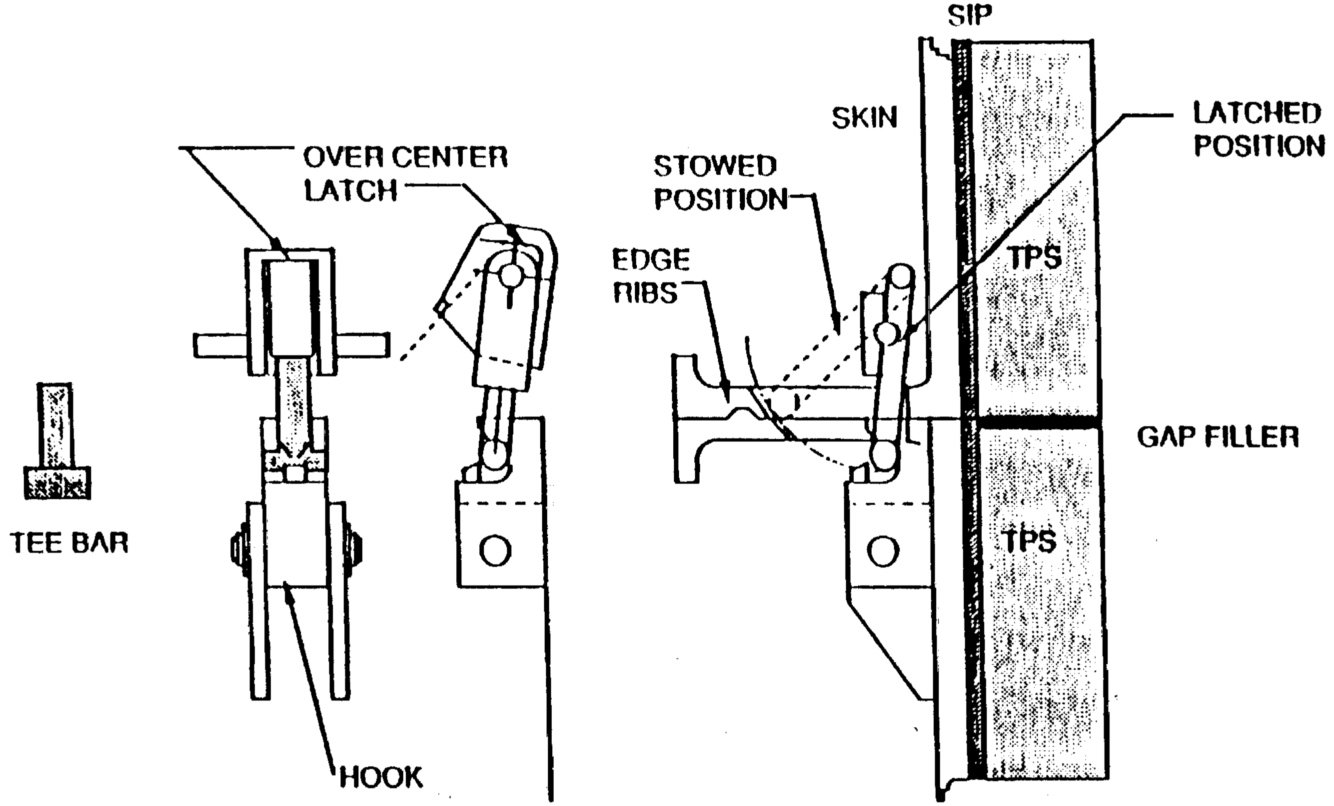
Figure 4.13-Illustration of the mating of the aerobrake to the LTV. Struts transfer outer aerobrake load while a marmon ring attaches the aerobrake to the crew module.



PETAL UNIT
FOR 10 PETAL
HEATSHIELD

LaRC SEI

Figure 4.14-One petal section showing the structural members, the center core attachment points, and the detachable over-center drive system location.



PETAL OVER CENTER LATCH

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Figure 4.15-Closeup of the petal section over-center latch.

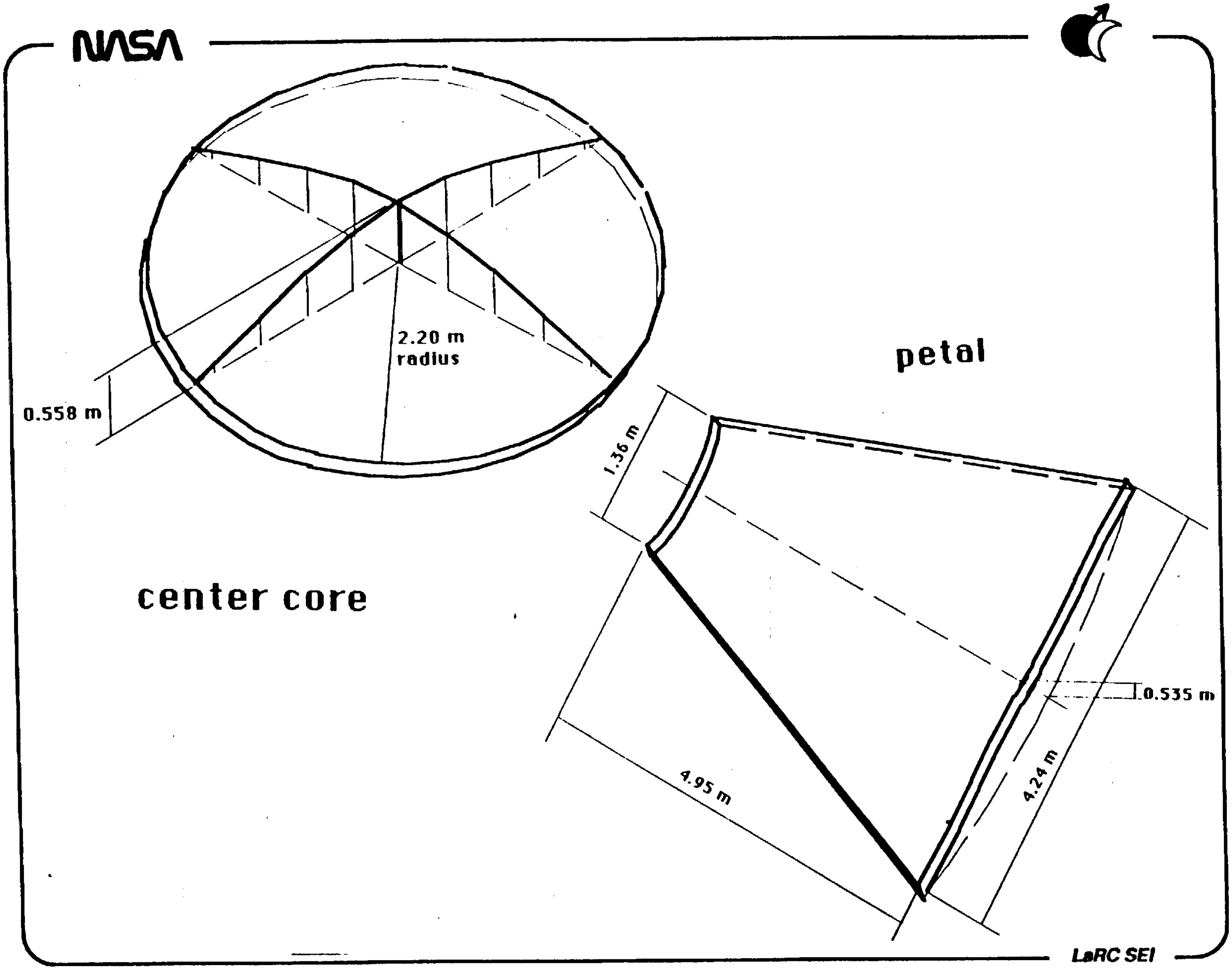

Figure 4.16-Illustration of the center core and one petal.

PACKAGING OF PETALS FOR LAUNCH AND ON-ORBIT ASSEMBLY

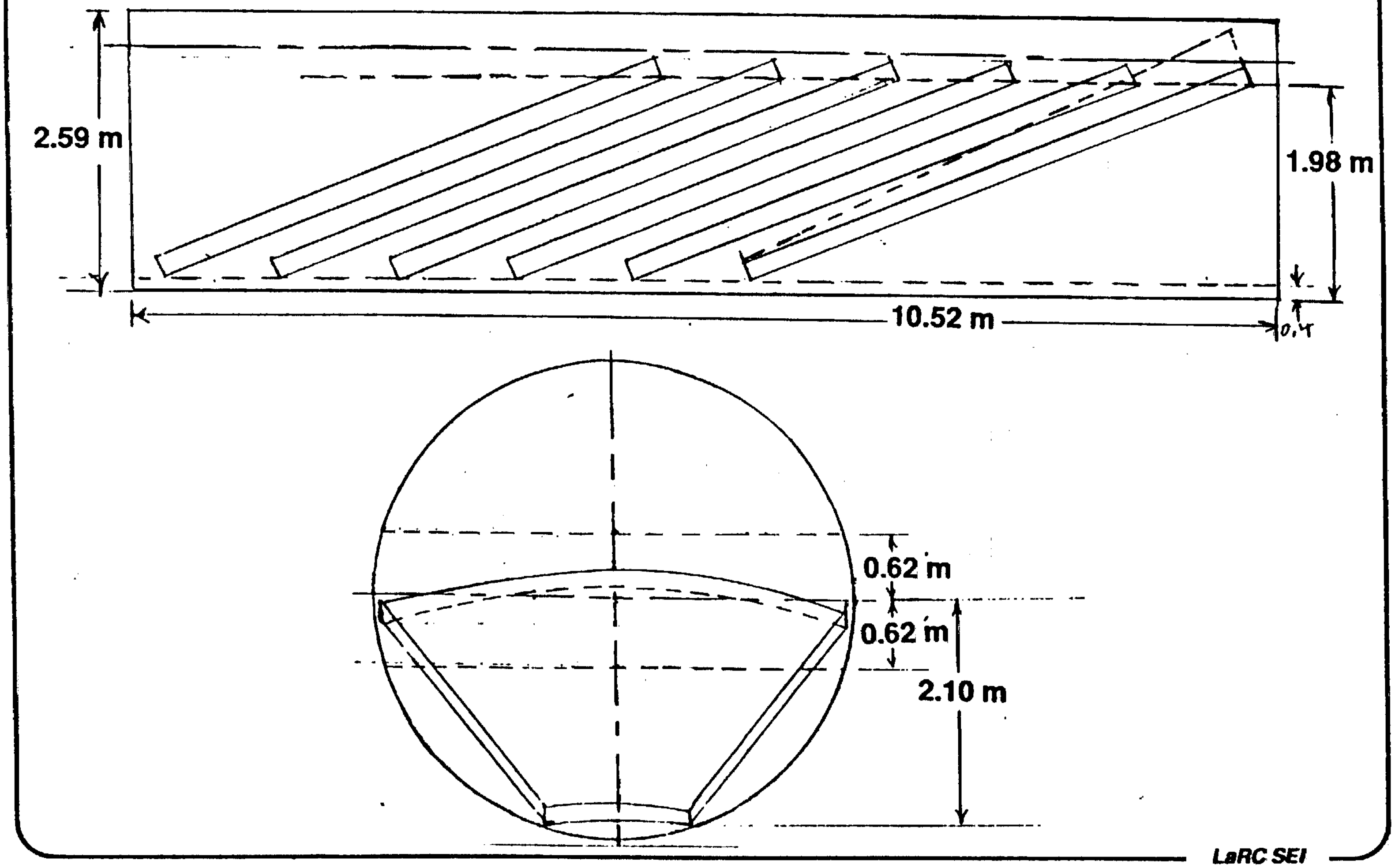

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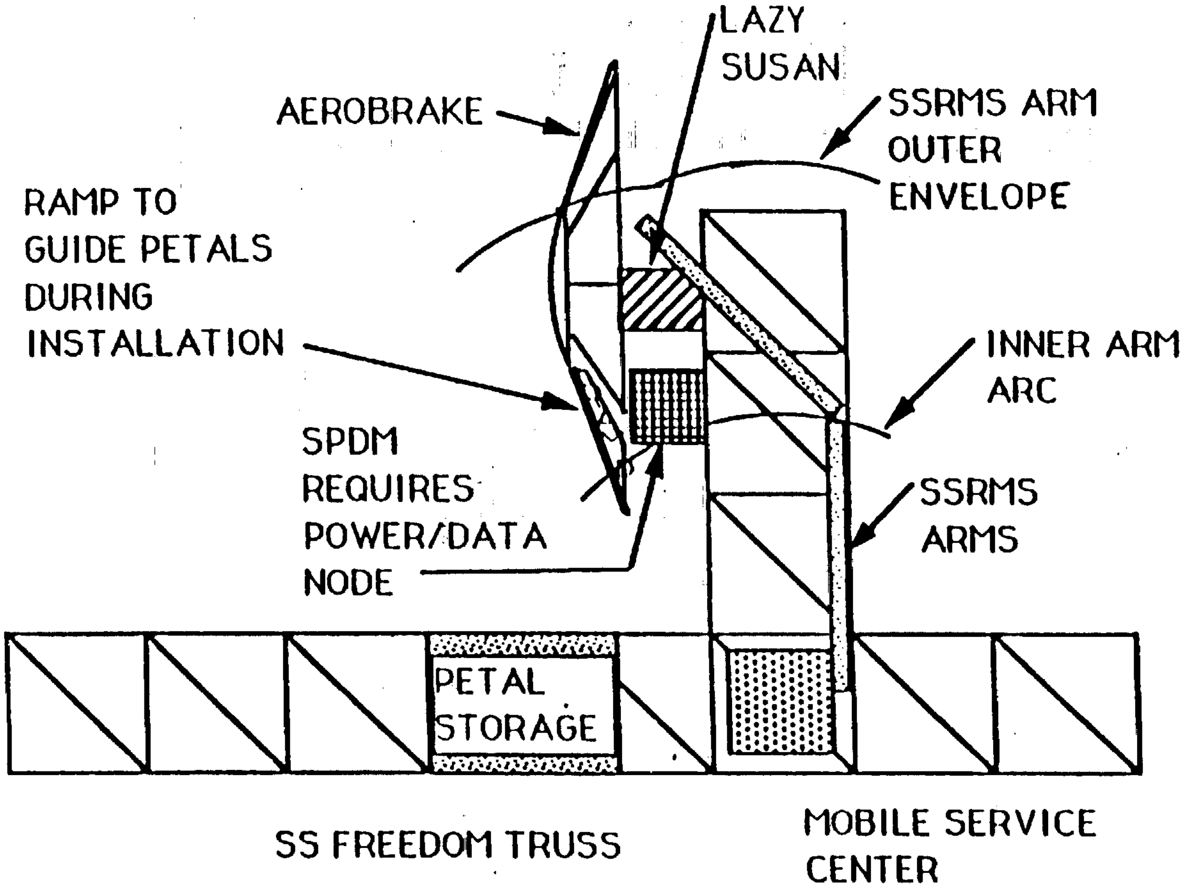
Figure 4.17-Packaging of the petals for launch within a pre-integrated canister.



SIDE VIEW OF AEROBRAKE AT ASSEMBLY AREA

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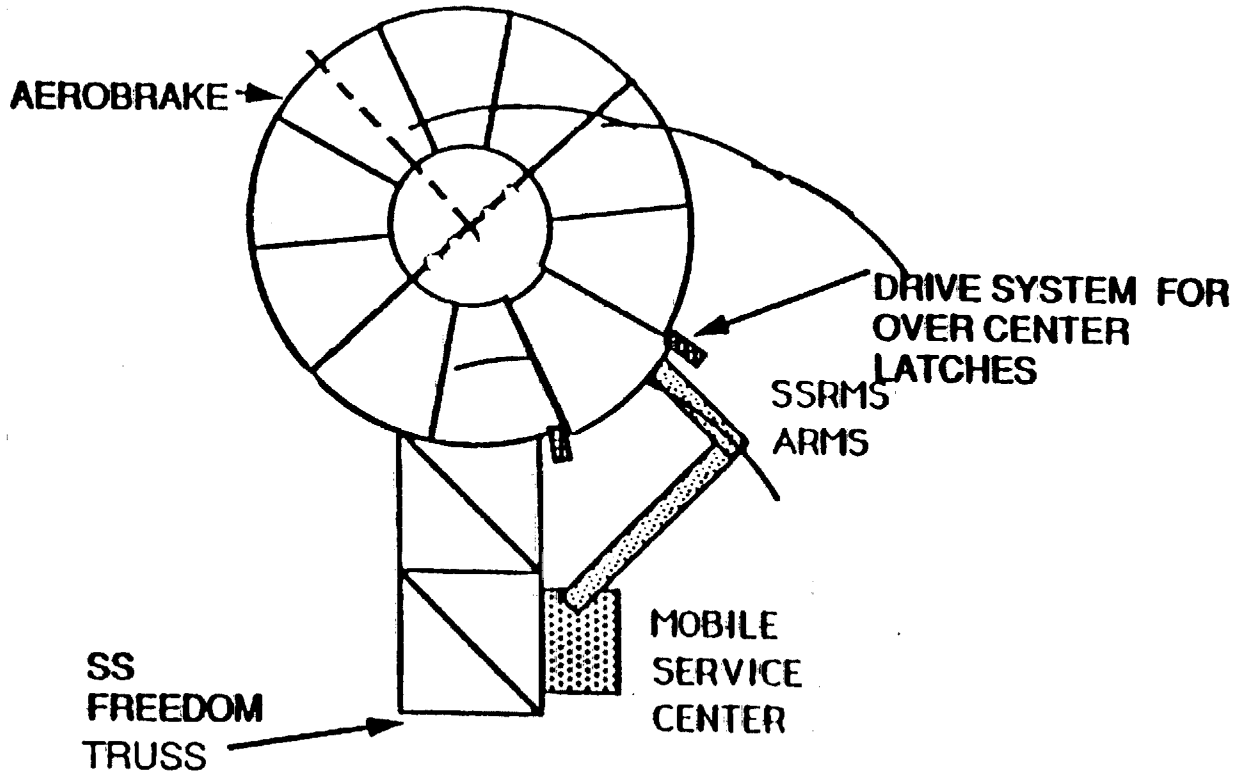
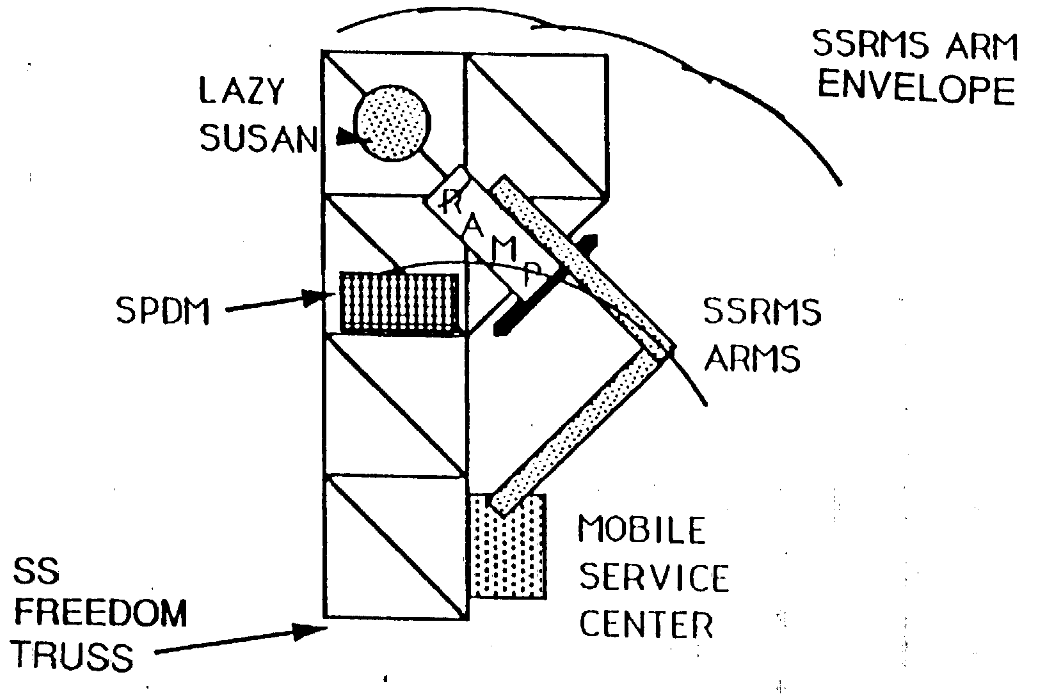
Figure 4.18-Side view of the core-petal assembly system on Space Station Freedom.



PLAN VIEW OF AEROBRAKE ASSEMBLY SITE

LaRC SEI

Figure 4.19-Plan view of the core-petal assembly system on Space Station Freedom.



PLAN VIEW OF AEROBRAKE ASSEMBLY SITE W/O AEROBRAKE

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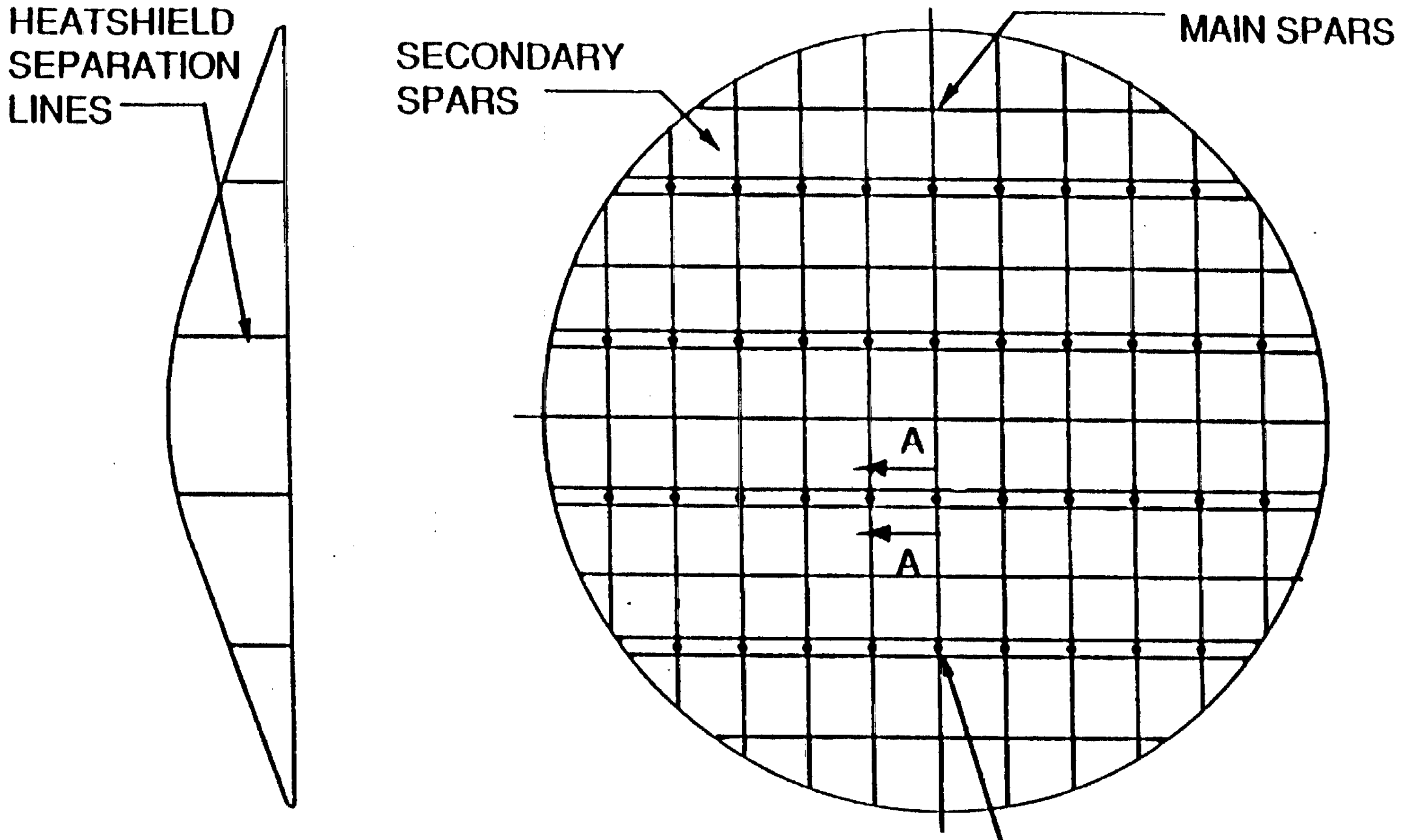
Figure 4.20-Illustration of the core-petal assembly system on Space Station Freedom.



SPHERE/ CONE CONFIGURATION WITH ORTHOGONAL SPARS

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Figure 4.21-Structural schematic of the orthogonal spar assembly concept.

orthogonal spar center section

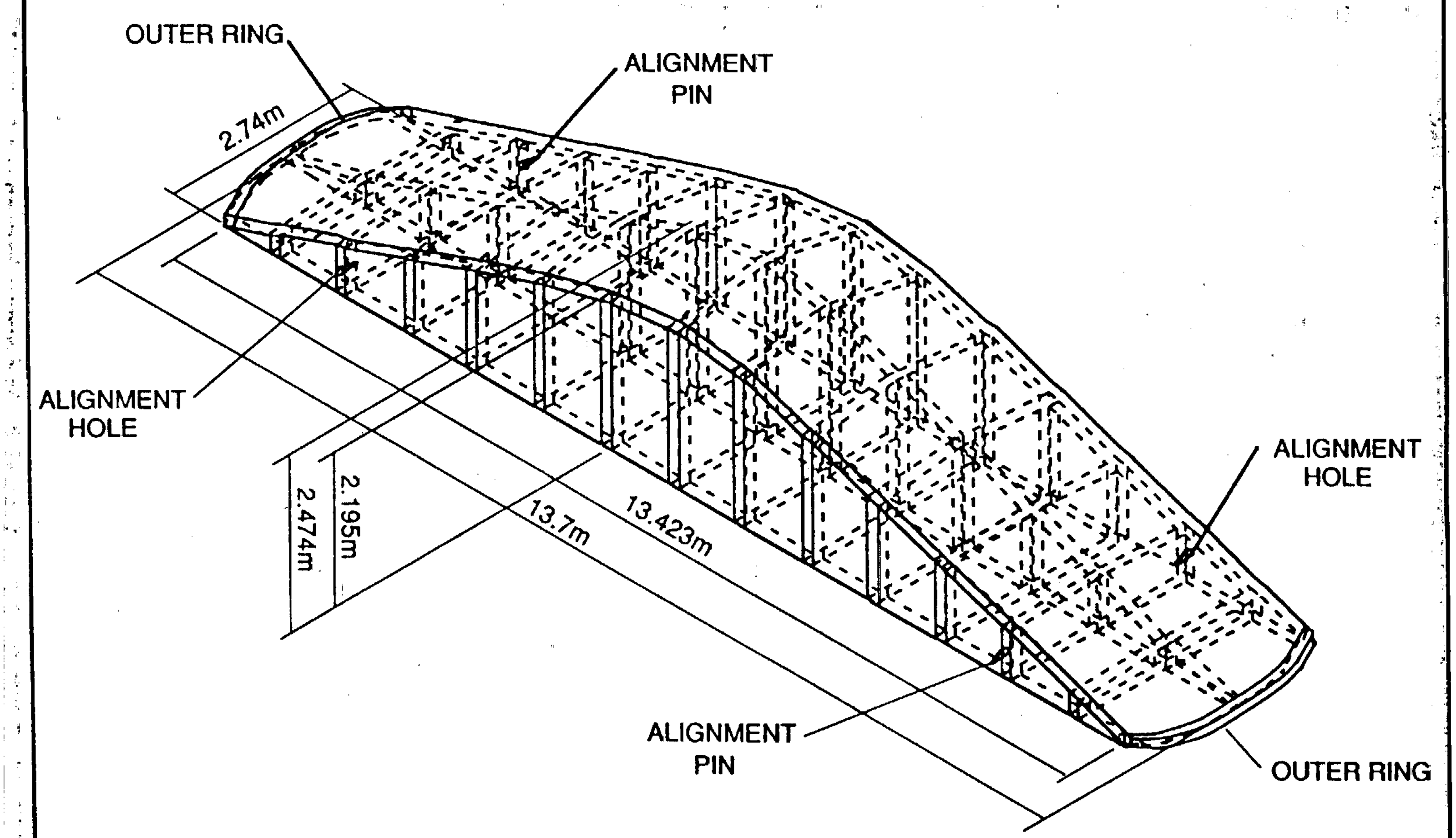

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Figure 4.22-Central section of the orthogonal spar aerobrake sturctural concept.

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orthogonal spar midsection

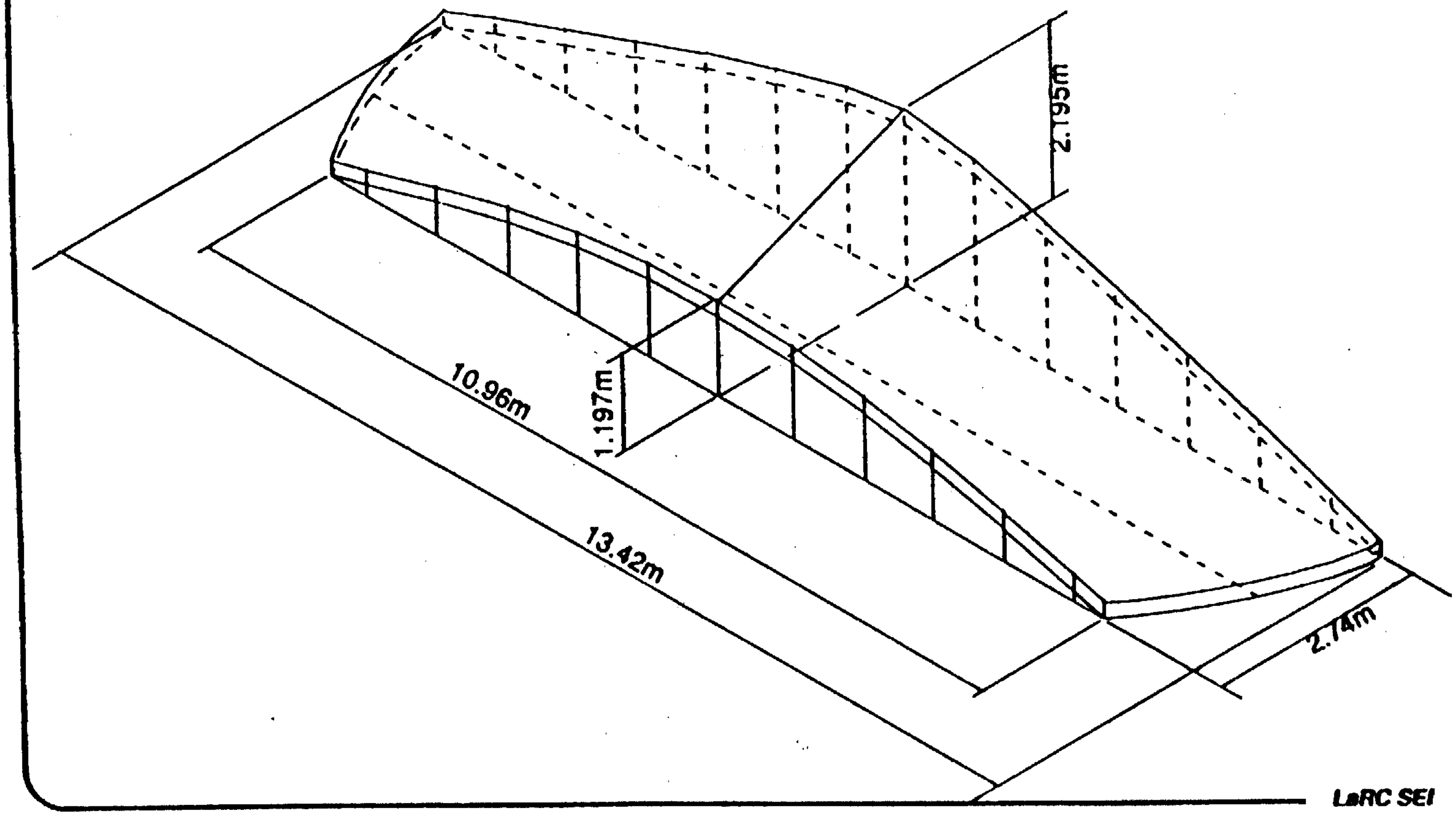

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Figure 4.23-Orthogonal spar midsection structural schematic.

orthogonal spar end section

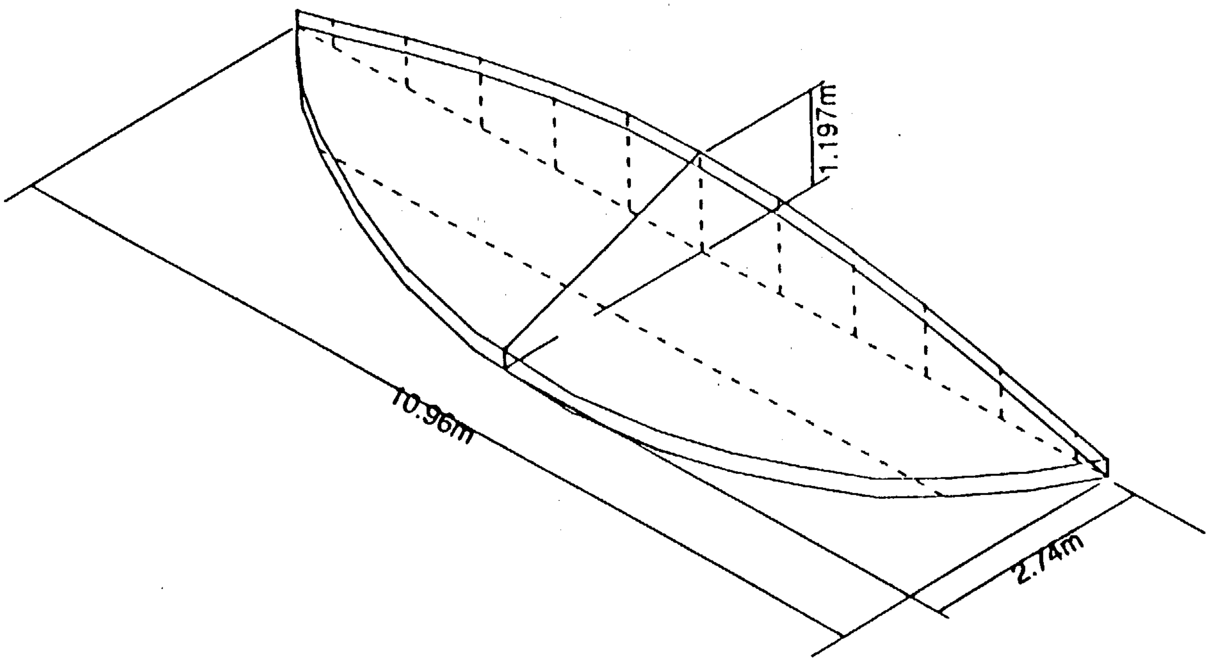
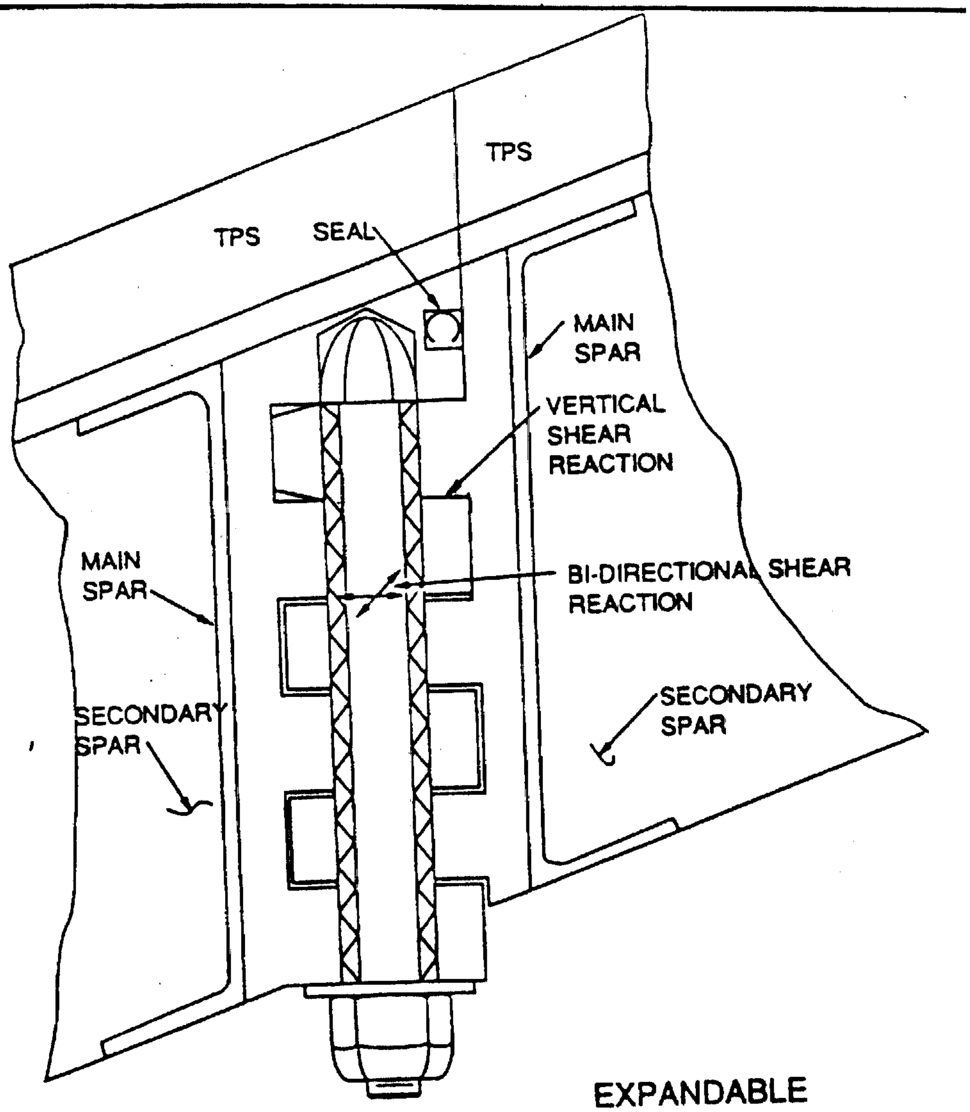


Figure 4.24-Orthogonal spar end section structural schematic.



EXPANDABLE
DIAMETER
FASTENER

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Figure 4.25-Illustration of the expandable diameter fastener inserted into a section of structure at a join.

orthogonal spar assembly

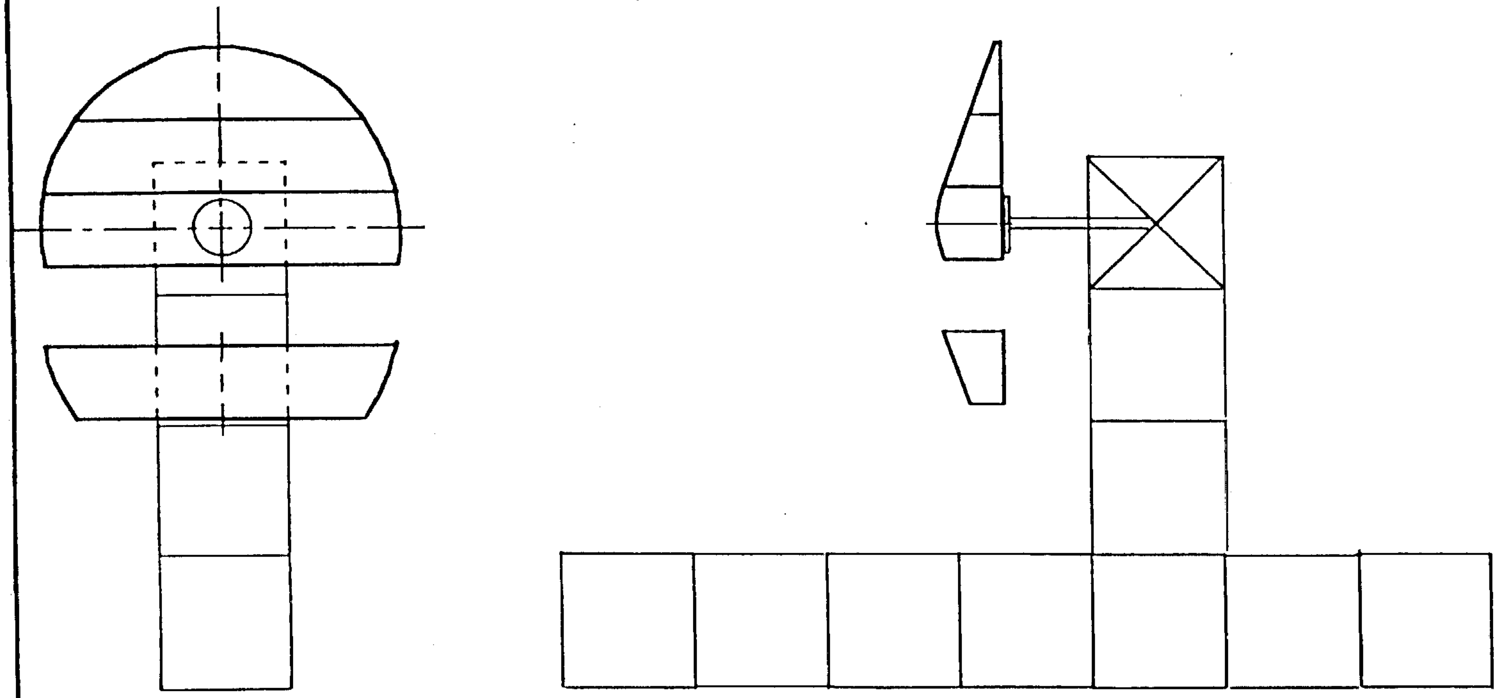

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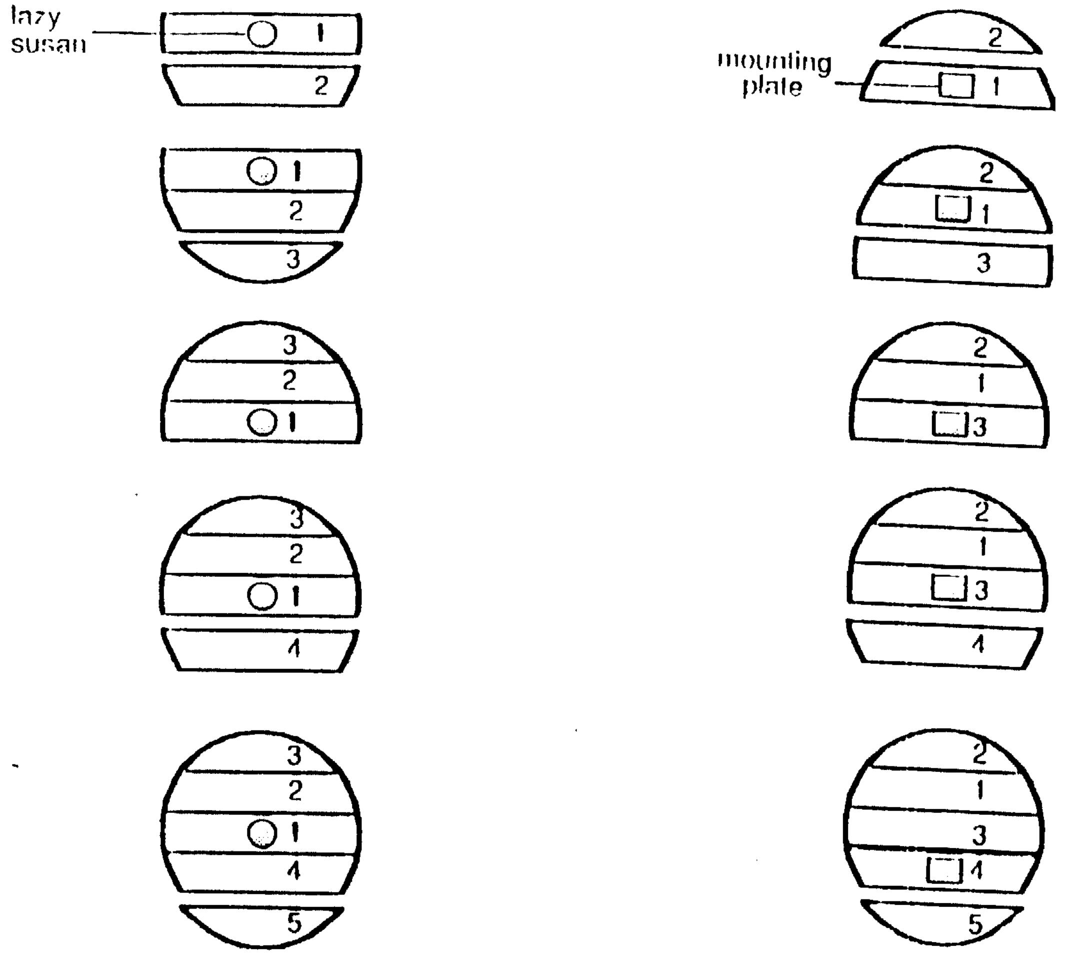
Figure 4.26-The assembly area for the orthogonal spar concept. Note that, as was the case with the core-petals, only three Space Station Freedom bays are required for clearance.



A. ASSEMBLY WITH LAZY SUSAN

B. ASSEMBLY WITH MOUNTING PLATE

ORTHOGONAL SPARS ASSEMBLY SEQUENCE

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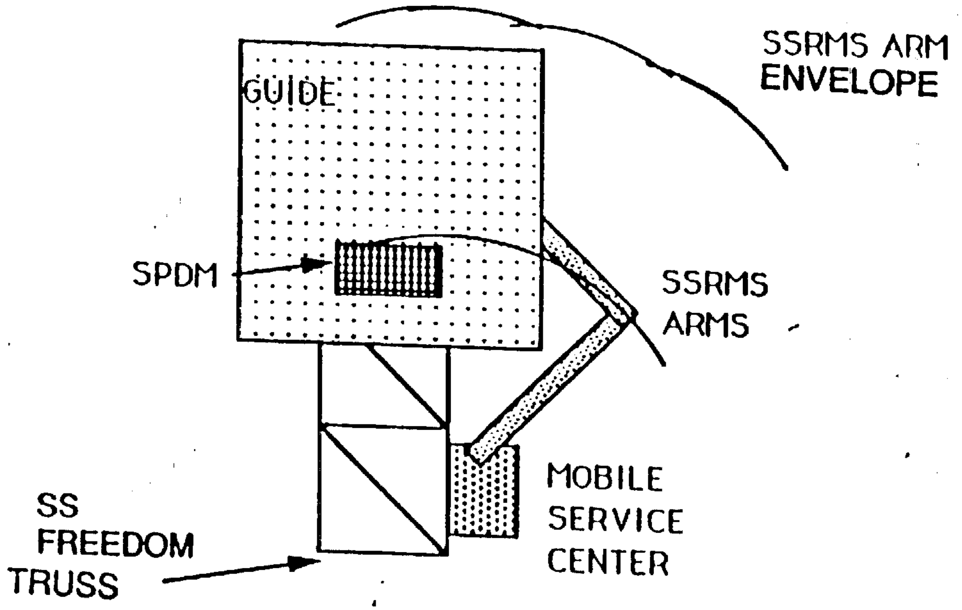
Figure 4.27-Order of assembly of the orthogonal spar sections.



PLAN VIEW OF ORTHOGONAL SPAR ASSEMBLY SITE

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Figure 4.28-Plan view of the orthogonal spar assembly area.

FACILITY FOR AUTOMATED ASSEMBLY OF LARGE TRUSS STRUCTURES

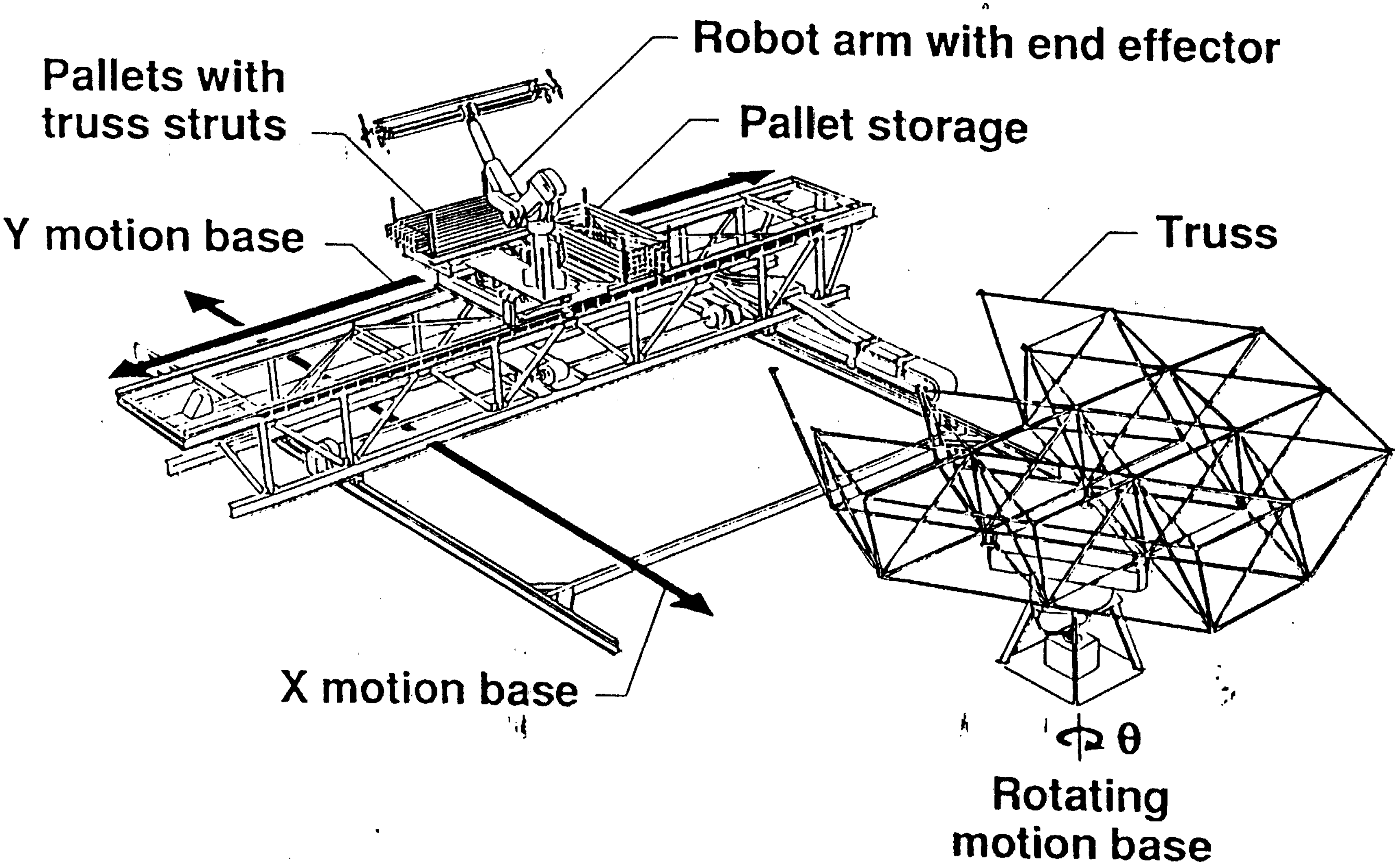

Figure 4.29-Illustration of the laboratory assembly demonstration of the tetrahedral truss with panels concept.

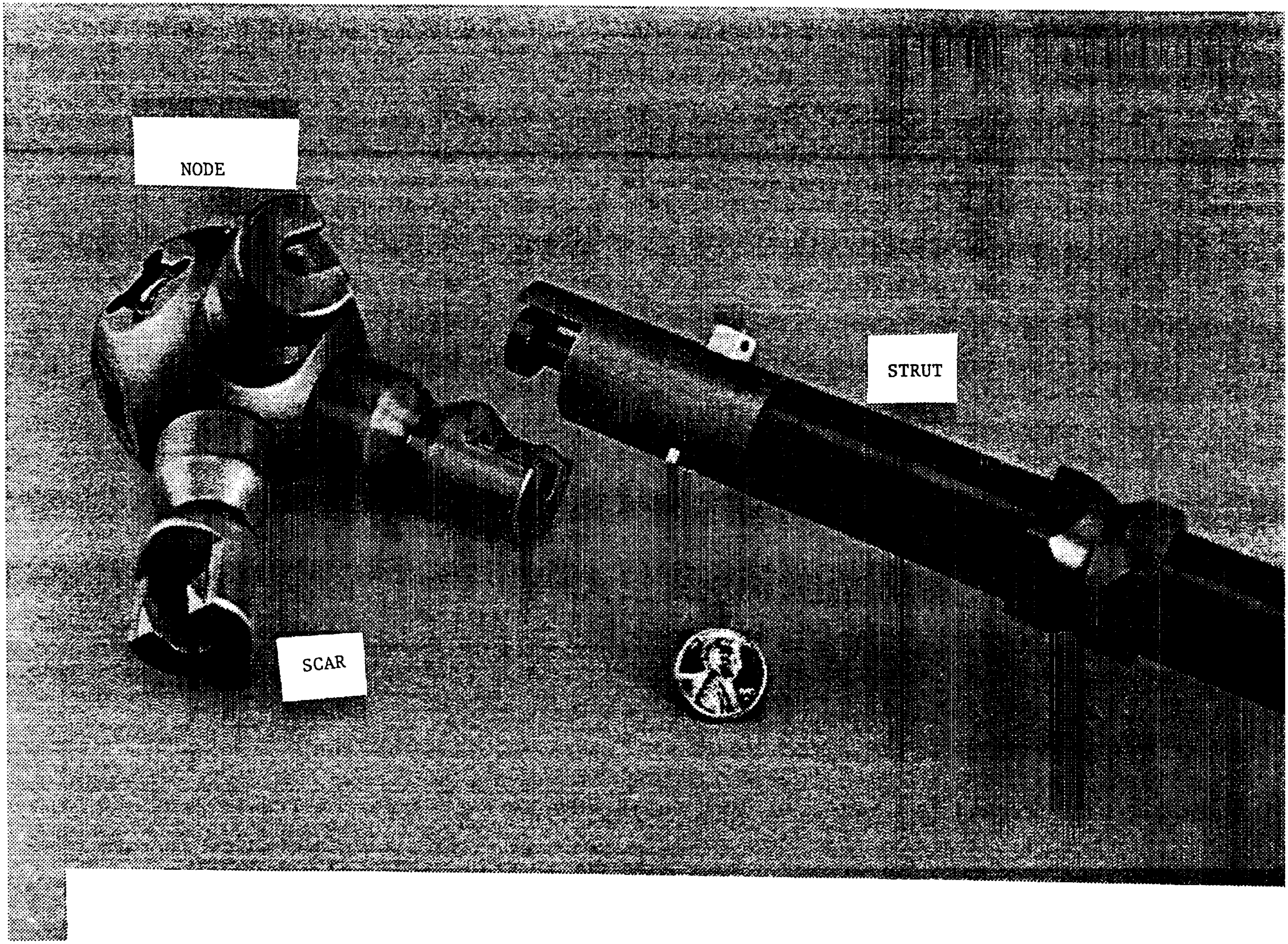

Figure 4.30-Illustration of one truss joint and connection node of the tetrahedral truss with panels concept.

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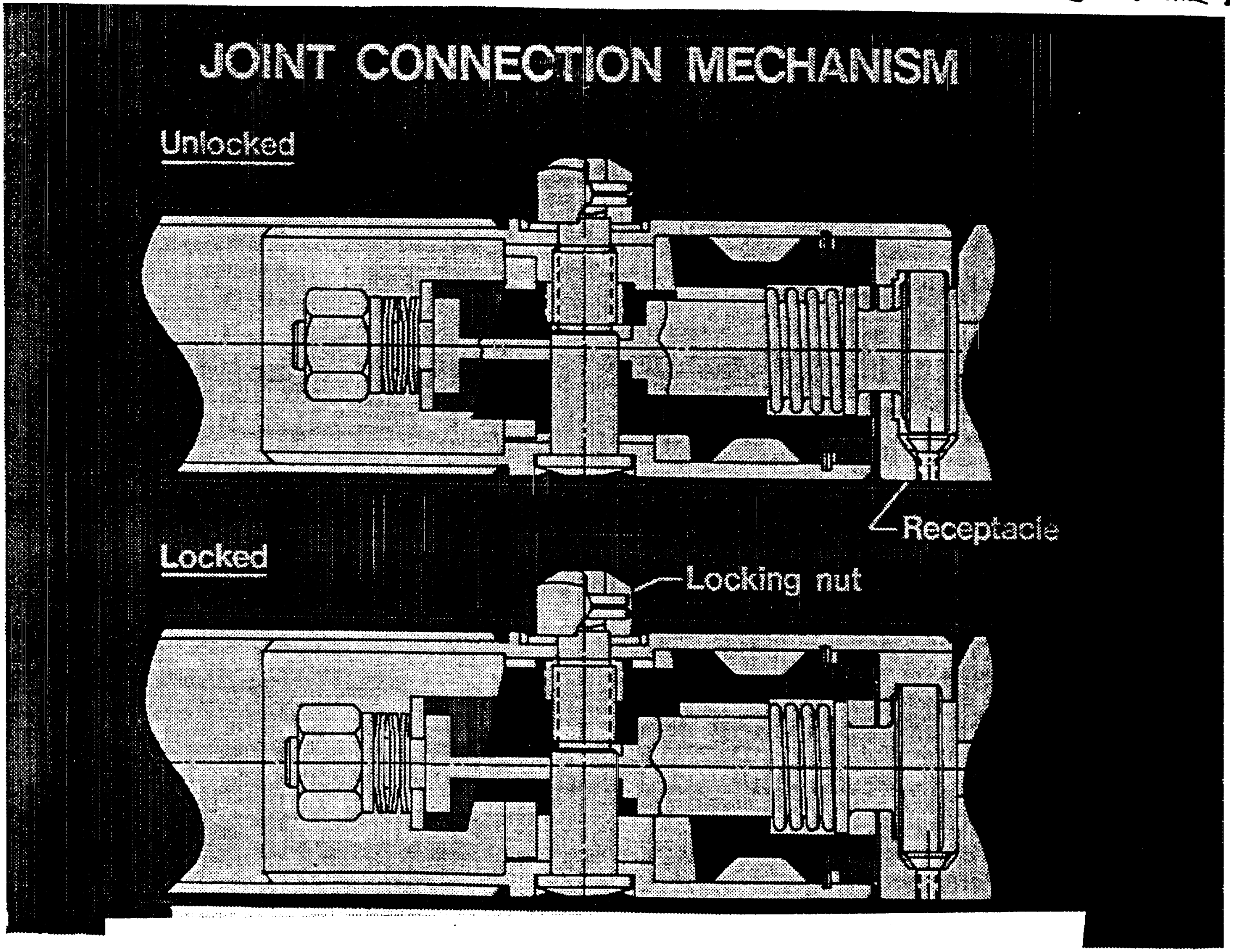


Figure 4.31-Section view of truss joint connecting mechanism.

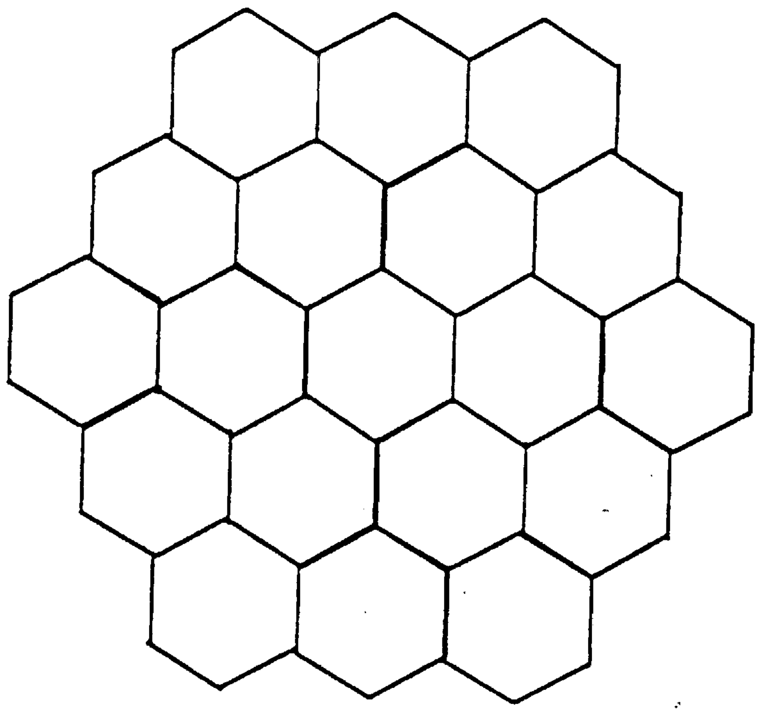
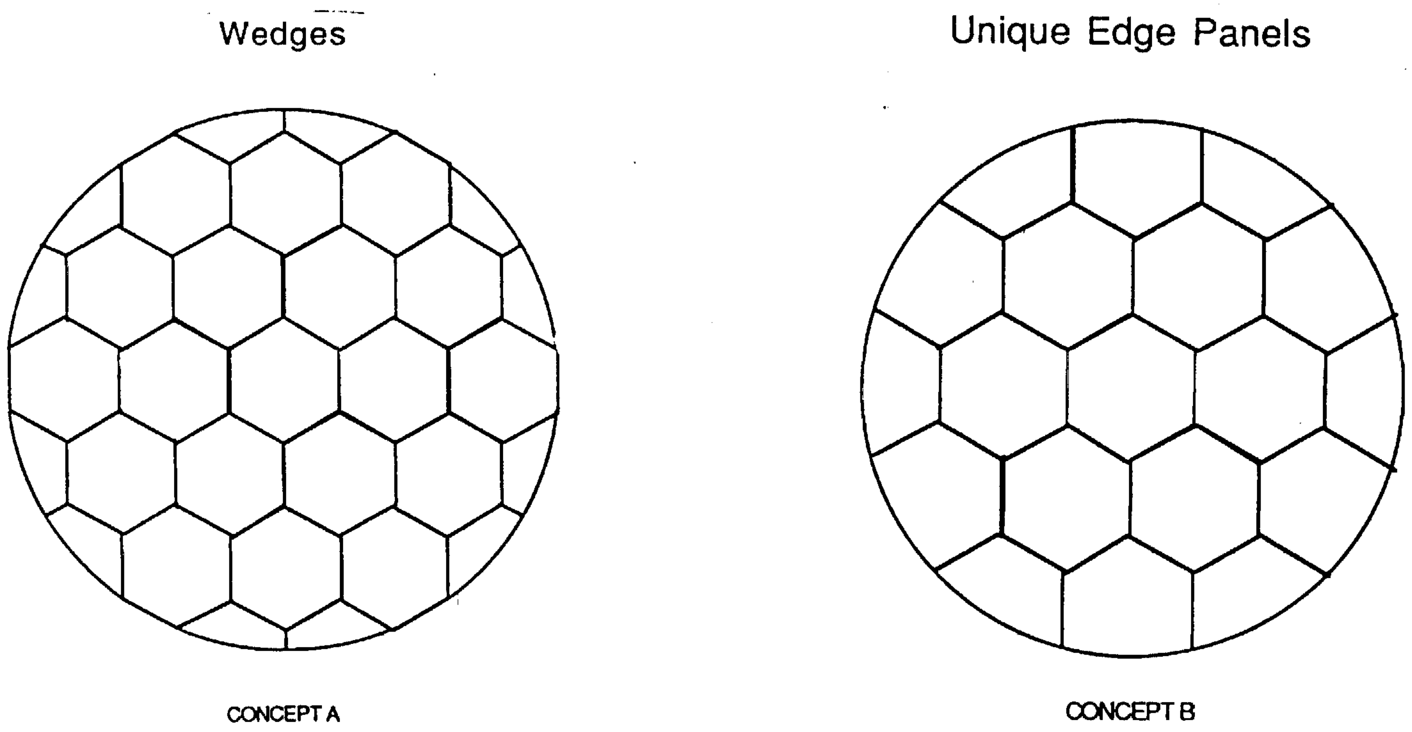


Figure 4.32-Plan view of a completed aerobrake tetrahedral truss with panels support structure.



Options For Improved Aerodynamics

Wedges

CONCEPT A

Unique Edge Panels

CONCEPT B

Figure 4.33-Options for circularizing the tetrahedral truss with panels support structure.

TPS Close Out

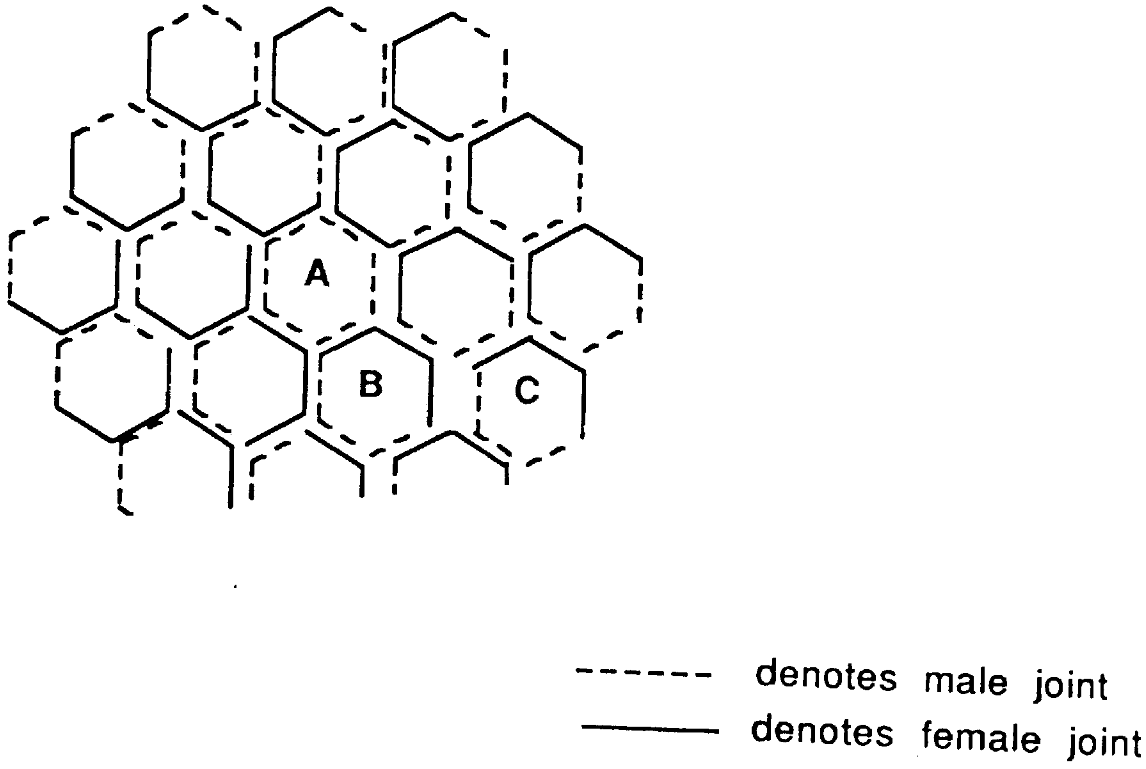


Figure 4.34-Illustration of a possible TPS close-out approach for the tetrahedral truss with panels approach.

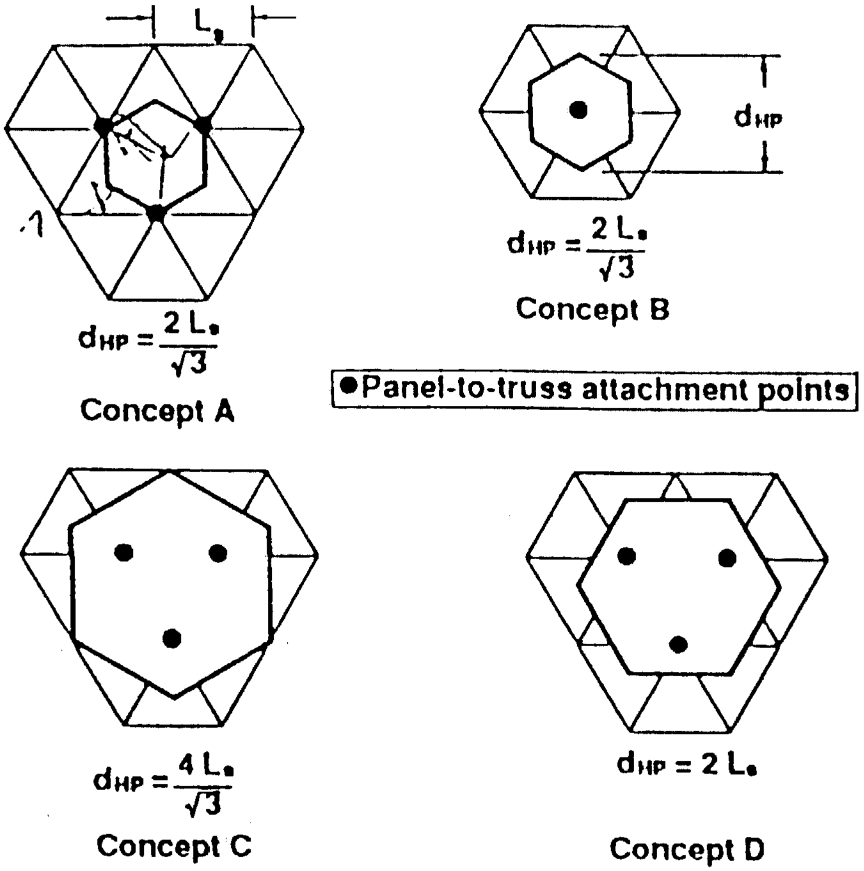


Figure 4.35-Panel attachment concepts for tetrahedral truss. (After Dorsey and Mikulas, AIAA Paper No. 90-1050, April 1990)

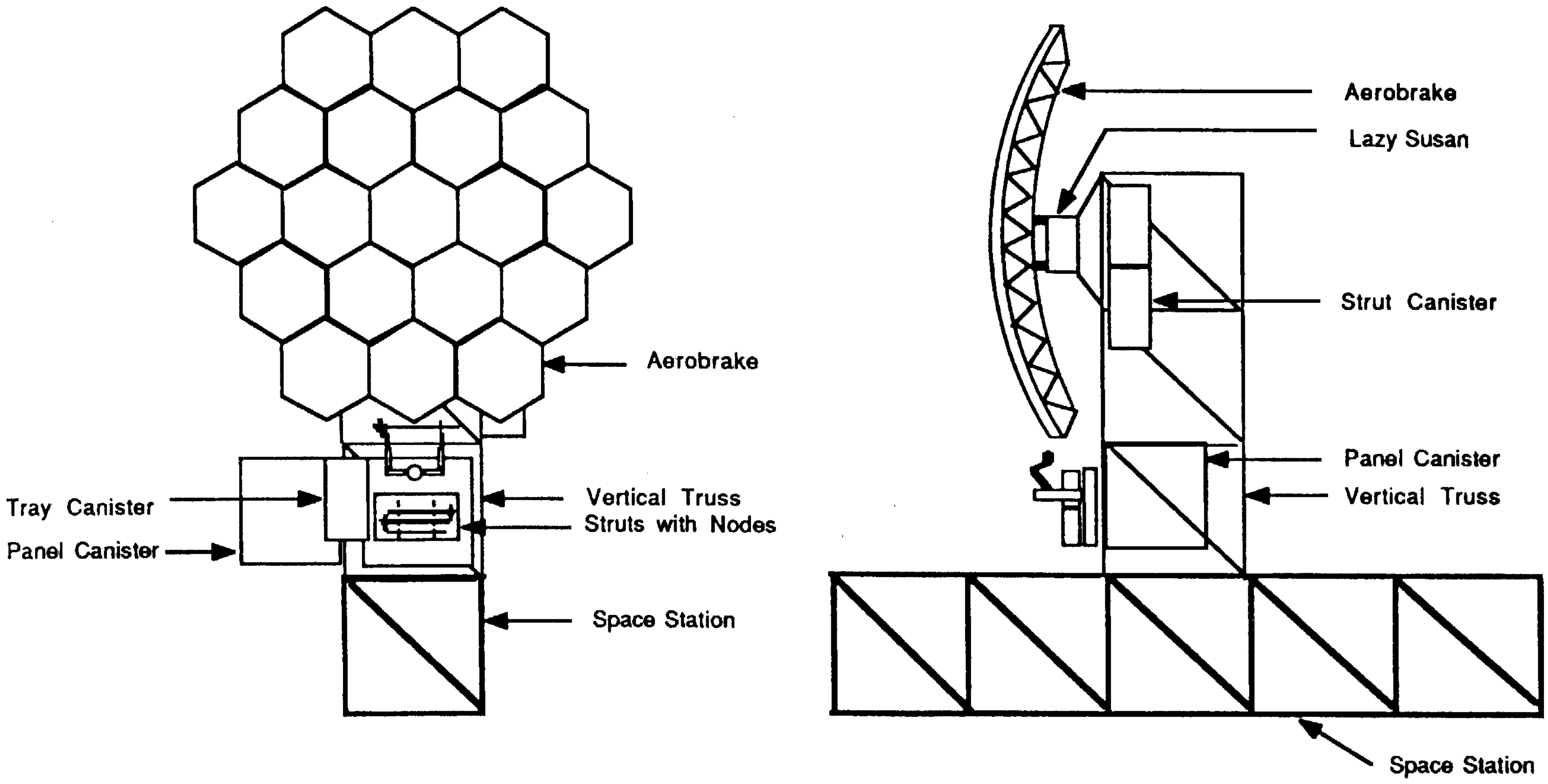


Figure 4.36-Illustration of the tetrahedral truss with panels assembly area on Space Station Freedom. Again note only three vertical bays of truss are required.

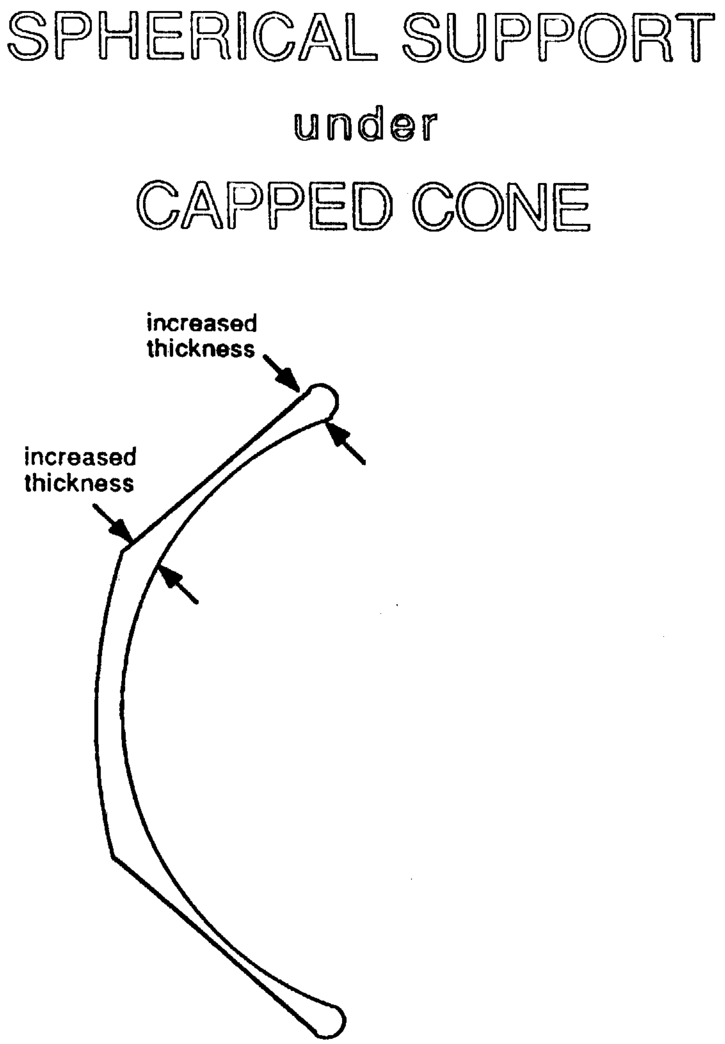


Figure 4.37-Spherical support under a capped cone.

Aerobrake Areas and Perimeters

	Sphere-Cone	Apollo	AFE-Shape
Area	$157M^2$	$173M^2$	$198M^2$

	Sphere Cone (0.5 meter x 0.5 meter tiles)		
	Solid Cone w/Petals	Orthogonal Spars	Tetrahedral Truss w/Panels
Perimeter*	806 meters	755 meters	575 meters

* Estimates based on area and structural sketches

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Figure 4.38-Areas and perimeters requiring inspection on the three selected aerobrake shapes.

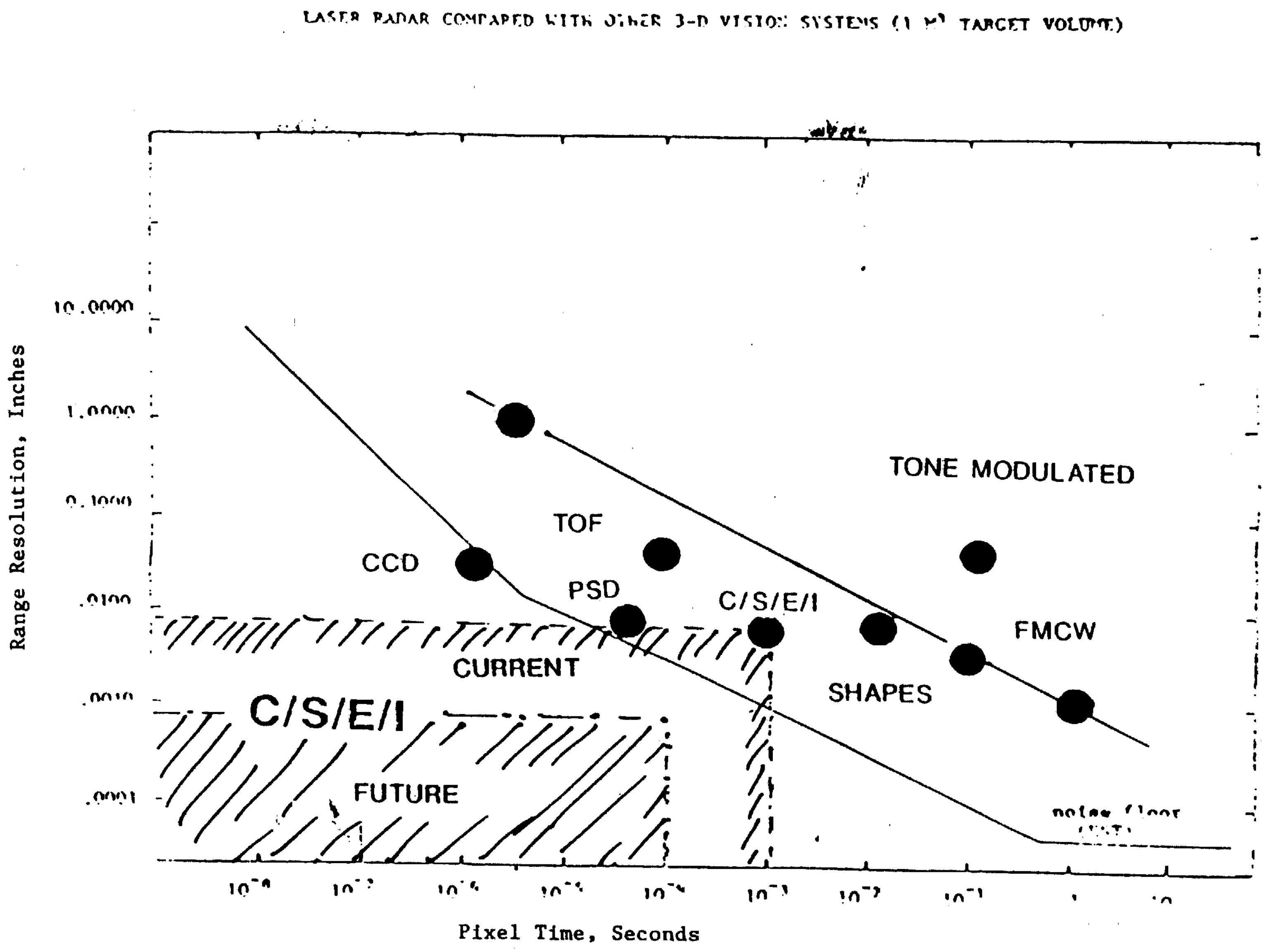

Figure 4.39-Illustration of capabilities of optical ranging systems to measure small displacements and at what rate.

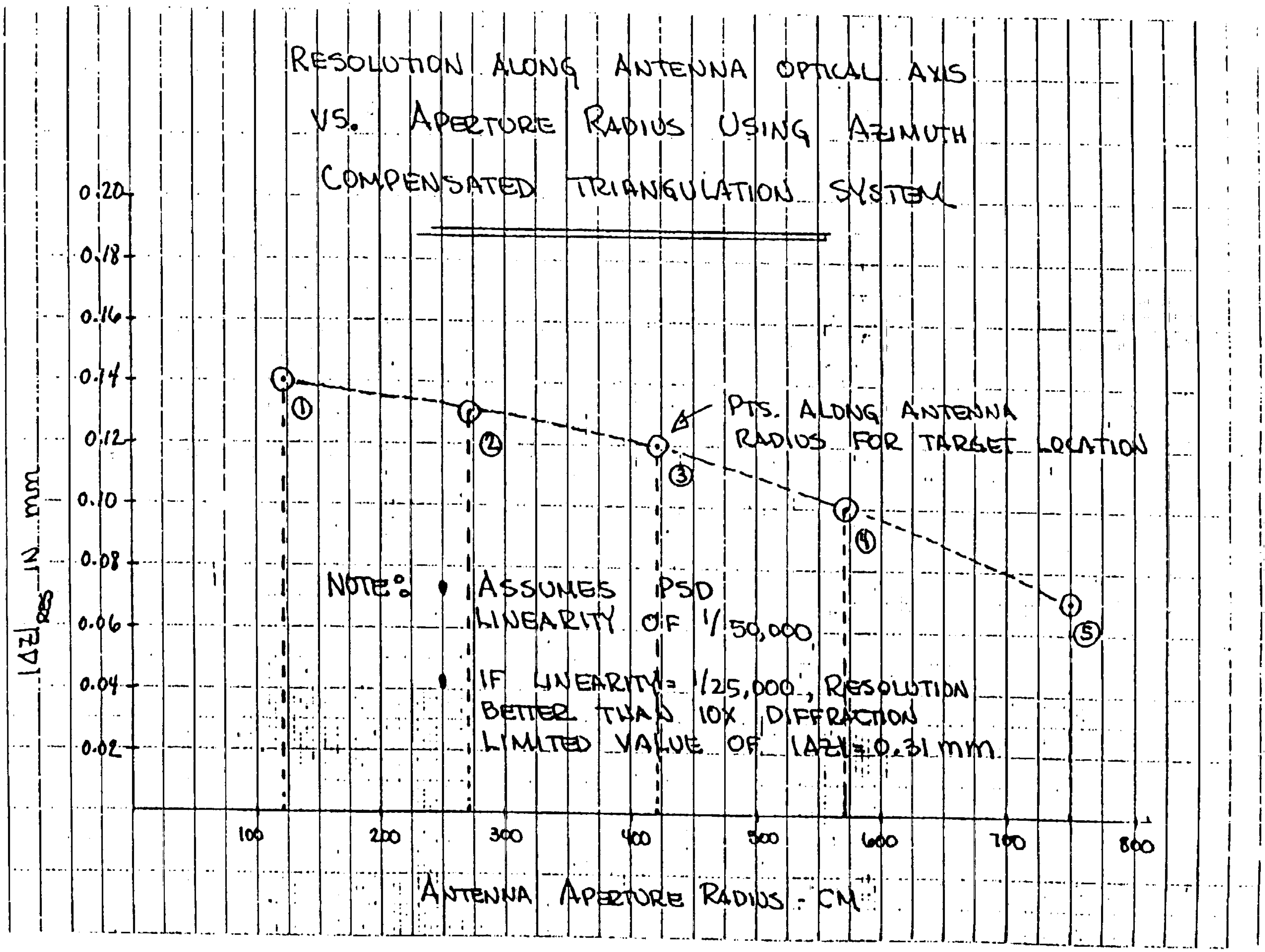

Figure 4.40-Illustration of predicted performance of a position sensitive detector applied to a large antenna application, showing the ability to detect range increments below the 0.3mm postulated for the aerobrake surface.

Probability of Debris Impact (One Year Time Interval)

$PC = 1 - \exp^{(-VR*AC*SPD*T)}$

where

PC = probability of collision
VR = relative velocity, km/s
AC = collision cross-section, km^2
SPD = spatial density, #/km^3
T = time at risk, sec

Table 2. "Simplified" PC Calculations

No.	SPD 1970	SPD 1989	PC/yr 1970	PC/yr 1989	('70-'89)
1	4.43×10^{-10}	1.28×10^{-9}	2.89×10^{-6}	8.07×10^{-6}	189%
2	2.04×10^{-9}	4.08×10^{-9}	1.29×10^{-6}	2.57×10^{-6}	99%
3	1.36×10^{-9}	4.58×10^{-9}	4.29×10^{-7}	1.44×10^{-6}	236%
4	6.81×10^{-10}	5.97×10^{-9}	4.30×10^{-7}	3.77×10^{-6}	777%

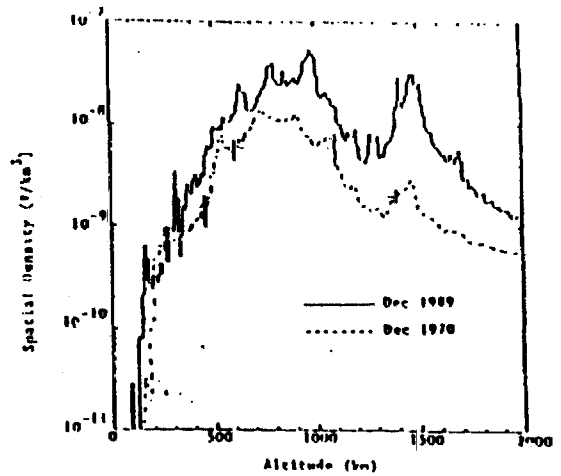

Figure 1. From 1970 to 1989 the LEO spatial density has increased by a factor of three on the average

AIAA-90-3902

Historical Growth of Quantities Affecting On-Orbit Collision Hazard

D. McKnight, USAFA/DFP, CO and
P. Anz-Meador, Lockheed/EMSCO
Houston, TX

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Figure 4.41-Information abstracted from Reference 9 on probability of debris impact on a space vehicle.

Aerobrake Assembly Characteristics

- **Weight Breakdown:**

– Aerobrake shell =	4190 kg
– "Lazy Susan" structure =	2000 kg
– Three bays of truss =	340 kg
– Three bays of utility trays =	459 kg
	6989 kg

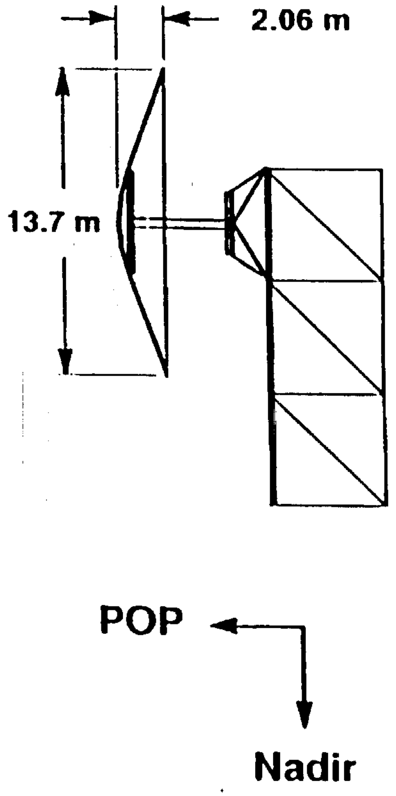

Figure 4:42-Illustration of mass estimates used by the Langley Research Center Space Station Freedom Office to assess impacts of aerobrake assembly on Space Station Freedom.

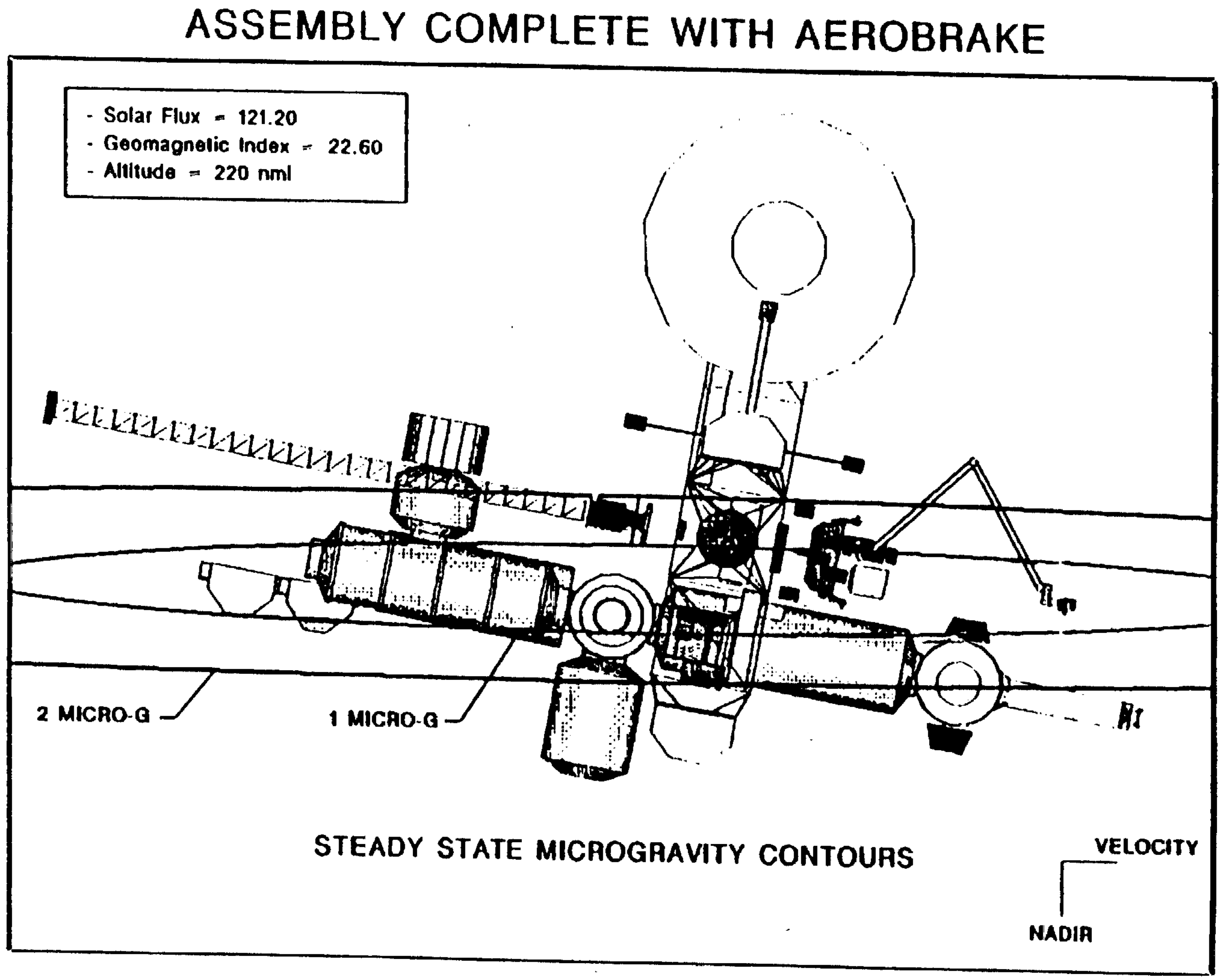

Figure 4.43-Micro-G contours on Space Station Freedom when accommodating the aerobrake assembly.

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Theresa Hurban: North Carolina State University, Raleigh, North Carolina.
Stephen J. Katzberg, David H. Butler, and William R. Doggett: Langley Research Center, Hampton, Virginia.

16. Abstract

A study has been performed to investigate the minimum Space Station Freedom accommodations required for initial assembly, repair, and refurbishment of the Lunar aerobrake. Baseline Space Station Freedom support services have been assumed, as well as reasonable earth-to-orbit possibilities. A set of three aerobrake configurations representative of the major themes in aerobraking were developed. Structural assembly concepts, along with on-orbit assembly and refurbishment scenarios were created. The scenarios were exercised to identify required Space Station Freedom accommodations. Finally, important areas for follow-on study were also identified.

17. Key Words (Suggested by Author(s))
Aerobrake, Space Station Freedom, Space Exploration Initiative, Space Operations Lunar Transfer Vehicle, Orbital Nodes

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