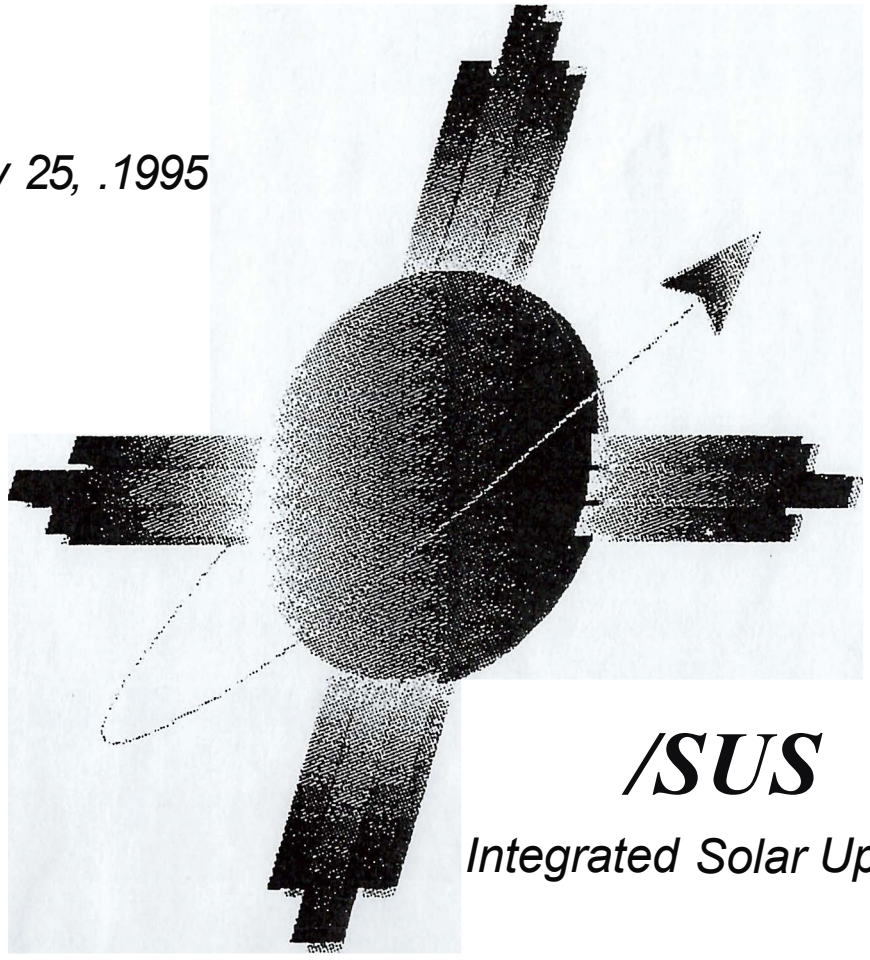
Solar Concentrator
Conceptual Design for the /SUS
Advanced Technology Demonstration

APEC Corporation
for
National Aeronautics and Space Administration
Lewis Research Center

July 25, .1995



/SUS

Integrated Solar Upper Stage

ER 1012
Final Report

Conceptual Design of a Deployable Solar Concentrator

for the
Integrated Solar Upper Stage (ISUS) Advanced Technology Demonstration (ATD)

Prepared for the:

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An Integrated Solar Upper stage would permit such realignment to smaller vehicles but would also change the current expendable stage paradigm to a reusable one. ISUS would remain with the satellite following orbit insertion and function as its electrical power and propulsion subsystems. Since a satellite's power subsytem represents as much as 30% of its total mass, using the upper stage to replace an onboard photovoltaic/battery system will purchase additional mass for sensors and communication packages. The timely demonstration of an ISUS system, before the turn of the century, will permit such devices to be fielded in the early 2000's and in time to fly aboard major satellite block changes.

1.2 PURPOSE OF PROGRAM

The ISUS ATD program was established to demonstrate the feasibility of designing and fabricating an integrated upper stage that can deliver a payload to orbit and be operated for several years. The purpose of this phase of the program, was to establish a design concept that could be developed further into a qualified spacecraft without requiring new technology development.

A team of engineers representing the Phillips Laboratory, Naval Research Laboratory, NASA-LeRC, the Idaho National Engineering Laboratory and industry experts have developed a baseline space demonstration system definition for ISUS during Phase I of the technology development program. A conceptual design of the three major ISUS subsystems RAC, CATS and CSPFS (Receiver Absorber Converter, Concentrator Array and Tracking System and Cryogenic Storage and Propellant Feed System) has been produced and will provide the basis for Phase II of the program which is component development and testing.

Solar concentrators have been functioning in ground applications for many years and the technology is well known. However, the requirements of space operation are quite different. Concentrator mass must be minimized by using a light weight construction of aluminum or composite materials. In addition, the concentrator must be fabricated in sections on the ground, stowed in the launch vehicle during launch, and then deployed to final position on orbit. The effect of the space environment on materials, especially atomic oxygen, must be considered and thermal gradients across the concentrator must be minimized to prevent excessive surface distortion.

Much of the current technology for solar concentrators in space was developed in the 1960's by the same personnel who performed the work on this project for APEC Corp. Improvements in materials and processes using aluminum or graphite composite structures have been made since then, and the basic technology is well developed and documented. The purpose of this Concentrator design effort was to produce a conceptual design for the ISUS ATD flight demonstration.

1.0 INTRODUCTION

The Air Force Phillips Laboratory (PL) has a current progam to develop concepts and quantify benefits of an Integrated Solar Upper Stage (!SUS). It is a bimodal configuration which generates both thermal thrust and electrical power, and is being considered for future space applications.

This unique concept, which utilizes concentrated solar energy as the power source, has been analyzed in a feasibility study and was proposed for further development. The bimodal engine concept is based on technologies that are at an advanced development status, and therefore an early flight demonstration is considered attainable. The Phillips Laboratory recently entered into a more detailed Phase I conceptual design of the proposed concept to evaluate technology, cost and schedule for an advanced technology ground and flight demonstration in the 1997/1998 time frame.

The NASA Lewis Research Center was selected to provide solar concentrator design support because of the technology recently developed for the:

- Space Station Freedom (SSF)
- Solar Dynamic Ground Test Demonstrator (SDGTD)
- Two meter diameter concentrator advanced technology project
- Application of micro sheet glass to aluminum or composite substrates.

This report describes the work conducted by APEC Corporation on the Integrated Solar Upper Stage Advanced Technology Demonstration (ISUS ATD) program for NASA LeRC. The work was conducted under subcontract to Analex Corporation.

1.1 BACKGROUND

Air Force Space Command has identified lack of affordability and responsiveness as the two primary deficiencies of this nations space launch architecture. Placing satellite systems on-orbit is an increasingly expensive proposition, relying on 1950s-era ICBM technologies and one-of-a-kind satellites that hamper payload and vehicle processing. A truly operational spacelift capability requires inexpensive, responsive space launch systems.

While efforts are ongoing within the national community to define requirements for evolved expendable launch vehicles (EELV) and reusable launch vehicles (RLV), little work has focused on the upper stage, a device that is required for high-orbit payloads. With a significant fraction of military and civilian satellites going to high orbits (e.g. geosynchronous), a high-performance upper stage could minimize the need for costly booster programs and help answer spacelift's key deficiencies. By permitting smaller vehicles to launch large payloads, significant reductions in launch costs can be enabled. Additionally, smaller launchers tend to have shorter processing requirements, improving responsiveness.

1.3 PROGRAM REQUIREMENTS

The mission statement of the ISUS ATD program is defined in Figure i. The objective of the Phase I design was to make the many trades between launcher, payload, bus and engine subsystems to show that an ISUS ATD can be launched with a user designated payload by 1998. As the program progressed, system requirements changed often and evolved based on information developed during the program and from potential payload users. The major requirements are as follows:

Envelope	- Titan IIG Fairing
Payload mass	- 330 kg (720 lbs)
Orbit transfer	- From LEO to Molniya in 30 days
Orbit	- Molniya 12 hour orbit 63.4° inclination
Power	- 1000 watts from the thermionic diodes to the payload
Life	- 3 years in orbit
On orbit repositioning-	90° in 72 hours

To assure program success, these requirements must be met within the established budget and schedule constraints.

1.4 SOLAR CONCENTRATOR DESCRIPTION

The ISUS solar concentrator system consists of primary and secondary concentrators. The primary focuses solar flux into the secondary which further concentrates it into the receiver, absorber, cavity (RAC) of the ISUS engine. Two concentrator arrays are located 180° apart, one on each side of the Titan IIG launch vehicle, Figure ii.

The primary concentrator consists of three panels wrapped around the liquid hydrogen (LH) tank during launch. In orbit, the panels unfold and the primary concentrator is deployed on a boom to the offset geometry. The reflective surface is pointed toward the sun and maintained in that position by a solar tracking device. A spot positioner device between the boom and primary corrects for deployed position errors.

The primary concentrator is an asymmetric portion of a paraboloidal surface determined by the offset geometry. The baseline design is of aluminum sandwich construction, although graphite composite facets are being constructed and evaluated by NASA LeRC as an alternate construction method. The panels are stiffened in areas where hinges, positioners and locks are attached or where mount points are required for launch support.

The secondary is a Winston compound parabolic concentrator (CPC) and is mounted at the RAC aperture but is thermally insulated from it. The secondary is actively cooled by heat pipes surrounding the reflective surface to maintain an acceptable operating temperature.

When the ISUS ATD program was organized, the design of the primary concentrator and the overall optical design of the concentrator system were assigned to APEC Corporation. Deployment , tracking, and secondary concentrator construction details were assigned to other organizations with peripheral participation by APEC Corporation.

2.0 STATEMENT OF WORK (SOW)

The SOW for the conceptual design of the Solar Concentrator was established to cover the anticipated tasks for the ISUS program based on knowledge available at the start. The overall role for APEC was to support the NASA LeRC and the Air Force Phillips Laboratory in generation of an ISUS concentrator concept design that could be used to demonstrate the readiness of the ISUS for a useful application. Tasks were established based on this role and knowing that the work assignments could not be defined specifically at that time. The Phillips Laboratory personnel stated that many trades were expected and flexibility in making many iterations would be required. The SOW agreed to by APEC and Analex was defined by APEC ER 1010, "Conceptual Design of a Deployable Concentrator for the Integrated Solar Upper Stage (ISUS) Advanced Technology Demonstrator (ATD)".

The task descriptions are summarized as follows:

Task 1. Prepare sketches of potential concentrator concepts and packaging/deployment schemes

Task 2. Define requirements and perform analyses of several concentrator designs.

Task 2a. Define concentrator engineering requirements.

Task 2b. Conduct trade studies to optimize concentrator conceptual design.

Task 2c. Perform ray trace analyses of primary/secondary concentrator combinations to predict performance characteristics.

Task 2d. Perform limited structural analyses on selected concentrator designs.

Task 3. Prepare a detail conceptual design for the concentrator system selected in Task 2 including development plan, cost estimates, and schedule.

Task 3a. Conduct structural, thermal, and dynamic analyses on the final selected concentrator design.

Task 3b. Evaluate candidate materials of construction for the concentrator.

Task 3c. Prepare conceptual layouts of the final selected concentrator design.

Task 3d. Identify tests and hardware required in the ATD development phase to qualify the concentrator for flight.

Task 4. Prepare bi-weekly progress reports, presentation material for program reviews, and a final report.

The initial schedule called for completion of the above tasks by June 1, 1995 but the Phillips Laboratory revised the program schedule and completion was extended into July.

3.0 SUMMARY OF RESULTS

The Concentrator conceptual design for the ISUS ATD program was accomplished per the plan prepared by the Phillips Laboratory. The initial portion of the conceptual design was directed toward establishing the requirements. This resulted in several decisions that impacted the concentrator design since space vehicle selection and payload size and power requirement underwent several iterations. The final selection of the Titan IIG space vehicle and a 1000 watt payload power requirement produced a much larger concentrator than was originally envisioned. Requirements were originally established in the Requirements Review meeting at NASA LeRC on March 2 & 3, 1995 and further defined at the Mid-Term Program Review at Phillips Lab on March 28 & 29, 1995.

Following selection of a final launch vehicle and payload power requirement, the concentrator concept configuration was selected. The concept consisted of two primary concentrators on booms, 180^0 apart focusing into two secondary concentrators located at the inlet to the RAC. The next phase of the program evolved trade studies to finalize performance estimates, deployment mechanisms, materials of construction, reflective materials, and envelope details. The results of this effort were presented at the concept Design Review held at NRL on May 16 & 17, 1995.

During the final portion of the program, the concentrator design was further refined to provide details of mounting and attachment to the launch vehicle, designing a fine pointing actuation system to adjust for tolerances in manufacture and construction, and finalizing performance estimates. In addition, the concentrator section of the final report was written and a cost estimate for ground testing of the concentrator prepared. The results of this work were presented in a Final Program Review at Phillips Lab on June 21 and 22, 1995.

The technical details of the concentrator program are presented in Appendix A and consist of the written work presented to Phillips Lab for inclusion as Section 5.2, Concentrator System, in the Air Force final report.

The cost estimates for the ground test demonstration are presented in Appendix B and consist of the estimates supplied to Phillips Laboratory for inclusion in the Air Force final report.

In summary, the ISUS ATD concentrator conceptual design was completed by APEC Corp. for Analex and NASA LeRC as required. All technical requirements were met and the concentrator conceptual design was conducted on schedule and within budget.

4.0 CONCLUSIONS

The ISUS ATD concentrator concept design has been completed. It is concluded that present solar concentrator technology can result in the design and fabrication of a concentrator that can be launched to operate on orbit and meet requirements. There are some issues and concerns related to design and fabrication that should be attended to in order to constrain costs and meet schedule milestones to launch. They are identified and discussed in appendix A so that the solar concentrator contractor is made aware.

ISUS ATD
Mission Statement

While satellite assets continue to demonstrate the value or space *to* both military and civilian users, placing payloads on orbit is an increasingly expensive and inf1exible proposition. Boosters require months or years or preparation, at costs or hundreds or millions of dollars per launch. The high cost and complexity or these systems prevents all but the largest national programs from developing space systems to meet their requirements.

The Integrated Solar Upper Stage ATD is intended to improve the affordability and responsiveness or the US spacelin fleeL High-performance propulsion, coupled with electrical power production in a single integrated stage, provides drastic weight reductions that permit (1) large payloads to be moved to smaller, more operable boosters; and (2) operational payloads to be launched from very small boosters, without a substantial increase in the transfer time to final orbiL

P IMARY OBJECTIVE

Demonstrate the feasibility and operational utility of a solar bimodal system for military and civilian space applications

SECONDARY OBJECTIVES

- **Provide tactical users with access to space via a combination of small launch vehicle and low cost payload**
- **Shift the paradigm from expendable boosters and stages to integrated systems and standardized bus architectures**
- **Permit large space assets to be launched from smaller, cheaper, more operable booster systems**

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Figure i ISUS ATD Mission Statement and Objectives

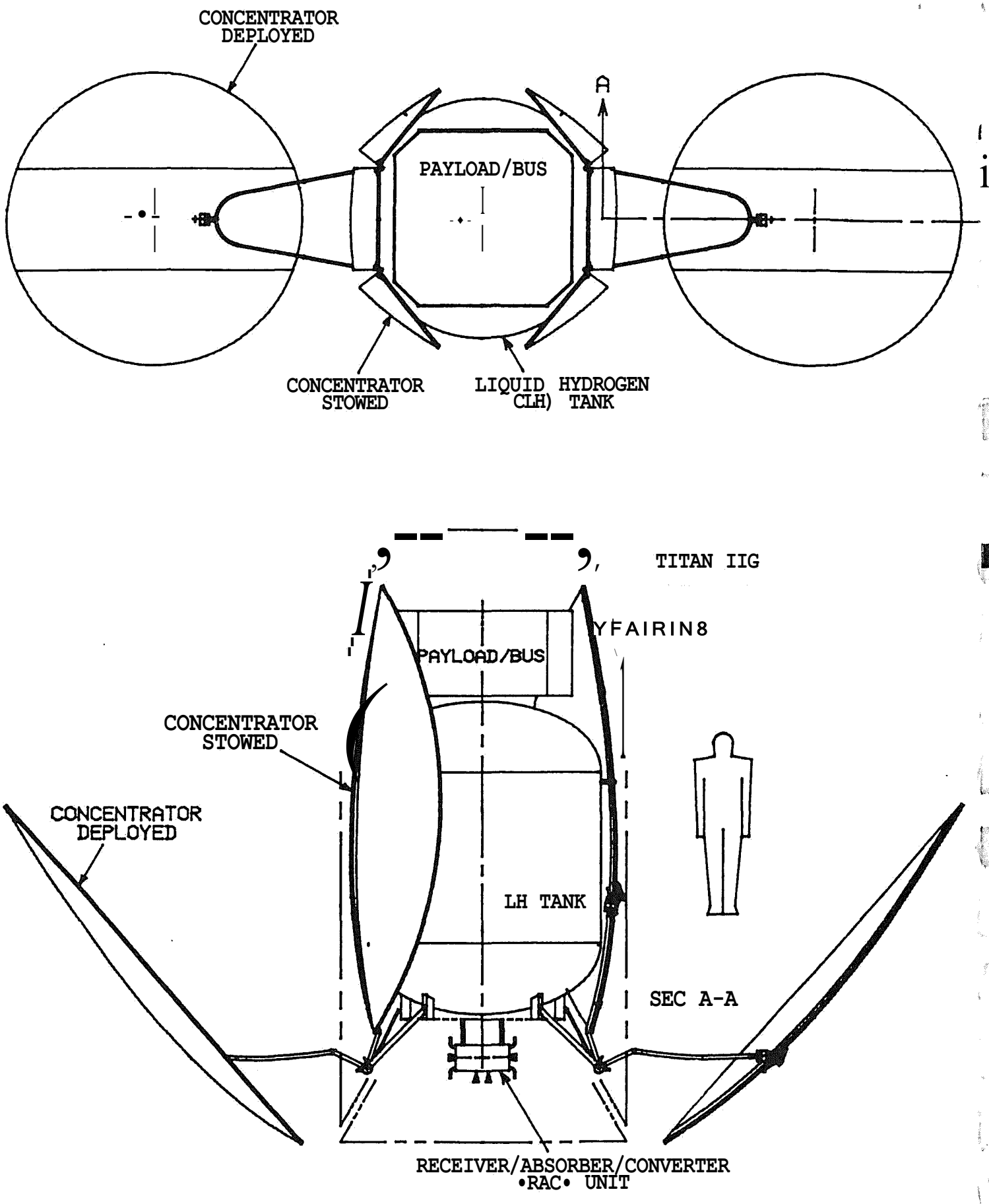


Figure ii Integrated Solar Upper Stage Advanced Technology Demonstration (ISUS ATD)

APPENDIX A

CONCENTRATOR DESIGN AND ANALYSIS

AS PRESENTED TO PHILLIPS LABORATORY AS SECTION 5.2 OF THE ISUS ATD PHASE 1 FINAL REPORT

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5.2 Concentrator Array and Tracking System

The concentrator array and tracking system consists of those subsystems and components needed to supply required solar energy to the ISUS ATD Receiver/Absorber/Converter (RAC) unit. The concentrator is a major component of the ISUS engine system, and maximum flexibility in making trades was emphasized and achieved during the design study because of the close interrelation between the various sub-systems. The trades were also constrained by the Air Force PL request that the design meet the short launch schedule and limited budget. This required that the resulting design utilize component technology of an advanced development stage where sufficient experience and hardware evaluation has been accumulated.

5.2.1 Concentrator Derived Requirements

5.2.1.1 ISUS Engine

The ISUS engine is composed of three major components:

- Solar concentrator.
- RAC unit (Receiver/Absorber/Converter).
- Liquid hydrogen (LH) tank.

The final derived requirements for the solar concentrator are listed in Figure 1. The solar concentrator supplies highly concentrated solar flux to the RAC unit, which operates at a cavity temperature in the range of 1900-2500 degrees kelvin depending on whether the ISUS is in the orbit transfer mode or final orbit operational mode. Reflux losses back out of the cavity aperture become very large at these temperatures because of the fourth power of temperature radiation factor. The cavity aperture must therefore be very small and results in a concentration ratio in the 8000-10,000 range.

The thermal power required by the RAC unit was modified three times as the electrical power from the thermionic converters changed from 500 to 800 and finally 1000 We total output. During the period when 500 W was specified, the concentrator diameter was sized by the Phillips Laboratory at 3.1 and 2.1 meters depending on whether a single or double offset configuration

was being considered. Later when the 800 and 1000 W power levels were required, the solar flux entering the RAC unit aperture was specified at 10.0 and 13.0 Kwt respectively for a single concentrator and divided in half for dual concentrators. The reflux loss back out of the cavity is within the RAC unit thermal budget.

5.2.1.2 Envelope and Payload

The concentrator configuration is affected significantly by the surrounding envelope , especially considering that it is the largest component in area on the vehicle. Two factors are the most important:

- Vehicle fairing envelope.
- Arrangement of the payload/bus, LH tank and engine relative to one-another.

As the electrical power requirement changed, so did the launch vehicle from the Taurus, to LLV1 and to Titan II G with fairings shown in Figure 2. Three arrangements of the vehicle components were considered in top-to-bottom fashion on the launcher as follows:

- Concentrator/RAC - Payload/bus - LH tank.
- Concentrator/RAC - LH tank - Payload/bus.
- Payload/bus - LH tank/concentrator - RAC.

The large volummetric size of the LH tank and the need to provide as much freedom to payload/bus requirements as possible placed major constraints on the concentrator design.

5.2.1.3 Deployment and Positioning

The concentrators are required to be segmented, folded and supported on the vehicle within the fairing during launch. At the proper time in LEO, the concentrators must deploy automatically in sequence controlled fashion as dictated by the concept considered. Boom extended configurations must be capable of maintaining focus with the RAC unit aperture during concentrator operation without excessive loss of collected solar flux.

The capability to concentrate solar flux into the RAC unit while simultaneously thrusting, and not requiring major vehicle attitude changes between heat and thrust sequences, were highly desirable features for the concentrator system. Dual offset concentrators allow this. While this is a design study for the ATD application, the selection of the concentrator had to consider the payload/bus requirements for future missions wherein the concentrator design causes minimum constraints on the payload/bus capability.

5.2.1.4 Launch

The preliminary design limit loads used in consideration of the final design concept were for the Titan II G launcher as follows:

		Acceleration Loads (G's)	
Case	Event	Axial	Lateral
1	Liftoff	-0.5 to 3.0	±3.0
2	Maximum Airloads	1.0 to 3.0	±3.0
3	Stage 1 Shutdown	4.0 to 9.0	±2.0
4	Stage 2 Shutdown	4.0 to 10.0	±2.0

5.2.1.5 Environment and Life

The space environment will be a sequence starting with a short term in LEO (7 days max.), transfer to Molniya (Approx. 23 days) and 3 years in Molniya orbit with 1000 km perigee, 40,000 km apogee at 63 degree inclination.

5.2.1.6 Concentrator Performance

The concentrator size and configuration depend on the solar flux that must be delivered through the RAC aperture and the cavity temperature. Because of the need to be in the 8000-10,000 concentration ratio range, the concentrator must consist of a primary reflector to intercept the required solar flux and a secondary concentrator at the RAC unit aperture to further concentrate the flux from the primary. Experience with segmented unfurlable concentrators of the type being

considered has shown performance in the 1000 to 3000 concentration ratio range is achievable and would be insufficient by themselves.

The flux levels that exist at various locations through the concentrator system are shown in Figure 3. Size of the primary concentrator depends on several factors that were evaluated in the design analysis:

- Total flux required by RAC unit.
- Primary geometry (Symmetrical vs offset).
- Surface quality due to panel fabrication, assembly and unfurling
- Reflectivity to solar flux.
- Shading due to members (such as boom) within the concentrating flux.
- Degradation of surface reflectivity due to condensibles and space environment.
- Positioning of primary relative to secondary as result of boom deployment and sun pointing

5.2.1.7 Concentrator Surface Quality

The various deviations from a true concentrator surface are usually considered individually. When this is done the deviation may not seem large relative to the design requirement for a given concentration ratio. But when considered together these deviations add up to produce a significant effect on concentrator efficiency. It is therefore necessary to establish a realistic budget of deviations to determine whether ot not a given method of concentrator construction will meet the design requirement. Figure 4 is an example that illustrates and lists the surface deviations determined for a two meter Sunflower concentrator design recently completed for NASA LeRC, Reference 1. Similar types of errors were identified and quantified for the ISUS ATD concentrator, and their effect on concentration efficiency was evaluated. All of the surface deviations listed will be encountered on the ISUS ATD concentrator but will vary in magnitude as a function of the final design configuration. There are nine sources for deviations as follows:

- Surface specularity
- Print through from core , if used
- Edge and attachment construction

- Cure tool deviations
- Panel replication of the tool during cure.
- Panel assembly to mounting ring or one to another
- Panel deployment and position control
- Thermoelastic deformation on orbit
- Surface degradation on orbit

The magnitudes of most of these deviations are highly dependent on the materials of construction and cross sectional configuration.

5.2.1.8 Concentrator Construction and Mass

Construction and mass of the concentrator is dependent on the design configuration , materials of construction and fabrication methods. The design configuration is highly dependent on the envelope constraints due to the spacecraft and launch vehicle fairing. And mass is highly dependent on the design configuration. Accessory hardware mass can become a significant amount considering the need to mount and support for launch, unfurl to shape, deploy to position and maintain position relative to the focal point. There are lesser differences in areal mass for the several materials and fabrication methods that are in advanced development stage, as required by this application. No limit has been placed on the concentrator system mass, but the objective, of course, has been to be as frugal as possible in holding it down. An areal density of 2.0 kg/M^2 maximum for the reflective surface panels is considered achievable. Minimizing concentrator surface area was a major objective.

5.2.2 Concentrator Configuration Study

5.2.2.1 Concepts Evaluated

The 19 configurations that were considered during the evolution to a final design choice are listed in Figure 5. The evaluation process was extensive and many layouts were accumulated as the location of other systems and the launch vehicle changed. The selection process reduced the number to seven and then two at scheduled review meetings. A more detailed optical and structural analysis was then made on the final choice.

The Sunflower concept was given early consideration because of its advanced development as a 10 meter diameter solar concentrator and a 3 meter antenna that was fully qualified for flight. The concept offers a packaging advantage because the volume within the stowed panels can be used for other components such as the RAC unit itself. A major disadvantage is that two concentrators could not be stowed side-by-side or one-over-the-other inside any of the fairings. So only single configurations of the Sunflower were considered, and this places some restrictions on the payload/ bus performance. The advantages and disadvantages of the 19 concepts are discussed as follows:

The Sunflower fixed to the LH tank with the RAC unit stowed within the stowed panels is shown in Figure 6. This configuration has the concentrator directly attached to the LH tank and the RAC unit is nested within the stowed panels and extends into position on orbit as shown. A disadvantage is the need to deploy the RAC unit away from the concentrator to reduce the entrance angle to the secondary concentrator (in order to achieve a high concentration ratio system). This requires deployment mechanisms and a long, deployable line to transfer cryogenic hydrogen to the thruster. In addition, the thruster is fixed relative to the concentrator and would not allow simultaneous solar collection and engine propulsion.

A single, offset paraboloid Sunflower is stowed upside down in the fairing, Figure 7. The panels would deploy open first followed by extension of the booms to place it in the offset position. While this configuration allows simultaneous collection and thrusting, it has several disadvantages. It requires a counterbalance mass, has a small centerdish with long narrow panels, requires many tool shapes to fabricate panels and a large support structure extending above the LH tank.

By using a Cassegranian arrangement of the Sunflower , Figure 8, the concentrator and the RAC unit are fixed to the LH tank. This avoids deploying the RAC unit, and the secondary Cassegranian reflector is also fixed. This is a tertiary mirror system when including the

nonimaging CPC as the third reflector. The entrance angle to the tertiary is advantageously smaller, but the Cassegranian secondary causes an additional reflection loss and additional positioning errors to cause ray deviations. In addition, the hot hydrogen gas must be transferred through a long passage from the RAC unit, along a tripod leg out to the thruster mounted on the backside of the secondary mirror.

The LH tank shape was modified significantly to allow the Sunflower to be mounted lower down in the fairing, Figure 9. This allows, the RAC unit to be in a fixed position within the fairing but with a smaller entrance angle into the secondary concentrator which is optically beneficial. The major disadvantage is that the LH tank must be an unconventional shape and also longer for the same propellant volume. The shape adds significant fabrication costs and the added length reduces volume for the payload/bus.

In Figure 10 the Sunflower is deployed at an angle to the LH tank axis. This would not allow simultaneous solar collection and engine thrusting but would avoid reorienting the entire LH tank and payload/bus each time as is necessary with the concentrator fixed to the LH tank. Only the concentrator/RAC unit would require an attitude change when alternating between collection and thrusting. This configuration would require a significant structure to the tank and many deployment sequences during the multiple thrust cycles to Molniya orbit.

Figure 11 shows the Sunflower deployed on a boom after the panels have been deployed into position. This allows the concentrator to be pointed at the sun while the thruster operates. It adds the additional requirement that the thrust vector pass through the center of vehicle mass while the concentrator is pointing, a complex mechanical design. An additional attitude control system would likely be required for the extended configuration.

A total of nine configurations of multiple panel, double offset concepts were considered. The "irregular shaped" panel concept with five, seven or nine panel configurations are stowed above the LH tank with the panels close to parallel with the LH tank axis, Figures 12-15. Two configurations of the "seven hex" panel concept are also stowed above the LH tank but with the

panels perpendicular to the LH tank axis, Figures 16 and 17. The "wrap around panel" concept is stowed with the panels wrapped around the LH tank. Three and five panel configurations were considered and were placed toward the forward or aft directions in the fairing, Figures 18, 19 and 20.

The four configurations of the irregular panel concept would not stow in the Taurus fairing with enough panel area to provide 500 We power. The fairing is deceptive because the cross section looking at the side view allows stowage of ample panel lengths, but when looking down on the top of the tank, the panel widths extend outside of the envelope in all cases. It became apparent that stowage of panels nearly parallel to the LH tank axis and with enough area was not efficient and could not be achieved.

The two configurations of the stacked seven hex panel concept were much more effective and could be stowed in the Taurus and provide 500 We power. In addition the concept draws on similar technology developed for the Space Station Freedom concentrator. The seven hex concept in Figure 16 involves a rotate and translate set of motions of six panels from the center panel. One stack of facets is stowed above the other and the upper stack must be deployed on its boom first and then the second stack follows. Once extended on the booms, the stacked facets would be sequentially rotated and translated into place. Number one first, number two second and so on to number six for both stacks. This concept involves a complex set of mechanisms to achieve the sequenced rotate-and-translate kinematics.

The seven hex concept in Figure 17 is similar to the previous concept. The stacks would be deployed on the booms in the same way, but the facet deployment would be simpler. Each of the outer six panels are hinged along one of the edges of the center panel. The facets would have to be sequentially deployed as in the above case but with a simpler hinged mechanism. This concept is the preferred configuration of the two because of simpler deployment mechnisms. The seven hex concept is the only double offset that could provide enough collection area for the power required in all three fairing configurations.

The wrap around concept configuration can not provide enough power in the LLV1 fairing but can in the Titan II G. The concentrator is divided into panels where the separation lines are parallel to the major axis of the elliptically shaped primary. The three (or five) panels can be stowed forward or aft in the fairing, but the aft stowage case is better. Stowing aft allows the payload/bus to be placed at the top of the vehicle which is the traditional launch position, and gives more freedom in the resulting payload configuration. A five panel configuration allows a slightly more efficient stowage of the panels around the tank, but requires more deployment mechanisms and very narrow panels.

Four concepts in the miscellaneous category were considered. The Wrap Rib (LMSC) configuration is an umbrella like construction that has been successfully used in many flight qualified antenna applications. A reflective membrane is stretched between the ribs as in an umbrella. But instead of folding the ribs in the usual way, they are wrapped in spiral fashion around the optical axis into a surprisingly compact volume and the mass is low. Unfortunately the stretched reflective surfaces are portions of a parabolic trough (not paraboloidal) and can not achieve a high enough concentration ratio for this application.

The Rolled Inflatable (ASIC Corp) configuration is not a rigid surface concept but was suggested for consideration. Figure 21 shows a 3.1 meter diameter design deployed, and also deflated and rolled up into a cylindrical volume. The reflective membrane achieves its accuracy by inflation of the toroidal ring and memory in the membrane surface. Besides its primitive development stage with questionable surface accuracy, the stowed cylindrical volume is far too long to be stowed in the fairing envelope shown.

The Fan (Acurex Corp) concept in Figure 22 utilizes rigid panels stacked in a panel dispenser and fed out one-by-one as shown. The stacked panels stowed in either of two orientations relative to the LH tank axis, can not be stowed in the fairing. This concept also involves complex deployment mechanisms which have not been demonstrated.

The Splined Radial Panel (Harris Corp) concept in Figure 23 has been designed and built into a working model and offers a small stowage volume that would allow two units to be stowed. The reflective surfaces are quasi paraboloidal and held in place by an intricate network of fine wires that stretch between radial ribs which are themselves articulated outward by a deployment mechanism in the hub. Once extended the ribs are taut enough to make the cross wires taut. This concept was not considered because of the many links, joints, wires and reflective panels that could ensnare on deployment; and the questionable surface accuracy of the quasi paraboloidal surface.

Elimination of 12 of the 19 configurations based on the previous discussion resulted in the 7 candidates in Figure 24 remaining for consideration. Further evaluation resulted in dropping all four of the Sunflower concepts because of the disadvantages already discussed and the limitations placed on the payload/bus. The double offset concept places the least constraint on payload/bus pointing and tracking. In addition the dual units allow partial power in case one of the concentrators does not deploy properly. Of the remaining 3 concepts, the three panels stowed forward was dropped because the unconventional LH tank shape would not be the preferred configuration of a cylinder capped with oblate spheroid domes.

The seven hex panel concept and the three wrapped panel (stowed aft) concept were compared based on the 10 criteria listed in Figure 25. Both concepts are capable of providing 1000 W electrical power in the Titan II G. The comparison was close with four criteria advantages each for both concepts. The three panel concept was chosen due to the larger payload/bus volume located on top of the launch vehicle with a potentially more accurate concentrator. Detailed optical, thermal and structural analyses were then made on the three panel concept.

5.2.2.2 Deployment Boom

The dual offset concentrator concept requires deployment devices to extend them to final position. Depending on the concept, this deployment occurs before or after the concentrator unfurls from the stowed configuration. The deployment device design is also highly dependent on

the concentrator concept. Specific design of deployment booms did not begin until many of the configurations, including the fixed Sunflower, were discarded.

Initial boom designs were tripods, example in Figure 12, because they appeared to stow well and offered dynamic stability to the deployed primary. There were two major disadvantages. More complex mechanisms are required with associated higher failure risks. And the elevation gimbal bearing for the primary sun pointing control must be mounted on the outer surface of the RAC unit, where heat rejection surfaces require good view factors to space. Figure 26 shows the required attitude control axes for the spacecraft and the offset primary concentrators. The spacecraft control system corrects about the yaw, pitch and roll axes shown for spacecraft pointing (either for thrusting from LEO to Molniya or for payload/bus attitude control requirements in Molniya). The dual offset concentrators are independently controlled by using the yaw and elevation axes. First, the yaw motion is made by rotating the entire spacecraft, including concentrators, until the LH tank axis and sun vector are in the same plane. Then the concentrators are rotated about the elevation axis until the concentrators are pointed at the sun.

The tripod boom was replaced by a single boom with the elevation axis control achieved by placing the gimbal rotary actuator near the boom-to-primary attach point, Figure 27. The axis of the rotary actuator should be coincident with the RAC unit axis, but will not be exact because of the boom/mechanism manufacturing tolerances and thermal deflections on orbit. For this reason, a spot positioner device was considered necessary and is discussed in Section 5.2.4. This device corrects for any misalignment of the gimbal elevation axis from the RAC unit axis that could cause significant degradation of the primary concentration efficiency. The difficult design aspects of the boom are:

- Keeping the structure and deployment mechanisms simple
- Where to attach the boom to spacecraft
- And providing stability between the large spacecraft and concentrator masses.

Early layouts with a 22 ° entrance half angle to the secondary concentrator at the RAC unit required an articulated boom having two links and three pivot points. A significant trade analysis

was made, Section 5.2.3.1, to try and design the boom with one link and two pivots. In addition, attachment of the boom to the LH tank wall was to be avoided. The tank shape has large dimensional changes when going from low cryogenic to much higher on orbit temperatures.

A bifurcated, single link boom with two pivots was achieved, Figure 28, primarily by increasing the entrance half angle to 30 °. The boom must be shaped as shown in order to fit between the stowed concentrator and the LH tank. The location of the base first pivot is as shown in order to use a single link but it is within the cone of concentrating solar flux. A view factor layout showed nearly 4 per cent shadow loss, probably more with thermal insulation. Bifurcating the boom reduces the loss to less than 2 per cent and also adds stiffness, stability and more precise positioning to the boom. There are two rotary actuators at the fork ends, and are supported from the flange ring where stage separation occurs, not from the LH tank.

The sequence for concentrator deployment occurs in three stages as in Figure 29. The side panels unfurl, latch and lock to the center panel while the center panel is still fastened to the space craft. In stage two the center panel is released and the boom rotates the assembly about the base pivot so that the boom is in final position. In stage three the concentrator rotates to position about the second pivot so that the concentrator is in final position. The three stage sequence is necessary to avoid unpredictable and uncontrolled motions that could occur if all deployment actions were initiated simultaneously.

The boom cross section should be shaped to minimize shading the concentrating solar flux; and be made of graphite composite to minimize defocussing the primary during 150 °F temperature changes under sun/shade conditions. The thermal distortion due to the unusual shape and cross section may be of concern however and should be evaluated.

5.2.2.3 Mounting and Support

The primary concentrator panels are large, lightweight, flexible structures and require adequate mounting and support during launch. Secondarily, the deployment loads must be absorbed. The fixed Sunflower concentrator was easiest to mount where launch loads were transferred into

typical transition skirts or struts to the LH tank. The seven hex stacked concept could utilize a similar support into the LH tank but with a supplemental structure extending out to support the two stacked assemblies at three points each. The supplement structure would add significant mass because of the long members between tank and stacked assemblies and is a disadvantage to this concept. The wrap around concept does not require such long mount supports, but the long panels require mounts at several places over the length of the spacecraft. This is a disadvantage because most of the spacecraft length is the LH tank. Attachment to the LH tank was avoided wherever possible to minimize heat transfer into the cryogenic liquid.

Two mount and support configurations were evaluated for the wrap around concept. The first supports the panels at mount points that stand off from the payload/bus at the top and from the boom and separation flange structure at the bottom, Figure 30. A hoop placed around the circumference of the stowed panels at mid section restrains the stowed bundle against the mount points and from unfurling. The second configuration supports the panels at the ends the same as above but also restrains the three panels at their midsections by a Sepnut mounted to the LH tank as shown.

The first configuration avoids added heat leaks into the LH tank. The second configuration avoids large lateral movement of the panel center section under lateral inertial loads (where contact with fairing or tank insulation might otherwise occur) and allows a more controlled deployment. The first configuration would unfurl the side panels simultaneously with release of the center panel where motion is less predictable. The advantages of the second configuration and its similarity with previous solar panel array designs outweighed the LH tank thermal disadvantage (A heat leak calculation indicated a manageable amount).

The final mounting and support configuration is shown in Figure 30 and with more detail in Figures 31 and 32. The panels are placed against the six upper snubber mount stand off points as in Section A-A and B-B. And against the four lower snubber mount points as in Section D-D. The two lower snubbers for the center panel are mounted on the bifurcated boom. The two lower snubbers for the side panels are stand offs from the lower stage separation flange structure.

The snubber points have a hemispherical surface on the mount portion and a side floating conical cavity member attached to the panel. The freedom to move sideways a limited amount is necessary because of the flexible nature of the panels. With the panels in place, the three Sepnuts will be torqued down at the mid span Sepnuts as in Section C-C. The panels will be deflected about 0.4 inch from free shape during torque down. This will result in enough preload at the snubber points to prevent disengagement under lateral launch loads. Concentrator deployment occurs by first releasing the side panel Sepnuts until the panels engage and lock into the center panel, and then the center panel Sepnut is released to start boom deployment.

Many mount and support design ideas were suggested by the Naval Research Laboratory (NRL), and in joint consideration with APEC Corporation many are incorporated in this final configuration.

5.2.3 Trade Studies and Analyses

Trade studies, in addition to the concentrator configuration just discussed, included the following:

- Primary/Secondary geometry
- Effect of primary surface errors on efficiency
- Materials of construction
- Reflective coating material
- Thermal distortion on-orbit

This section reviews the results.

5.2.3.1 Concentrator Performance Analysis

The overall concentration efficiency of the primary and secondary reflectors depends on many factors. Some of these factors can be more firmly predicted than others and will be noted during this discussion. The thermal flux levels at various points in the concentrator system are shown in Figure 3, and the overall concentrator efficiency factor is Q6 divided by Q1. Early sizing of the primary concentrator diameter was done by using an overall concentration efficiency factor of 0.80, as a first approximation, but ended up at 0.71 as will be reviewed here.

Thermal losses occur because of various factors including:

- Surface errors due to manufacture
- Surface errors due to on orbit thermal gradients
- Surface errors due to panel assembly and unfurling on orbit
- Primary positioning by deployment boom
- Surface reflectivity to solar energy
- Degradation of surface reflectivity on orbit over mission lifetime
- Area loss due to boom shadowing, gaps between panels and support points for launch mounting
- Sun pointing accuracy

Concentrator geometry and surface accuracy of the fabricated surfaces have the most influence on the efficiency factor, and optimization trades were therefore made. The analysis was not started until the single versus dual offset configurations were evaluated when the conclusion was to proceed with the dual offset. It should be noted that the lower achievable concentration ratio for a single symmetrical primary with its inherently larger entrance angle was a major reason for selecting a dual offset design. It is questionable whether a symmetrical primary with secondary concentrator can achieve greater than about 5000:1 in this application.

The primary geometry evolved into the upper configuration shown in Figure 33. A cone with its axis coincident with the RAC unit axis is projected to intercept the paraboloidal surface. This was done primarily to reduce the entrance angle into the secondary concentrator and results in projecting a circular area toward the sun for intercepting the solar flux. The classical offset concentrator used in most previous studies has the axis of rotation passing through the center of the primary as shown by the lower geometry. This provides a lower moment of inertia for attitude control, somewhat shorter ray lengths and lower surface area (mass). But the advantages are minor when traded against a higher secondary concentration ratio achieved with the smaller and equal entrance angle case.

Initial layouts used a 22° half entrance angle as an estimated optimum value to achieve a high efficiency factor. A small entrance angle increases the secondary concentration ratio but also

increases ray lengths that result in larger deviations at the focal plane. A large entrance angle has the opposite effect on ray deviation , therefore an optimum angle exists. A major reason to increase the angle is its relationship with the boom length required to extend the primary to position. Early layouts with the 22° angle required a double link, three pivot articulation of the boom. A single link, double pivot design is highly desirable because a reduction of mechanisms increases deployment reliability and improves the positioning and dynamic stability of the primary; all major factors.

A trade analysis of entrance half angle from 18° to 46° was made and the following parameters were evaluated:

- Secondary configuration and concentration ratio
- Primary concentration ratio required to achieve 8000:1 overall.
- Ray deviation at focal plane.
- Surface area (mass).
- Stowage considerations.

The 8000:1 ratio is considered an achievable value with the segmented, unfurable primary and the secondary that are being considered here and will be discussed.

The significant effect on primary and secondary concentrator geometry is graphically shown in Figure 34. As the angle increases, the primary arc length increases in size while the secondary dimensions decrease in size, and the effect on stowage is pronounced. The secondary geometry becomes fixed when the entrance half angle is specified, therefore its concentration ratio varies as in Figure 35. If an overall concentration ratio of 8000:1 is required for the primary and secondary, then the primary concentration ratio also varies as shown. A simple ray trace analysis was performed to get an approximate effect on the efficiency factor before a more comprehensive ray trace analysis was made. The "representative" ray was projected from the maximum areal increment located along the minor elliptical axis and having a two sigma value of 2 milliradians for the surface error, and includes solar image effect. The effect of entrance angle on miss distance is shown in Figure 36. The ratio of ray miss distance to secondary entrance radius increases rapidly

after 30° half entrance angle indicating high spillage loss outside the secondary. Later ray trace analyses verified this.

The outline of the primary is elliptical and as entrance half angle increases so does the major axis, and therefore mass increases as shown in Figure 37. Again the increase is rapid after 30°.

Some physical problems also occur with large entrance half angle as shown in Figures 38 and 39. More curvature and length of the parabolic curve as entrance angle increases cause difficulty stowing the primary in the launch fairing and also reduces payload/bus volume. And as entrance angle increases the primary gets closer to the vehicle, where at larger angles some shadowing from the LH tank and payload/bus can occur. The detail analysis on the effect of secondary entrance half angle on efficiency, mass and stowage of the primary is reported in Reference 2.

A ray tracing code was prepared for a comprehensive computation of the primary concentration efficiency factor in Reference 3. All of the parameters that affect concentration efficiency were evaluated including:

- Secondary entrance half angle
- Solar limb darkening
- Panel fabrication errors (Replication, print through, specularity)
- Assembly and deployment errors
- On orbit thermal gradients
- Solar reflectivity, including effect of incidence angle
- Boom positioning of primary
- Sun pointing

The ray tracing code evaluated the primary concentrator only and determines the flux dispersion in the focal plane (Entrance to the secondary concentrator). The secondary concentration efficiency factor is then considered in order to obtain the overall concentration factor for the

primary and secondary. Two other parameters were included in the efficiency factor evaluation after the above parameters were considered:

- Loss due to boom shading, gaps between panels and mount point hardware.
- Degradation of reflectivity due to on orbit environment and condensibles from RAC unit or spacecraft.

Most of the parameters can be determined fairly accurately but panel fabrication errors and reflectivity degradation are highly dependent on materials of construction, fabrication methods and on orbit conditions. Data from previous projects such as Space Station Freedom (SSF), the Solar Dynamic Ground Test Demonstration (SD GTD) and Reference 4 through 8 helped quantify the effect of fabrication and materials of construction on surface accuracy for the ISUS ATD primary concentrator.

An optimization of the secondary concentrator exit aperture required consideration of the reflux loss back out of the RAC unit cavity, Figure 40. The upper curve shows the flux level delivered through the secondary exit aperture into the RAC cavity with the focused spot centered and displaced. The lower curve shows the reflux loss back out of the RAC unit aperture at a cavity temperature of 2500°K. Therefore, the net flux retained in the RAC cavity is the difference between the two as shown, and an optimum entrance aperture can be selected. The surface quality of the primary concentrator and the boom position and sun pointing values are as shown.

The upper curve was determined by using a 30° entrance half angle geometry for the secondary (Concentration ratio 4:1). The scale of the secondary was changed as the entrance aperture varied so that the exit diameter was always half that of the entrance. The area of the primary (Intercepted solar flux) was held constant and the overall concentration ratio therefore varied as shown.

The 30° entrance half angle was used because of the trades discussed previously; primarily to simplify the boom design. However, the primary concentration efficiency at this angle is relatively high as shown in Figure 41. The spillage factor is defined as the fraction of concentrated flux from the primary that enters a given aperture diameter in the primary

concentrator focal plane. The data is presented only to show how the primary concentration efficiency varies with entrance angle, with and without spot displacement. The spillage factor decreases as entrance angle increases and more rapidly beyond 30°. An optimum entrance angle appears to be somewhat smaller than 22°, but the long, complex boom that would be required does not justify the slight gain (About 0.02) in spillage factor.

The conclusion to this entrance half angle parametric study was:

- The optimum angle is close to the 22° first selected.
- And the increase in spillage loss is not severe at 30° .

Layouts with a 30° half angle show that a single link boom can be used and the angle was set at that value. The geometry of the primary and secondary concentrators is shown in Figure 42.

The surface quality for the primary concentrator used in Figure 40 was selected based on previous hardware, References 4-8, and modified for the ISUS ATD primary concentrator using engineering judgement. The best replication accuracy achieved on previous hardware resulted in a close approximation to a normal distribution curve with a one sigma value of 0.5 mrad. Print through from the core, panel edges and reinforced areas (and surface specularity effects) add to ray dispersion but do not necessarily follow a normal distribution curve. The distribution of some surface slope errors can be very different depending on the cause and will be briefly discussed to highlight the effects.

The upper profile in Figure 43 is a trace over the surface of an aluminum honeycomb sandwich specimen with pronounced print through and shows the characteristic profile shape. It has a repetitive shape and was compared with the pi cosine and 2 pi cosine profile cases superposed as shown. When the pi cosine and 2 pi cosine profiles are represented by the models in Figure 44, they result in the slope error distribution curves shown and are compared with a normal curve. This print through can cause more serious ray dispersion than replication errors. The core print through is more pronounced as face thickness decreases and adhesive fillet size increases. This

limits the areal mass density achievable for concentrator panels, especially for a high concentration ratio application like the ISUS ATD.

The surface accuracy for a specific concentrator configuration and construction can not be precisely predicted, but historical data give some confidence in predicting an error budget. The following values were selected for the ISUS ATD primary concentrator:

- Fabrication: One sigma of 2.0 mrad (Includes tool, replication, print through and specularity errors)
- Assembly: 1.0 mrad maximum (Includes assembly and unfurling of side panels on orbit)
- Thermal gradient: 0.5 mrad maximum (Gradient across panel thickness).

The fabrication error of 2.0 mrad is four times higher than the value achieved for previous smaller, more symmetrical concentrators because there is little recent experience with long and narrow panels with a 4:1 ratio. The Sunflower panels were similar but fabrication methods have improved considerably after that early work. A potential large slope error, where the four corners are racked relative to one another, remains a question until large panels with a 4:1 length to width ratio are fabricated. There is some conservatism in selecting the 2.0 mrad fabrication error.

The secondary concentrator allows some direct through pass rays as in Figure 45 and the remainder reflect as shown. There is a pronounced non uniformity of the flux profile incident on RAC cavity walls. The through pass rays impinge on the back wall while the reflected rays impinge in an annular pattern on the cavity diameter and toward the entrance aperture. The heat transfer properties of the cavity material must have a high thermal diffusivity to avoid hot spots. The percent of direct pass through rays reduces as entrance half angle increases, Figure 46. Development of the Winston CPC secondary geometry in three steps is shown in Figure 47. The early evaluation of single primary concentrators such as the Sunflower showed a deficiency with CPC secondaries, where the entrance half angle has to be large (45° - 60°). The CPC concentration ratio reduces to 2:1 or less at these angles and was not enough to amplify the expected 2000:1 primary into the 8000-10000:1 overall concentration ratio range required. A

Winston hyperbolic funnel (CHC) was considered as a possible alternate but was rejected as too inefficient. A ray trace code was developed and resulted in the performance shown in Figure 48. Rays into the entrance aperture at selected values of -x and +x as listed travel paths that reflect 0, 1, 2 or more times. The range of entering theta angles where 0, 1 and 2 reflections occur are shown. Rays reflected 2 times or more end up coming back out of the entrance aperture. The ineffectiveness of this type of secondary is apparent and was not considered any further. There have been reports of other types of secondary geometries but appear to be proprietary. There was no time or funding available on this project to analyze independently other surfaces.

The determination of required intercepted flux requires an iteration, after an initial area determination is made, to account for the following losses:

- Reflectivity degradation of primary and secondary over life time on orbit (L1 and L2)
- Loss due to boom shading, mount point hardware and panel joints (L3)

The total area of intercepted solar flux is determined as shown in Figure 49. This results in a 117 inch (2.97 meter) diameter for the circular area that intercepts solar energy. With the 1.27 inch (3.22 cm) aperture into the RAC unit, the areal concentration ratio for the ISUS ATD concentrator system is 8500:1. The confidence in the above factors that determine the primary diameter vary widely. Two are subject to some significant unknowns. The primary concentration efficiency factor (K1) depends heavily on surface accuracy due to fabrication, assembly and on orbit thermal distortion. The degradation factor (L2) of the secondary reflective surface depends heavily on how the silver coating maintains properties at 1000° K operating temperature and how much out gassing from the RAC cavity condenses out on the silver surface. The factors chosen are considered reasonable based on engineering considerations to date, but will require some rigorous engineering design to be achieved.

5.2.3.2 Reflective Surface Coatings

The reflective surface for the primary concentrator consists of a reflective coating usually silver (Ag) or aluminum (Al) and a protective overcoat which prevents damage to the reflective coating from the space environment and from oxidation and handling on Earth prior to launch. A considerable amount of data was reviewed for the purpose of selecting a reflective coating system

for the primary solar concentrator. Since Ag and Al have the highest reflectivity of candidate coatings, Figure 50, the evaluation of reflective coatings was restricted to them. Protective overcoating materials considered were SiO_2 and Al_2O_3 both of which are commonly used in optical systems.

In addition, recent work with forming microsheet glass has shown promising results which could allow its use as a protective overcoat. Since the reflective coating is applied to the back of the microsheet glass, in addition to providing a protective overcoat, microsheet glass provides a smooth surface for applying the reflective coating.

Orbit environmental considerations are presented in Figure 51 where concentrator concerns are identified for several environmental parameters. Of the parameters indicated, those of most concern and which were examined most carefully were proton, electron and atomic oxygen bombardment. These parameters are concentrated mostly in LEO and decrease in intensity with higher orbits. Since the ISUS ATD spends approximately one week in LEO before beginning transfer to Molniya and during the transfer spends a portion of the orbit in LEO environment, a period of time exists when the concentrator must withstand the high concentrations of protons, electrons and atomic oxygen found in LEO. Once the concentrator reaches final Molniya orbit, the perigee is high enough that LEO concentrations are no longer encountered.

High flux levels of protons and electrons in the energy range of 0.1-4.0 MeV cause the concern for degradation of coatings and composites. The flux for both protons and electrons in this energy range is approximately $10^8/cm^2$-sec for LEO orbits. Based on the orbital flux study for an orbit similar to the ISUS final Molniya orbit but with a lower perigee (data provided by NRL), anticipated fluxes are as follows:

Protons	$10^6 - 10^7$ p^+ $/cm^2$-sec
Electrons	$10^7 - 10^8$ e- $/cm^2$-sec

NASA calculated atomic oxygen fluence of 8 x10^{19} atoms/cm^2 for the Molniya orbit with the lower perigee. This is much lower than the atomic oxygen fluence levels of approximately 10^{21} atoms/cm^2 that are normal to LEO orbits. Thus, once the ISUS ATD reaches final orbit, the influence of proton, electron and atomic oxygen bombardment will no longer be a major concern.

Several factors must be considered in the selection of a specific reflective material for the primary concentrator. Substrate material, protective coatings, coating thicknesses, and environmental conditions such as exposure to atomic oxygen must be considered. Reflectivity data from several sources were gathered and compared to assist in selecting a reflective material for the ISUS concentrator and to establish a reflectivity value that would be representative for the selected material, Reference 9.

The substrate material is a critical element in all film coated products. The substrate material provides the base to which the reflective material is applied and as such must be smooth, free of defects, and provide a specular finish. Since the surface on most face sheets of aluminum is not smooth enough as manufactured, a leveling layer must be applied. In addition, on honeycomb type structures, print through of the honeycomb onto the face sheet is common and must be minimized. Any defect in the surface of the substrate material will be duplicated in the reflective surface and result in dispersion of the reflected light.

A figure of merit (the solar spectral reflectance) can be calculated by integrating the product of the reflectivities and the relative solar spectral irradiance over the wavelengths of 0.2 to 2.5 microns (the significant range). Some data have suggested high values for Ag of 0.95 and Al of 0.93. However, the actual solar specular reflectance that can be achieved by current manufacturing techniques appears to yield lower values especially for the large surface areas required for solar concentrators.

The protective material plays a crucial role in the long-term performance of the concentrator. While the initial performance will largely depend on substrate and reflective material

characteristics, maintaining the initial performance over the operational life of the concentrator will depend on the protective material(s).

Al, while having a lower reflectivity, has a significant advantage over Ag in terms of oxygen corrosion resistance. Oxygen corrosion can occur in Earth atmosphere and due to atomic oxygen while in orbit. The natural formation of Al_2O_3, a native oxide on Al, provides protection. The susceptibility of unprotected Ag to significantly degrade in performance due to atomic oxygen attack was considered

A considerable amount of data was reviewed for the purpose of recommending the reflective coating system for the ISUS ATD primary solar concentrator. Only two reflective materials were considered. Ag has the highest solar specular reflectance followed by Al. However, actual reported reflectance values for each material varied considerably because of differences in manufacturing technique and quality of specimens or facets.

Based on the data reviewed, an as-fabricated solar specular reflectance of 0.92 and 0.88 at normal incidence appears achievable for Ag and Al respectively with a suitable protective coating. It should be noted that a uniform Ag reflectance value of 0.92 has not been demonstrated on large facets or large surface areas and a development of the application process will be necessary.. A reflectance loss of 1-2 % for both Ag and Al is estimated will occur due to the projected atomic oxygen fluence level for the proposed orbit. The cross sections for proposed Ag and Al layers are shown in Figure 52.

For a proposed ISUS ground test demonstrator, an Al reflective surface concept has been selected for the primary concentrator. Al was chosen in lieu of Ag because of manufacturing considerations and corrosion resistance. For the design calculations, a solar specular reflectance of 0.88 is considered typical.

While Al has been selected for the ground test demonstrator, a Ag reflective surface is recommended for the ISUS ATD operational flight hardware because of the potential for a 4 to

5% improvement in reflectance. A thorough evaluation of the Ag application process with appropriate ground testing (and flight testing, if possible) is recommended prior to the commitment of this material for operational hardware. Fabrication of large concentrator surfaces is required to demonstrate the manufacturing process repeatability and control. Extensive evaluation of this hardware including tests for solar specular reflectance, adequate Ag-to-substrate adhesion, protective coating quality, and atomic oxygen corrosion resistance is recommended. For the proposed ISUS ATD conceptual design, an initial Ag solar specular reflectance of 0.92 is considered achievable. A reflectance loss of 1-2 % is projected over the orbital life.

While the detail design of the secondary concentrator is not the responsibility of APEC Corporation, the design of the secondary surface contour and the reflectance material characteristics are important to the overall concentrator system design. The Phillips Laboratory has chosen silver (Ag) as the reflective material on a metallic structure operating at a temperature up to 1000° K. The following comments are offered regarding this selection.

Ag appears to be a good choice for the reflective material for the secondary concentrator. A review by the NASA LeRC materials Division indicates that at temperatures above 300 ° C, an oxide layer on Ag reconverts to metal (Basically, the reverse of the oxidation process). Also, the operating temperature of the secondary concentrator is significantly below the Ag melting temperature of 960° C (1234° K). Thus in the orbital operating environment, no protective coating appears to be required.

Prior to and during launch, it would be necessary to provide an oxidation protection for the Ag. A permanent protective coating or a sacrificial coating, such as SiO_2 is not recommended since they tend to ball up and form islands on the surface of Ag at high temperatures. Extensive testing of coatings is recommended prior to commitment to flight hardware.

Regarding fabrication of the secondary concentrator, the key to effectively using Ag at this operating temperature is a good bond and a close match of the coefficient of thermal expansion

with the metallic structure. To assure a good bond, it is recommended that the secondary concentrator be baked at 400 to 500° C in an inert, circulating gas to clean the surfaces after normal chemical cleaning but before deposition of Ag reflective coating.

The reflectivity of Ag to solar flux varies with surface temperature of the Ag and decreases as temperature increases. Data at 1000° K could not be found, but using an established method (Reference 10) an estimated value of 0.84 at normal incidence was calculated.

A major question concerning the reflective surface of the secondary is degradation over operational life. Outgassing from the nearby RAC cavity surface could be a significant degrading factor especially if it is carbon from the graphite heat storage material. Until test experience is gained by operating components under simulated conditions, a 5 percent degradation in reflectance has been assumed for performance calculations.

Recent reflective coating work at NASA LeRC, Reference 11, has resulted in application of Al and Ag to microsheet glass with high reflectance values. Coated microsheet specimens were mounted on several substrate materials (Aluminum, graphite composite and magnesium) with a space qualified film adhesive. Second surface specular reflectance values of 0.85 and 0.92 were achieved with Al and Ag, respectively.

5.2.3.3 Structural and Thermal Analysis

The three panels are placed against the snubber support points as described in Section 5.2.2.3 in order to transfer launch loads to the spacecraft. The Sepnut bolts are inserted at each panel midspan, and the panels are intentionally deflected during bolt down. The panels were considered simply supported at the ends and loaded and deflected at mid span. The 1.0 inch thick cross section of aluminum honeycomb sandwich requires 0.4 inch deflection to snub the panels down at the support points in order to prevent panel separation during lateral launch loads. The natural frequency for the panel size and cross section is 5 Hz and well above the attitude control pulsing rate expected when the concentrator is in deployed position.

The thermal environment on orbit can cause thermal gradients across the panel thickness cross section and radially and circumferentially over the surface of the primary concentrator. Analysis indicates that the thermal deflections due to cross section gradients can cause significant slope errors on the panel surface while the radial and circumferential gradients are second order and negligible to the error budget. Cross section gradients are a function primarily of the surface absorptivity to solar and other thermal fluxes; and emissivity of the concentrator surfaces on the sunside and backside of the panels. A typical temperature versus orbital sun/shade position is shown in Figure 53 for an aluminum honeycomb cross section. With emissivity and absorptivity values shown, the temperature level of the panels would vary between 0° and 150°F and the maximum gradient across the thickness would be about 6°F, reference 12. This gradient can result in significant surface slope errors of 0.5 mrad maximum for the 1.0 inch aluminum sandwich section; and has been included in the ray trace analysis to determine concentration efficiency.

The temperature level of the concentrator on orbit can also significantly affect surface slope errors, especially core print through onto the front face. The difference between adhsesive and aluminum coefficients of expansion will cause more pronounced print through as the temperature levels vary above or below the panel cure temperature during lay up. The ideal cure temperature for the 0° to 150°F temperature level range specified in Figure 53 is room temperature. Print through errors increase above and below 80°F. If the cure temperature is elevated, then print through increases even further at the lowest temperature level. The final desired temperature range will depend on the selected materials of construction, and tailoring of absorptivity and emissivity factors will be required for the aluminum sandwich cross section.

The temperature level change from high to low during sun shade cycling can be changed by tailoring the back side radiative properties as shown in Cases 1 and 2 on Figure 53. The temperature at location 1 is always higher than at location 2 because the angle of incidence of the solar flux at location 2 is 60° and at location 1 is 30°. More flux is absorbed for a unit of surface area at 1 than at 2. In addition, the temperatures will be higher in LEO than in Molniya orbit because of the added Earth thermal and albedo in LEO. Since the primary concentrator must be more efficient during LEO to Molniya transfer, the concentrator thermal design should consider

LEO temperatures more than in Molniya, if it is necessary to minimize core print through errors. An adhesive that cures above room temperature may give the optimum conditions. Most adhesive systems can be cured at a wide variety of temperatures. The lower the cure temperature, the longer the cure time. Several post cure "annealing" cycles are also recommended for some adhesive systems to stabilize the adhesive cure shrinkage and coefficient of thermal expansion.

If specific radiative properties are needed on the back surface, they might not be achieved by using a single material. Consideration can be given to a matrix of two types of back surface materials to achieve the desired temperature levels. The matrix pattern can also be varied between locations 1 and 2 to more equalize temperatures at those locations.

5.2.3.4 Mass

The estimated mass for the concentrator and associated hardware for mounting, unfurling and positioning is categorized and totaled in Figure 54. The areal density for the panels is 2 kg/M^2 (0.41 lb/ft^2) and makes up the major part of total weight. Two concentrators are predicted to be 57.44 kg (126.42 lbs). The specific mass, defined as total mass divided by area of intercepted solar flux, is 4.1 kg/M^2 (0.84 lb/ft^2).

5.2.4 Concentrator Deployment Mechanisms

The mechanisms and devices used for actuating deployment and positioning the concentrator must be simple, reliable, proven and low mass. All of these aspects have been considered and incorporated by using designs from previous reflector programs and especially the in depth spacecraft experience of the Naval Research Laboratory. A description of the actuation and positioning mechanisms is shown on Figure 55 and subsequent Figures in more detail.

Unfurling the two side panels is initiated by actuating the Sepnuts, Figure 56, at the mid span of both panels Section A. The Sepnut is a space rated (SR) mechanical release mechanism that is similar to the unclamping from a lathe chuck when initiated. Torsion spring actuators and uniball bearings are located at both ends of the panel views B and C in Figures 57 and 58, also SR. The uniball bearings are used, instead of the more common linear hinges, because of the flexing that

occurs when the panels are snubbed against the mount points and their more inherent reliability. The torsion springs accelerate the panels until the positioner/lock mechanism, views C and D in Figures 58 and 59, engage. As the side panel nears the center panel a leaf spring is engaged and deflected; and when the ball has contacted the conical seat of the positioner, the leaf spring has already snapped against a ramp and locked the panels with zero backlash engagement. Figure 60 shows a space qualified mechanism of similar configuration used on the Sunflower antenna. Because of the accurate surface shape required for a solar concentrator, the mechanism is also capable of being adjusted very precisely with a wedge that has a 0.0002 inch per inch taper. The 34 inch long antenna petals were adjustable to within +/- 0.002 inch at the tip and maintained that range with repeated actuations. Four positioner/lock mechanisms are equally spaced along the edge joint between each side panel and the center panel to provide adequate stiffening to the unfurled assembly.

The boom deployment is initiated by actuating the center panel Sepnut. The bifurcated boom is attached to the spacecraft at the base pivot axis view E, Figure 61. Two dc motor driven gear box rotary actuators at the boom end points accelerate the primary concentrator to the extended position, also SR. Use of this type of actuator under space conditions is all right when performed within the planned several day envelope after insertion in LEO. Dual actuators provide uniform torque at the two end points although design for one actuator failure should allow for successful deployment. One failed actuator can be overcome by overhauling with the good unit and deploying more slowly. Positioning and locking the base pivot joint will be achieved by the same positioner arm, leaf spring lock configuration as the side panel to center panel positioner lock concept. During boom deployment the primary has been kept engaged with the two snubbers located on the two boom members.

The rotary actuators located at the boom-to-primary junction are shown in stowed position in Section F, Figure 62. The mechanisms must stow within the annular volume between the outer surface of the LH tank insulation and the dynamic envelope of the vehicle fairing. Adequate clearance with the mechanism was achieved by making a hole in the primary surface so the gimbal rotary actuator would nest sufficiently. The pivot axis for deploying the primary

concentrator to the final angular position relative to the boom is located at the end of the boom. The remaining mechanisms shown are associated with the spot positioner.

Section G, Figure 63, shows the primary in deployed position relative to the boom where the positioner arm is locked in place (Similar to Figure 61). The gimbal rotary actuator is used to point the primary at the sun in the elevation axis attitude. The actuator is a stepper motor with sufficient resolution to achieve 0.1° maximum sun pointing accuracy and enough holding torque to sustain position.

An analysis of the boom positioning accuracy that results from structural and mechanism manufacturing tolerances, and possible thermal deflections, shows the need for a spot positioner device to overcome the excessive as-deployed spot displacement from focus. A spherical bearing mounted on the webbed flange is placed between the boom and primary for freedom to adjust the primary. Two linear actuators are attached as shown in view H, Figure 64, also SR. The actuator is a dc brushless motor driven lead screw with built-in position encoder. Plus or minus voltage is supplied from the controller that senses a feed back bias voltage from the sensors located around the entrance aperture of the secondary concentrator, Figure 65, Reference 13. The pattern of four thermocouple sets arranged just outside the secondary entrance diameter provide the bias voltages to the control. Four couples in each set are used for two reasons; 1) redundancy in case of a failure and 2) the shape and temperature of the concentrator flux profile will be valuable diagnostic data on initial operation and throughout the life time. The outer set of couples would provide the as-deployed position information in order to initiate coarse alignment of the spot into the control band of 0.05° maximum spot positioning.

The form and positioning tolerances required to achieve as-deployed position of the primary are identified in Figure 66. The various datum axes and surfaces are annotated "A" through "F" and will require tight manufacturing tolerances as can be achieved with precision fixtures and CNC machining methods. If the tolerances shown are achieved, the as-deployed primary will have a focussed spot centered at just over an inch from the focus, as in the enlarged view of the focal plane. Thermal effects will have to be included in this tolerance budget. The position of the

boom pivot axis (Datum C) must be especially closely controlled. There will be a large number of members between the focal plane datums (A and B) and datum C. Therefore to keep fabrication costs within bounds, the pivot axis datum will require adjustment on assembly to the spacecraft. Probably utilizing an optical alignment method and done within controlled room conditions such as in a prelaunch assembly area away from the pad.

The sensor for position feed back to the sun pointing control is mounted to the webbed flange (View J, Figure 67), and will require bore scope positioning relative to the center panel paraboloidal surface. This figure shows how the primary rotary actuator is positioned at 90° to the gimbal axis. The actuator will require precise machining of the rotation axis, and distance between bearings should be as large as possible to achieve the position tolerances of datum axis E.

5.2.5 Concentrator Fabrication Processes

Methods of fabricating high concentration ratio panels with low areal mass using aluminum and graphite composite materials are developed, and cross sections are shown in Figure 68. The most advanced construction for use on the ISUS ATD, and considered the baseline, is an adhesive bonded aluminum sandwich construction. A specular finish is achieved by application of a thin polymer leveling layer. And high solar energy reflectivity results by vacuum evaporation of aluminum or silver, with a protective coating, onto the leveling layer. Accurate surfaces have been demonstrated by various sources, References 4-8.

The second fabrication method uses microsheet glass as a leveling layer with a back surface reflective coating and has also been demonstrated, References 11 and 14. The microsheet is heat formed by either of two methods and adhered to a structural substrate by use of a film adhesive. This construction offers advantages such as protection of the reflective layer, high thermal emissivity and reduced fabrication cost. But there is a slight increase in areal mass .

The third and most recently developed method uses a graphite polymer composite substrate and a unique process for achieving a specular leveling layer, Reference 15. The composite substrate is first layed up and cured on a master tool that has a highly polished surface. The substrate is

removed and the same master is then used to form the leveling layer. Three layers of material are then vacuum evaporated, during the same vacuum cycle, onto the master in the following sequence:

- Separation layer material
- Protective layer material (Such as SiO_2 or $MgF1_2$)
- Reflective layer material (Such as aluminum or silver)

A thin adhesive layer is applied to the concave surface of a composite substrate, and the substrate is placed onto the vacuum evaporated layers while the latter are still on the master. After the adhesive cures, the assembly is separated from the master. This method of construction is being evaluated at NASA LeRC, reference 15, where two cross section configurations are being fabricated. One is a membrane with peripheral reinforcement. The second is a honeycomb sandwich section. Initial inspection of the two facet panels indicate surface slope errors of 1.1 and 0.7 mrad maximum, respectively. The graphite composite construction offers one large advantage over aluminum, a near zero coeffcient of thermal expansion. This would lower any on orbit thermal distortion errors to second order effects. The construction also offers potential lower fabrication cost and lower areal density (1.5-2.0 kg/M^2).

All three materials of construction are considered feasible for achieving performance requirements of the ISUS ATD, and there may be other potential configurations in advanced development not known to this design effort. However, the aluminum cross section is considered the most advanced and most likely to meet program cost and launch schedule constraints. Considerable hardware evaluation has been achieved as reported in the listed references and will be briefly reviewed.

The 10 meter diameter Sunflower, Figures 69-71, demonstrated that large light weight structures would survive launch and deployment loads and maintain surface shape. The Sunflower was not only the largest concentrator built with aluminum honeycomb construction, but was the first. Although fabrication methods were in early development and not sufficiently refined, the panels showed good concentration efficiency in the 500-1000:1 range.

Fabrication methods were refined by using stretch forming of the skins, fabricating the forming tool by CNC machining and application of a leveling layer to achieve required surface specularity. Smaller units were made and a 1.5 meter diameter fixed dish concentrator, Figure 72, achieved high concentration efficiency (Model III) out to the 10,000:1 range, Figure 73. While this is a benchmark to aim at, the ISUS ATD primary concentrator could not achieve such a high ratio because it is a segmented assembly, unfurled, deployed and more susceptible to on orbit thermal distortion.

Further evidence of development status is given by the 3 meter diameter Sunflower antenna, Figures 74 and 75. This unit was fully qualified for flight including launch inertial and vibration loads and simulated zero g deployment in vacuum at -180 °F. The surface requirements for the antenna were not as difficult as for a solar concentrator because of the longer electromagnetic wavelengths involved. However, the achieved "rms" value for the shape of the unit in orbital operation was determined to be 0.009 inch. While this gives little information on surface slope errors, which are more deleterious to solar energy reflection, the translational boundaries justify confidence that the ISUS ATD primary concentrator (4.5x3 meter elliptical shape) can achieve a deployed form within required true surface boundaries.

A pictorial sequence showing fabrication of the three meter antenna is shown in Figure 76 , and panel fabrication steps are listed in Figure 77. Fabrication of the ISUS ATD would use many of the same steps except where application of a leveling layer and the reflective/protective layer would replace the application of a thermal paint. Also, the assembly of the three panel ISUS ATD would differ from assembly of the Sunflower antenna petal configuration. However, this method would allow fabrication of the three panels as single panel parts. Each panel would not be made of sub panels fastened together into a panel assembly. One basic tool would be used to stretch form, lay up panels, trim to shape and assemble into a unit as shown in Figures 78-80. Each step will require specific tooling and fixtures to be added to the basic tool. There are no undeveloped fabrication processes required to make the ISUS ATD primary concentrator. New tools and fixtures would be required for obtaining the specific ISUS ATD geometry.

The panels have been sized as a 1.0 inch thick section (Possibly thinner) with 0.010 inch and 0.006 inch aluminum front and back faces, respectively. The core is aluminum Flex-Core (Hexcell Corporation trademark) with 40 cells per square foot and made of 0.001 inch foil. The sandwich is bonded with an epoxy of 0.015 inch fillet. An areal density of 2 kg/M^2 results.

The panels require attachment points for hinges, locks, snubbers, Sepnut bolts and the spot positioner. These points will utilize potted-in fastener nuts and skin doublers where necessary to transfer launch and deployment loads efficiently. Trimmed edges of the panels will require protection from peel back of the skins from the core. Fabrication methods are available for these purposes.

5.2.6 Baseline Concentrator Design and Specifications

The ISUS ATD baseline concept design is shown in Figure 81. It is a three panel primary wrapped around the LH tank and fitted within a Titan IIG launch fairing. Two units spaced 180 ° apart are required and deploy to the position shown. Details of mounting and support during launch, deployment and positioning have been described in previous sections; as have materials of construction . The solar concentrator system baseline design requirements are listed in Figure 82 and the resulting configuration parameters are listed in Figure 83. The primary concentrator is of aluminum sandwich construction based on developed technology, and a secondary concentrator is attached to the RAC unit to achieve the high concentration ratio required.

5.2.7 Conclusion and Recommendation

As a result of this study there is a high confidence that technology is available to fabricate the rigid, segmented, unfurlable and deployable primary concentrator design that will meet the performance, cost and launch schedule constraints of the ISUS ATD program. It is recommended that the next phase of work be initiated where it is planned to conduct a ground test demonstration (GTD) of an ISUS ATD engine, including the solar concentrator system, under simulated orbital conditions. There are several issues and concerns which should be identified for special attention in tasking the next phase and are listed in Figure 84.

The need for a positioner device that focuses the primary spot because of boom and mechanism fabrication tolerances was questioned when first proposed. The detail analysis indicates the positioner is definetely needed. And in fact, a very thorough mechanical and thermal analysis will be required to design the hardware. Alignment of the base pivot axis of the boom on assembly with the RAC unit at the prelaunch assembly area is one obvious requirement in meeting the tolerance stack up required.

The long, narrow four to one ratio of the panel dimensions should be analyzed with precaution. The resulting design must consider the potential larger replication errors and shape change that could be encountered during operational life that could be encountered. High accuracy solar concentrator surfaces that have been fabricated to date were either symmetrical or a 2:1 length to width ratio. Particular attention should be given to fabrication processes; such as the uniformity of adhesive fillet size for aluminum sandwich construction and to graphite ply orientation, type of matrix polymer and reinforcement configurations for composite construction.

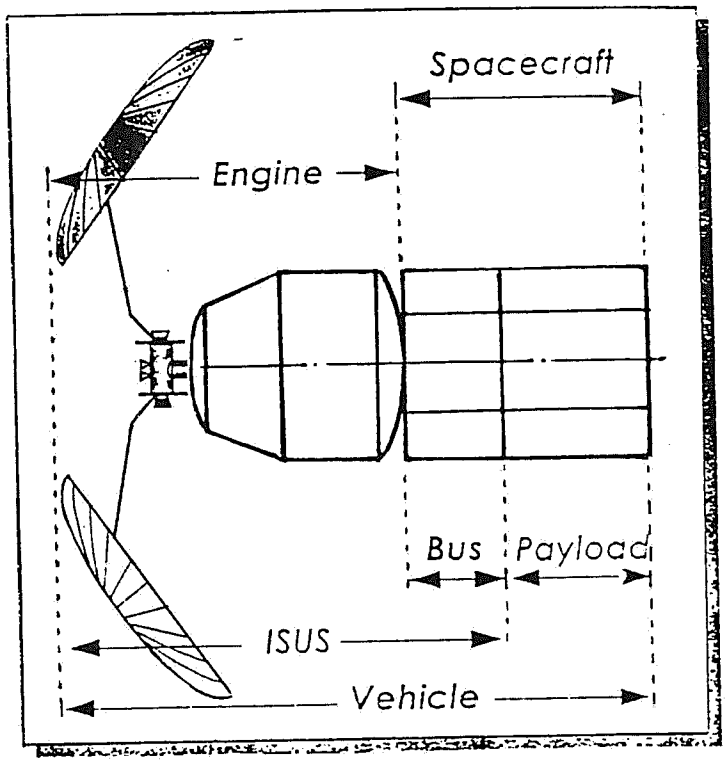
If panels are made in single pieces, without subpanels fastened together, the vacuum evaporation of reflective and protective coatings will require a large tank and specially arranged evaporators. While this manufacturing process is an established technology, the size places this hardware in a potentially costly category. Especially in guaranteeing a uniform, high reflectivity surface over the entire surface. Evaporation of silver will require tighter process controls than aluminum. It may be cost effective to use a government owned facility and personnel to apply the reflective coating.

Application of a polymer leveling layer to the large panels will require a special spray area utilizing clean room conditions and in establishing process controls for applying special polyimide formulations. Testing under simulated Molniya orbital conditions of sample cross sections with leveling layers coated with reflective and protective layers are required to demonstrate space compatibility.

The successful performance of the silver coating on the secondary surface at its operating temperature up to 1000 °K and within view of the potential outgassing of the 2500°K RAC cavity is not established and should be verified early by simulated testing of specimen surfaces.

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• *Construction*	*Rigid Panels, Segmented for Stowage, Unfurlable and Deployable*
• *Concentrated Flux, Total*	*13.0 kWt*
• *Concentration Ratio*	*8000-10000:1*
• *Receiver Temperature*	*2500 Deg K Max*
• *Launch Envelope and Environment*	*Titan IIG*
• *Orbital Environment*	*Molniya 12 hours*
(30 Day Transfer from LEO)	*63 Deg Inclination*
• *Life*	*3 Years*
• *Traceability*	*LLV3 Launcher Envelope*

Figure 1. ISUS ATD Nomenclature and Derived Requirements

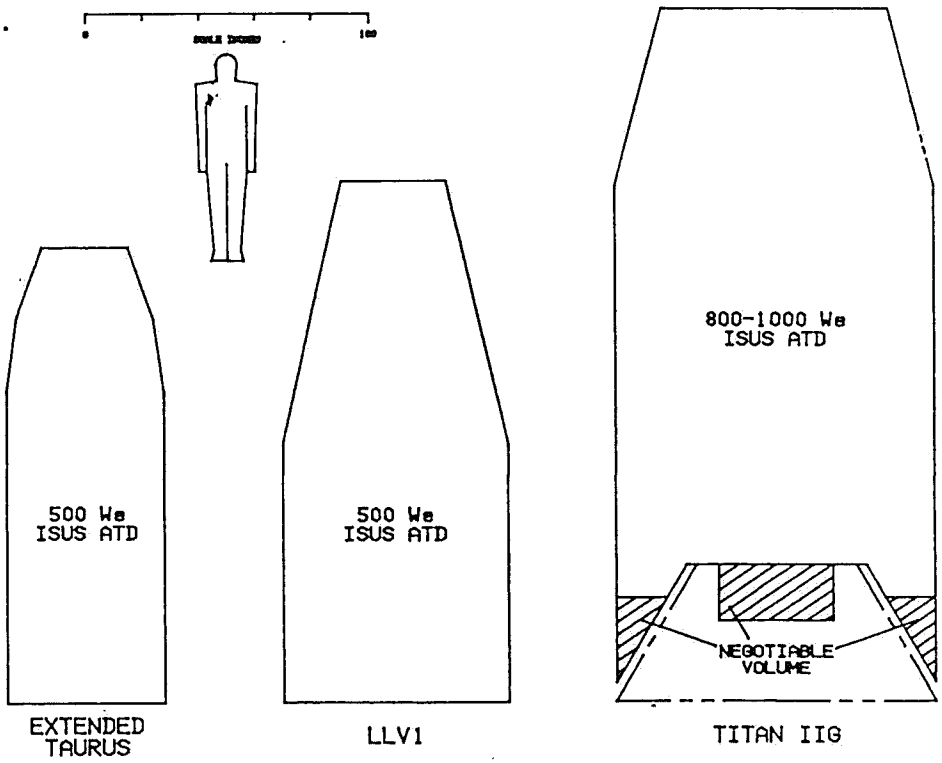


Figure 2. Launch Fairings Considered

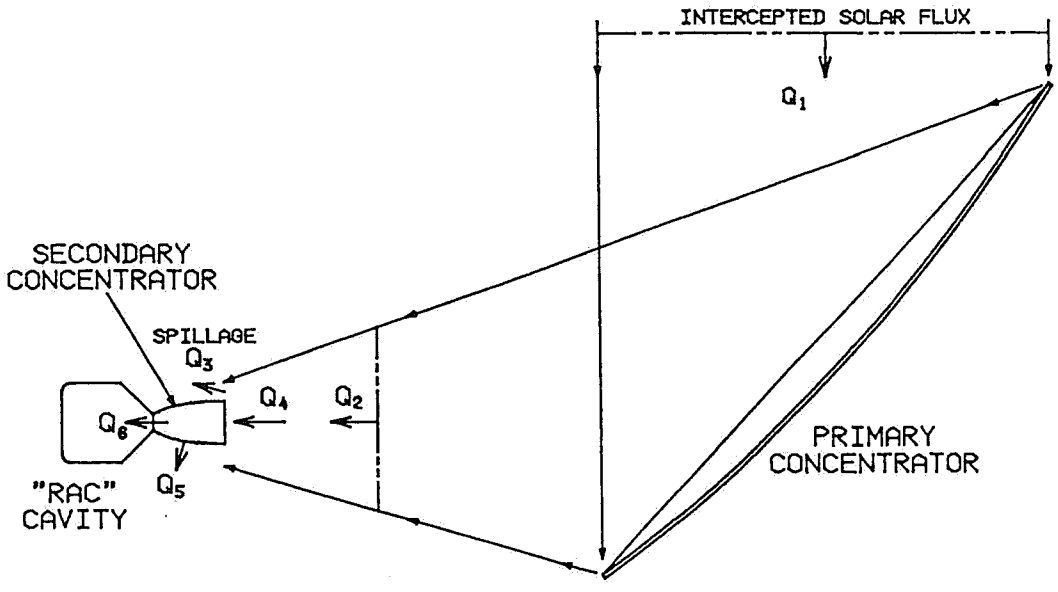
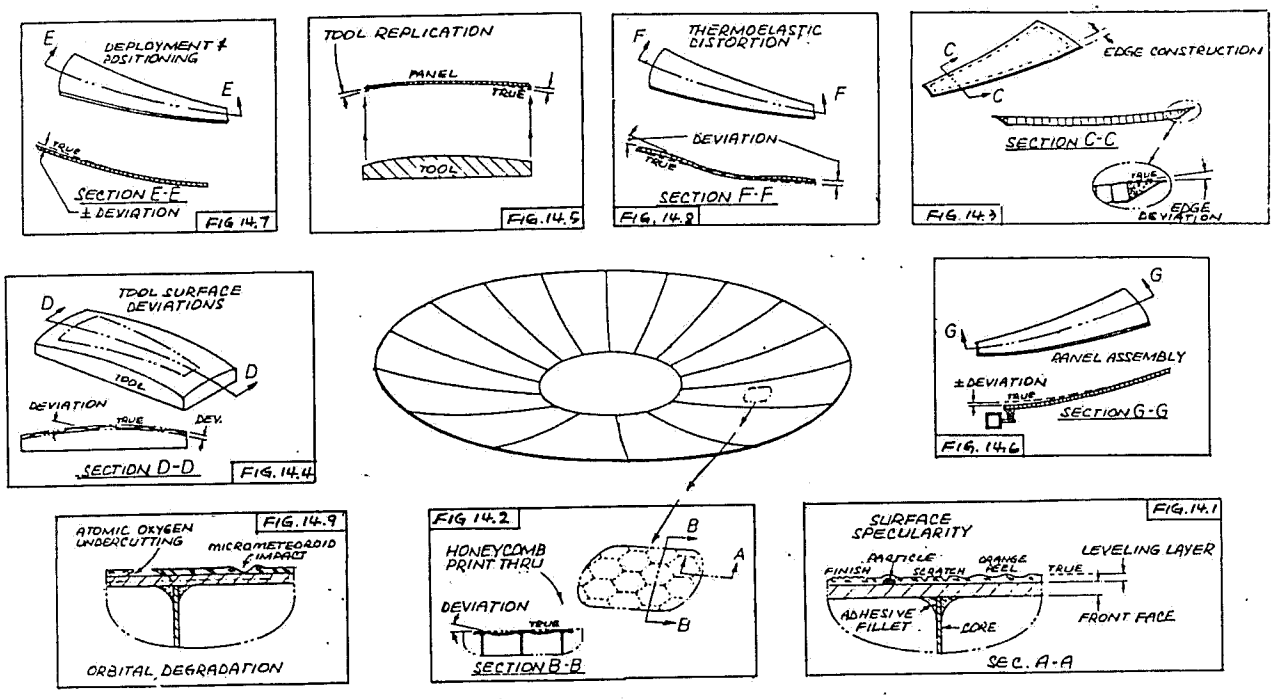


Figure 3. Flux Levels in Solar Concentrator System



SOURCES OF SURFACE DEVIATIONS

	SOURCE OF * DEVIATION	DEVIATION MAXIMUM VALUE	DEVIATION DISTRIB. CURVE	REFERENCE SOURCE
1	SPECULARITY		< 2% LOSS DUE TO η_4 FACTOR	REF. 4
2	HONEYCOMB PRINT THRU	<.0002" 0.3 MRAD	2π COSINE	REF. 3 AND 2 METER PROJECT
3	EDGE CONSTRUCTION	<.001" 1.0 MRAD	SYSTEMATIC	REF. 4
4	CURE TOOL SHAPE	0.3 MRAD ±.002" TOOL	NORMAL	2 METER
5	PANEL REPLICATION OF TOOL	±.010" 0.3 MRAD	NORMAL	REF. 7 AND 2 METER PROJECT
6	ASSEMBLY ACCURACY	±.005" 0.2 MRAD	SYSTEMATIC	REF. 7
7	POSITION CONTROL	±.005" 0.2 MRAD	SYSTEMATIC	REF. 7
8	THERMOELASTIC DISTORTION	±.012 1.0 MRAD	SYSTEMATIC	REF. 3
9	ON-ORBIT DEGRADATION		< 5% LOSS DUE TO η_8 FACTOR	
	COMBINED DEVIATIONS	±.030" 3 MRAD	CASE 6	REF. 3 (APPEN. B, PG. 6)

BUDGET OF SURFACE DEVIATIONS FOR TWO METER SOLAR CONCENTRATOR

REFERENCE 1

Figure 4. Solar Concentrator Surface Deviations

Sunflower, Single (6)

- *Fixed, Movable Receiver*
- *Offset*
- *Cassegranian, Deployed*
- *Modified Tanks, Fixed Receiver*
- *Deployed, Tilted*
- *Symmetric, Deployed*

Miscellaneous, Double Offset (4)

- *Wrap Rib*
- *Rolled Inflatable*
- *Fan*
- *Splined Radial Panel*

Multiple Panel, Double Offset (9)

- *Five Irregular*
- *Seven Irregular (2)*
- *Nine Irregular*
- *Seven Hex, Rotate/Translate*
- *Seven Hex, Hinged*
- *Three Panel, Forward*
- *Three Panels, Aft*
- *Five Panels, Aft*

Total Concepts: 8

Total Configurations: 19

Figure 5. Solar Concentrator Configurations Considered

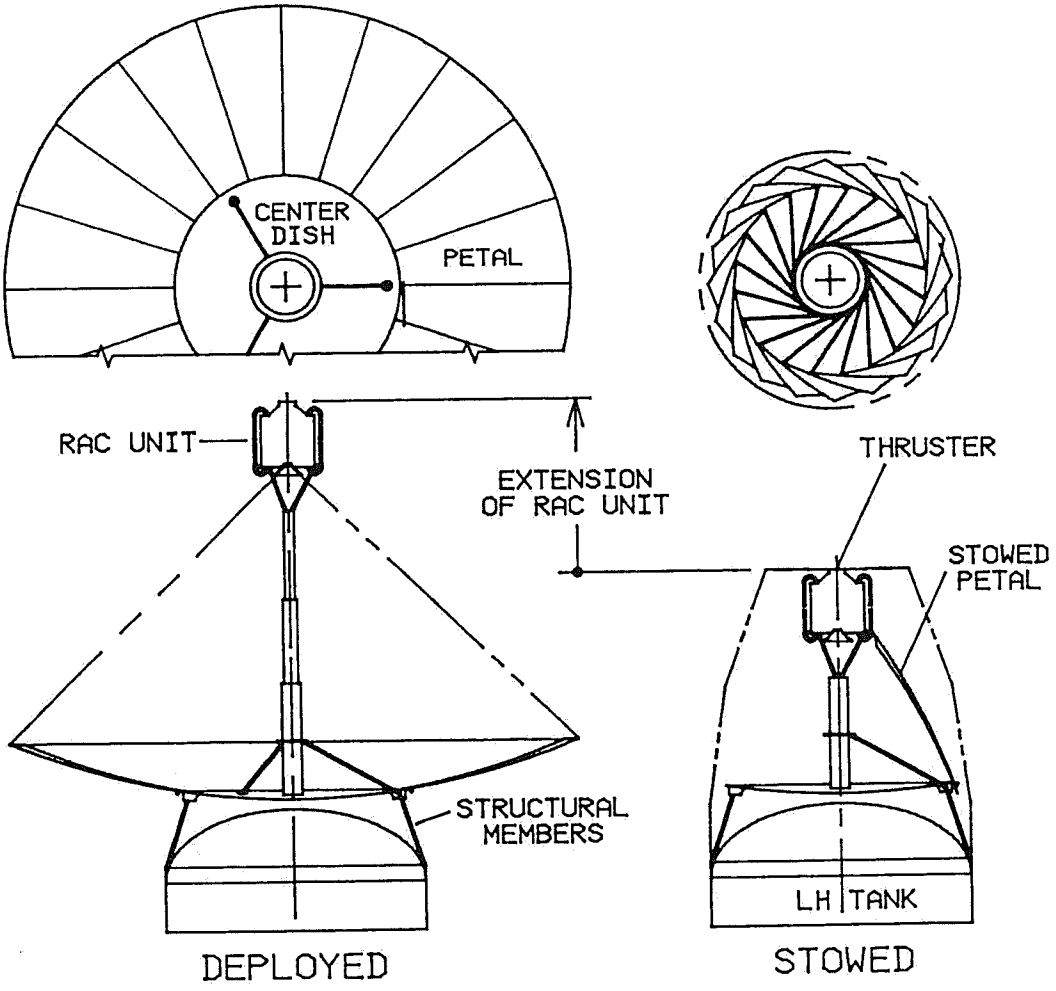


Figure 6. Single Sunflower Fixed to LH Tank

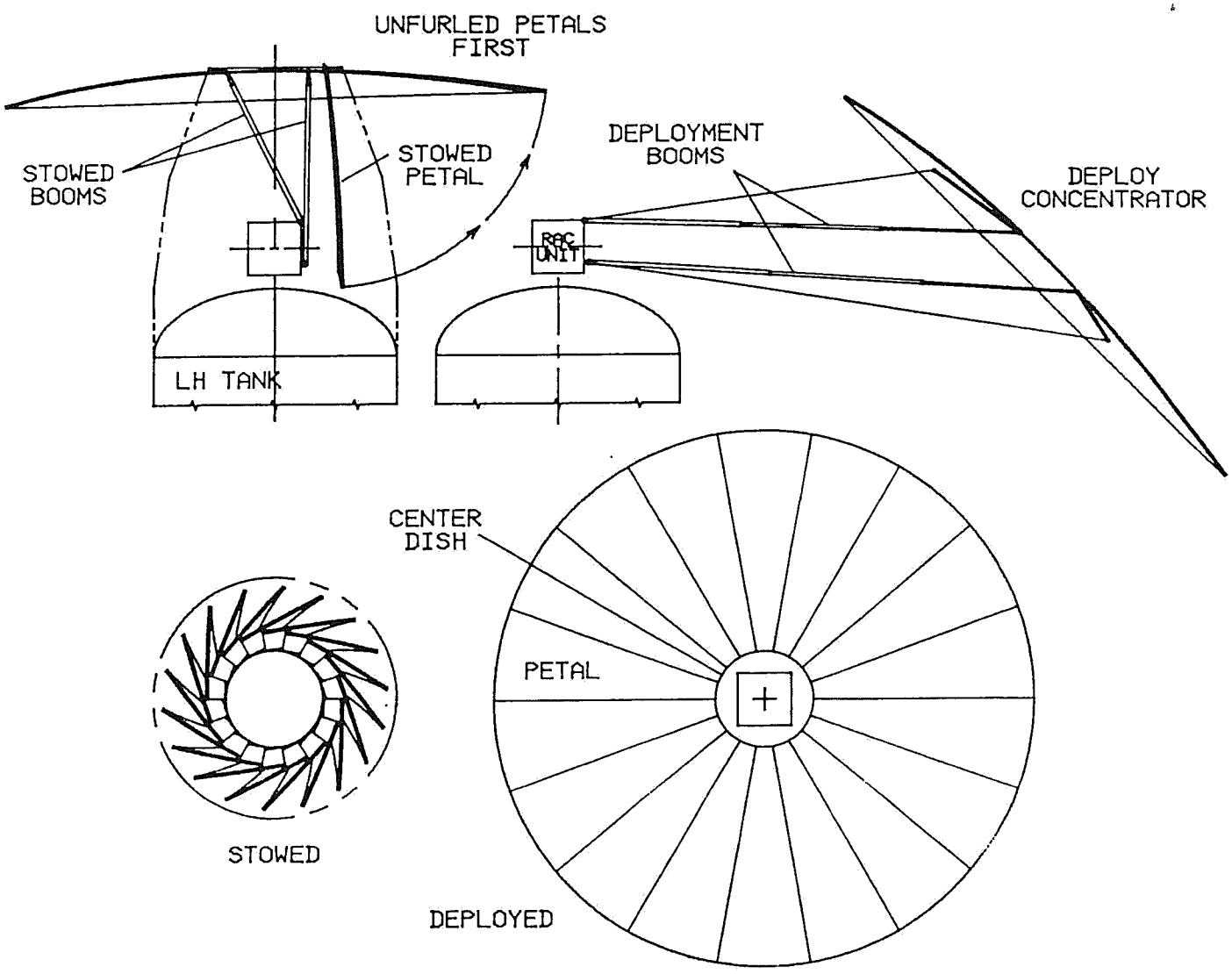


Figure 7. Single Offset Sunflower

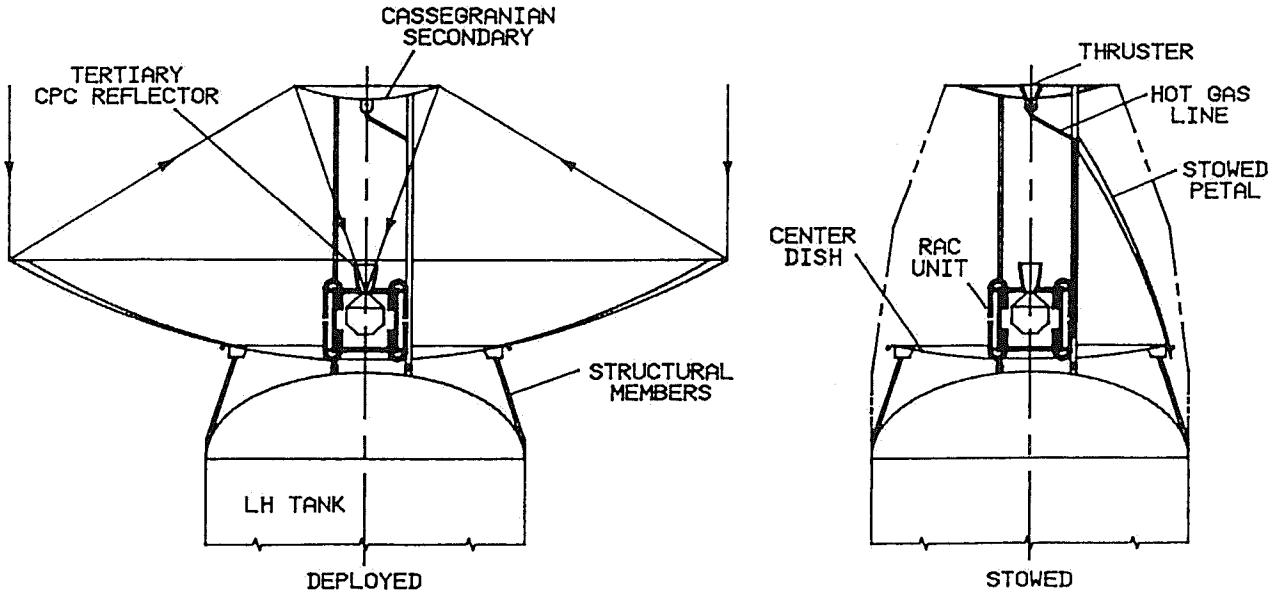


Figure 8. Single Cassegranian Sunflower

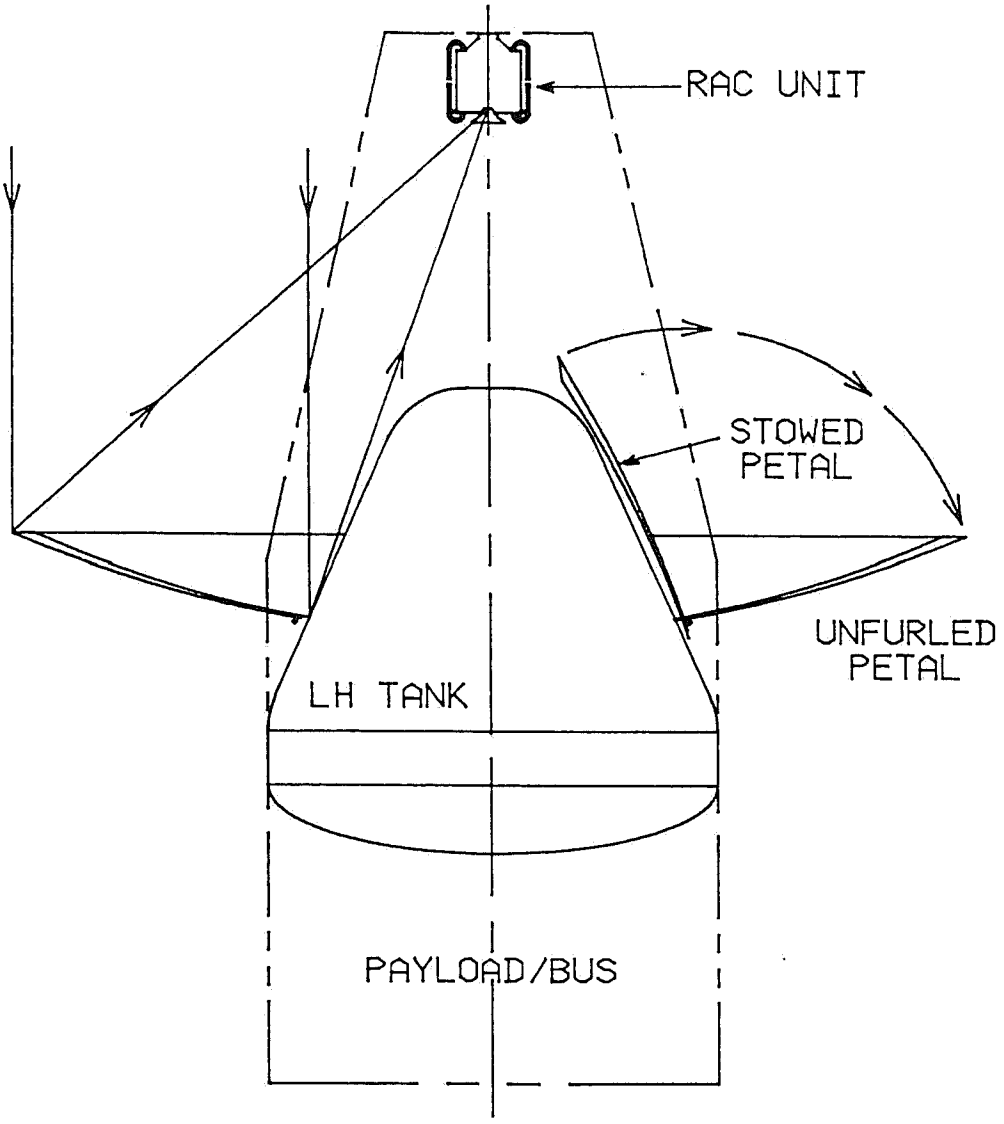


Figure 9. Single Sunflower on Modified LH Tank

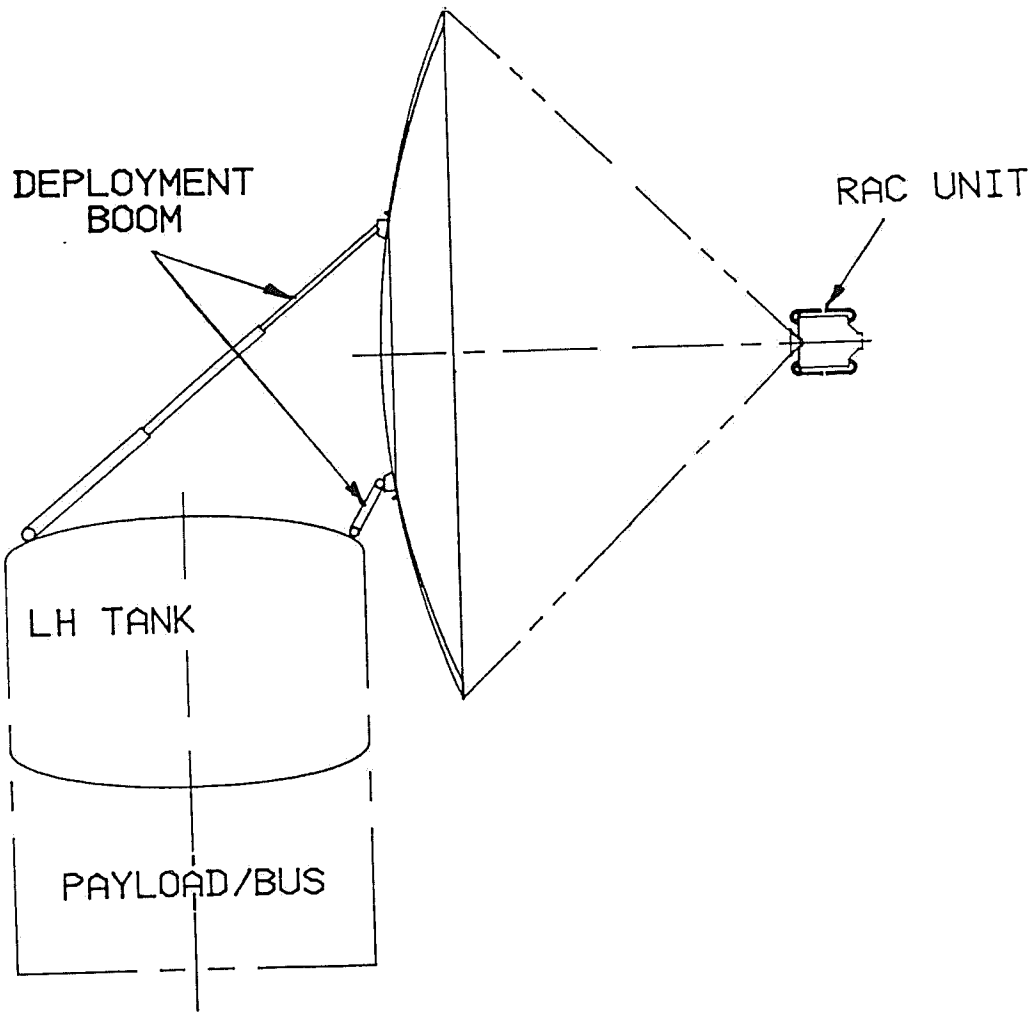


Figure 10. Single Sunflower at 90 ° to LH Tank

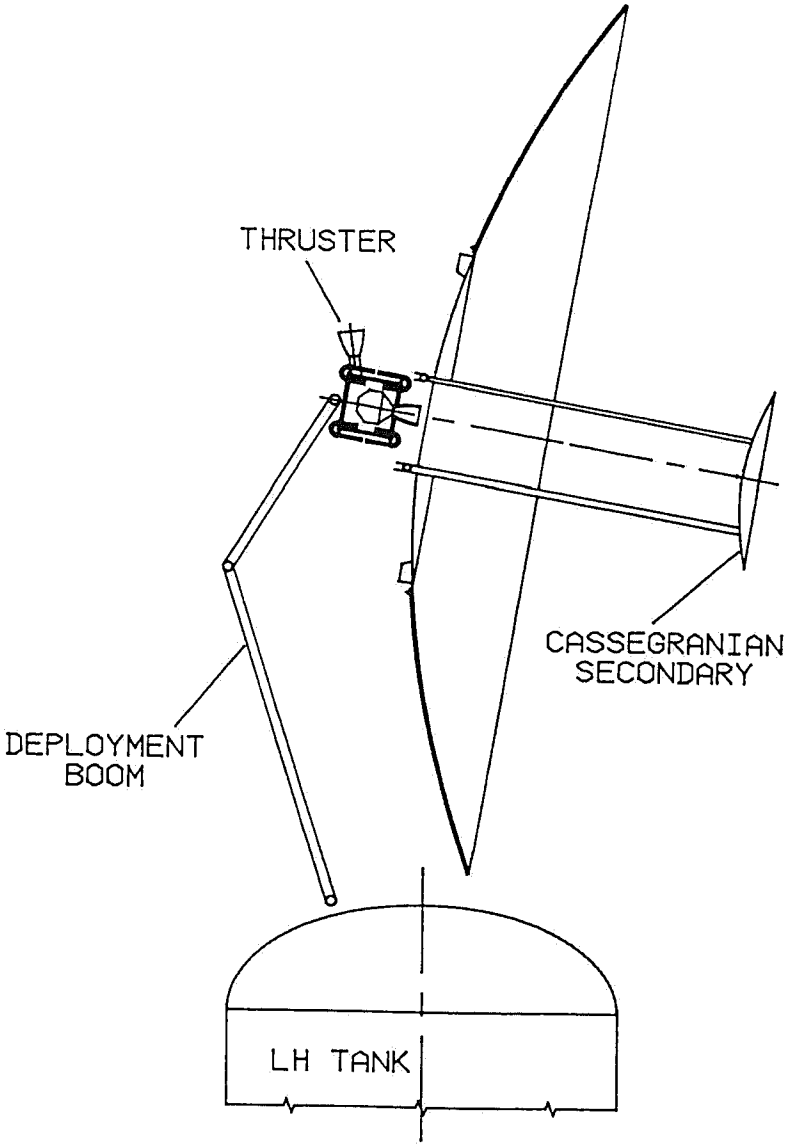


Figure 11. Single Sunflower Deployed on Boom

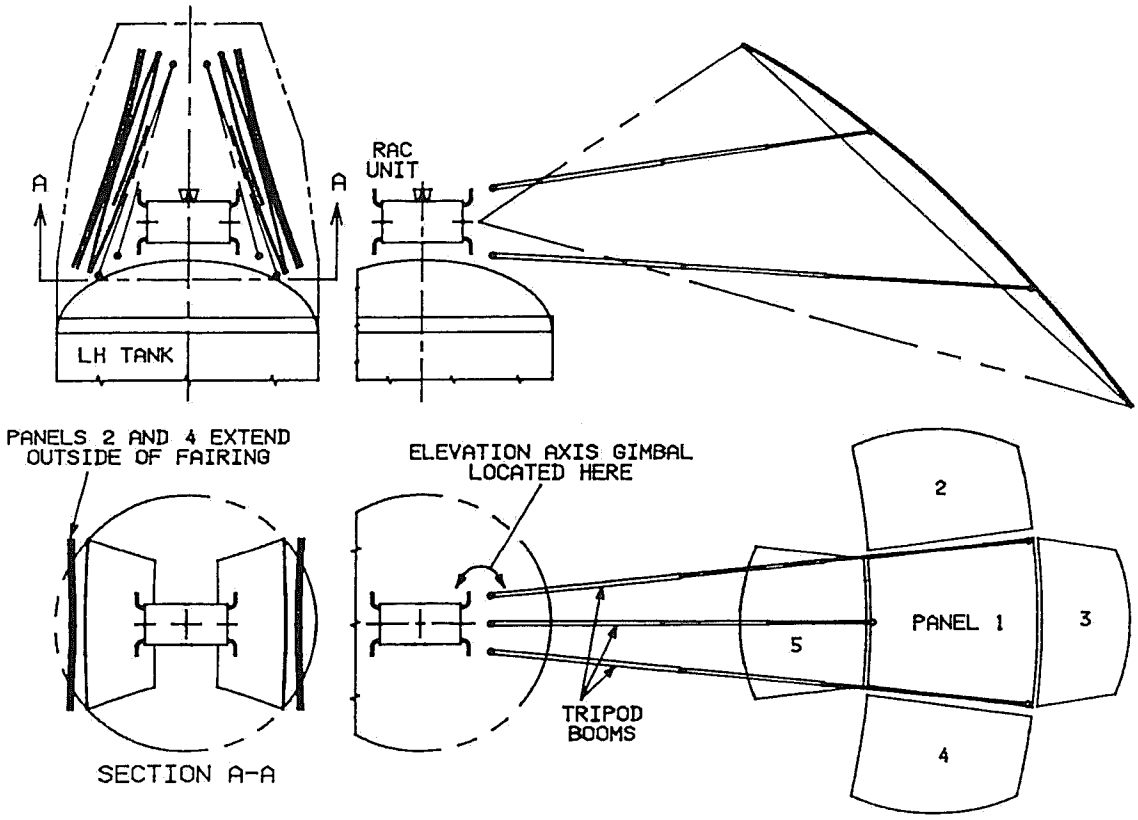


Figure 12. Five Irregular Panels

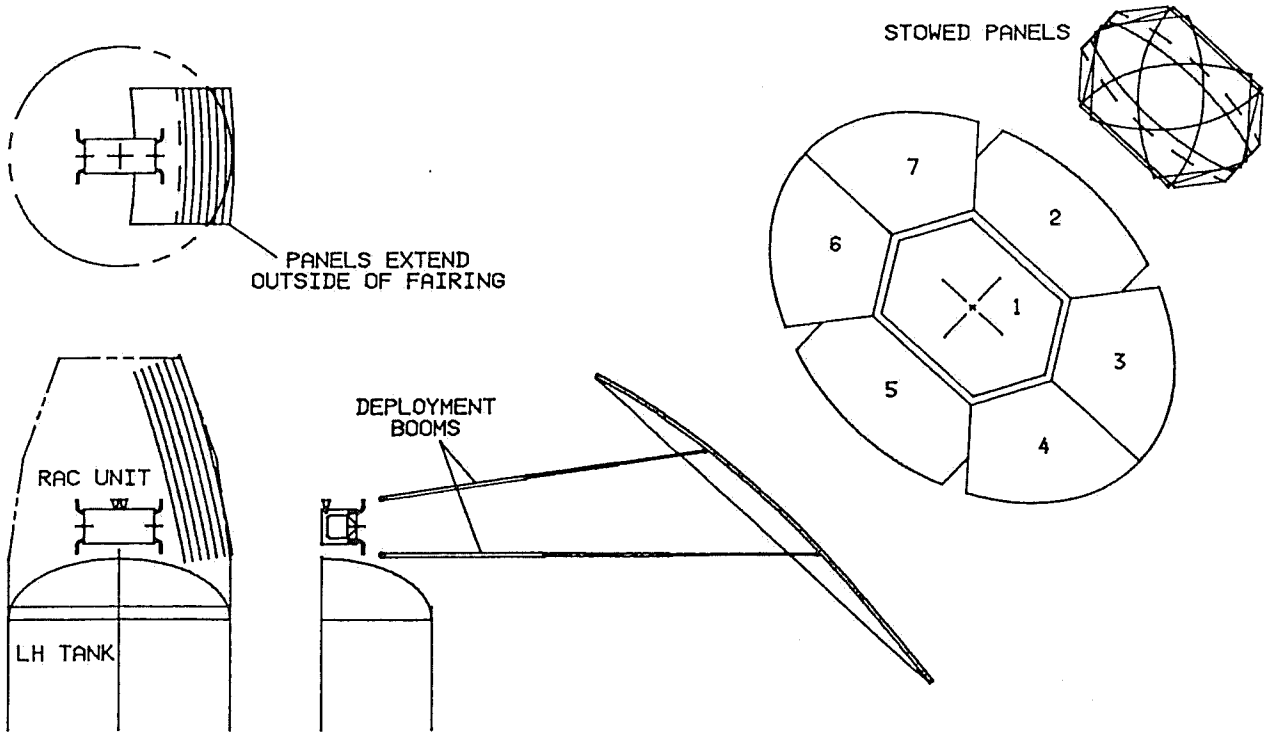


Figure 13. Seven Irregular Panels

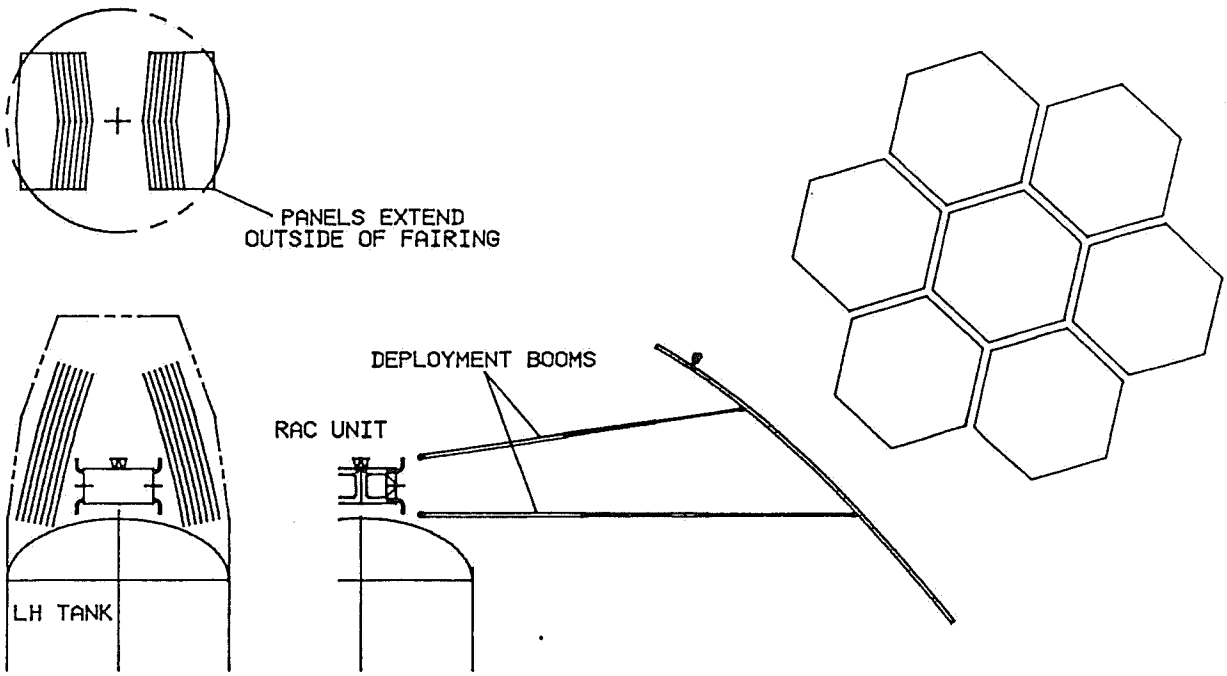


Figure 14. Seven Hexagonal Panels

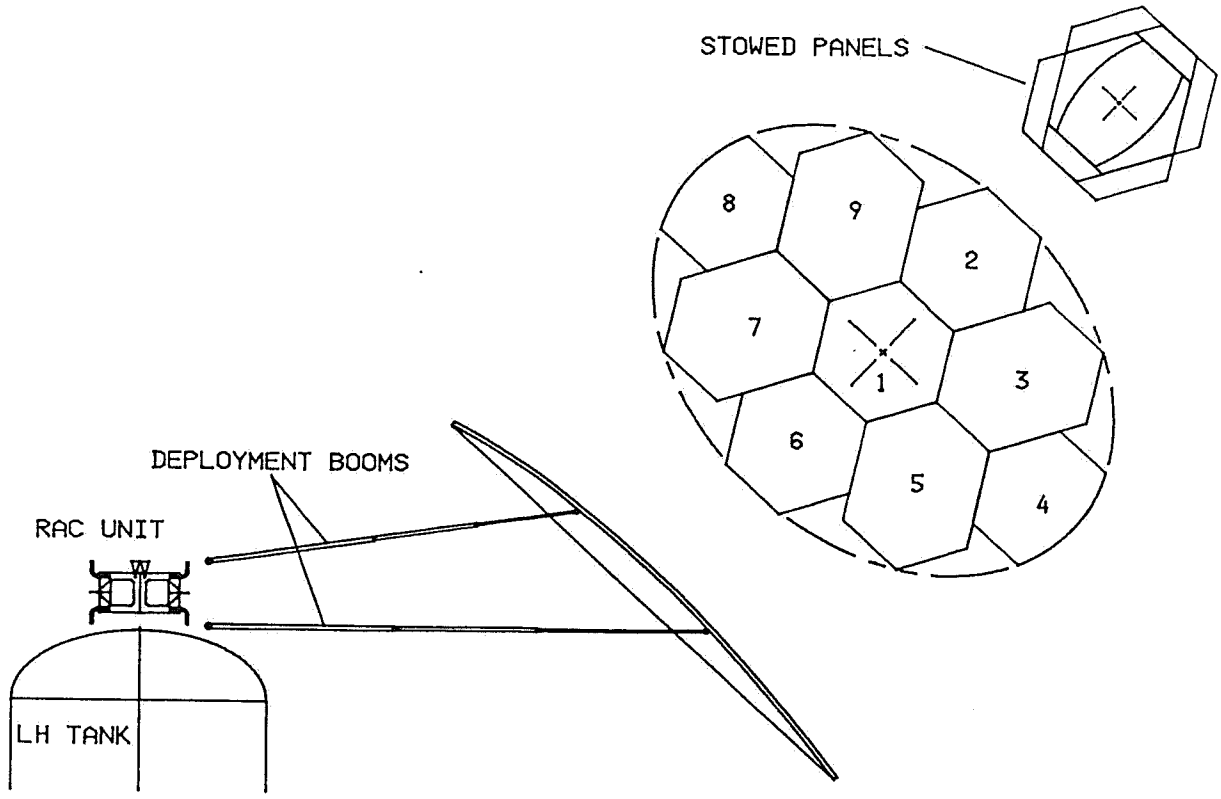


Figure 15. Nine Irregular Panels

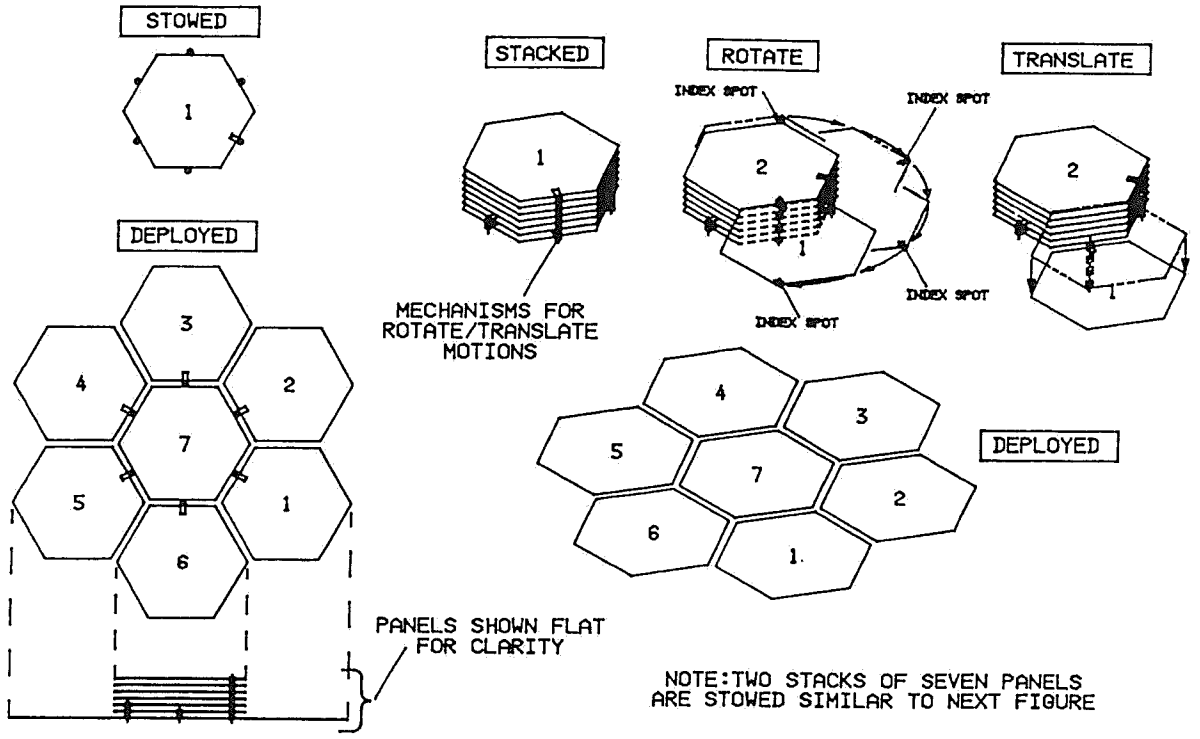


Figure 16. Seven Hex Panels, Rotate and Translate

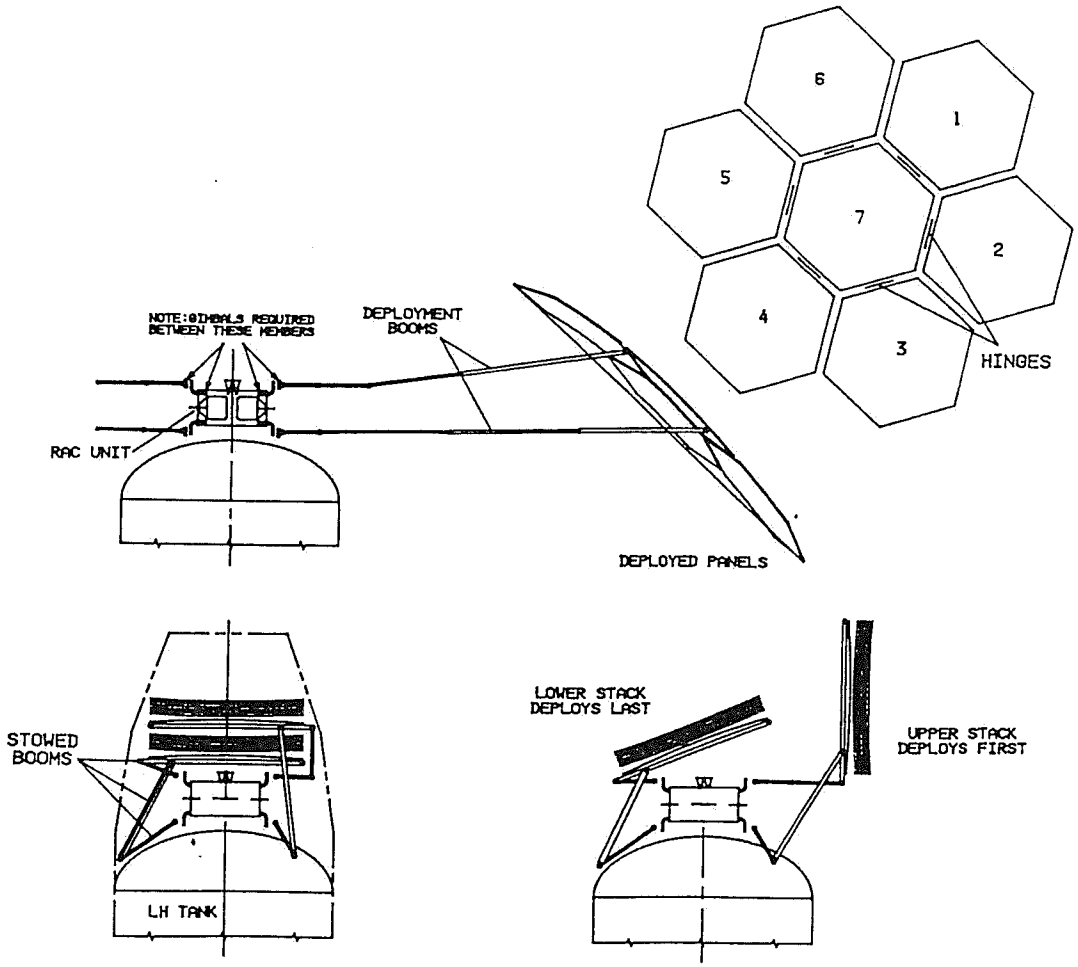


Figure 17. Seven Hex Panels, Hinged

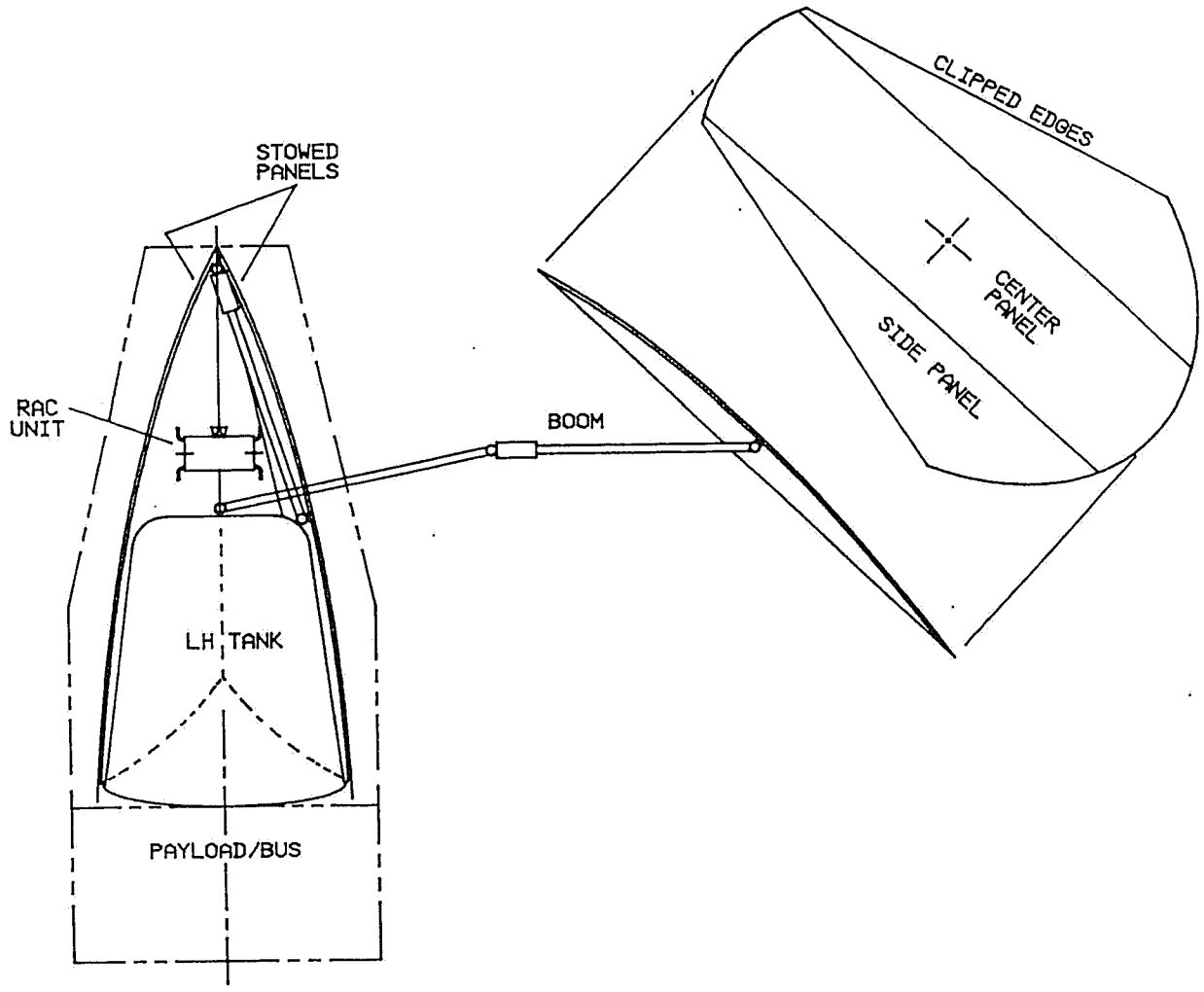


Figure 18. Three Panels, Stowed Forward in Fairing

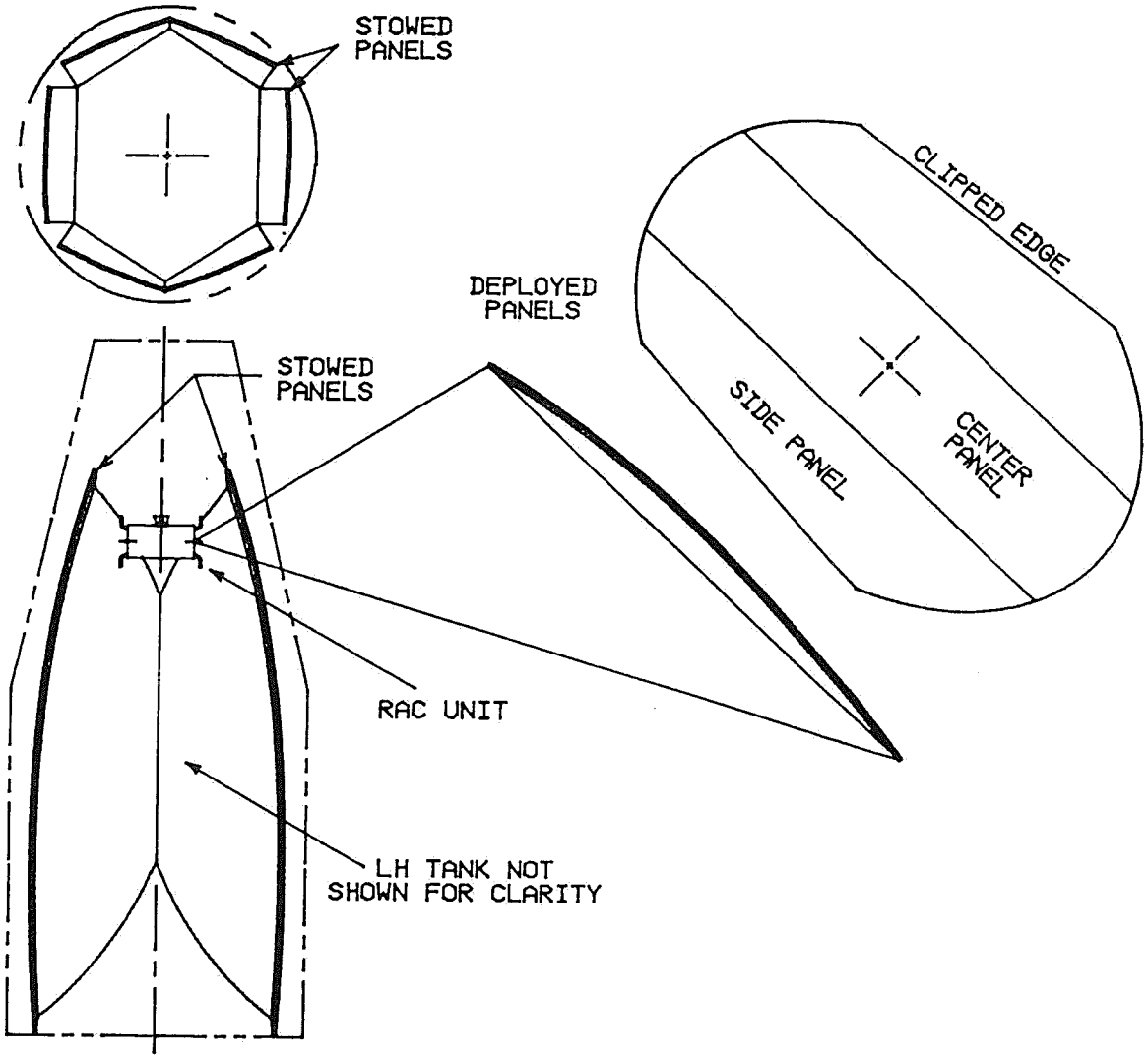


Figure 19. Three Panels, Stowed Aft in Fairing

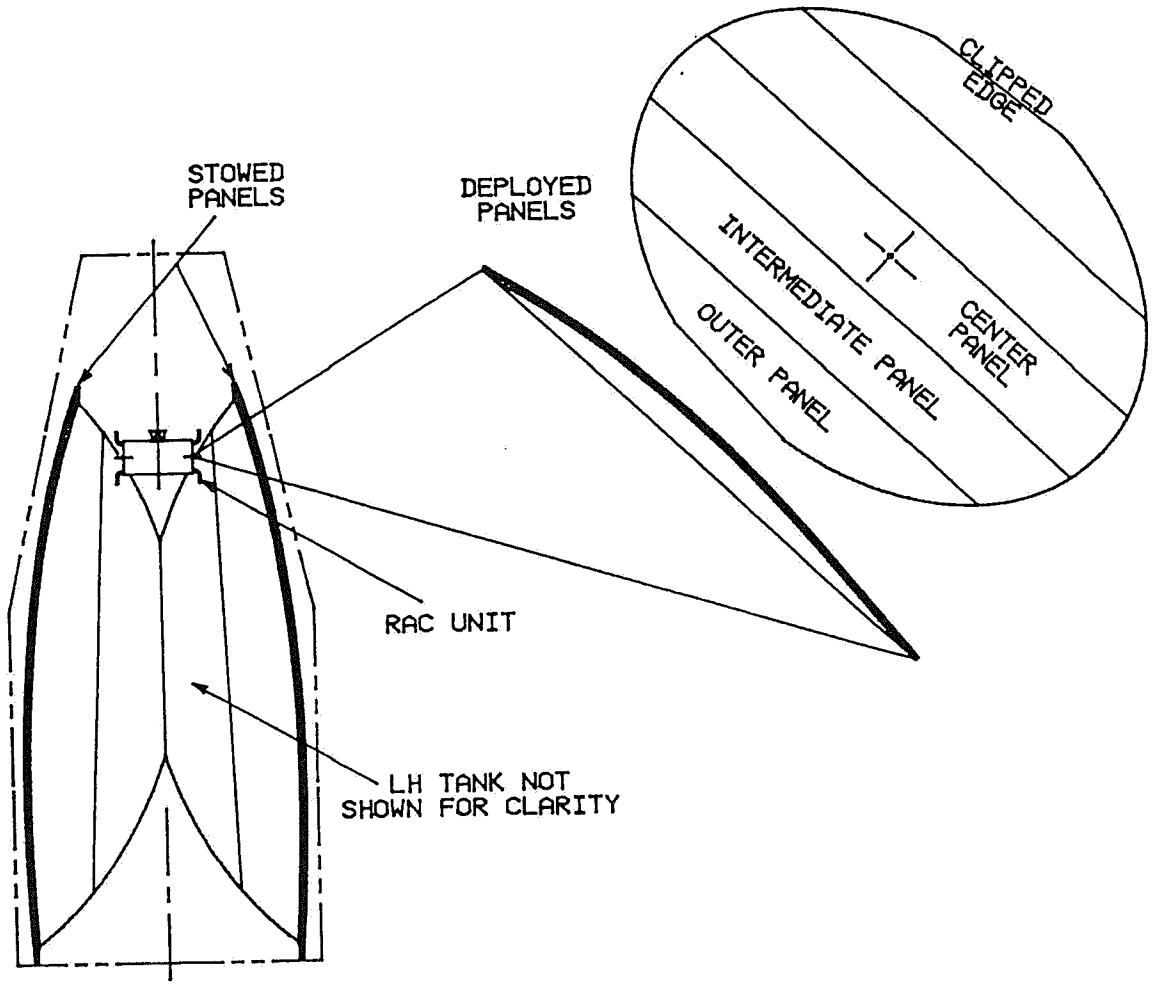


Figure 20. Five Panels, Stowed Aft in Fairing

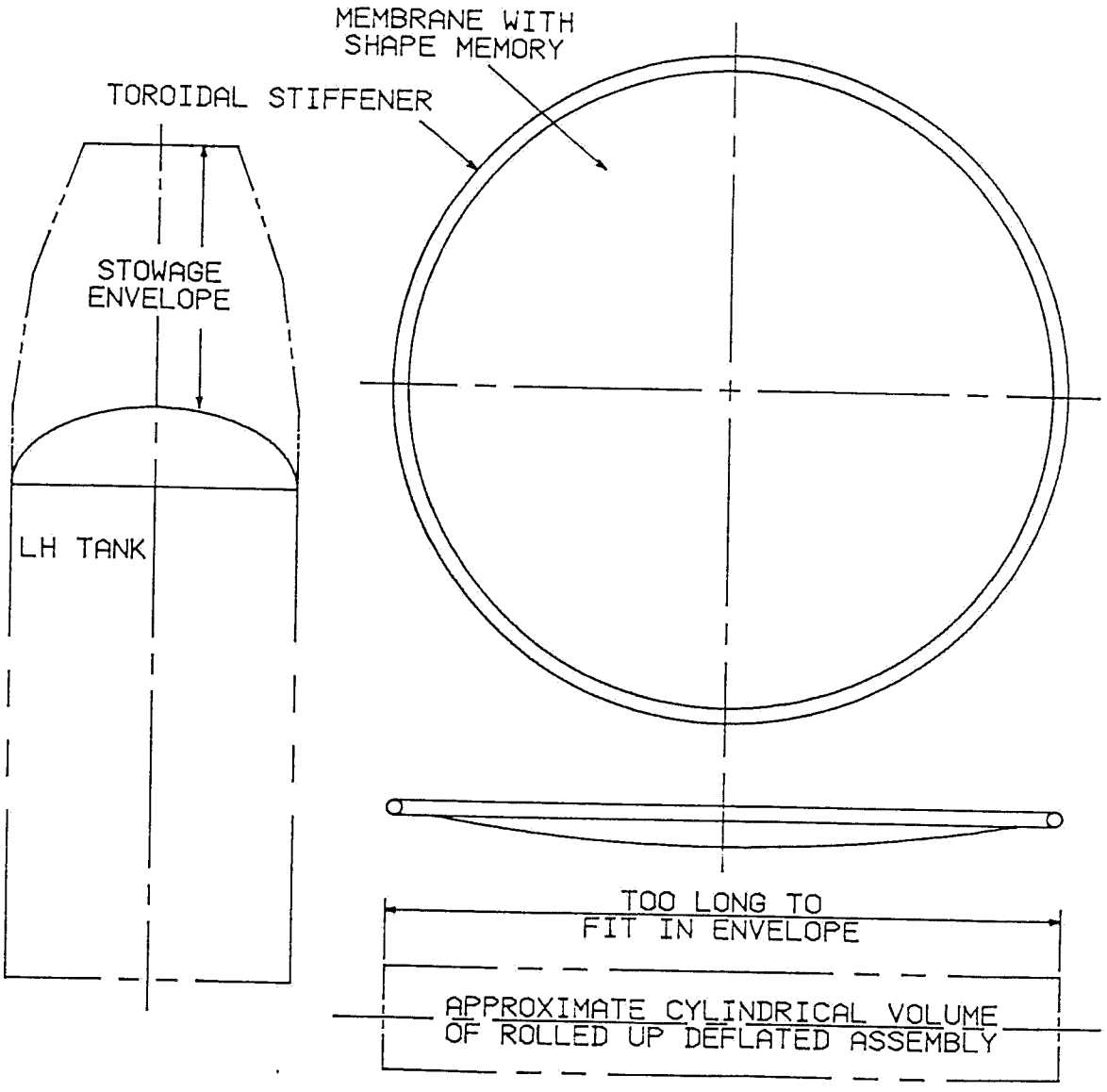
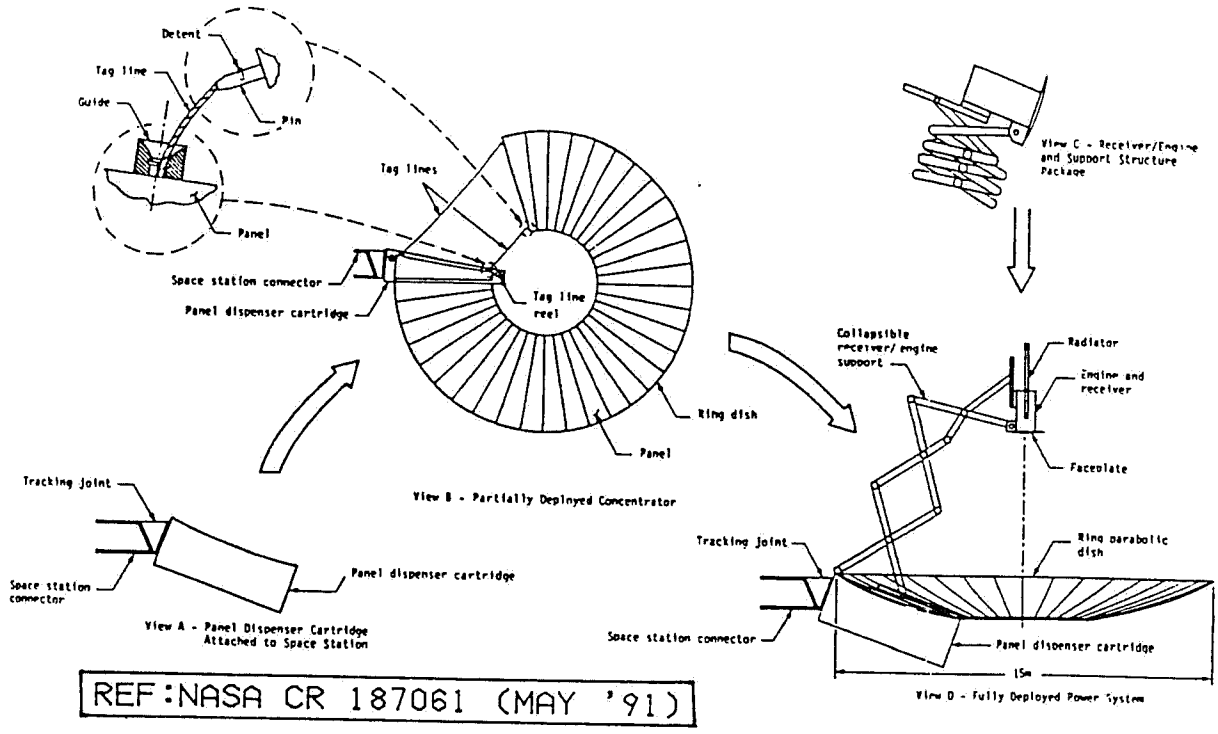


Figure 21. Rolled Inflatable Concept



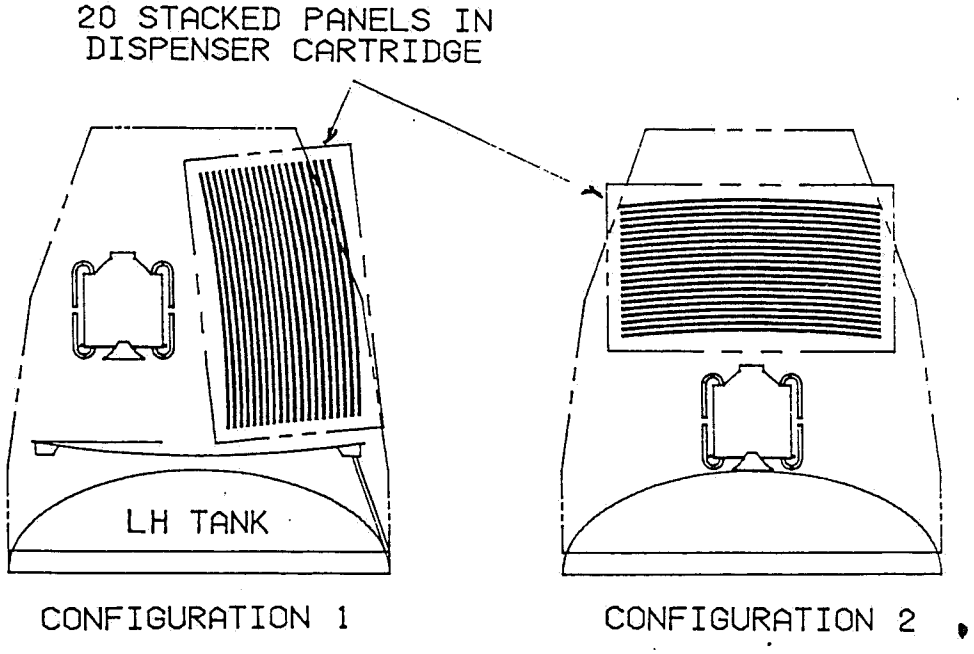


Figure 22. Fan Concept

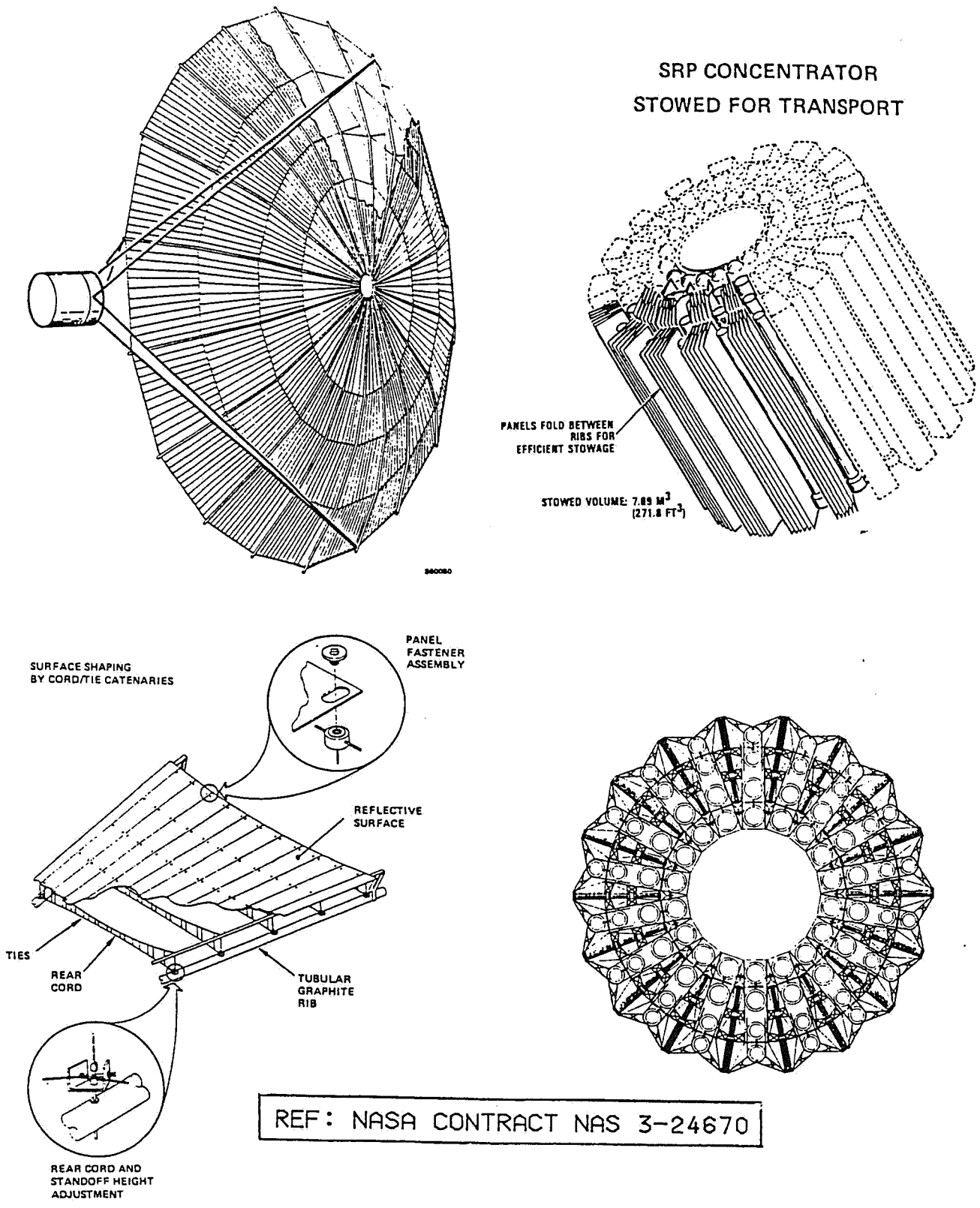


Figure 23. Splined Radial Rib Concept

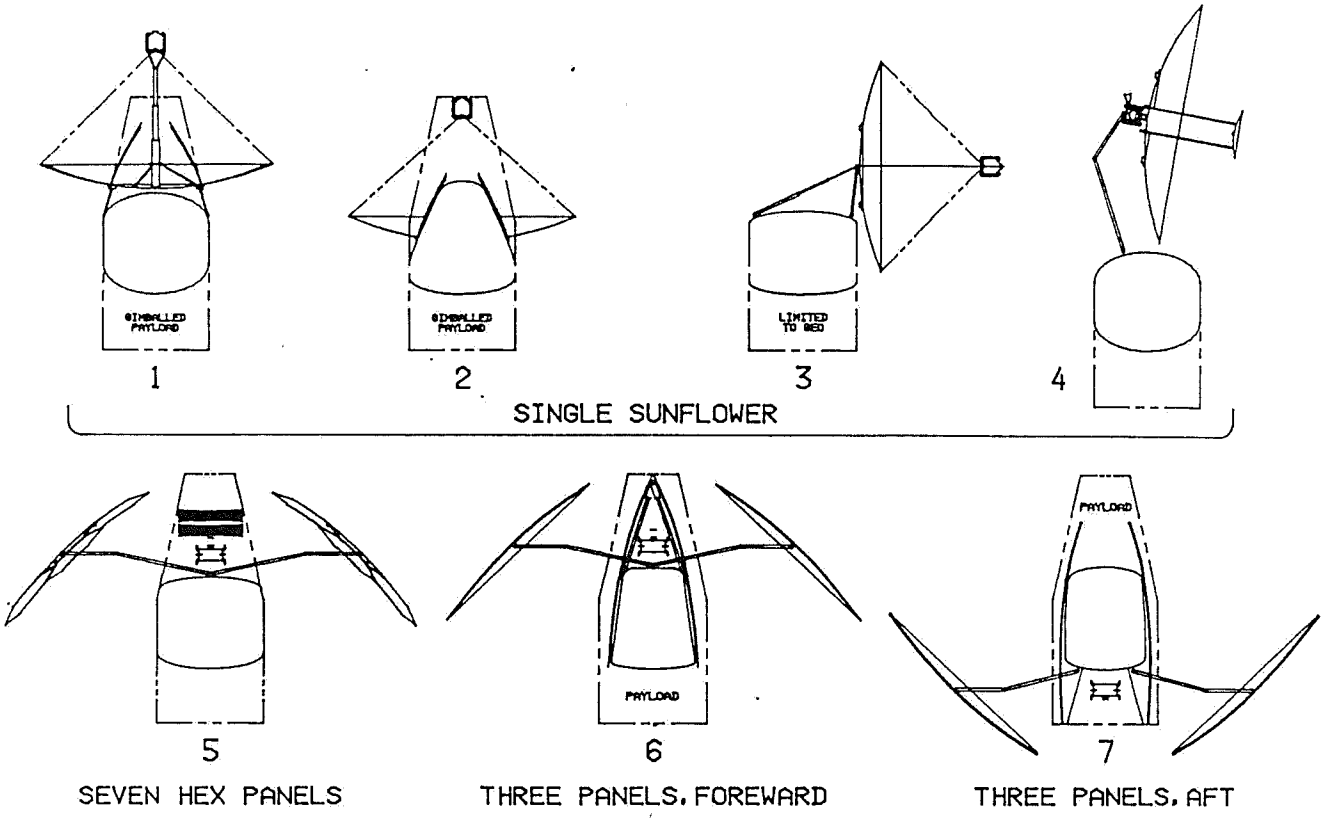


Figure 24. Seven Candidate Configurations

	THREE PANEL	SEVEN HEX
STOWABLE IN TITAN IIG?	YES	YES
1000 We ACHIEVABLE?	YES	YES
DEPLOYMENT COMPLEXITY	◎ LEAST	
SURFACE ACCURACY	◎ BEST	
FABRICATION COST		◎ LOWER
PREVIOUS EXPERIENCE	NONE WITH THIS CONFIGURATION	◎ SSF AND SD GTD
TRACEABILITY TO LLV3	2000 We MAX	◎ 2300 We MAX
PAYLOAD/BUS VOLUME	◎ LARGER	
PAYLOAD/BUS LOCATION	◎ TOP OF VEHICLE	
EFFECT ON LH TANK		◎ SHORTEST

◎ ADVANTAGE

Figure 25. Final Selection Comparison

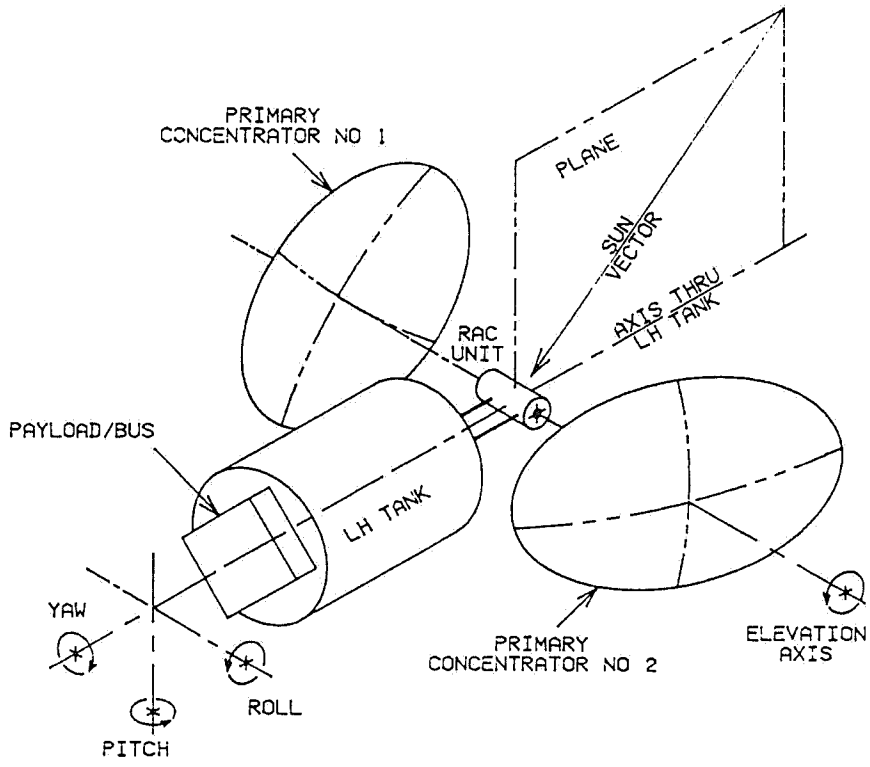


Figure 26. Spacecraft and Concentrator Attitude Control Axes

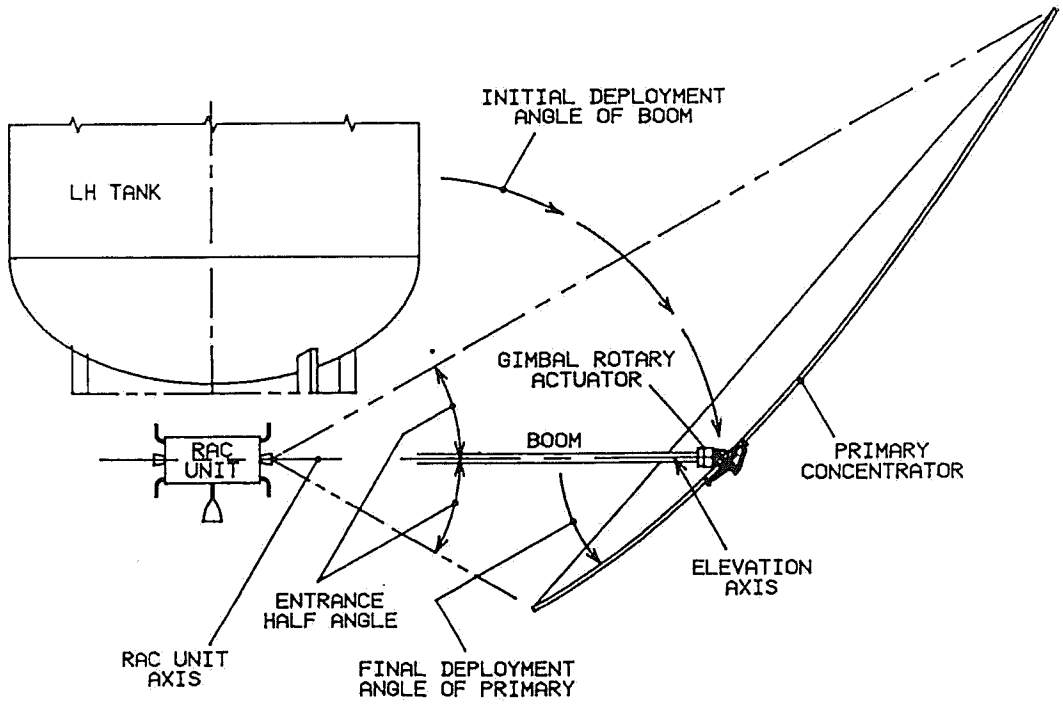


Figure 27. Single Boom Deployment

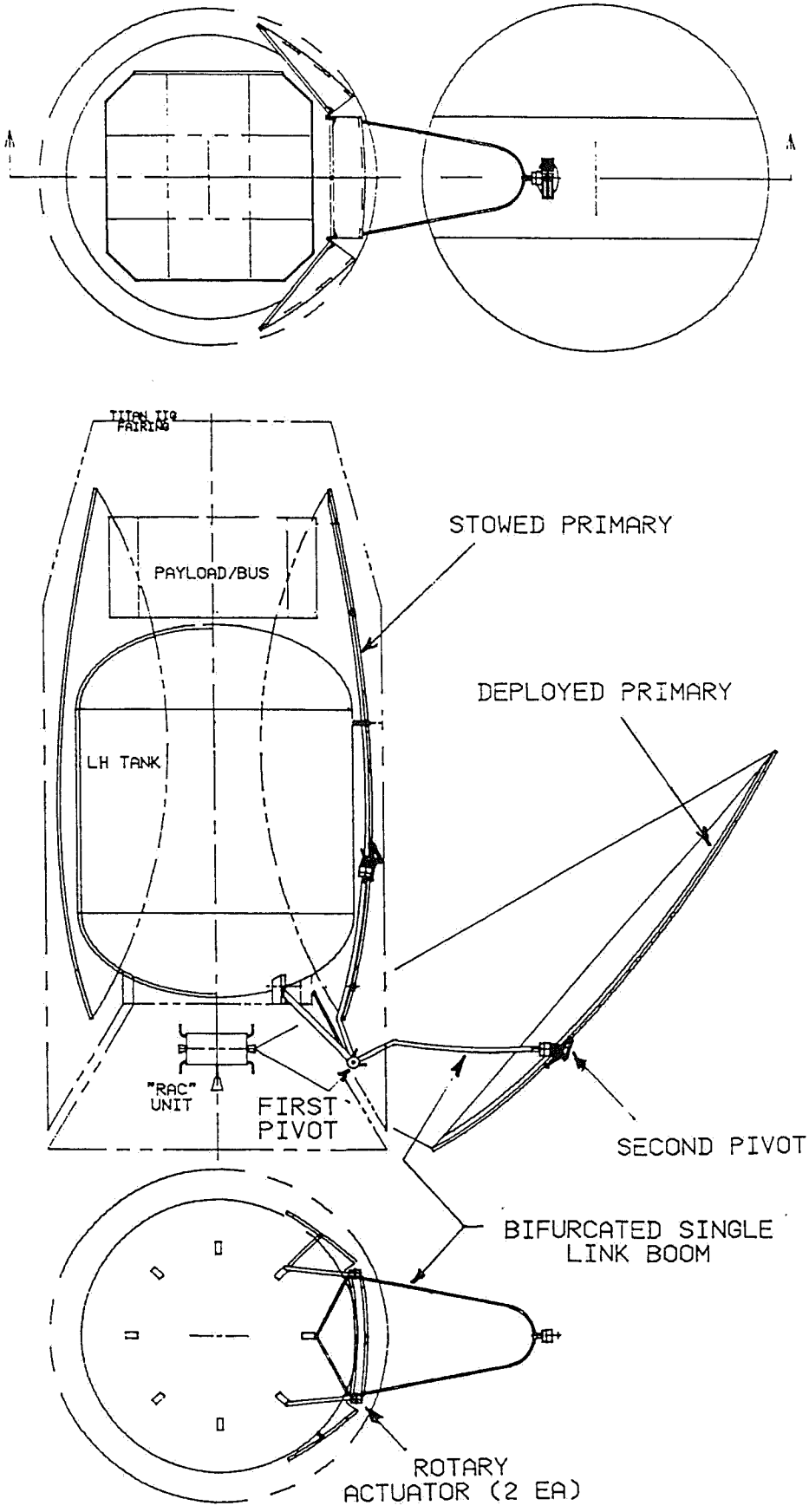


Figure 28. Bifurcated Single Link Boom

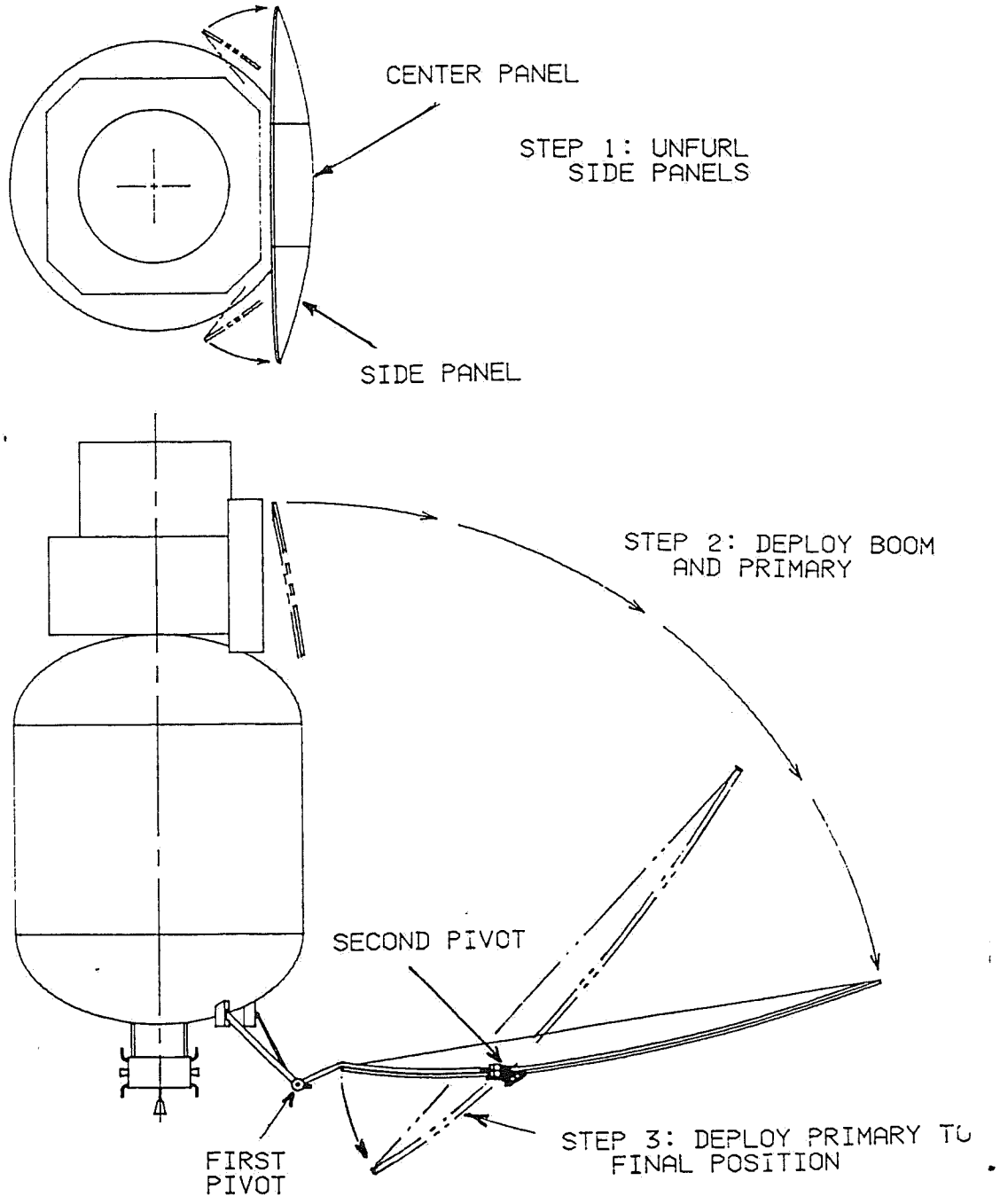


Figure 29. Concentrator Deployment Sequence

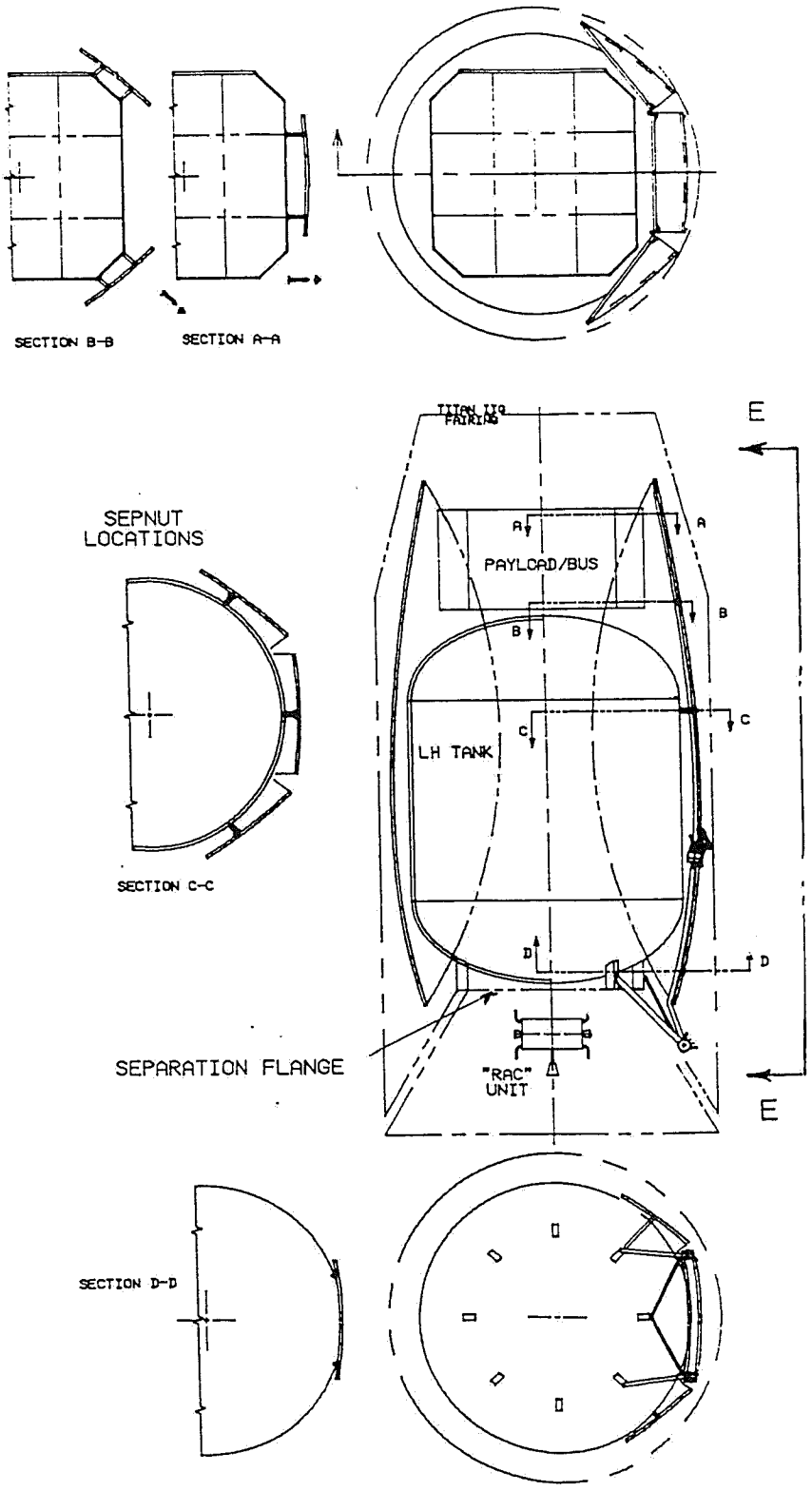


Figure 30. Mount and Support Locations

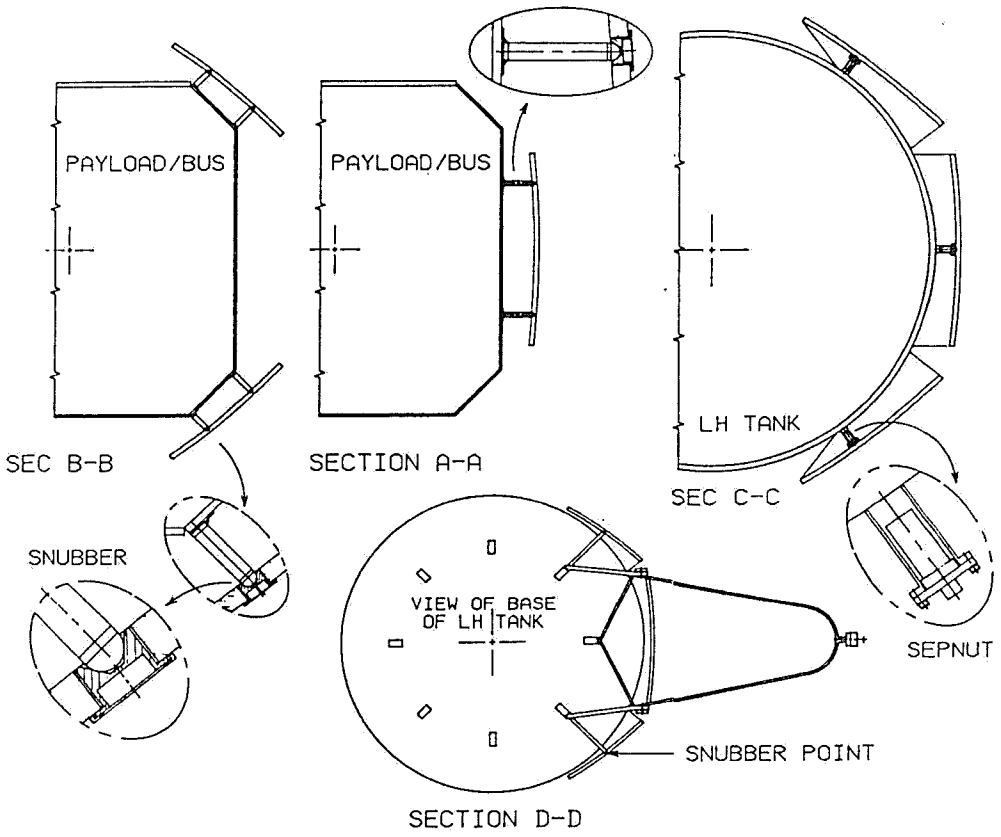


Figure 31. Mount and Support Locations

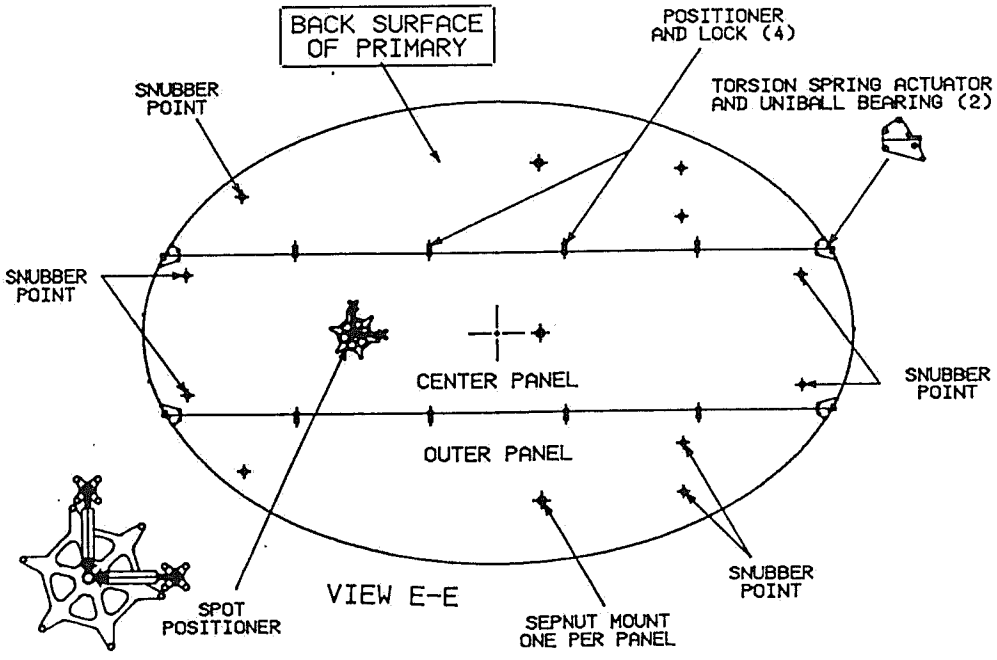


Figure 32. Mount and Support Locations

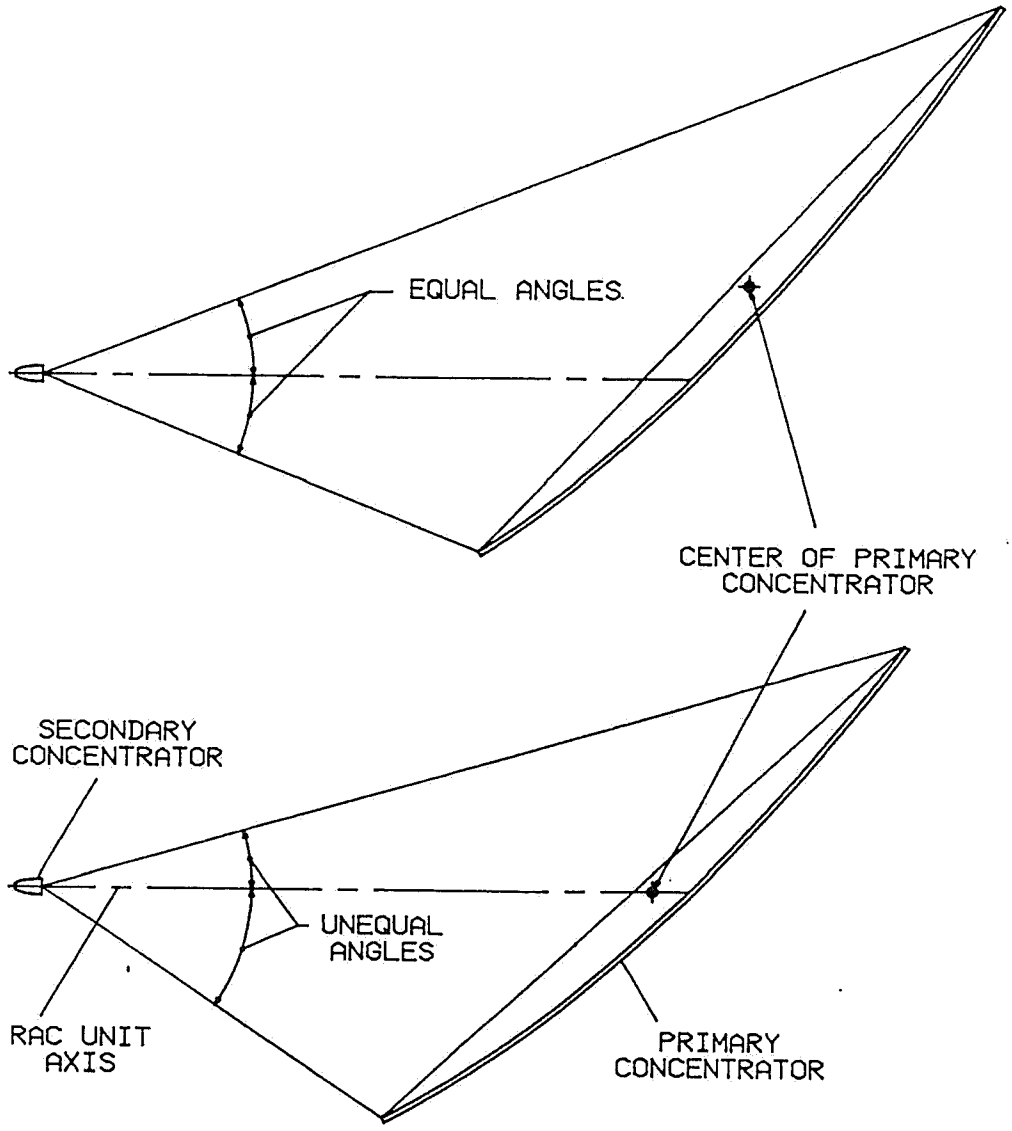


Figure 33. Secondary Concentrator Entrance Angle

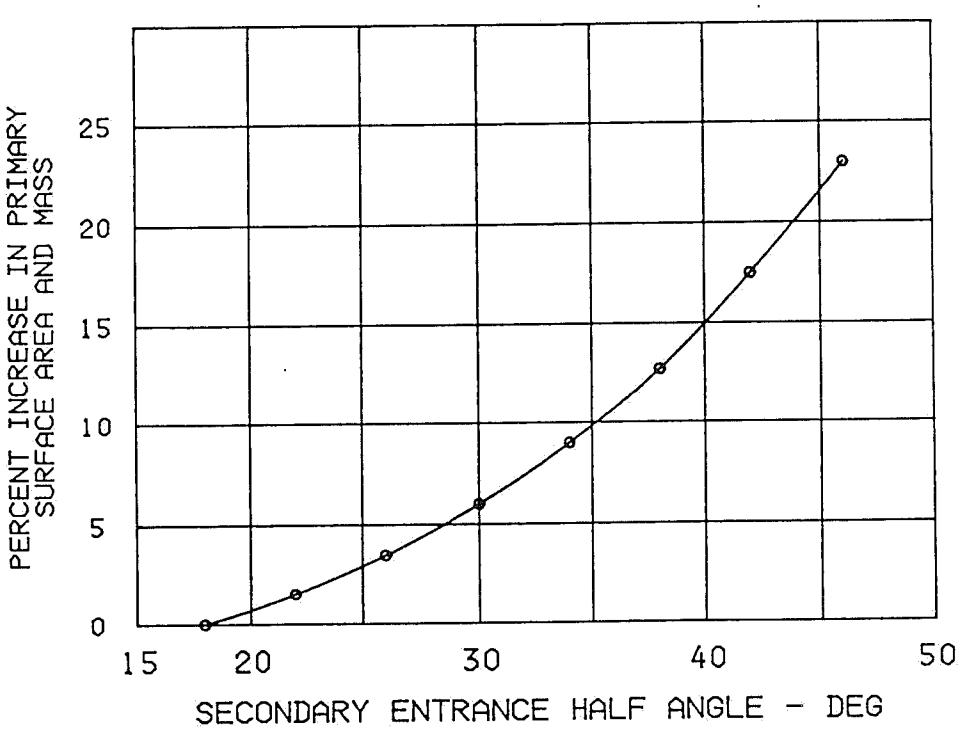


Figure 37. Mass Versus Entrance Angle

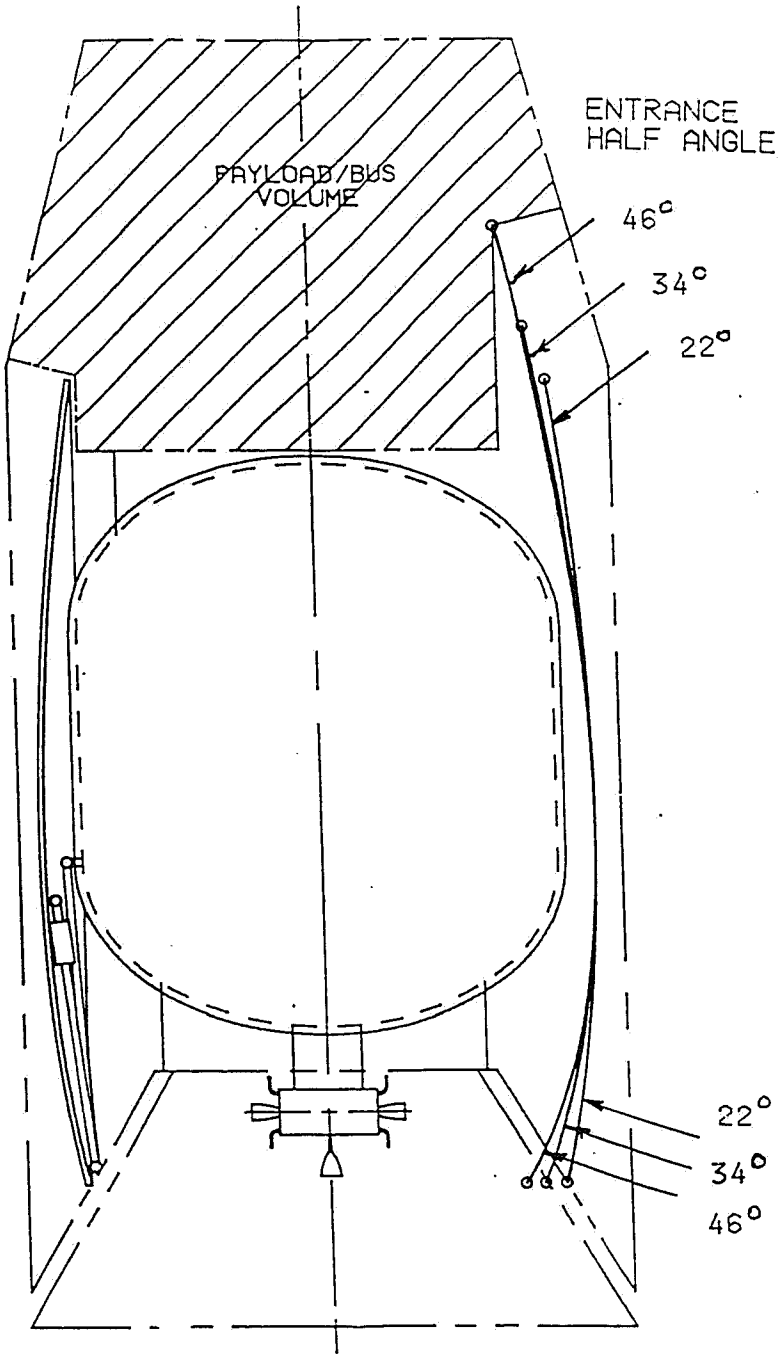


Figure 38. Stowage Versus Entrance Angle

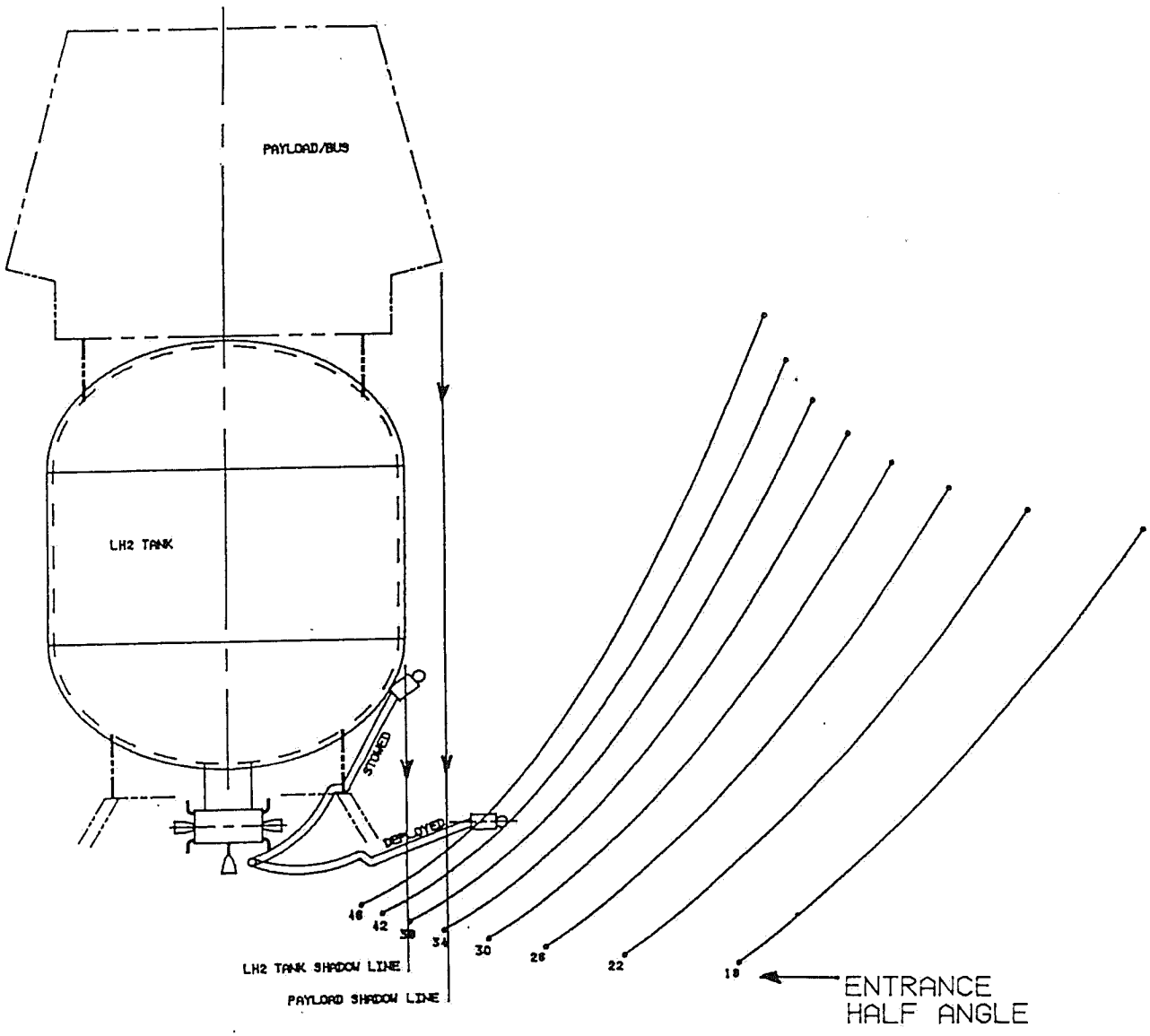


Figure 39. Shadowing Versus Entrance Angle

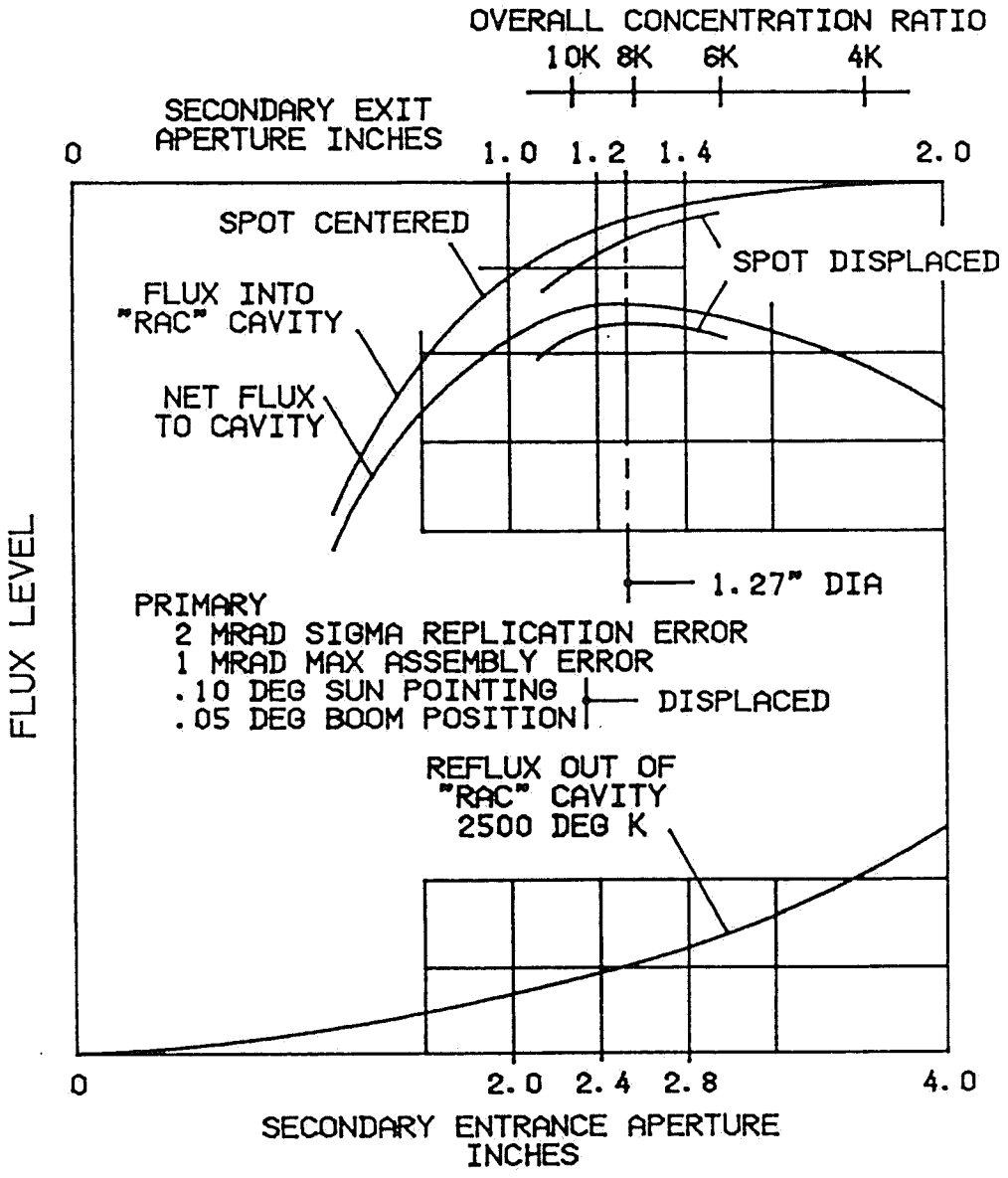


Figure 40. Flux Levels Versus Secondary Entrance Diameter

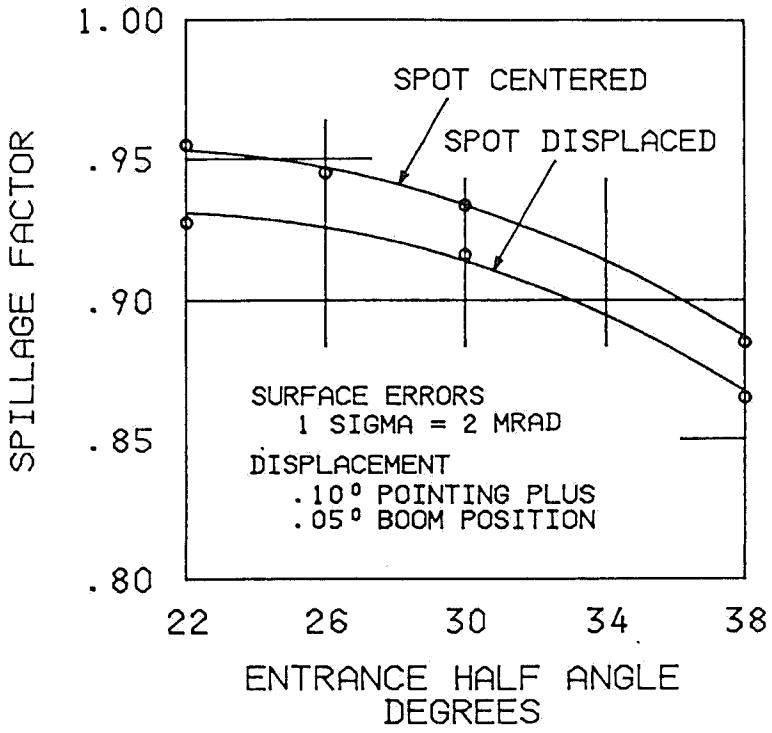


Figure 41. Spillage Factor Versus Entrance Angle

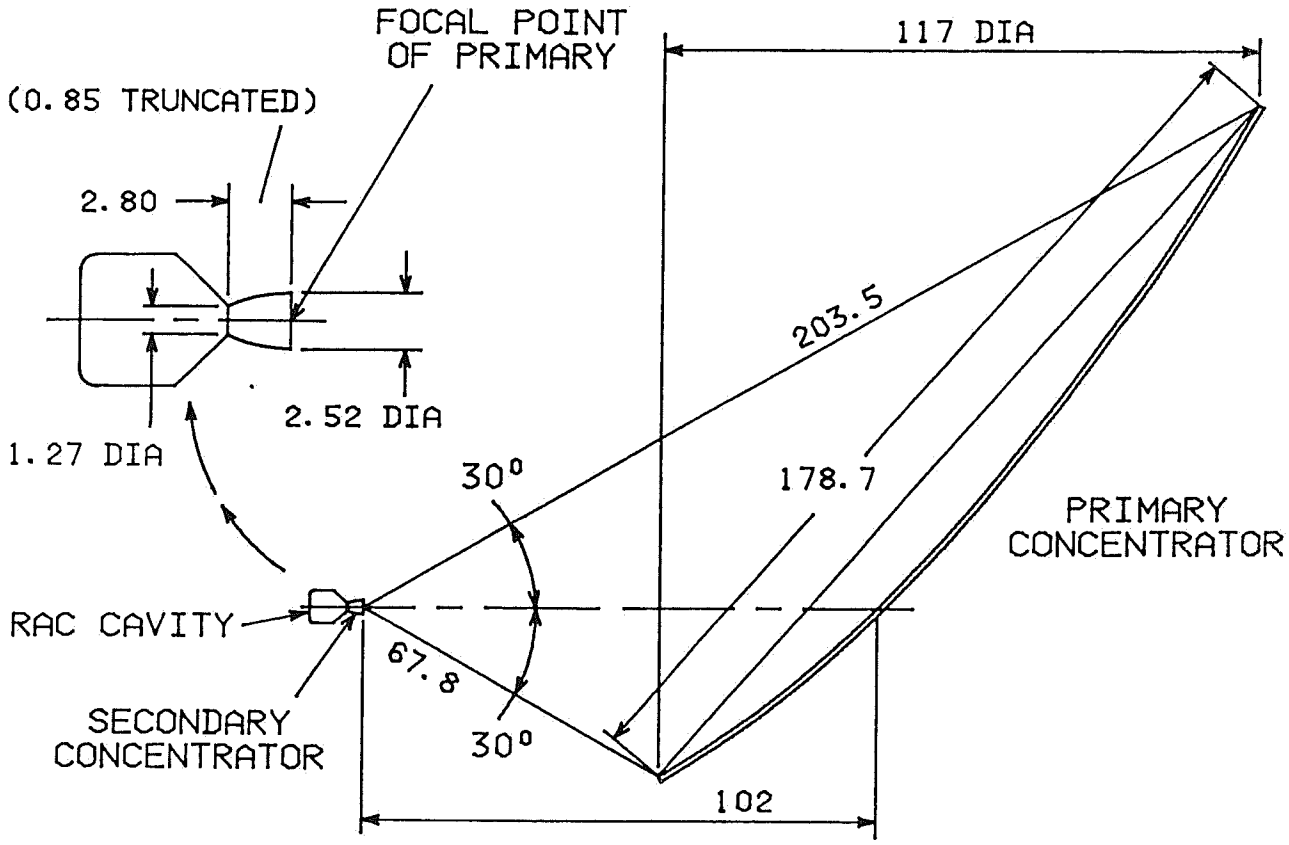


Figure 42. Primary and Secondary Geometry

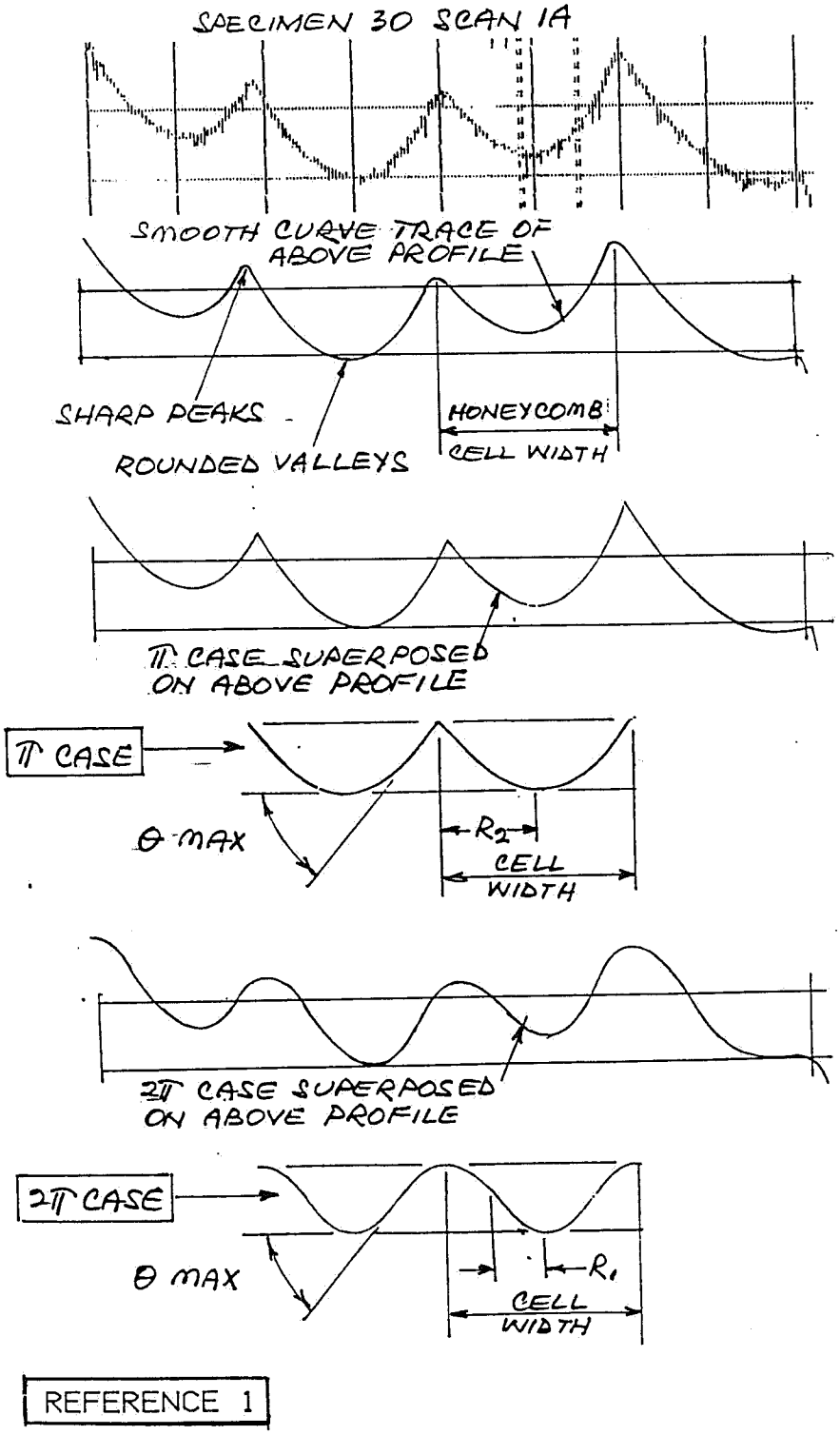


Figure 43. Honeycomb Print Through

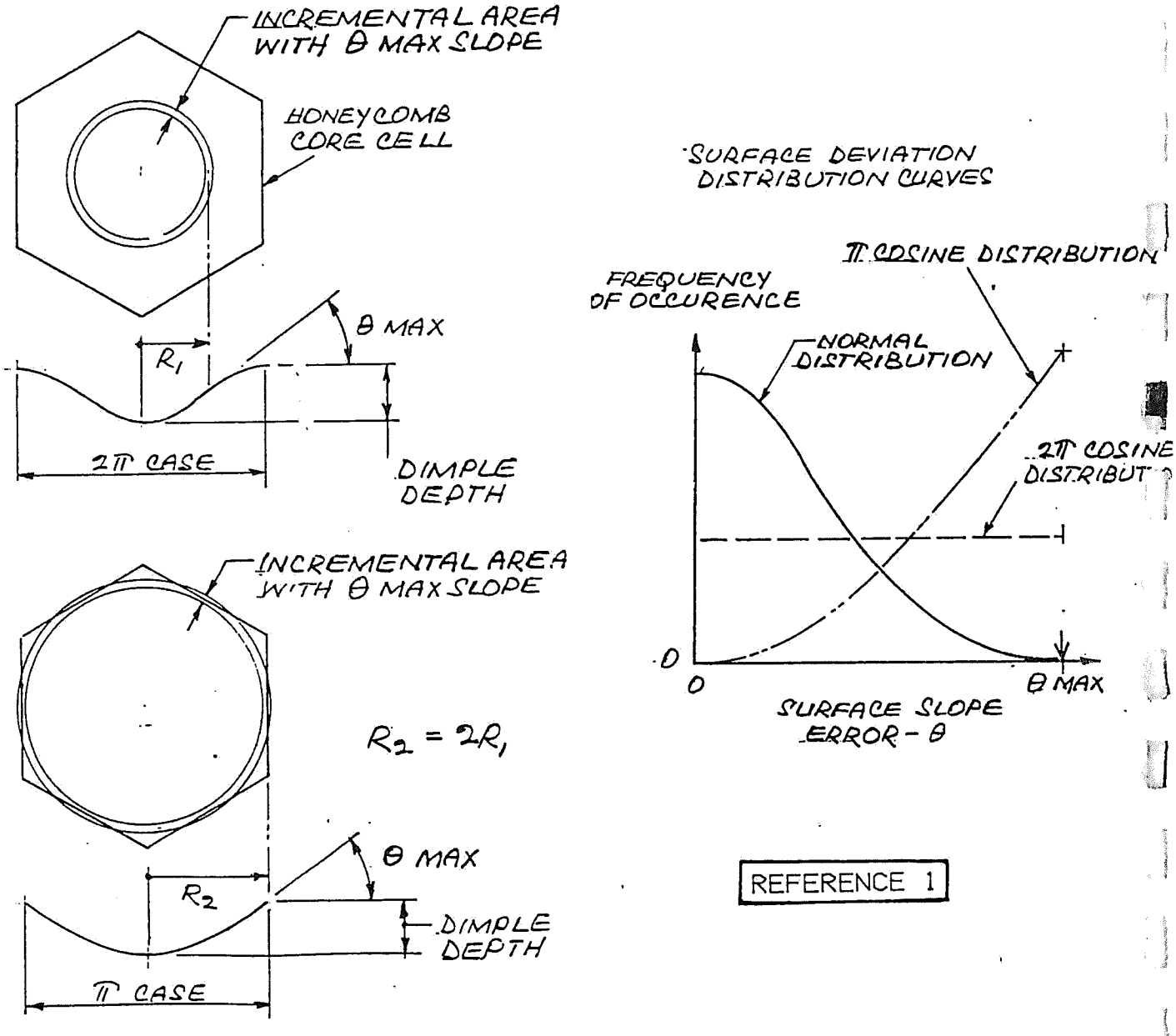


Figure 44. Print Through Models

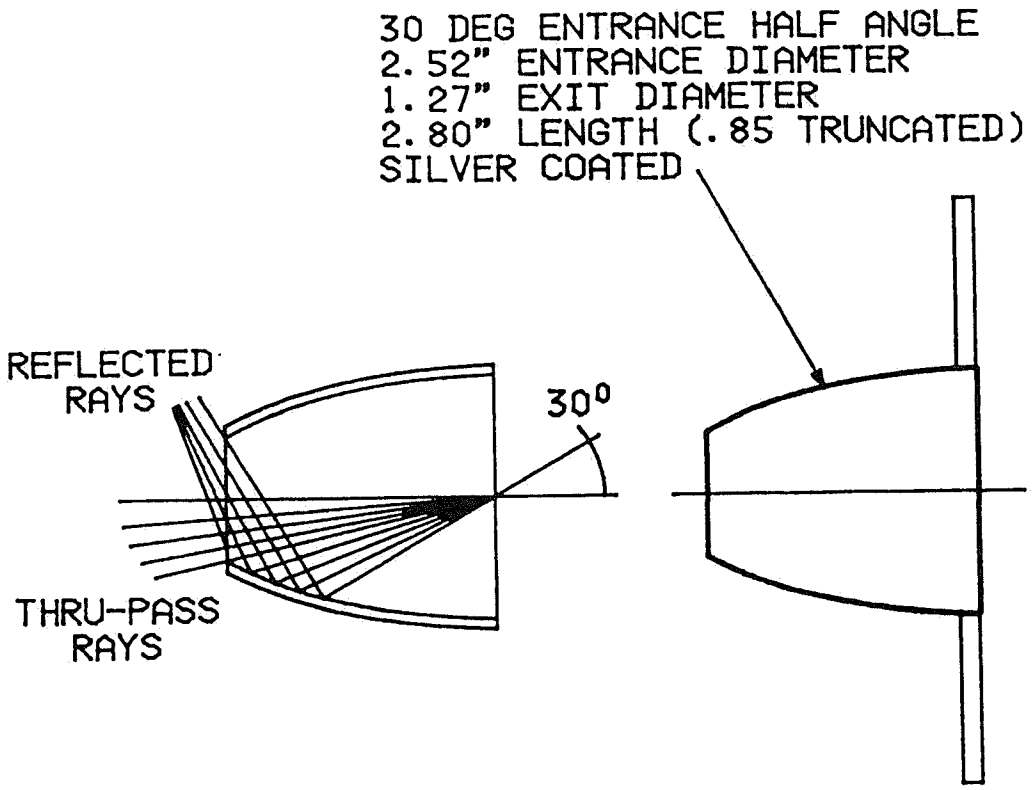


Figure 45.Secondary Concentrator Configuration

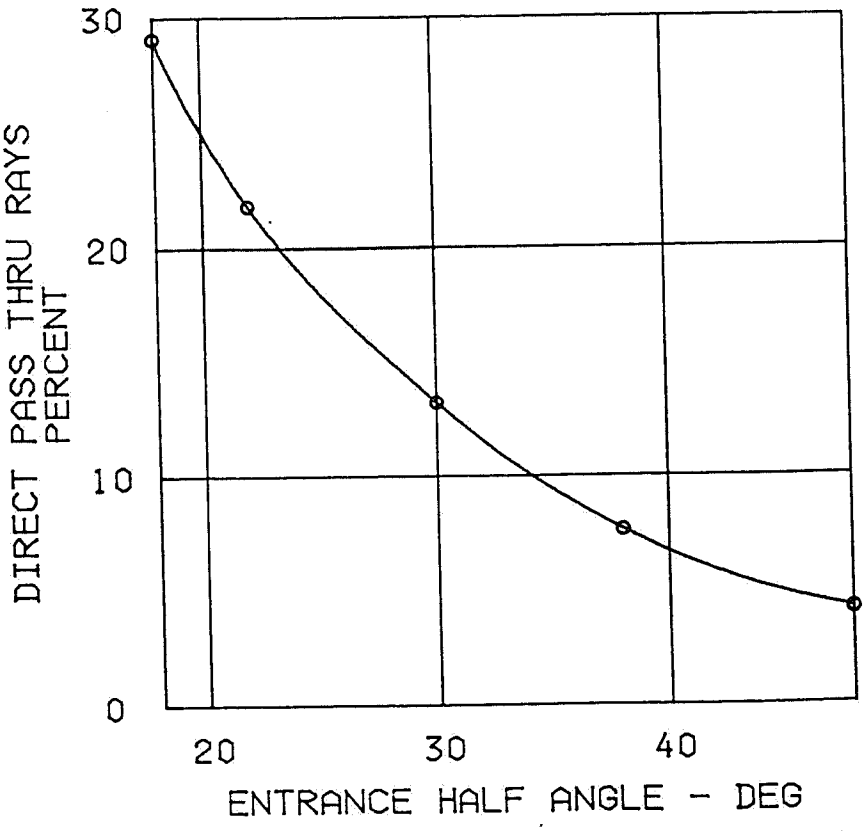


Figure 46. Direct Pass Flux Through Secondary Concentrator

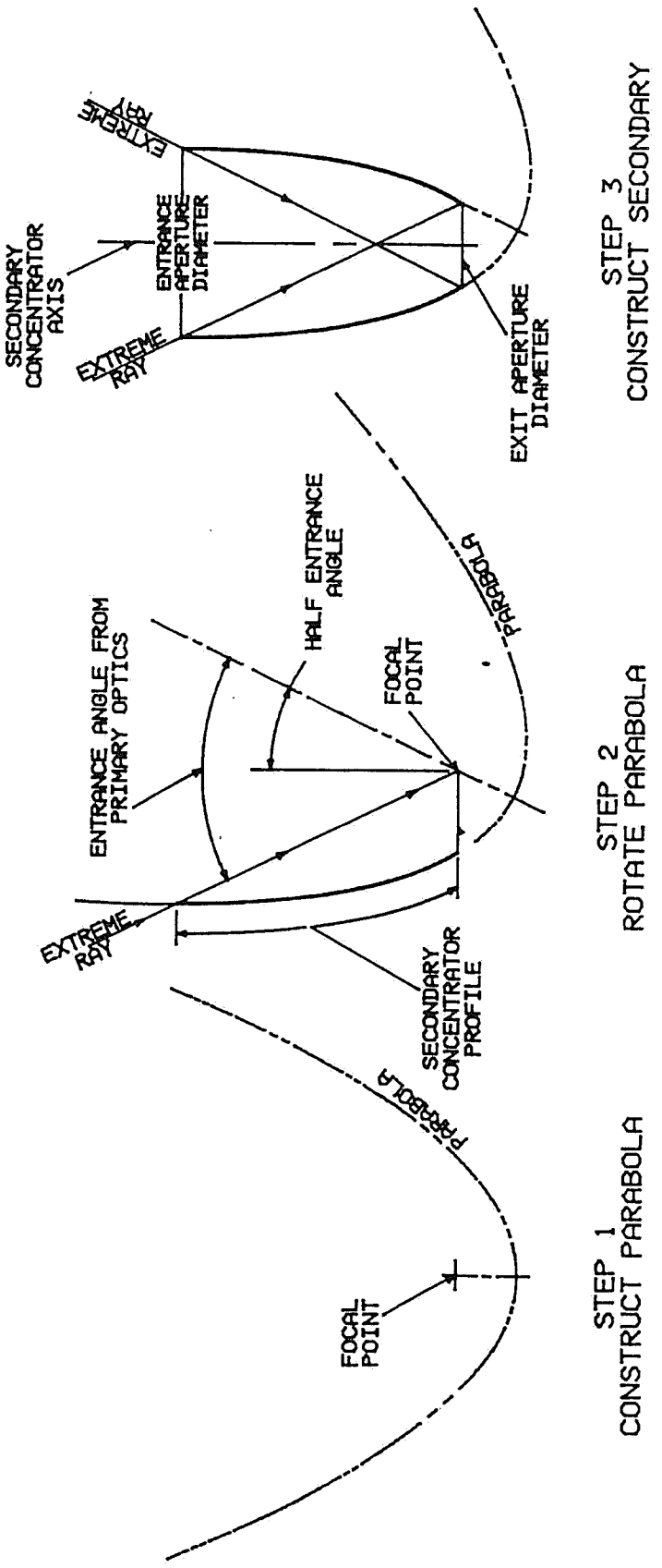
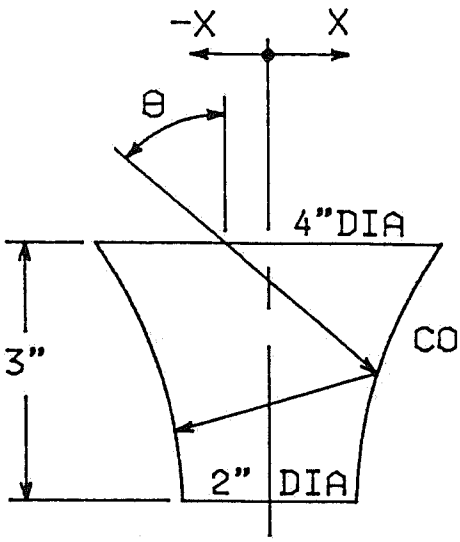


Figure 47. Development of CPC Secondary Concentrator



WINSTON (CHC)
COMPOUND HYPERBOLIC
CONCENTRATOR

$3X^2-Y^2=3$

ENTRANCE POSITION X	ENTRANCE ANGLE θ DEGREES	NUMBER OF REFLECTIONS
-1.5	0-39.5 40-48 48-49.8	0 1 2
-1.0	0-30 33-43 43-43.5	0 1 2
-0.5	0-26 26-37 37-40.5	0 1 2
0	0-18 18-31 31-34.5	0 1 2
0.5	0-9 9-23 23-27.8	0 1 2
1.0	0-14 14-28	1 2
1.5	0-4 4-12	1 2

Figure 48. Winston Compound Hyperbolic Concentrator (CHC)

$$A1 = \frac{Q6}{F1 \times F2 \times K}$$

WHERE:

Q6 = FLUX THRU RAC UNIT APERTURE (EXIT APERTURE OF SECONDARY)

F1 = K1 X R1 X (1-L1)(1-L3)

F2 = R2 X (1-L2)

K = SOLAR CONSTANT (MINIMUM)

A1 = AREA OF INTERCEPTED SOLAR FLUX

K1 = PRIMARY EFFICIENCY FACTOR

R1 = EFFECTIVE REFLECTIVITY OF PRIMARY

L1 = DERADATION OF REFLECTIVITY OF PRIMARY

L3 = SHADOW AND OTHER LOSSES

R2 = EFFECTIVE REFLECTIVITY OF SECONDARY

L2 = DEGRADATION OF REFLECTIVITY OF SECONDARY

F1 = 0.93 X 0.96(1-.02)(1-.02) = 0.86

F2 = 0.87(1-.05) = 0.83

F1 X F2 = 0.86 X 0.83 = 0.71
OVERALL CONCENTRATOR EFF. FACTOR

$$A2 = \frac{6.5}{0.86 \times 0.83 \times 0.122} = 74.6 \text{ FT2}$$

Figure 49. Overall Concentrator Efficiency

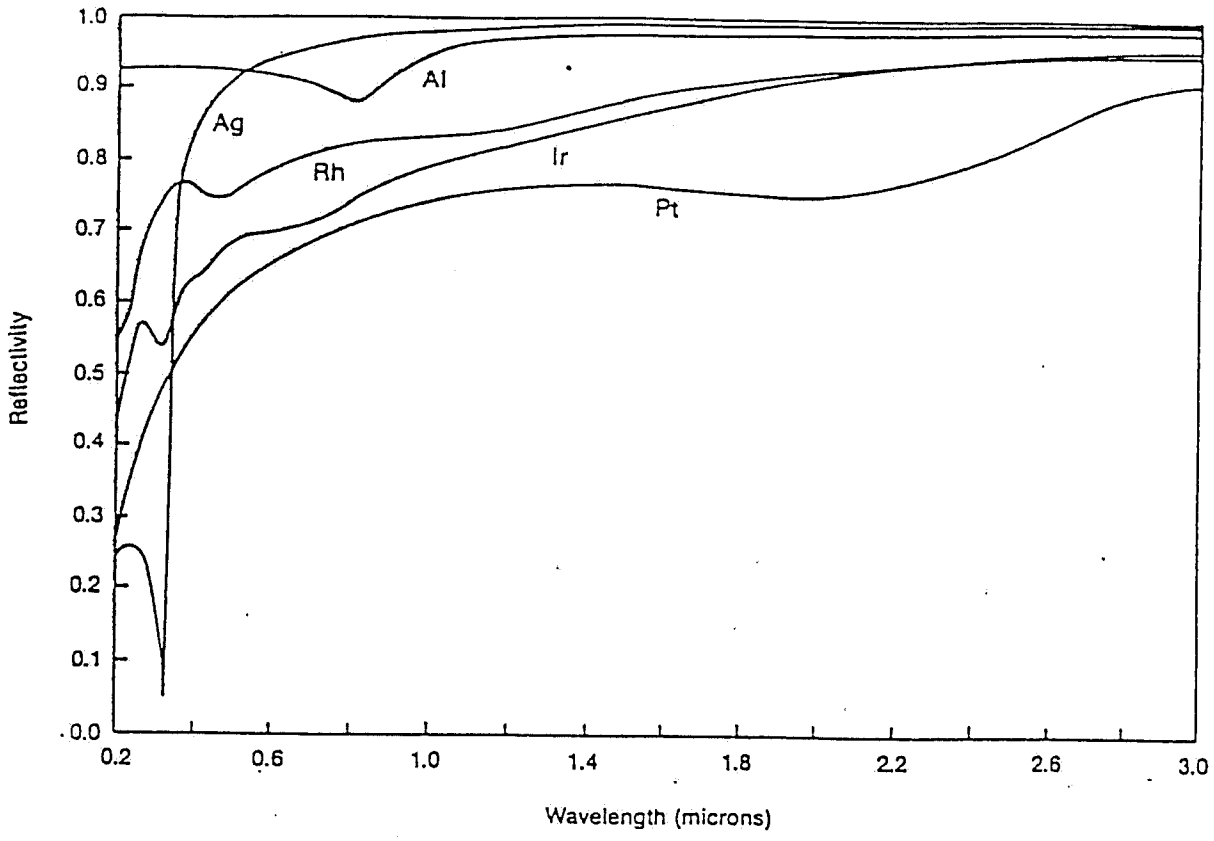
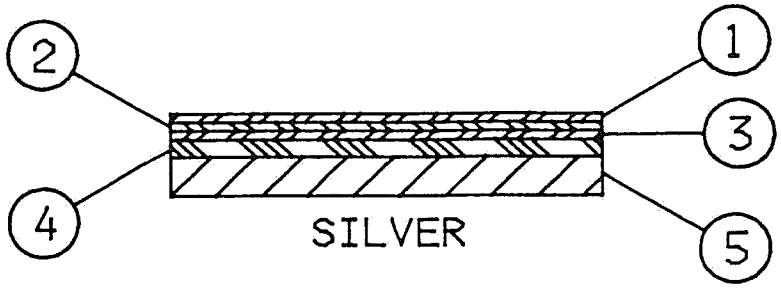


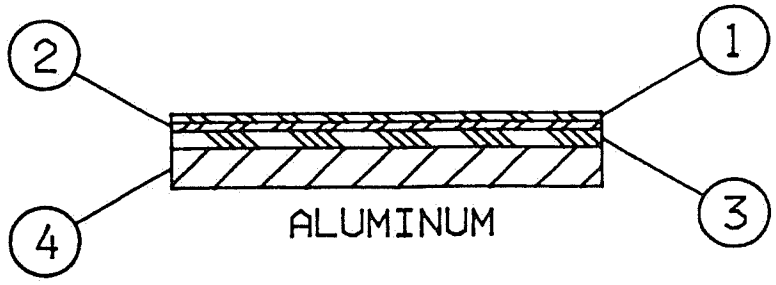
Figure 50. Spectral Reflectivity of Deposited Metals

Environmental Parameter	Concentrator Concerns
Vacuum	Outgassing results in loss of moisture and solvents resulting in dimensional and mechanical property changes. Outgassing could contaminate reflective surfaces resulting in loss in efficiency.
Ultraviolet	Degradation of coatings
Protons	Degradation of coatings and surface plies of composites
Electrons	Surface and bulk damage
Temperature Cycling	Microcracking, thermal distortion, deterioration of concentrator efficiency
Atomic Oxygen	Degradation of reflective surface, coatings, and composites
Micrometeoroid Debris	Concentrator surface damage

Figure 51. On Orbit Considerations

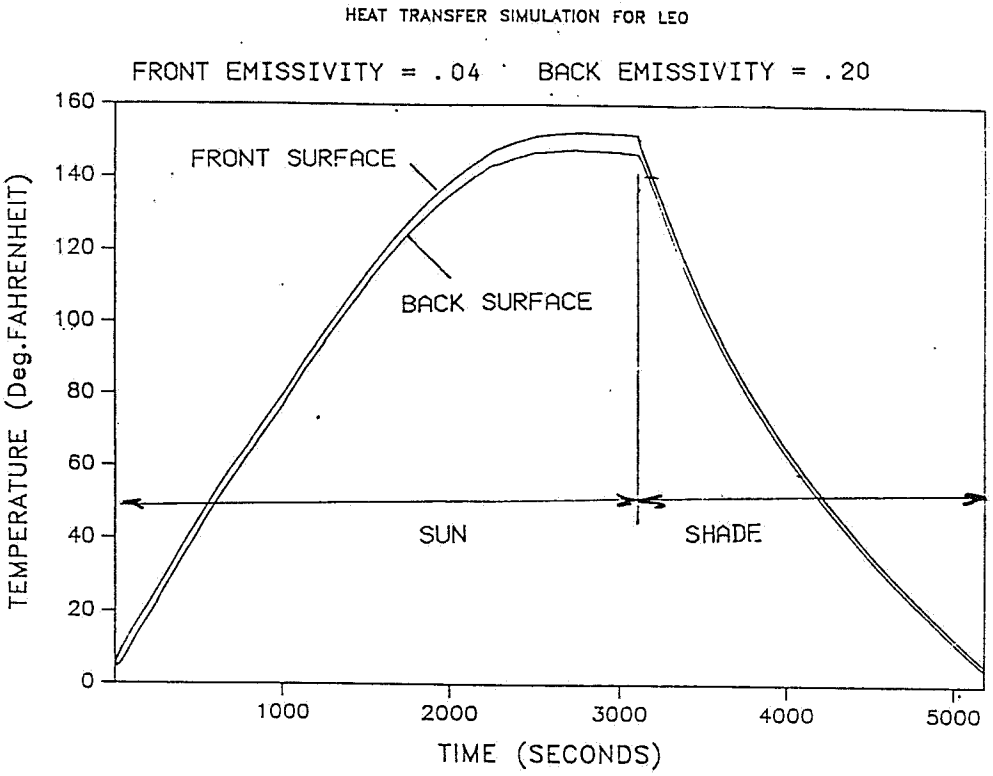


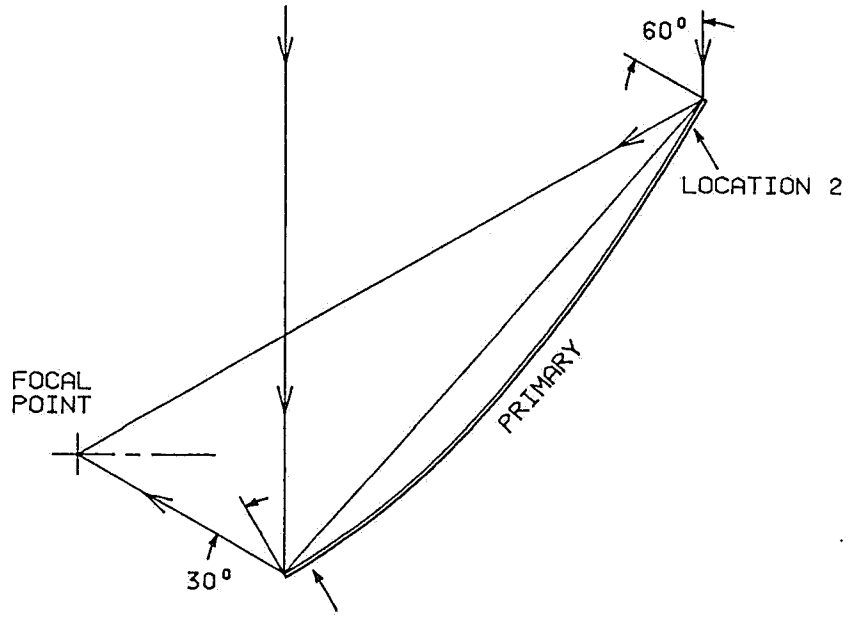
1. PROTECTIVE COATING	SiO2	1000	Ang
OVER	Al2O3	1000	Ang
2. REFLECTIVE SURFACE	Ag	2000	Ang
3. ADHESION PROMOTER	Cu	700	Ang
4. LEVELING LAYER			
5. SUBSTRATE			



1. PROTECTIVE COATING	SiO2	2000	Ang
2. REFLECTIVE SURFACE	Al	2000	Ang
3. LEVELING LAYER			
4. SUBSTRATE			

Figure 52. Silver and Aluminum Reflective Layers





CASE	RADIATIVE PROPERTIES		TEMPERATURE DEG F			
			LEO		MOLNIYA	
			LOCATION		LOCATION	
	FRONT	BACK	1	2	1	2
1	E1=.04 E2=.04 A1=.07 A2=.04	E3=.20 A3=.20	204	180	39	-25
2	E1=.04 E2=.04 A1=.07 A2=.04	E3=.10 A3=.04	198	155	111	38

Figure 53. Concentrator Temperature On Orbit

	POUNDS	KG
PANELS AT 2 KG/M2	47.60	21.60
SPHERICAL BEARING FLANGE	0.52	0.23
SPHERICAL BEARING	0.90	0.41
BEARING & SPOT POSITIONER SHAFT	0.37	0.17
SPOT POSITIONER SUPPORTS (2)	0.84	0.38
SEPNUTS & SUPPORTS (3)	1.29	0.60
STANDOFFS & SNUBBERS (3)	0.63	0.30
SPOT POSTIONER ACTUATORS (2)	0.60	0.27
SUB TOTAL	52.75	23.96
HINGES (4)	2.16	1.00
PANEL LOCKS (6)	2.14	0.96
PANEL DEPLOYMENT ACTUATOR ASSY (4)	6.16	2.80
SUB TOTAL	10.46	4.76
TOTAL CONCENTRATOR MASS		
SINGLE CONCENTRATOR	63.21	28.72
DOUBLE CONCENTRATOR	126.42	57.44

Figure 54. Concentrator Mass Summary

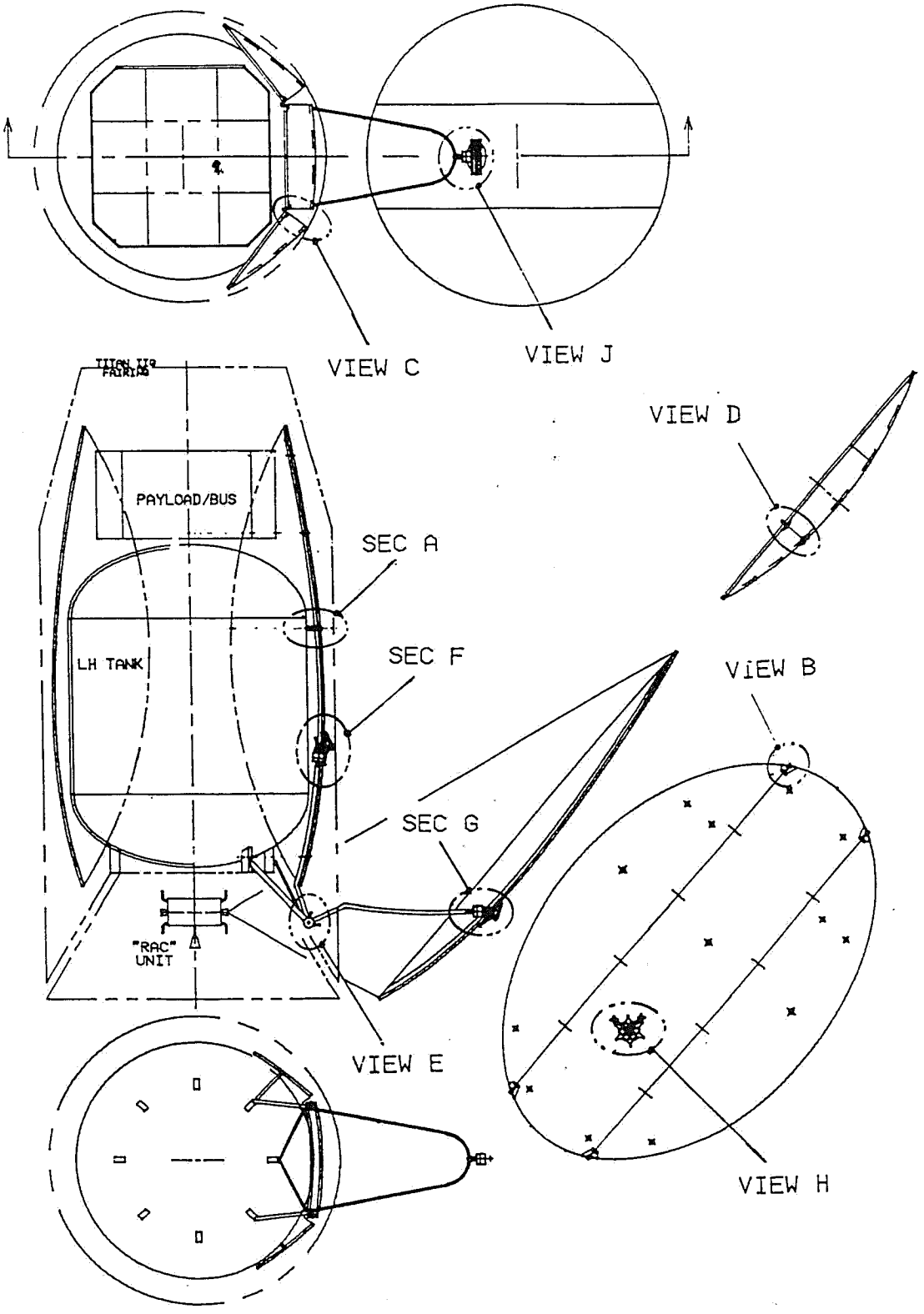


Figure 55. Actuation and Positioning

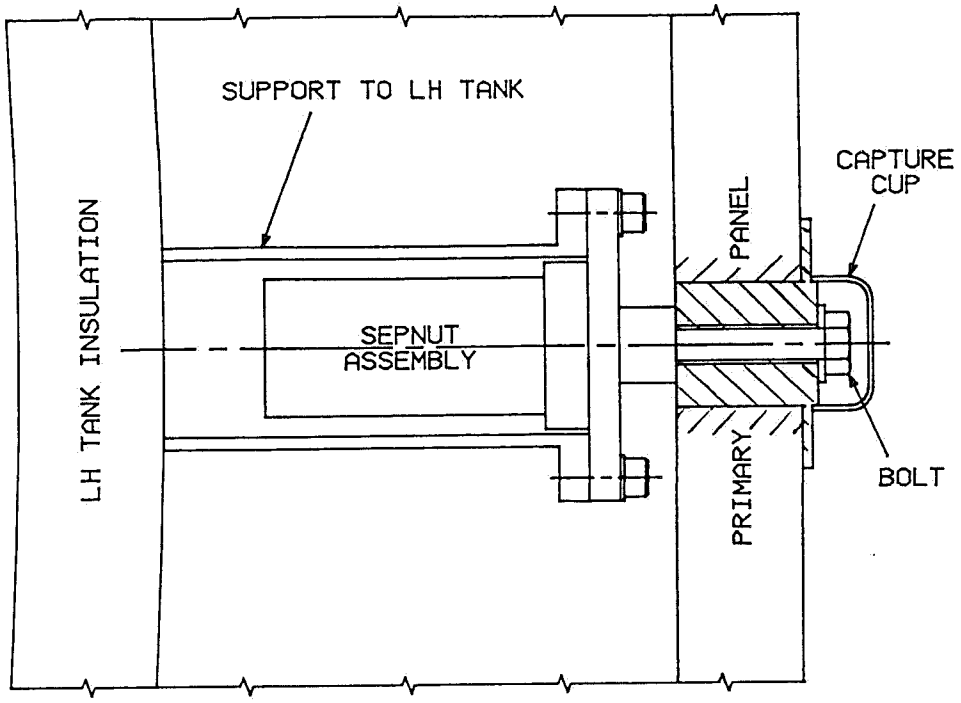


Figure 56. Sepnut Mount Point

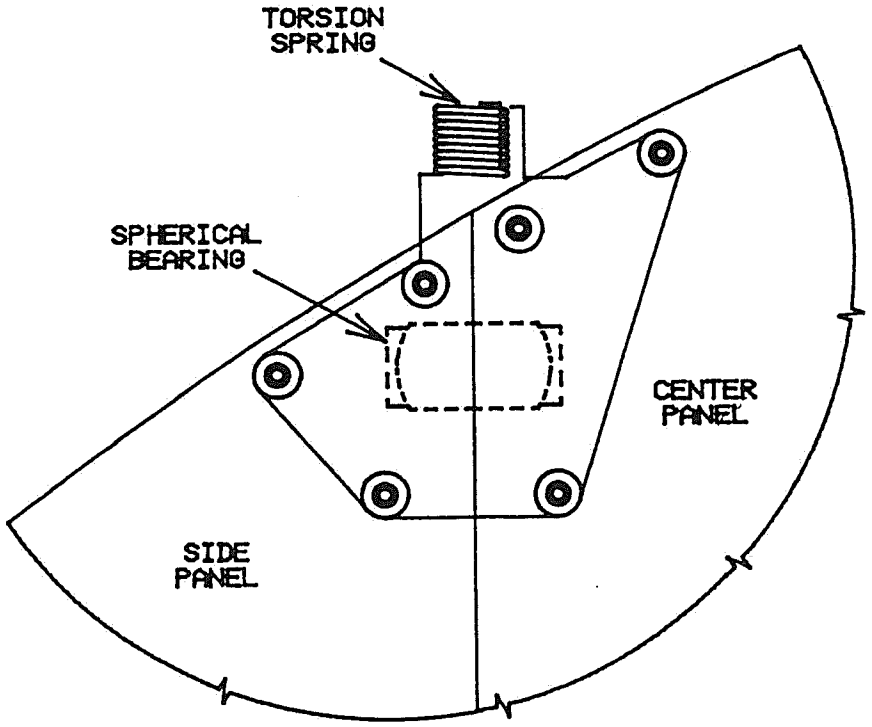


Figure 57. Torsion Spring and Spherical Bearing

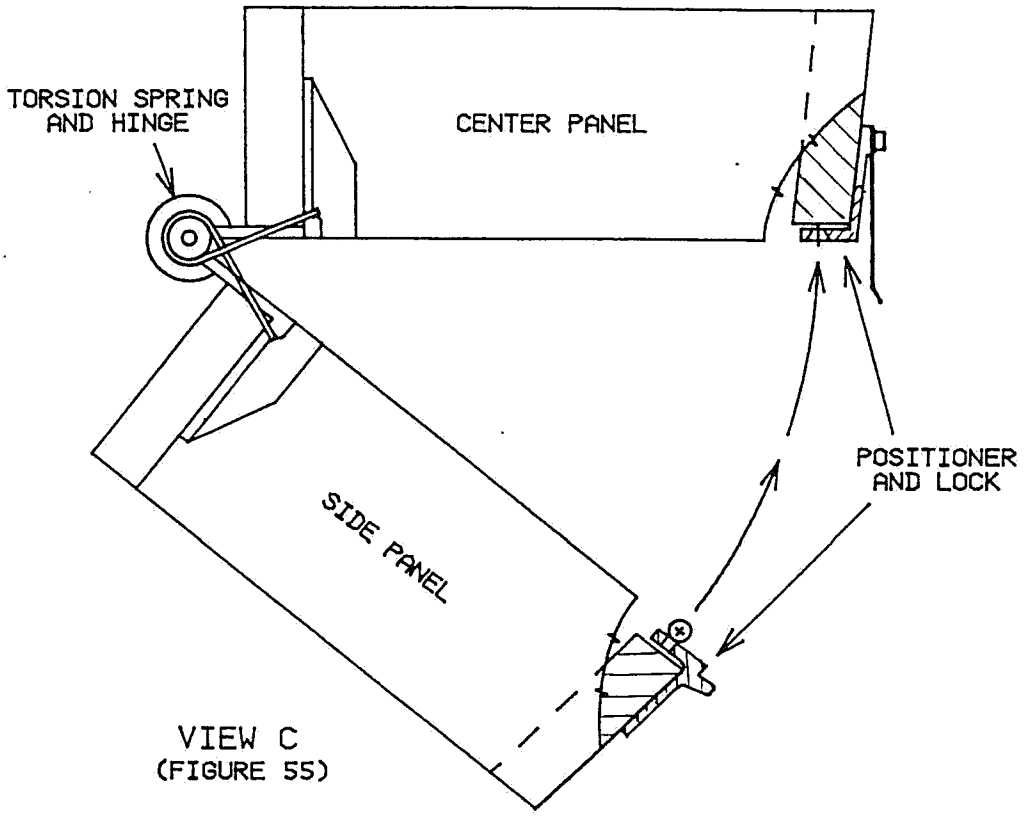


Figure 58. Hinges, Positioner and Lock - Stowed

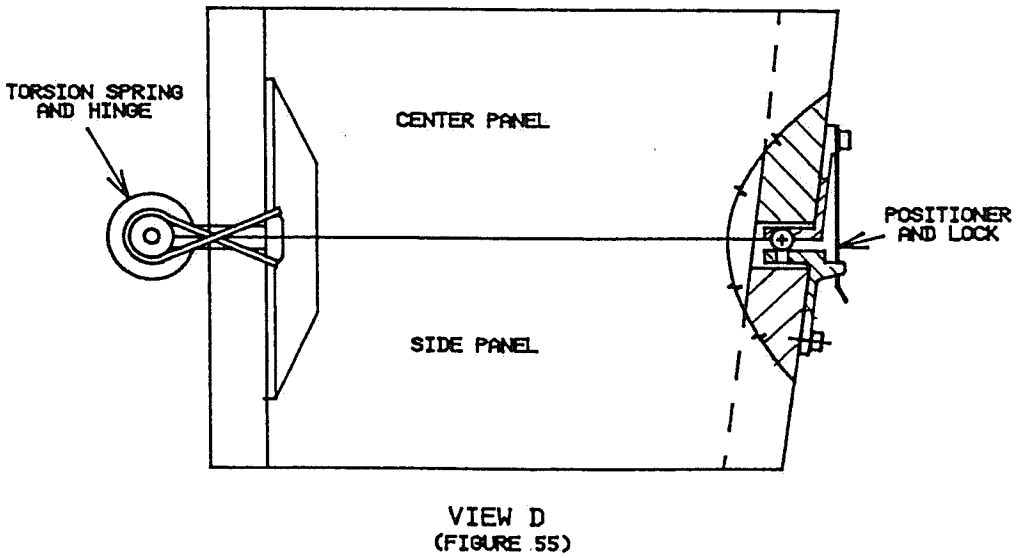


Figure 59. Hinges, Positioner and Lock - Deployed

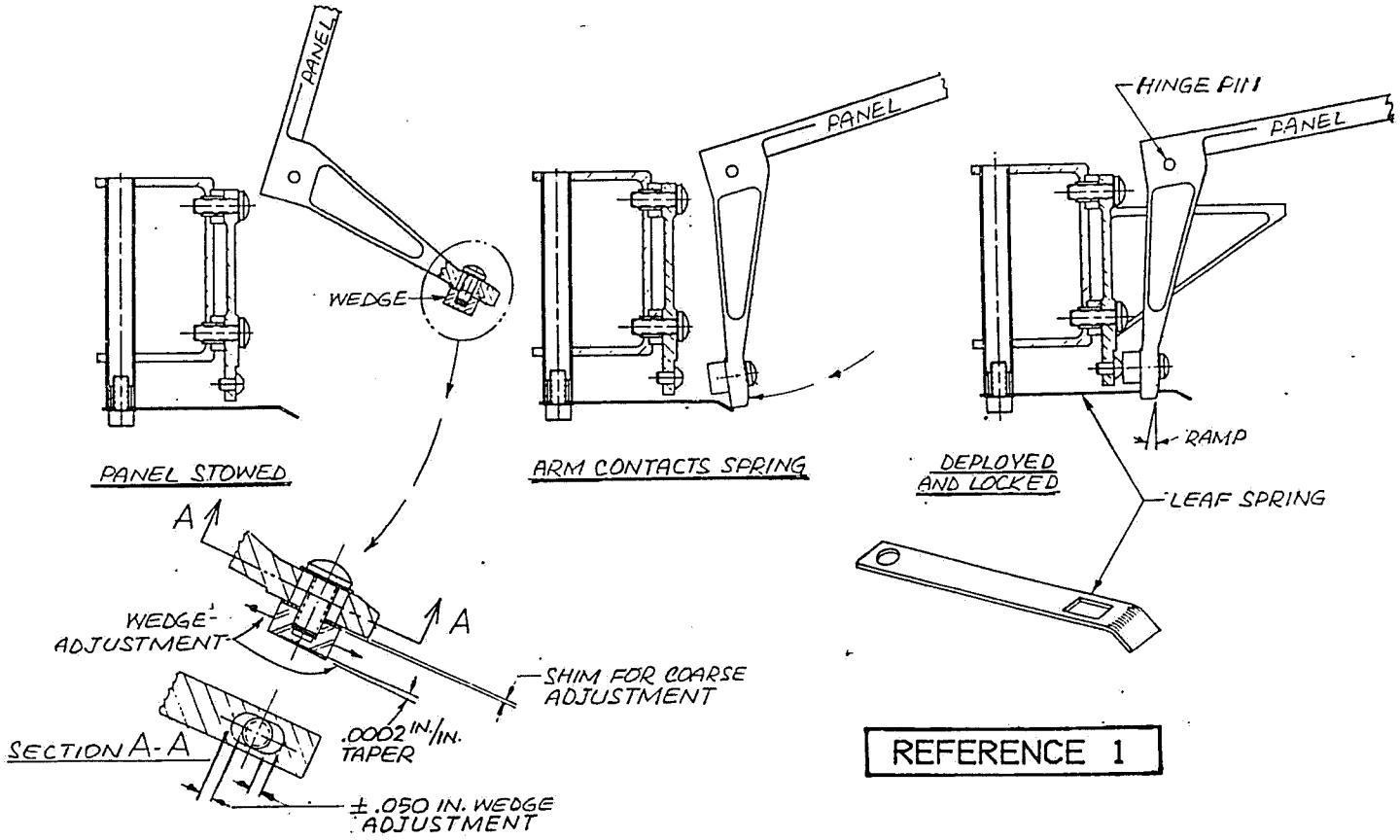
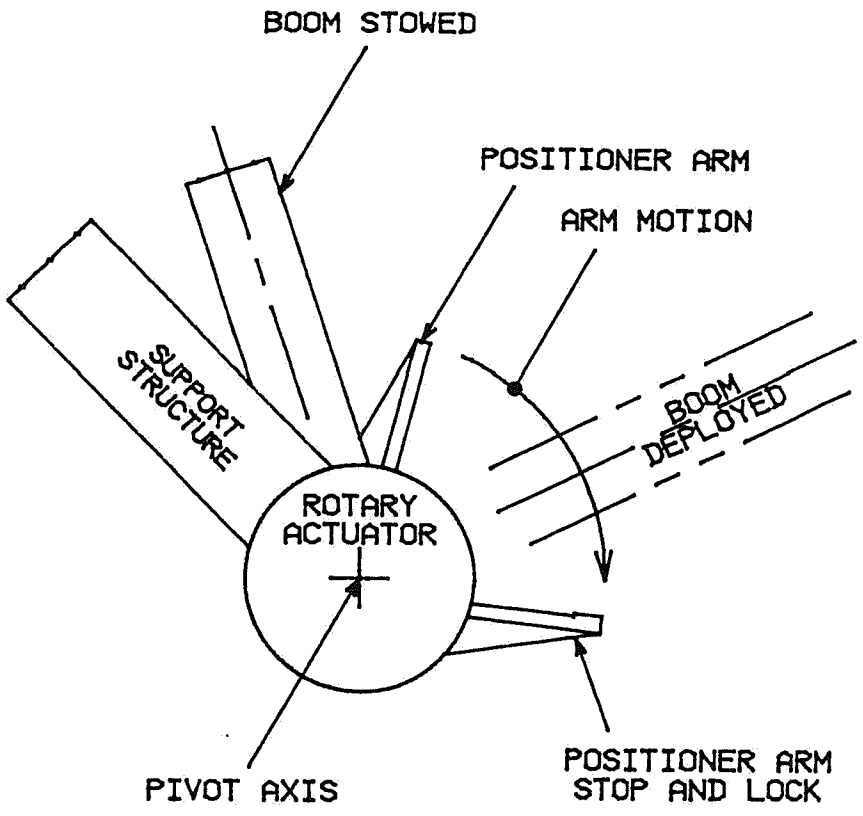


Figure 60. Sunflower Antenna Positioner and Lock



VIEW E
(FIGURE 55)

Figure 61. Base Pivot for Boom

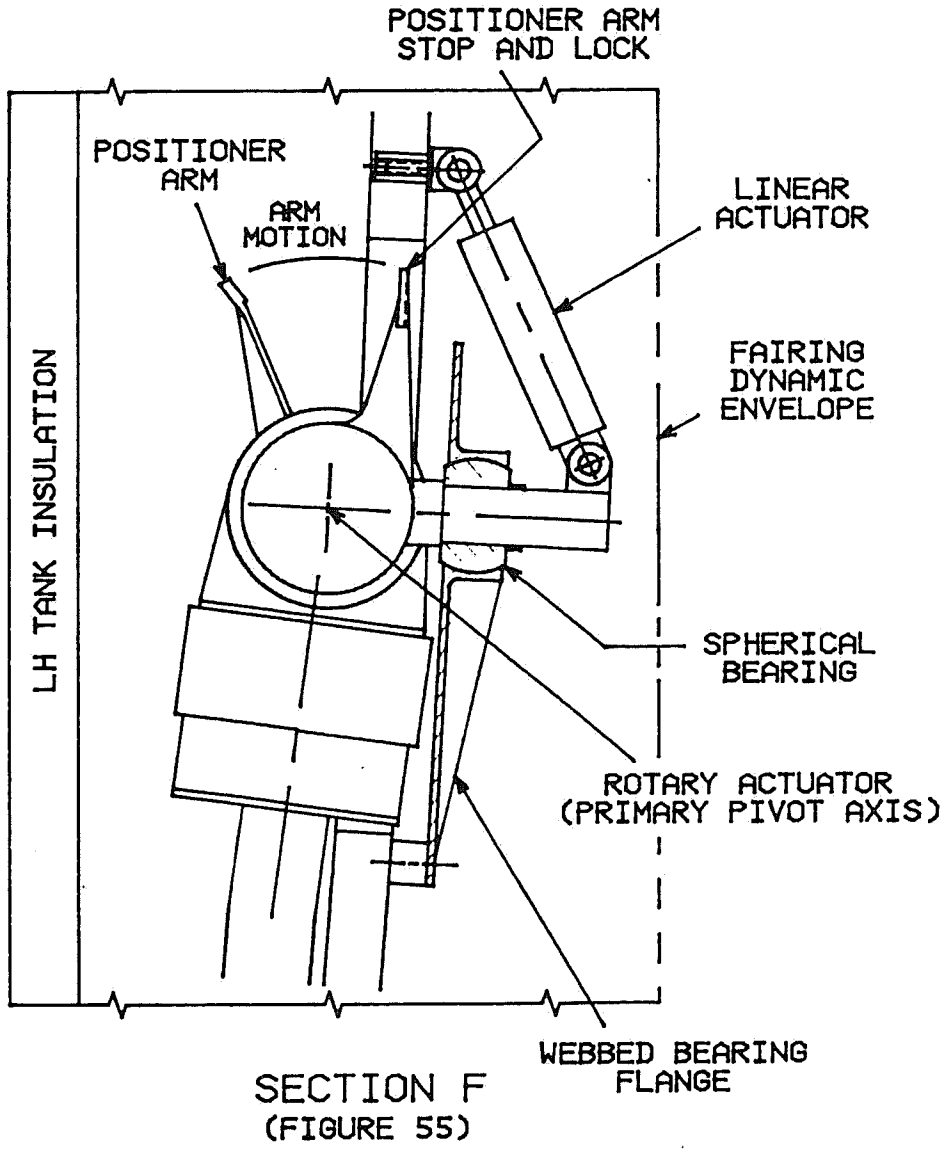


Figure 62. Pivot for Concentrator - Stowed

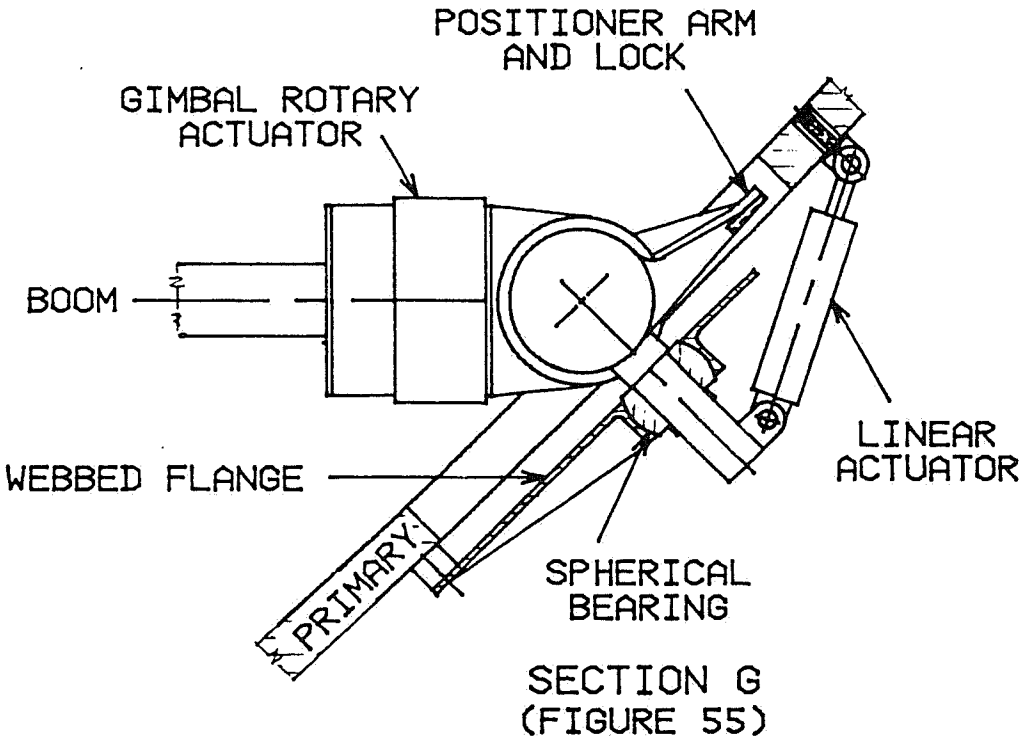


Figure 63. Pivot for Concentrator - Deployed

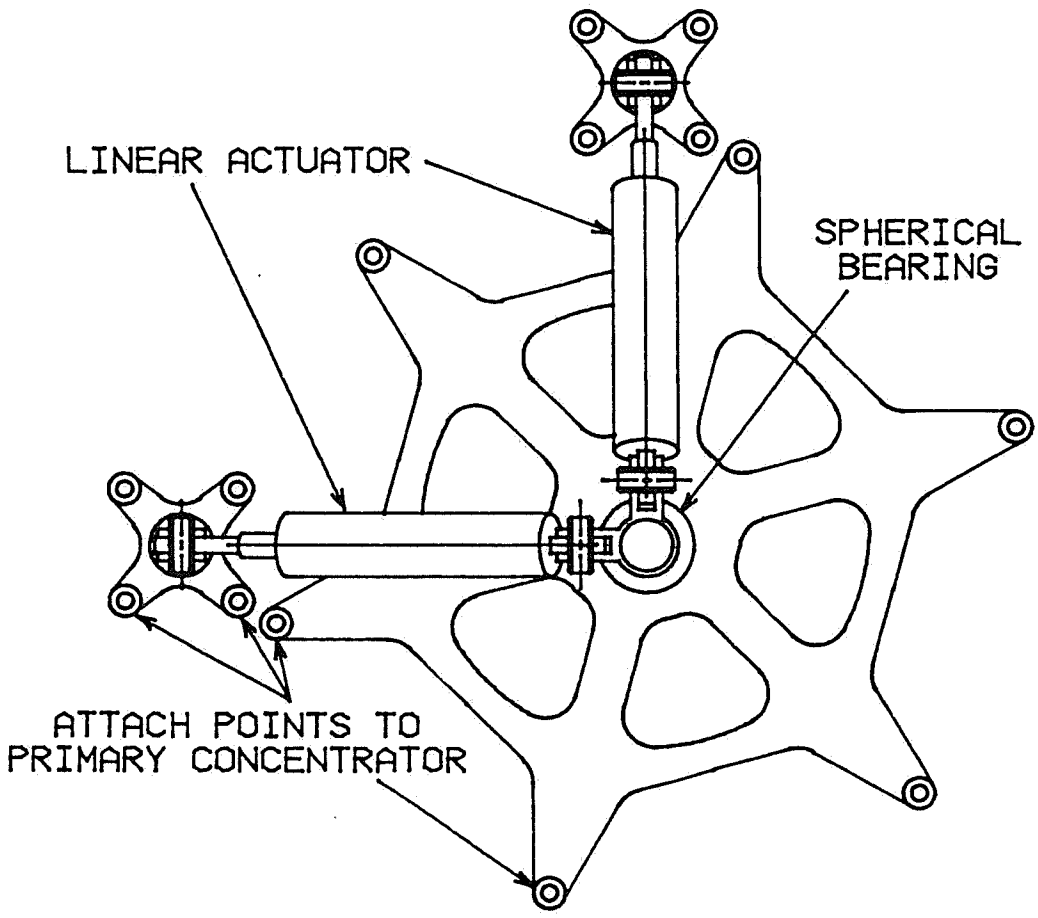


Figure 64. Spot Positioner Mechanism

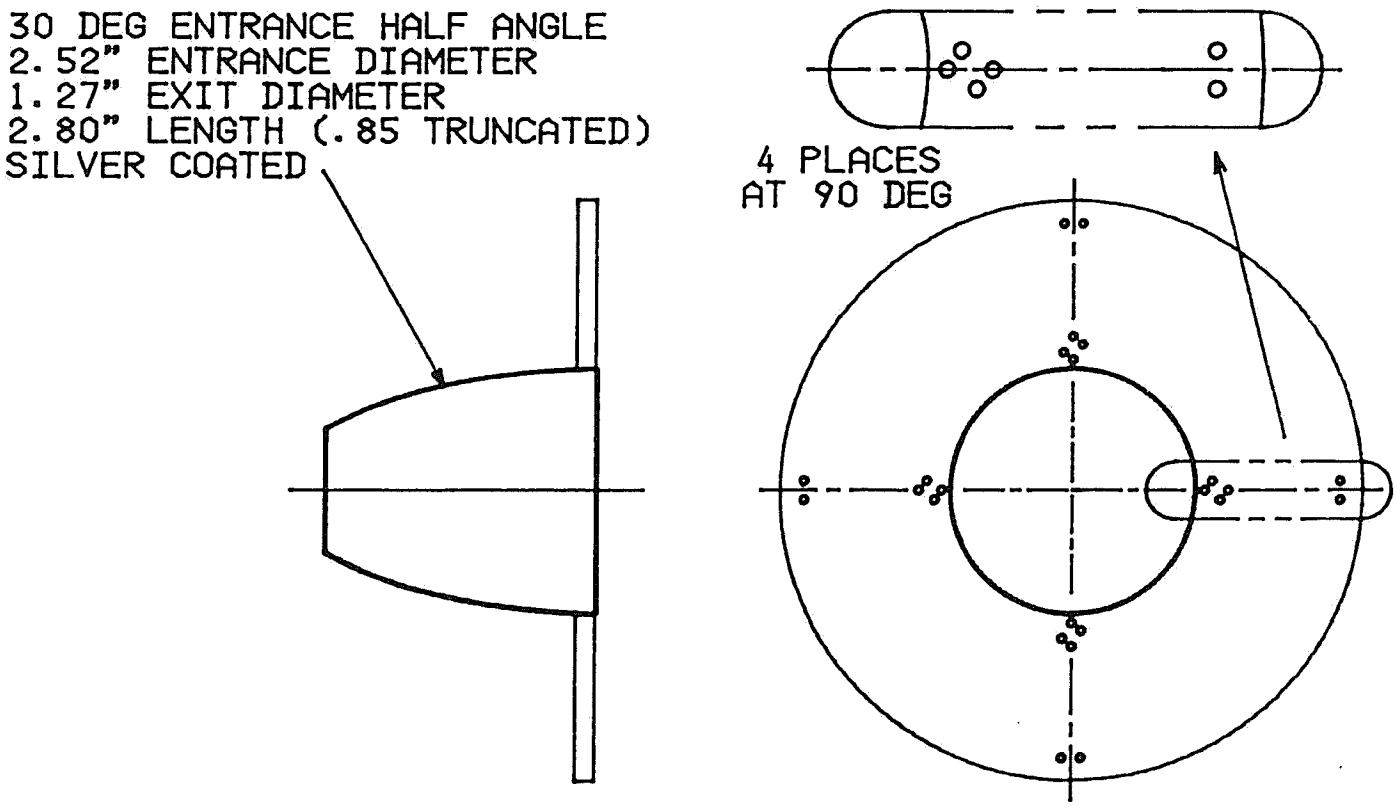


Figure 65. Thermocouple Pattern for Spot Positioner Control

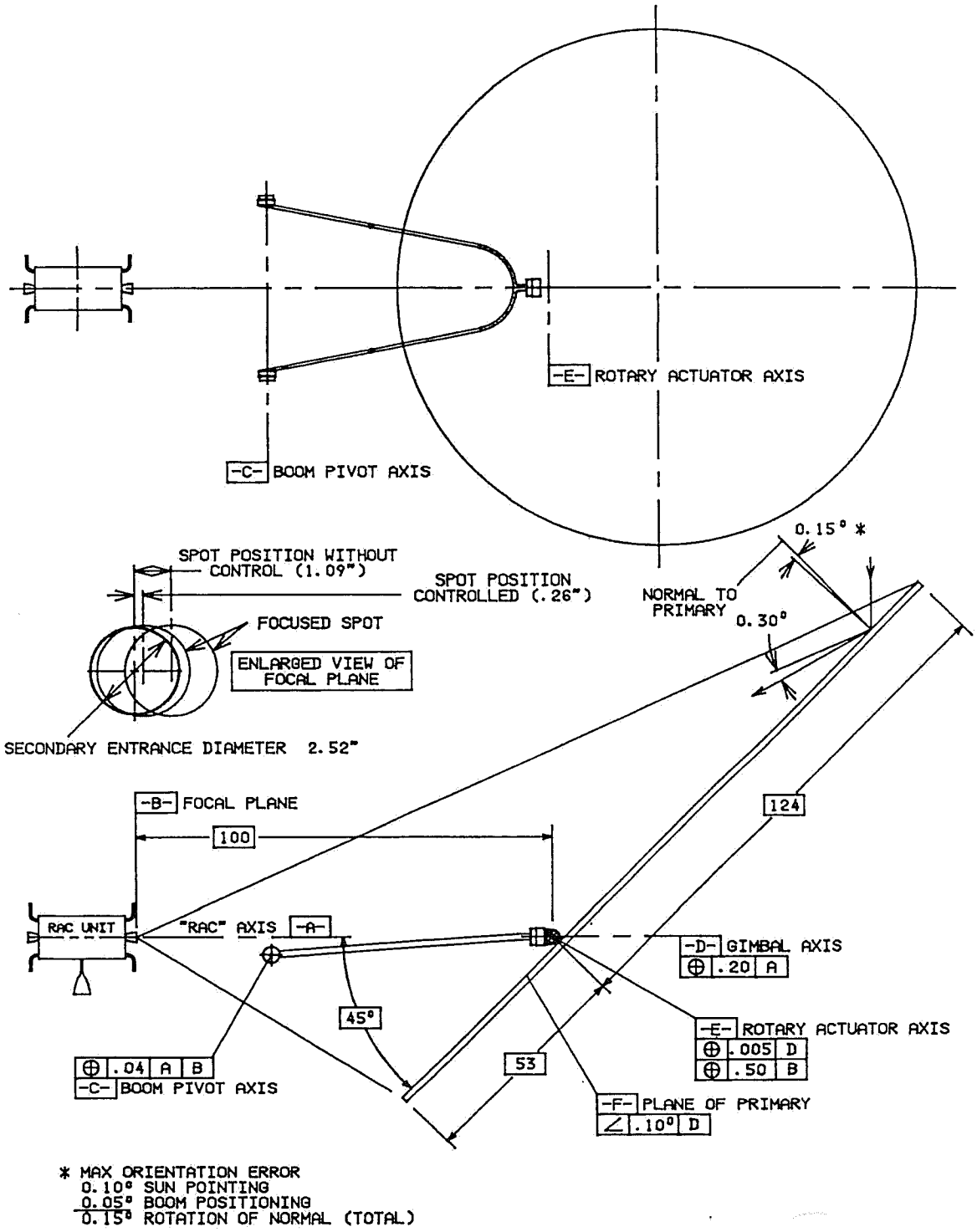


Figure 66. Boom Positioning Tolerance

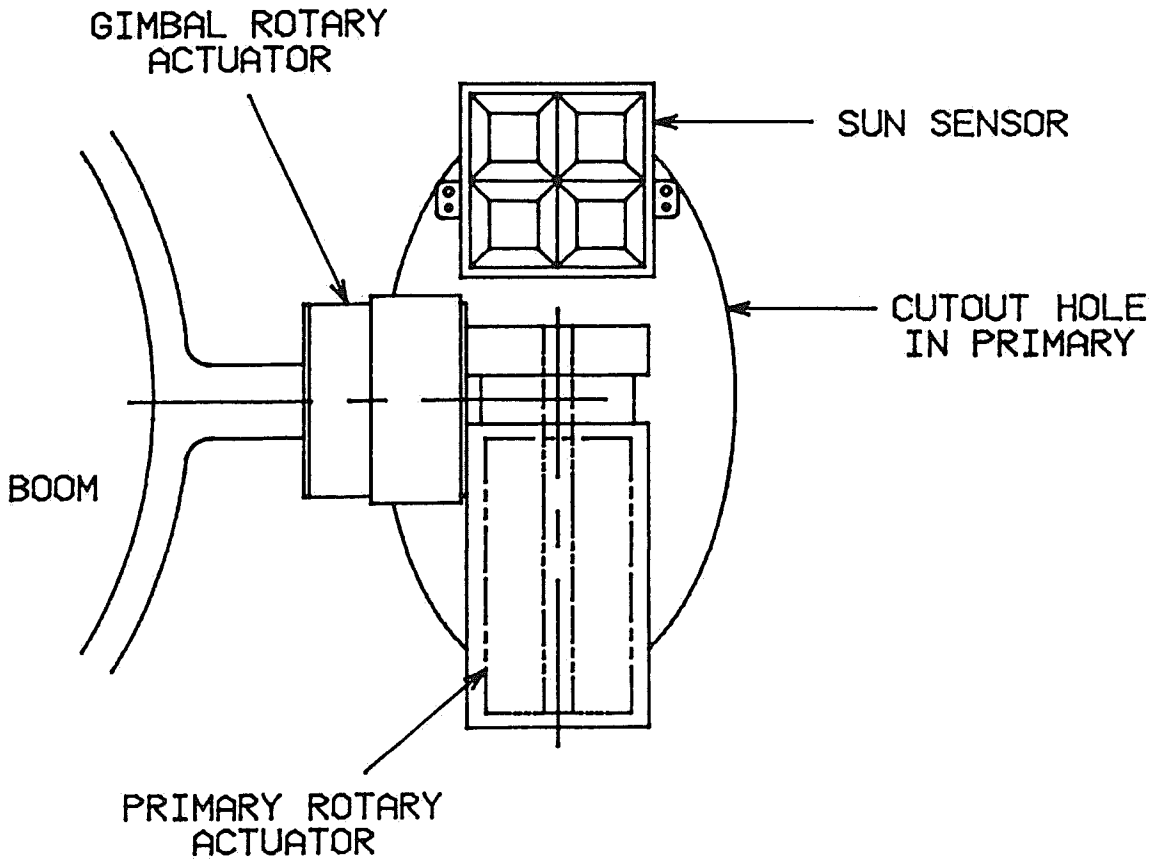


Figure 67. Sun Sensor and Rotary Actuator

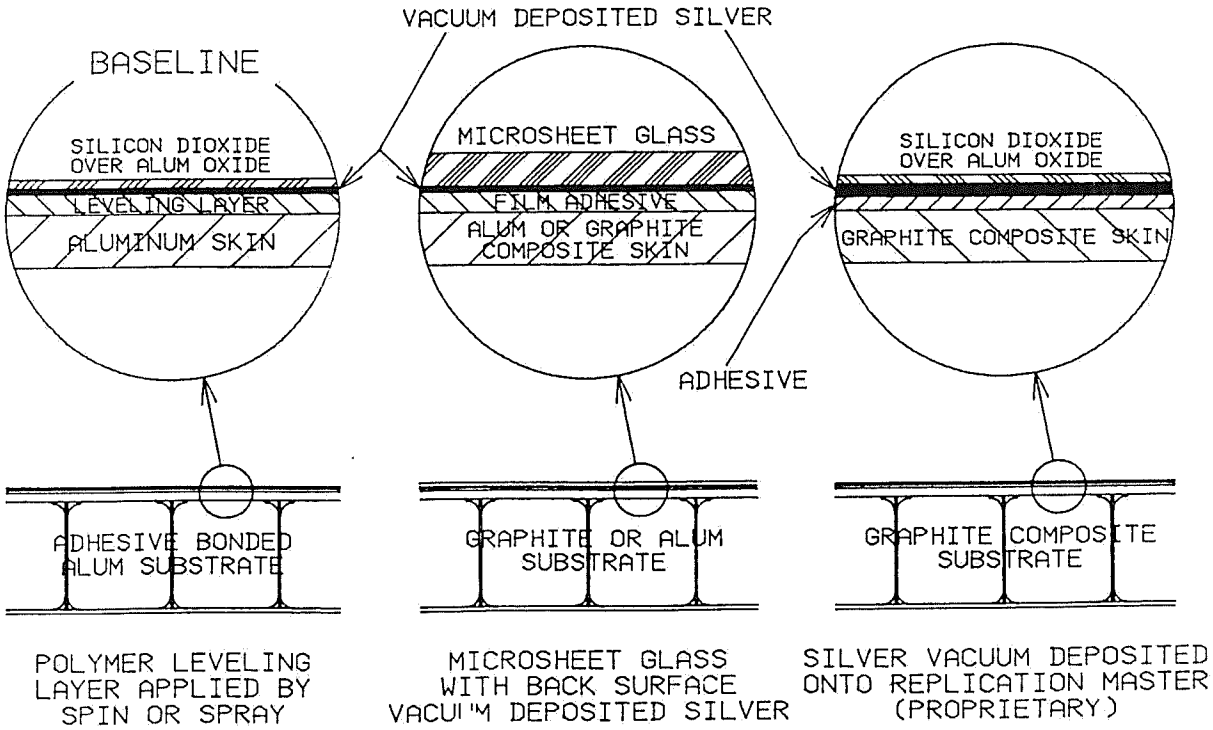


Figure 68. Primary Concentrator Materials of Construction

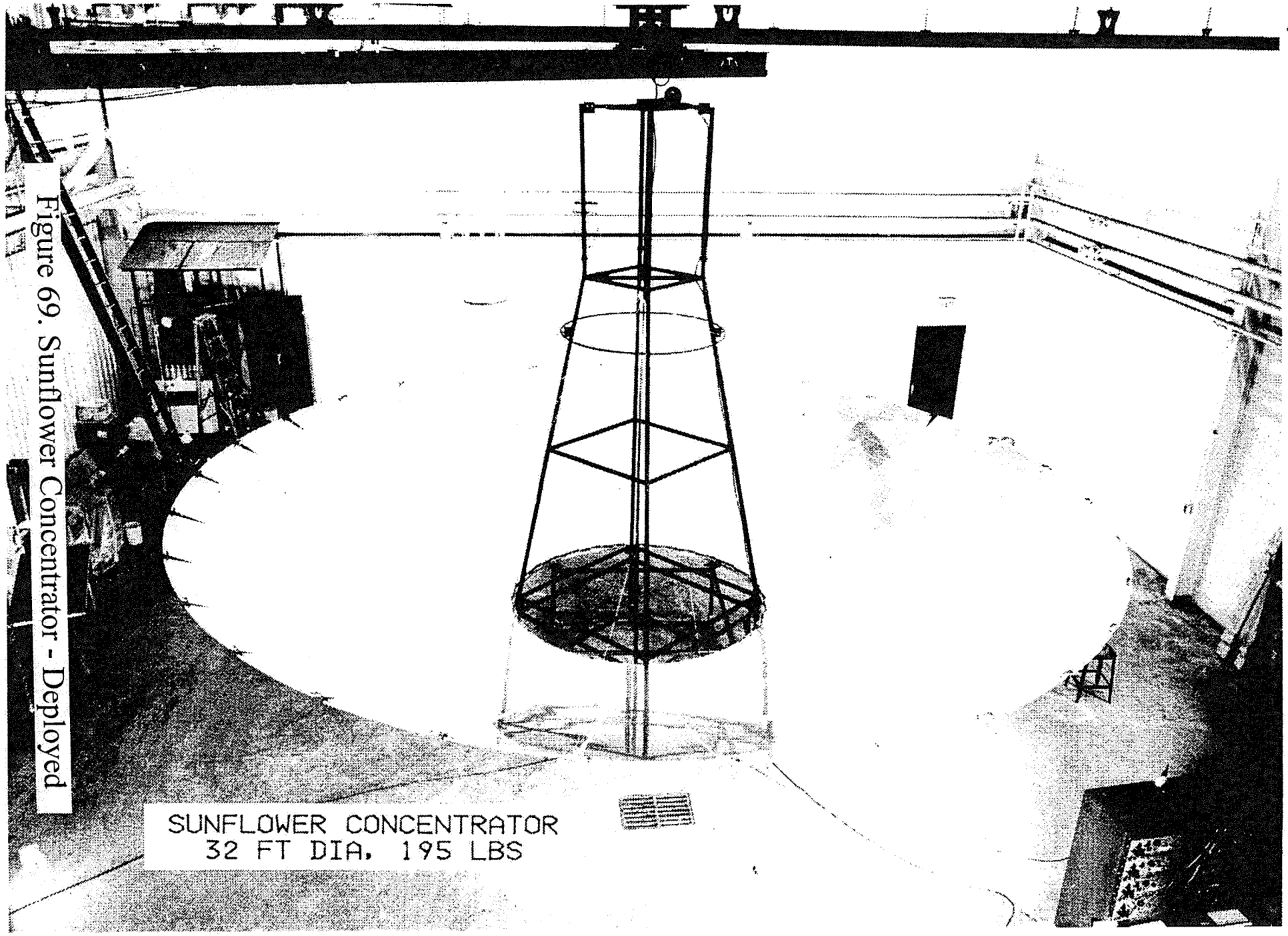


Figure 69. Sunflower Concentrator - Deployed

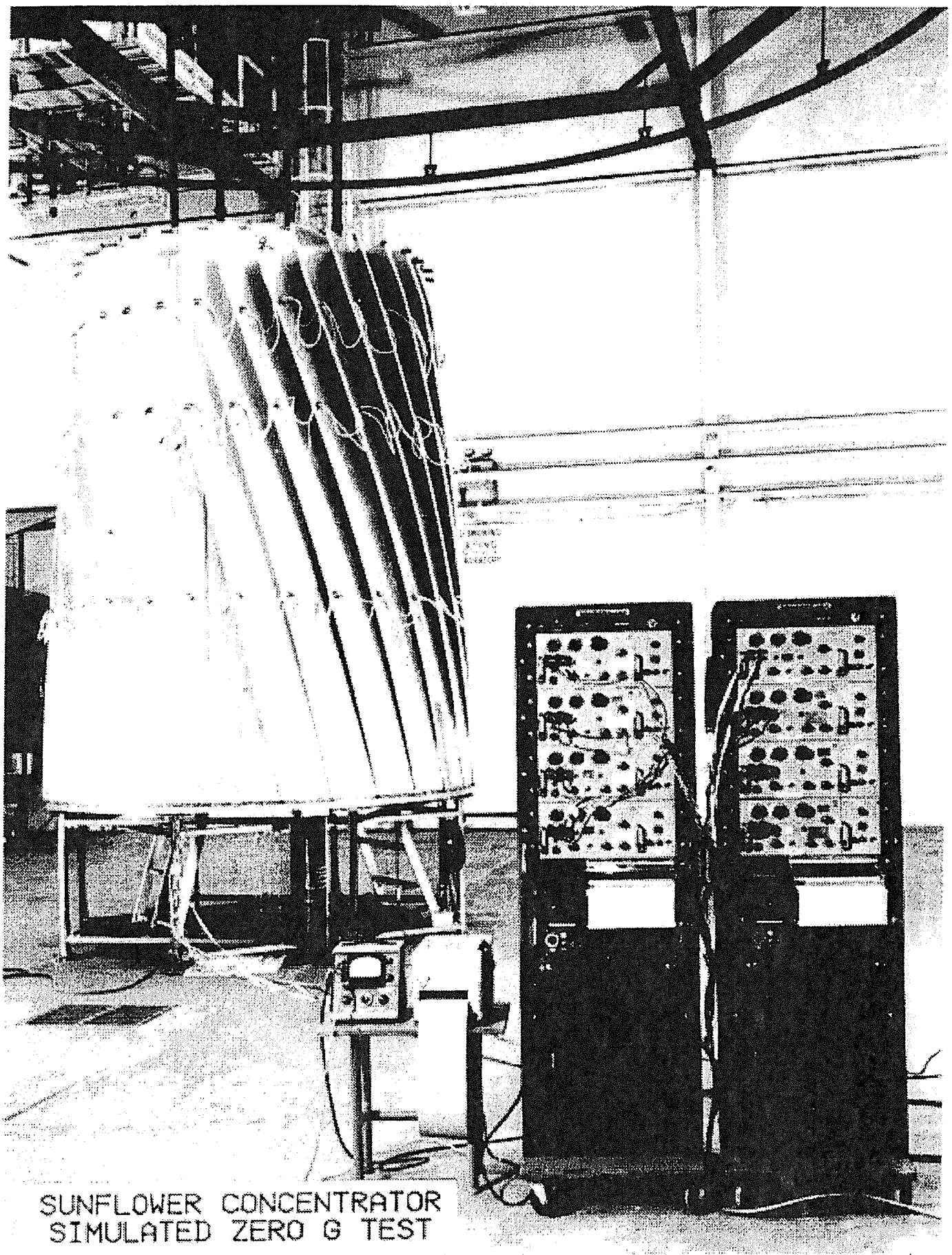


Figure 70. Sunflower Concentrator - Simulated Zero G Test

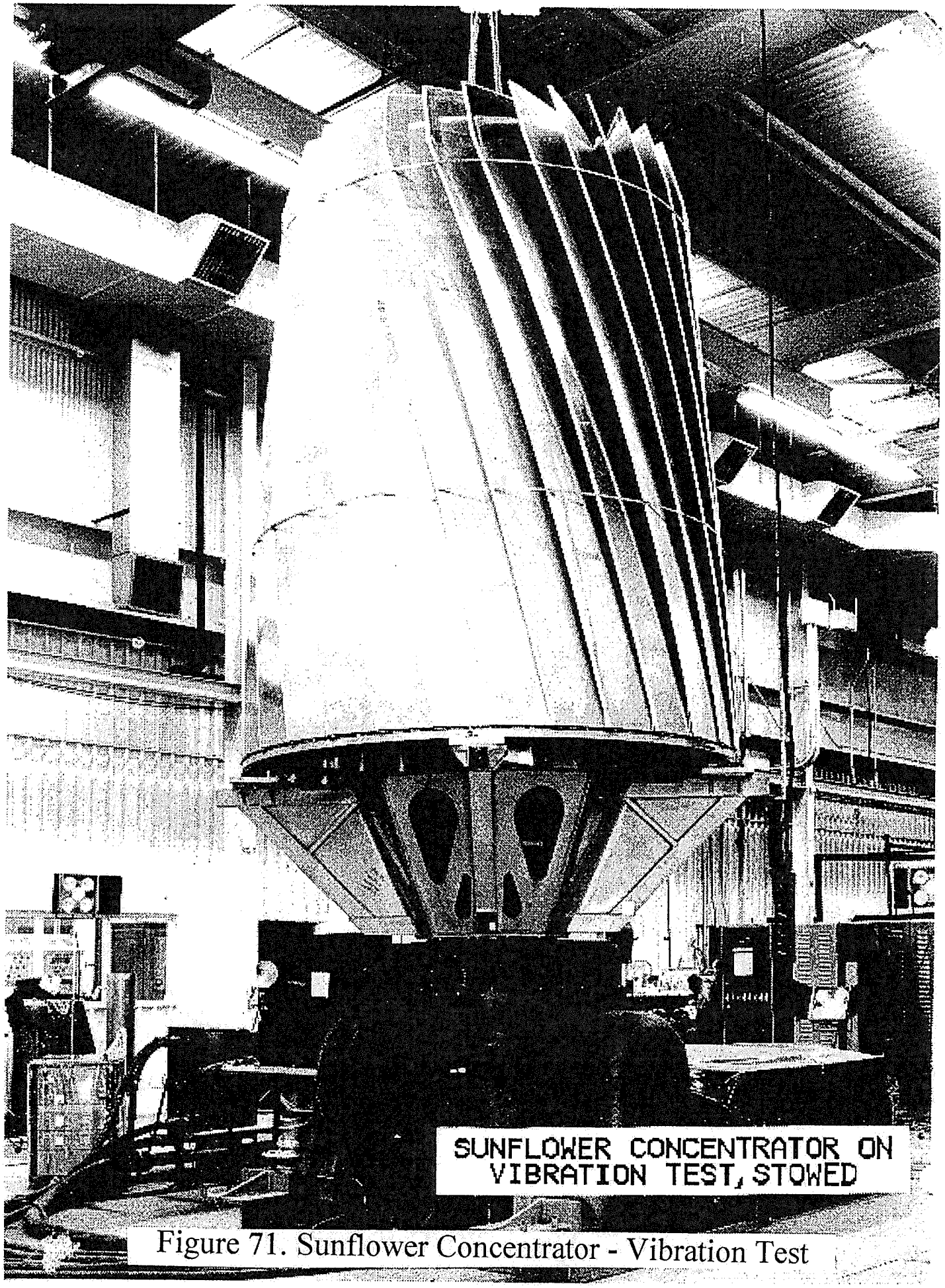


Figure 71. Sunflower Concentrator - Vibration Test

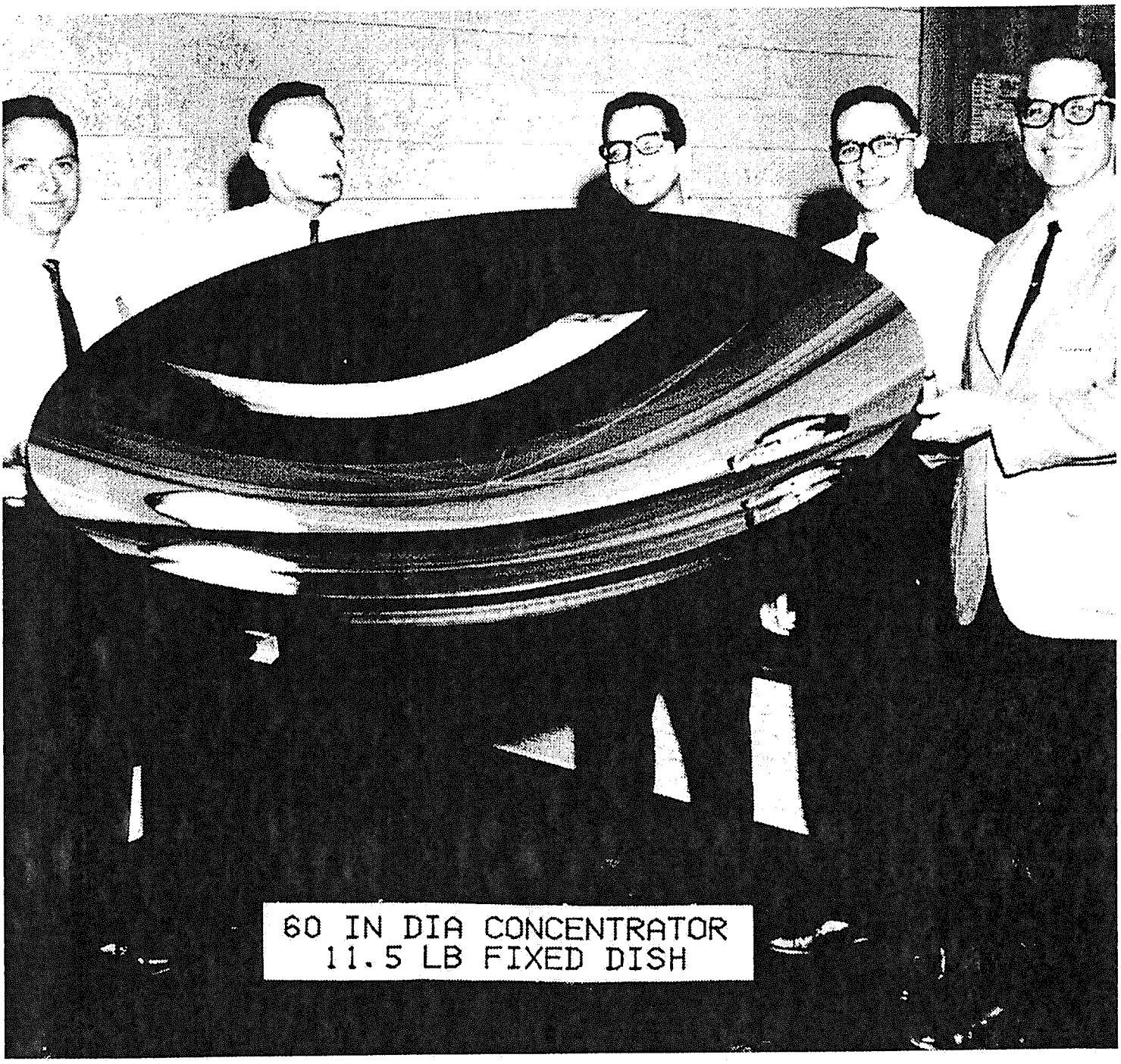


Figure 72. Fixed Dish Concentrator

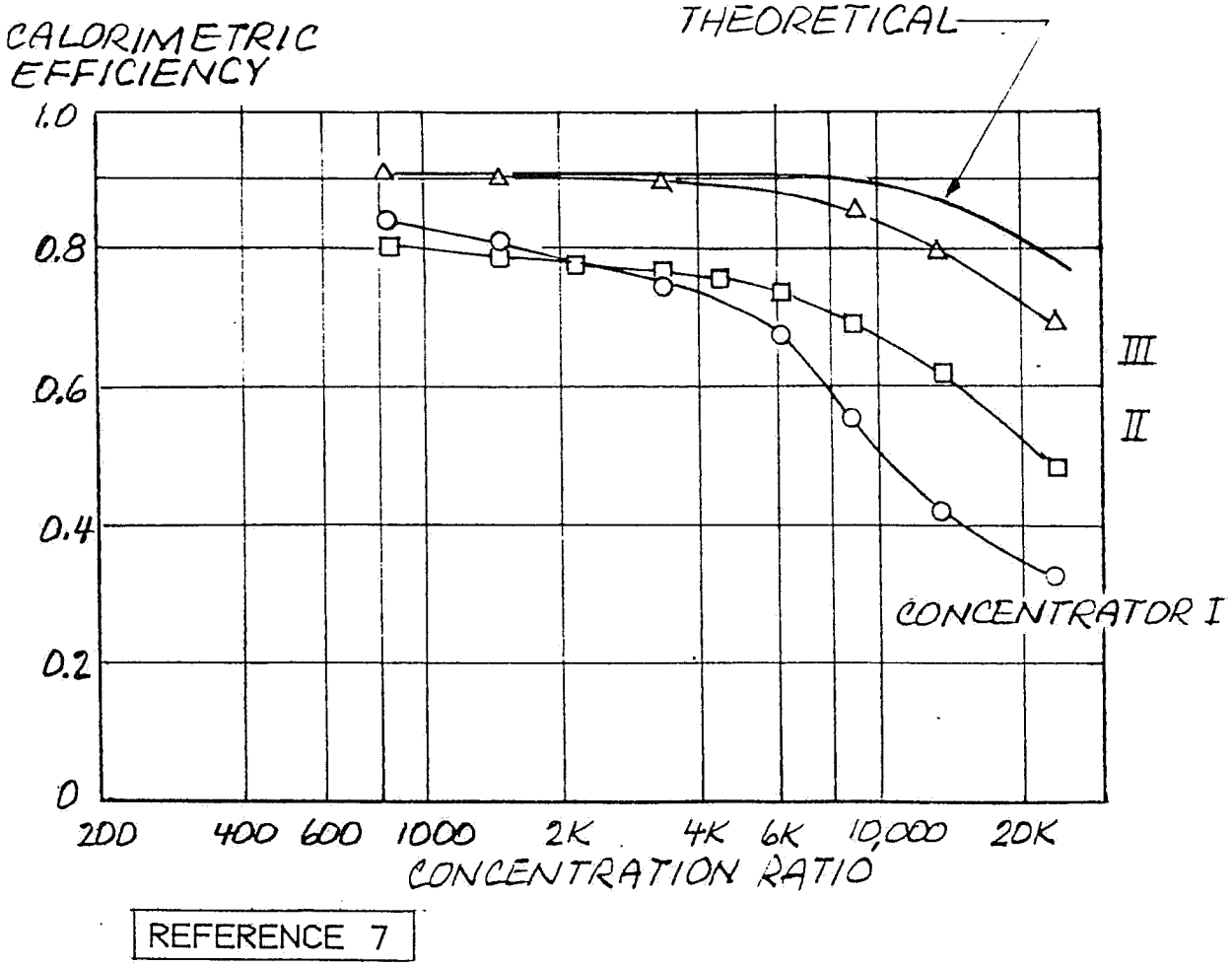


Figure 73. Fixed Dish Concentrator-Calorimetric Efficiency

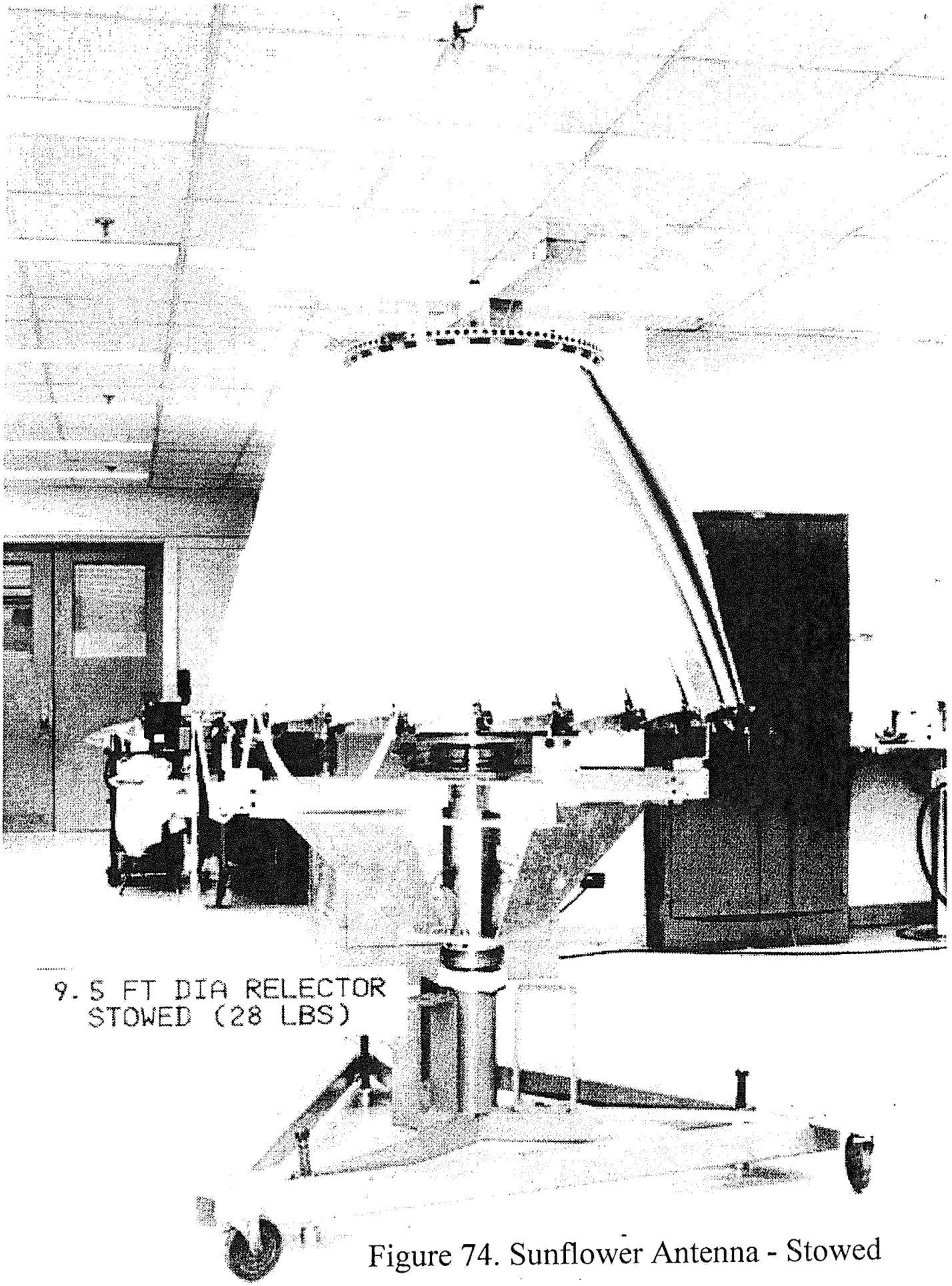
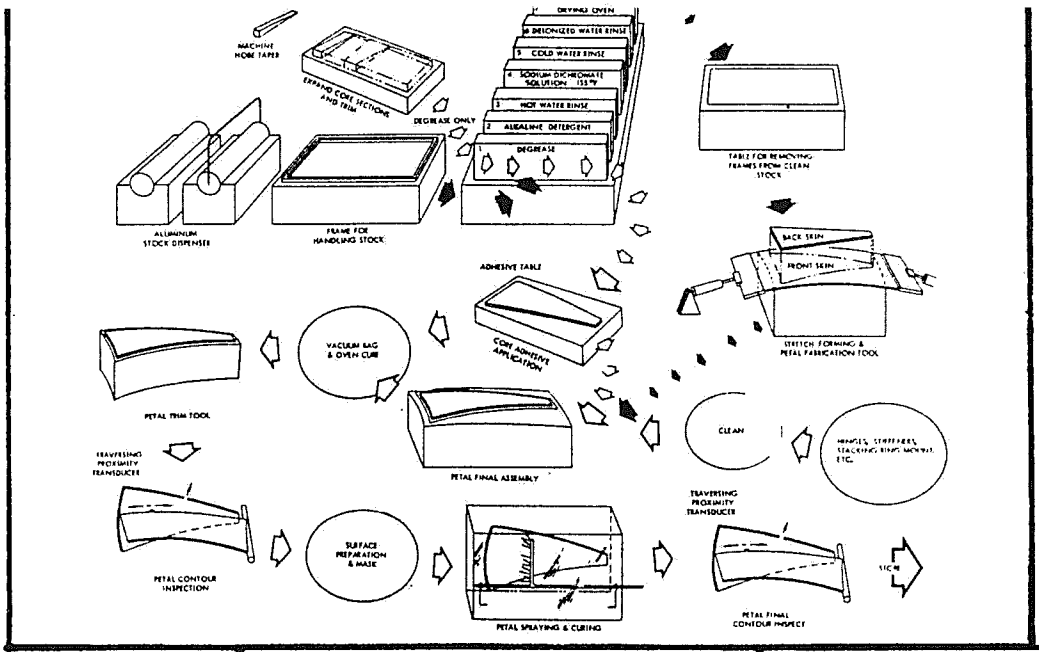
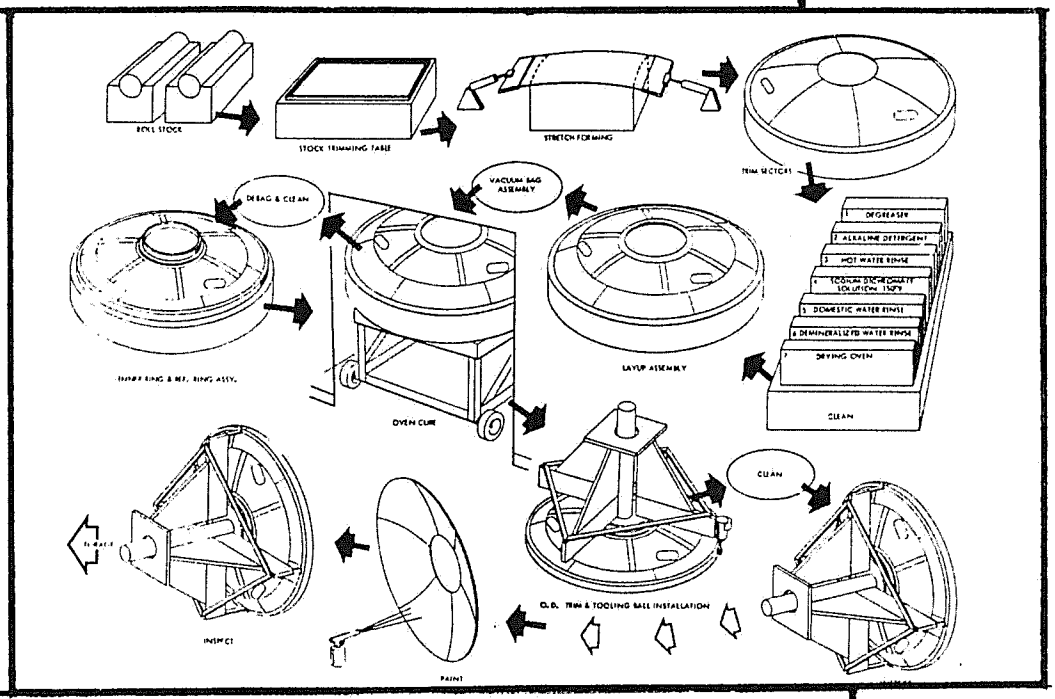


Figure 74. Sunflower Antenna - Stowed

Figure 75. Sunflower Antenna - Deployed





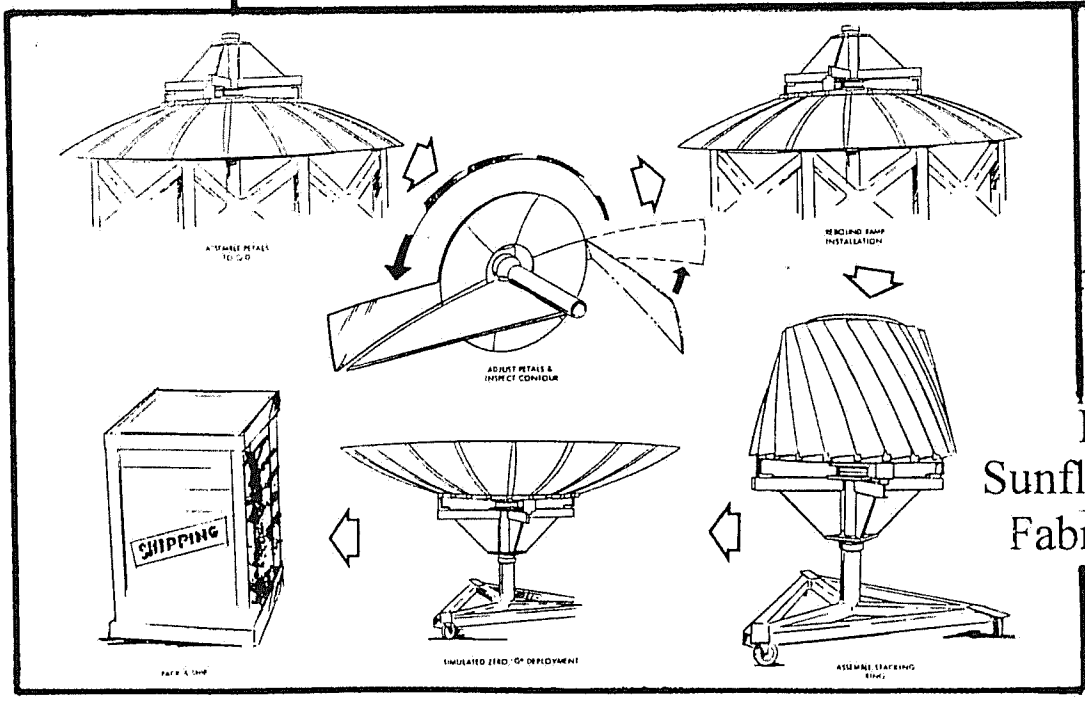


Figure 76.
Sunflower Antenna
Fabrication Steps

• *Established Process Procedures*	*- SKI Inc and CSU/AMC*
• *Face Sheets*	*- Stretch Formed*
• *Core*	*- Mill Hobe Faces, Expand and Cut Shape*
• *Clean Core and Face Sheets*	*- Degrease, Paste Etch and Clean*
• *Cure Panel*	*- Epoxy Bond under Vacuum Bag*
• *Trim Size*	*- Trim Edges, Bond in Inserts for Accessory Attachment*
• *Leveling Layer*	*- Spray Coat and Cure*
• *Reflective Layer*	*- Vacuum Coat Silver and Protective OverLayers*

Note: Graphite Composite Facet under Evaluation as Alternate Material

Figure 77. Sunflower Antenna - Fabrication Steps

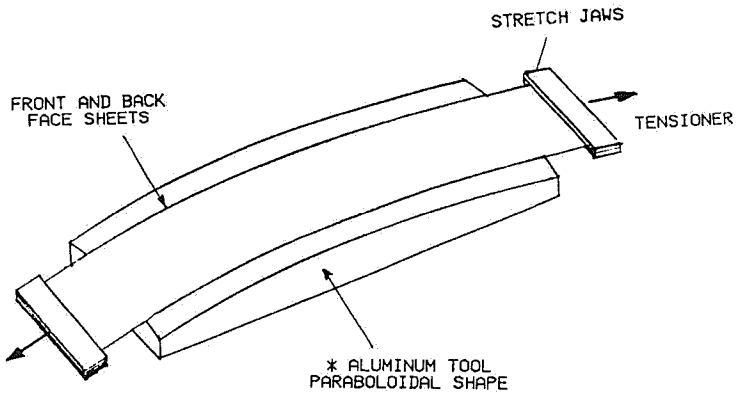


Figure 78. Stretch Forming Process

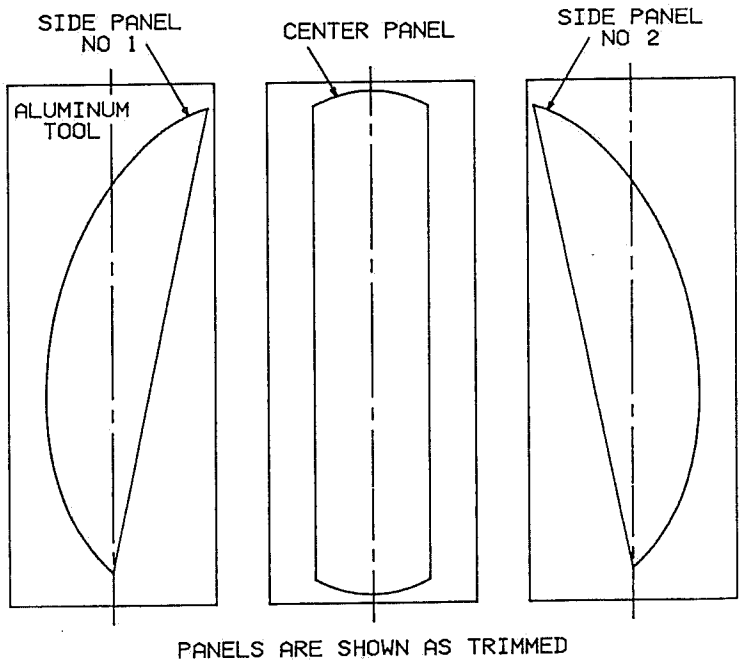


Figure 79. Lay up of Concentrator Panels

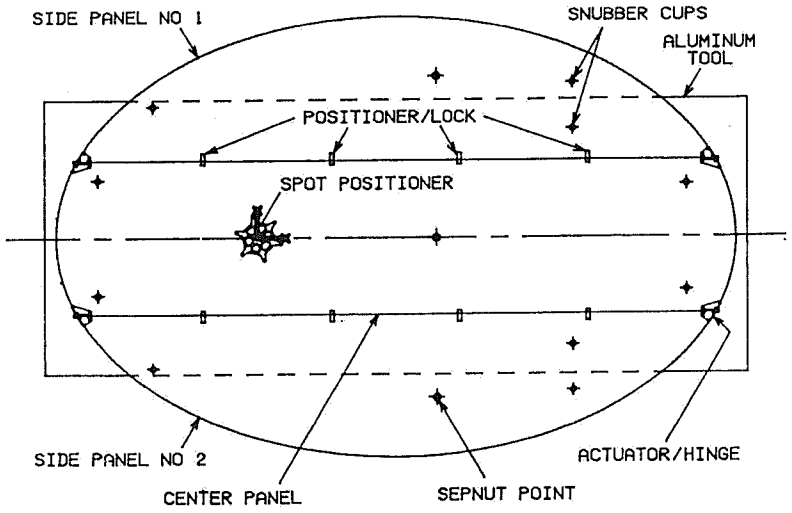


Figure 80. Assembly of Concentrator Panels

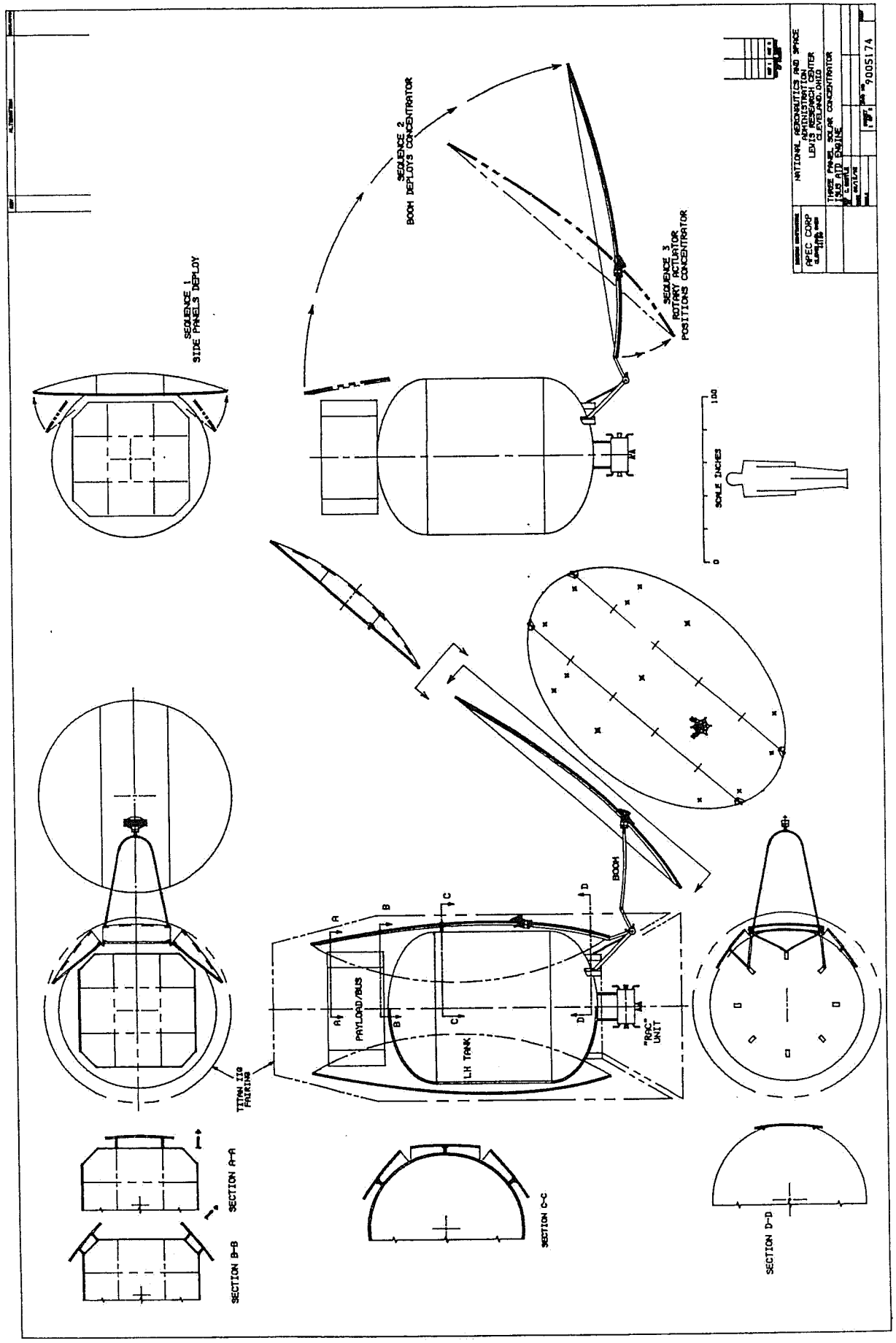


Figure 81. ISUS ATD Concept Design

• Concentration Ratio (Area)	8000 :1 Minimum
• Surface Quality	
Replication	2 Mrad (1 Sigma)
Assembly	1 Mrad Max
Thermal Gradients	0.5 Mrad Max
• Orientation	
Sun Pointing	0.10 Deg Max
Boom Positioning	0.05 Deg Max
	+/- 0.25 " Focus
• Surface Reflectivity (Normal)	
Primary	0.92 Min (Ag)
Secondary (At Temperature)	0.84
• Panel Areal Density	2 kg/Sq M MAX
• Operating Temperature	
Desirable	0 Deg to 160 Deg F
	-20 Deg to 70 Deg C
Allowable	-50 Deg to 250 Deg F
	-45 Deg o 120 Deg C
(Tailor Radiative Properties)	

Figure 82. ISUS ATD Baseline Design Requirements

• Configuration	Dual Offset Paraboloid
	Three Panels Around LH Tank
• Construction Materials	Aluminum Honeycomb
• Primary	2.97 M (117. ") Diameter
	to Solar Flux
	1.29 M (50.7") Focal Length
	6.93 Sq M (74.6 Sq Ft) Area
	to Solar Flux
• Secondary	30 Deg Entrance Half Angle
	2.52 " Entrance Diameter
	1.27 " Exit Diameter
	2.80" (0.85 Truncated)
• Concentration Ratio	2000:1 Primary
	4:1 Secondary
• Concentration Efficiency	0.71
• Reflective Material	Silver (Coated) Primary
	Silver (Uncoated), Secondary
• Mass (Total)	43.2 kg (95.2 lbs) Panels
	57.4 kg (126.4 lbs Total)
	* 4.1 kg/Sq M (0.84 lb/Sq Ft)

* Total mass divided by area of intercepted solar flux

Figure 83. ISUS ATD Configuration Parameters

• *Boom Positioning*	*Locate Pivot Point on Assembly to Vehicle* *Thermal Effects* *Mechanism Manufacturing Tolerances*
• *Long Narrow Panels*	*Larger Replication Errors than Previous Hardware*
• *Vacuum Coating Reflective Surface*	*Large Coating Facility and Cost to Coat* *Use NASA Facility (?)*
• *Leveling Layer*	*Space Compatibility* *Processing Special Polyimides*
• *Silver Coating on Secondary*	*Coated on Ground, Uncoated in Space*

Figure 84. Solar Concentrator Issues and Concerns

APPENDIX B

COST ESTIMATE FOR THE GTD

PRESENTED TO PHILLIPS LAB AS A SECTION OF THE ISUS ATD FINAL REPORT

X COST ESTIMATES

X.1 SOLAR CONCENTRATOR

X..1.1 COMPONENTS ESTIMATED

This cost estimate covers the components of the Solar Concentrator Array. These components include the solar panels, the hinges, panel locks, the spherical bearing and shaft for attaching to the boom, the structure within the panels for the Sepnuts and snubbers, and the actuators mounted on the back of the concentrator for fine positioning.

The cost estimates for the Deployment Mechanisms and Structures and the Pointing and Tracking System will be covered separately.

X.1.2 ASSUMPTIONS

In completing the cost estimate, assumptions were necessary to in order to provide reasonable estimates at this stage in the development of the ISUS concept.

Because of differing manufacturing methods and different materials possible in fabricating the concentrator, one method had to be selected for the cost estimate. At this point, more is known about the construction of the solar panels using an aluminum honeycomb structure. The processes and materials have been developed and construction of panels has been demonstrated during the Sunflower and other NASA programs. Thus, all cost estimates are based on aluminum honeycomb panel construction.

The use of composite materials and alternate methods of fabrication have not been precluded from use on the ISUS program and it is likely that they will be used to some extent. However, for purposes of this quote, it was assumed that costs for design and fabrication of aluminum honeycomb would be typical and representative for all methods of construction.

X.1.3 BASIS FOR COST

The Solar Concentrator cost estimates were prepared in accordance with the tasks described in the Concentrator Array and Tracking System Statement of Work (SOW) as revised on 14 June, 1995. The costs are itemized by reference to the paragraph number of the SOW.

Labor costs were based on the concentrator contractor performing the required task or a portion of the required task. Material costs were considered to be all raw materials, supplies, and other purchased operations that the contractor will have to obtain.

Concentrator contractor labor was estimated utilizing the estimator's experience with similar tasks. Labor costs were calculated using a rate of $70 /hour times the number of hours for the task.

Material costs and costs for purchased operations were obtained from suppliers where available and were estimated from experience when supplier quotes were not available.

Costs for Government facilities for conducting the ground tests at NASA LeRC were not included as it is understood that those costs have been submitted separately.

X.1.4 FACILITIES

Some new facilities may be required by the concentrator contractor because of the size of the concentrator. These facilities may exist to some extent at present, but it is likely that they are not large enough to accommodate the ISUS concentrator. The option to obtaining new facilities is to build the concentrator in small sections and then assemble the sections to form the full size concentrator. The problem with this approach is that it may not be possible to obtain the required accuracy with the assembly. The preferred approach is to obtain the new facilities. As a minimum, a full size optical inspection facility will be needed to be able to verify that the concentrator has been built to the required configuration.

The probable new facilities are as follows:

A clean room will be needed for fabrication and assembly of the concentrator facets. To provide sufficient space for concentrator fabrication, the room should be approximately 20 feet by 20 feet. Within the room, a laminar flow bench is needed which meets Class 100 conditions per Federal Standard 209b. The laminar flow bench should be 15 feet long by 39 inches wide minimum.

A spray booth to apply the leveling layer will be needed. The booth should be at least 16 feet long by six feet wide and meet the cleanliness standards of the clean room to prevent contamination of the leveling layer. All required spray guns, nozzles, and related equipment must be provided for spraying the leveling layer and fixtures for holding the concentrator panels must be designed and fabricated.

To inspect the optical quality and conformity of the panels, an optical test facility will be needed. Since this facility will be unique to the ISUS concentrator, no design currently exists. A system using reflected light or lasers has been used in similar applications. The contractor will be responsible for developing the system and verifying system capability and accuracy.

The estimates for the Clean Room and Spray Booth facilities are included in the costs in SOW Section 3.1.1 Materials and Coupon Testing since the facilities will first be needed during that phase of the program. The estimate for the Optical Inspection facility is in Section 3.1.2.5 Facet Inspection.

X.1.5 COST ESTIMATES

The cost estimates for the concentrator are summarized in Tables 5.1 and 5.2.

3.1.2.3 Inspect Tooling-	Labor- 3 man-months, inspection monitoring	480 hours	
	Materials- inspection vendor		$15K
3.1.2.4 Fabricate Concentrator-	Labor- 26 man-months, devel. process, stretch form face sheets, bond assembly, close ends, apply leveling layer, pack and ship	4160 hours	
	Materials- face sheets, honeycomb, adhesives, reflective coating vendor.		$202K
3.1.2.5 Inspect Facets-	Labor- 2 man-months	320 hours	
	Facility- optical inspection		$10K

3.1.3 DEPLOYMENT MECHANISMS AND STRUCTURES *

3.1.3.1 Design Deployment Mechanisms and Structures

3.1.3.2 Fabricate Deployment Mechanisms and Structures

3.1.3.3 Test Deployment Mechanisms and Structures

3.1.4 POINTING AND TRACKING SYSTEM DESIGN *

3.1.4.1 Design Pointing and Tracking System

3.1.4.2 Model/Analyze Performance

3.1.5 CONCENTRATOR PERFORMANCE TEST (CPT)		**560 hours,**	**$11.2K**
3.1.5.1 Prepare Test Plan-		40 hours	
3.1.5.2 Participate in the Test Readiness Review		40 hours	
3.1.5.3 Collect and Analyze Test Data-	Labor- .5 person 5 months	400 hours	
	Materials- 75 days at $116/day + travel		$8.7K
	5 trips at $500 each		$2.5K
3.1.5.4 Report Test Results-		80 hours	

* Provided by NRL

TABLE 5.1
CONCENTRATOR COST ESTIMATE

OUTLINE FROM DRAFT STATEMENT OF WORK DATED 14 JUNE 1995

3.1 CONCENTRATOR (less deployment and tracking)		**15,290 hours, $710K**	
3.1.1 MATERIALS AND COUPON TESTING		530 hours,	25K
	Facilities	80 hours,	$102K
- Test Program Planning		40 hours	
- Coupon Design		20 hours	
- Coupon Fabrication (10 coupons leveling, 10 coupons reflectivity, 10 coupons substrate)			
Labor- 3 hours/coupon		90 hours	
Materials			$5K
- Coupon Testing			
Test Monitoring- 6 hours/coupon		180 hours	
Test Operations- 4 hours/coupon		120 hours	
Test Materials			$10K
- Contingency Testing (Additional Testing if Needed)			$10K
- Costing , Scheduling, and Reporting		80 hours	
- Facilities			
Clean Room			
Labor- Specifying, Purchasing, Installation		40 hours	
Materials- Purchased Items			$92K
Spray Booth			
Labor- Specifying, Purchasing, Installation		40 hours	
Materials- Purchased Items			$10K
3.1.2 TOOL AND FACET CONSTRUCTION		**11,840 hours, $560K**	
3.1.2.1 Design Concentrator and Tooling-	37 man-months design, analyses, drafting	5920 hours	
3.1.2.2 Fabricate Tooling-	Labor- 6 man-months, tooling vendor support	960 hours	
	Materials- tooling vendor		$333K

3.2 PROGRAM SUPPORT — 2280 hours, $11.8K

3.2.1 COST, SCHEDULE, AND PERFORMANCE TRACKING

Labor-	.75 person for 15 months	1800 hours	

3.2.2 ATTEND GOVERNMENT REVIEWS

Labor-	7 reviews at 40 hours/review	280 hours	
Travel Expenses	7 trips- 2 days at $116 + $500 each		$5.8K
As Needed Support to EGD Testing-	Labor- 40 hours/month for 5 months	200 hours	
	Travel- 5 trips at $1200 each		$6K

CONCENTRATOR COST ESTIMATES	TABLE 5.2			6/15/95
Manhour ate = $70/hour	Labor Hours	Labor $K	Material Cost $K	Total $K
3.1 CONCENTRATOR	**15,290**	**1070.3**	**710**	**1780.3**
3.1.1 Materials and Coupon Testing	**530**	**37.1**	**25**	**62.1**
Facilities	**80**	**5.6**	**102**	**107.6**
3.1.2 Tool and Facet Construction	**11840**	**828.8**	**560**	**1388.8**
3.1.2.1 Design Concentrator and Tools	5920	414.4		414.4
3.1.2.2 Fabricate Tools	960	67.2	333	400.2
3.1.2.3 Inspect Tools	480	33.6	15	48.6
3.1.2.4 Fabricate Concentrator	4160	291.2	202	493.2
3.1.2.5 Inspect Concentrator	320	22.4	10	32.4
3.1.3 Deployment Mechanisms and Structures				
3.1.3.1 Design Deployment Mechanisms and Struct.				
3.1.3.2 Fabricate Deployment Mechanisms and Struct.				
3.1.3.3 Test Deployment Mechanisms and Structures				
3.1.4 Pointing and Tracking System Design				
3.1.4.1 Design Pointing Tracking System				
3.1.4.2 Model/Analyze Performance				
3.1.5 Co centrator Performance Testing	**560**	**39.2**	**11.2**	**50.4**
3.1.5.1 Prepare Test Plan	40	2.8		2.8
3.1.5.2 Conduct a Test Readiness Review	40	2.8		2.8
3.1.5.3 Collect and Analyze Test Data	400	28	11.2	39.2
3.1.5.4 Report Test Results	80	5.6		5.6
3.2 Program Support	**2280**	**159.6**	**11.8**	**171.4**
3.2.1 Cost, Schedule, and Performance Tracking	1800	126		126
3.2.2 Attend Government Reviews	280	19.6	5.8	25.4
As Needed Support to EGD	200	14	6	20