NI

NASA Technical Memorandum 58233

Satellite Power System
Concept Development and Evaluation Program

Volume VI
Construction and Operations

Harold Benson and Lyle M. Jenkins

April 1981

NASA
National Aeronautics and
Space Administration

NASA Technical Memorandum 58233

Satellite Power System
Concept Development and Evaluation Program

Volume VI
Construction and Operations

Harold Benson and Lyle M. Jenkins
Lyndon B. Johnson Space Center
Houston, Texas

CONTENTS

TABLES

FIGURES

I. SUMMARY

Studies of solar power satellite construction, operations, and mainte-
nance have led to an understanding of the manpower and time required to con-
struct a solar power satellite. Such a system would require approximately
600 workers in space together with orbital construction bases and equipment.
Results of these studies indicate that a satellite could be built in 6 months.
The rectifying antenna construction is typical of other Earth-based projects
but can benefit from the application of specialized machinery. Maintenance
of the entire solar power satellite system would involve satellite refurbish-
ment, primarily in the antenna; transportation of the refurbishment material
and manpower to orbit; and a moderate amount of rectifying antenna component
replacement on the ground.

These studies have identified the following technology emphasis for solar
power satellite construction and operations work which could be conducted on
the ground: (a) zero-g and space vacuum simulations, (b) analytical modeling,
and (c) automated construction equipment. This technology work will provide
a basis for detailed definition of early orbital experiments, later system-
level flight projects, and a solar power satellite "demonstrator."

II. INTRODUCTION

This report is a summary of the technical assessment activities on the solar power satellite (SPS) construction, operations, and maintenance requirements which took place during the Department of Energy (DOE)/NASA Concept Development and Evaluation Program (CDEP). It is one of a series of SPS CDEP technical summary and assessment reports. The SPS reference configuration referred to herein is described in reference 1.

The multicontractor concept development activity was conducted by the NASA Lyndon B. Johnson Space Center (JSC) and the NASA George C. Marshall Space Flight Center (MSFC) in concert with the Department of Energy. Utility interface requirements were evaluated and are described herein. Alternative concepts for utility interfaces, construction bases, and construction site locations are included.

In compliance with the NASA's publication policy, the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). As an aid to the reader, the SI units are written first and the original units are written parenthetically thereafter.

III. SPACE CONSTRUCTION

A. GUIDELINES

Two main guidelines were used in the space construction studies.

1. Two 5-gigawatt SPS's would be built per year.

2. Only materials derived from the Earth would be used.

B. SPS CONSTRUCTION LOCATION

Because of the size of the SPS structure, construction must take place in space. The absence of gravitational loads in space allows very lightweight, low-density structures to be used. Also, constructing the low-density satellites in space permits high-density payload packaging of materials and thus minimizes the number of launches.

Studies have shown that either low Earth orbit (LEO) or geosynchronous orbit (GEO) construction is feasible. The GEO construction location is used in the reference system. Construction of the satellite in GEO has several advantages. Gravity-gradient loads are two orders of magnitude lower than in LEO, aerodynamic drag loads are not significant, thermal effects from passing through the Earth's shadow are negligible, collision hazard from other satellites is low, and the construction sequence is simpler. Personnel logistics requirements and transportation costs for the construction base, on the other hand, are greater than in LEO, but the percentage cost impact is not significant.

Building the satellite as a complete unit in LEO for transport to GEO is not practical because of control requirements and loads to the structure due to gravity-gradient torques. The most effective mode of construction in LEO is to build the satellite in modules which have LEO-GEO transfer requirements sized to be compatible with the thruster requirements for the control of the SPS in GEO operation. The modules are then berthed together in GEO for final assembly.

Construction in LEO offers a potential transportation cost saving by using a self-powered mode, in which output from the partly deployed SPS solar cells is used to power a LEO-to-GEO electric propulsion system which uses high-efficiency ion engines. Although chemical propulsion could be used, the use of an independent electric orbital transfer vehicle (EOTV) concept for GEO construction could eliminate any cost differential between LEO and GEO sites. Radiation degradation of the solar cells during transit of the Van Allen belts remains a technical issue.

C. TASKS, EQUIPMENT, AND FACILITIES

Several construction approaches were evaluated. Because of the large scale of the operation, a high degree of automation can limit the number of personnel and reduce the total construction time. The personnel principally perform monitoring, repair, support, and other functions which

5

cannot be automated efficiently. The activities involved in one approach to SPS construction are shown in figure III-1.

Heavy lift launch vehicles deliver 400 tonnes of cargo to a LEO base at a rate of about 8 launches per week, or 400 per year. Similarly, personnel launch vehicles take 75 to 80 crewmen from Earth to the LEO base 32 times per year. Crew stay time for each trip is about 90 days. About 135 crewmen would be stationed at the LEO base all the time to handle cargo. The LEO base also constructs several electric orbital transfer vehicles that carry SPS materials to GEO in unmanned trips lasting about 6 months. The LEO base also provides a staging depot for personnel and supplies for transfer to chemically powered personnel orbital transfer vehicles for a 6-hour Hohmann transfer to GEO.

At GEO, the 6400-tonne construction base receives cargo from the electric orbital transfer vehicles and, with a crew of about 400 people, constructs each 5-gigawatt SPS in 6 months. Of the 400 people, about 270 are involved directly in construction, which includes deploying the solar energy conversion system, assembling the antenna, installing various subsystems, maintaining construction equipment (beambuilders, cherrypickers, transporters, manipulators, etc.), and performing base logistics and testing. The remainder of the personnel provide base operations and support functions (lodging, food, health, communications, etc.). The GEO base also serves as a staging area for maintenance crews and systems that travel periodically to operational SPS's, as well as a refurbishment center for disabled SPS components. The number of people required for the maintenance function varies with the number of SPS's in service. About 380 people are needed to maintain 20 operational SPS's.

It is assumed that crewmen rotate about every 90 days. A 90-day space stay time is considered a reasonable compromise based on the psychological effects of remote confinement, the effect of zero g on the body, and radiation exposure limits. Radiation exposure considerations are based on limited extravehicular activities and provision of "storm cellar" shielding for major solar events. For instance, with a high flux and nominal shielding, a quarterly maximum dose of 35 rem to blood-forming organs would be reached in about 90 days.

1. CONSTRUCTION BASE CONCEPT: BOEING/GRUMMAN

In the process of developing the concept for a construction base for the silicon solar cell SPS configuration, a number of alternative space construction concepts were evaluated. Conclusions derived from this work are summarized as follows.

   a. Two- and four-bay endbuilders provide higher production capability for equivalent cost of single deck.

   b. Eight-bay-wide base is not cost effective for 6-month construction cycle.

6

c. Coupling solar array deployment with longitudinal beam fabrication facilitates faster construction.

d. Synchronized operation of multiple beambuilders can be implemented with state-of-the-art feedback control techniques.

e. Aluminum solar array structure is feasible.

a. Overview

Several endbuilder construction concepts were developed by Grumman for direct comparison with a single-deck construction platform concept. These construction options are shown in figure III-2.

Ground rules for preliminary analysis for both the platform type and endbuilder construction concepts were to use a common antenna construction facility and to constrain SPS final assembly and checkout to one satellite every 6 months. All options were evaluated in terms of cost, performance, complexity, risk, etc. The eight-bay-wide endbuilder had the highest unit cost, and its production capability could not be fully used. The comparison of the multipass endbuilder and the single-deck platform concepts was nearly even. The four-bay endbuilder was selected, however, for additional definition work in Phase 2 because of its greater production rate growth capability.

During Phase 1, Grumman also performed preliminary studies on the feasibility of using aluminum alloys for the basic solar array structure of the SPS. Practical thermostructural design solutions were found for minimizing the effects of thermal transients on aluminum beams in orbit. An aluminum beam design, which can be fabricated in space for the SPS solar array structure, is shown in figure III-3. Preliminary analysis of several thermal design conditions indicates that the use of aluminum is feasible. The results of this analysis are compared with the baseline advanced composite SPS structure in the Phase 1 Final Report (NSS-SPS-B-RP008).

In the Phase 2 study activity, the operational requirements of the SPS GEO base were analyzed and the facility concepts of the four-bay endbuilder were updated. The analysis of GEO base operations was used to derive requirements for base command and control, crew operations support, base flight attitude control, satellite construction, and intrabase logistic operations. The four-bay endbuilder was defined with contiguous construction facilities for concurrent assembly of the SPS energy conversion system and its microwave antenna as shown in figure III-4. A top-down analysis of satellite construction operations was focused on the structural fabrication and assembly techniques for the SPS energy conversion system, including its major subsystem installations. The SPS construction technology issues were identified and alternate solutions were addressed through all levels of the analysis. Figure III-5, for example, illustrates the manner in which the solar array blankets might be temporarily anchored to the base so that they can be automatically deployed during longitudinal beam building operations. The illustration also shows two cherrypickers prepared to handle and connect opposite ends of a 667.5-meter solar array support beam to the SPS frame

after it emerges from the 12.7-meter beambuilder. The analysis of construction operations also developed requirements for SPS interface assembly and antenna/energy conversion final system mating.

The GEO base configuration has been amplified to include beambuilder substations and power bus dispenser stations in the solar collector assembly facility and the yoke/rotary joint assembly facilities. The updated four-bay endbuilder configuration is shown in figure III-6 during initial satellite construction.

The top deck of the GEO base, level J, provides facilities for cargo docking/unloading and distribution, crew quarters and operations, orbital transfer vehicle docking and servicing, and SPS maintenance support. The base flight control and electrical power subsystem concepts are included in the updated base arrangement.

A brief study was also performed to review and update the baseline 100-man crew habitat. Crew quarter design requirements were re-examined for internal crew module arrangements, GEO radiation protection, and environmental control/life support functions. Lastly, a concept for building the SPS GEO base was developed.

The major conclusions derived from the Phase 2 study of SPS construction operations and the GEO base definition are summarized as follows.

      (1) GEO construction operations are feasible considering

          (a) Satellite assembly steps

          (b) Crew operations support

          (c) Major base subsystems

          (d) Intrabase logistics

          (e) GEO base buildup

      (2) Add-on SPS maintenance support facilities are feasible on GEO construction base.

Satellite construction operations in GEO remain a feasible option for the SPS Program. Analyses of GEO base operations indicate that SPS maintenance support facilities can be included on the base as needed.

b.   <u>GEO Construction Base Design and Analysis</u>

The four-bay endbuilder construction base assembles the 5-gigawatt reference SPS entirely in geosynchronous orbit (fig. III-7). The eight-bay-wide satellite energy conversion system is constructed in two successive passes on one side of the base, while the microwave antenna is assembled on the other side of the base. On the first construction pass, the

GEO base builds one-half of the energy conversion system, a 4-bay-wide strip by 16 bays long. When this part of the satellite has been constructed, the base is indexed back along the edge of the structure to the first endframe. During the second construction pass, the four-bay-wide strip is attached directly to the assembled satellite systems. At the end of the second pass, the base is indexed sideward to mate the antenna with the centerline of the energy conversion system. After final test and checkout (C/O), the base separates from the satellite and is transferred to the next orbital position for SPS construction.

c. Satellite Construction Operations

The 5000-megawatt reference solar power satellite is to be constructed entirely in GEO and is to be fully assembled in 6 months. The reference satellite has a single antenna located at one end of a large photovoltaic energy conversion system as shown in figure III-8. The 8- by 16-bay energy conversion system features a hexahedral braced structure, lc _itudinal solar array (SA) blanket installation, and multiple power buses. The satellite construction approach includes the 2-pass longitudinal buildup of the energy conversion system and the 16-row lateral buildup of the power transmission antenna as defined in Boeing's Phase I final report (ref. 2). The GEO construction operation is to rely upon normal intravehicular-activity (IVA) assembly methods. A broad range of technology issues must be addressed to cover all aspects of the SPS construction process. As the reference system matures, the satellite construction approach must be reexamined for the energy conversion, power transmission, and interface systems. In addition, the struc ural assembly methods should be well understood to the level of beam fabrication, handling, and joining. Techniques for installing the major subsystems (i.e., solar arrays, buses, and subarrays) must be further developed, and the requirements for construction equipment need further refinement. In addition, the structural dynamic, thermodynamic, and control interactions between the base and the satellite should be investigated and defined. Other areas to be examined include methods for berthing or mating of large system elements, techniques for in-process inspection and repair, and concepts for implementing satellite final test and checkout. In the following subsections, the general construction approach is defined and the methods used to assemble, mate, and check out the satellite energy conversion system, power transmission system, and interface system elements are described.

(1) General Construction Approach

The GEO base structure supports the emerging satellite during all phases of construction. The SPS energy conversion system is assembled during two successive passes by the L-shaped framework shown in figure III-7. The width of this framework (3.44 kilometers) encompasses a five-bay segment of the energy conversion structure to provide a one-bay overlap for lateral and longitudinal indexing operations. The 700-meter-high open truss structure houses beam fabrication stations, solar blanket installation equipment, bus installation mechanisms, crew facilities, docking, storage, intrabase transport, etc. The other leg of the facility (913 meters long) guides and supports the satellite until all systems are mated and checked out.

9

The antenna assembly platform, which is located at the rear of the base, is arranged to facilitate the construction and attachment of the antenna and rotary joint interface. This open truss platform (2.74 by 1.65 kilometers) also supports the antenna/yoke assembly during the final lateral index and mating operations with the assembled 8- by 16-bay energy conversion system. The framework provided for the rotary joint/yoke assembly facility and antenna assembly facility is sufficient to house the required construction equipment as shown in figure III-6.

    (a) <u>Construction analysis emphasis</u> - Once the GEO base is built and operating in orbit, the construction of solar power satellites will become its primary mission function. Each satellite is constructed and placed in the required orbital location by the GEO base. Hence, after each construction cycle, the base transfers to another orbital site, where it builds the next SPS. The base will also support operational satellite maintenance, when needed.

    The SPS construction operations were analyzed from the top down, by defining the required steps at each level of the construction sequence. The top-level operations of the GEO base and a first-level breakdown of the construction operations flow are shown in figure III-9. Construction of the reference satellite system includes parallel assembly of energy conversion, power transmission, and interface elements. When these system elements are fully assembled, they are mated and integrated to form the complete solar power satellite. The construction cycle ends with final test and checkout of SPS systems.

    (b) <u>Four-bay endbuilder time line</u> - The SPS assembly operations commence with the construction of the energy conversion system, as shown in figure III-10. Assembly of the energy conversion system is timed for simultaneous completion and mating with the interface system and power transmission system. The 5-gigawatt monolithic satellite is constructed and checked out in GEO in 6 months.

    The 4-bay endbuilder uses 2 passes to construct the 8- by 16-bay energy conversion system; each pass provides a 4- by 16-bay module which contains the appropriate subsystems (i.e., structure, solar blanket, power distribution and control, attitude control, etc.). The main power bus is installed during the first pass in parallel with the fabrication of continuous longitudinal beams. The second construction pass is somewhat shorter since one side of the structure is already built and therefore less vertical and diagonal support beams are required. The energy conversion assembly process can be accelerated, if necessary, by increasing the rate of continuous longitudinal beam fabrication.

    The interface system is constructed separately and then joined to the power transmission system. The satellite is fully assembled when these systems are mated with the energy conversion system. The overall construction sequence is illustrated in figure III-11.

10

(c) Ground rules and assumptions - The Phase 2 SPS
construction analysis is keyed to the 5-gigawatt reference satellite concept
(i.e., silicon solar cells and a concentration ratio of 1.0) as defined in
reference 2. The following list of ground rules and assumptions was devel-
oped during Phase 1 and expanded during the Phase 2 analysis of energy con-
version system assembly operations.

[1] Construction of the solar power satellite is
to be accomplished at GEO.

[2] One 5-gigawatt satellite is to be assembled
in 180 days ± 5 percent.

[3] Free-flying assembly or construction equip-
ment is to be avoided.

[4] Extravehicular-activity (EVA) construction
tasks should not be required, except for in-
frequent maintenance and inspection tasks.

[5] The energy conversion system structure is to
be composed of a repeating hexahedral truss
arrangement 8 bays wide and 16 bays long.
These bays are 667.5 meters wide and 672.7
meters long, giving a 5.4- by 10.8-kilometer
structure when completed.

[6] A four-bay endbuilder construction facility
is to be used to construct the energy conver-
sion system structure in two passes. Each
pass through the endbuilder produces a 4- by
16-bay structural module.

[7] The endbuilder construction base concept
relies on semistationary beam machines in
synchronous operation to produce continuous
longitudinal members (10 776 meters) for the
energy conversion system.

[8] Mobile beambuilders operating autonomously
are to be used to produce the various lat-
eral, vertical, and diagonal beams as needed
to complete the structure in each bay.

[9] Structural beam segments are to be trans-
ported and installed by two cherrypickers,
one at each end. These cherrypickers are

[a] Controlled by one operator in the cherry-
picker

[b] Self-propelled by onboard power supply

11

[c] Operated from a rail track system on the energy conversion system construction facility

[10] Construction operations will be performed during two 10-hour shifts per day and at 75 percent efficiency.

[11] Concurrent with the construction of the energy conversion system structure, other nonstructural elements of the energy conversion system are to be assembled and installed as follows.

[a] Solar array

[b] Power distribution

[c] Attitude control

[d] Other subsystems

[12] The solar array blankets will be attached to 12.7-meter upper lateral beams and will be deployed longitudinally concurrent with the fabrication of the longitudinal beams.

[13] The GEO construction base interfaces with the energy conversion system structure by way of indexing/support machines that provide the capability to index in lateral and longitudinal directions. Those indexers are

[a] Mobile towers with mechanisms for attachment to hard points on the energy conversion system structure

[b] Self-powered with onboard power supply

[c] Remotely controlled/monitored from base command and control center and can be slaved

[d] Operated from a rail track system on the energy conversion system construction facility

[14] Construction equipment rates ranging from 0.5 to 20 m/min, shown in table III-1, are assumed to be reasonable. Low equipment use should be avoided.

12

[15] All construction equipment is modularized for ease of maintenance.

[16] Forty-four solar array blankets, 14.9 meters wide and 660 meters long, will be installed in each structural bay.

[17] The blankets will be deployed longitudinally between the 12.7-meter lateral beams and electrically connected to interbay jumpers, jumper buses, and acquisition buses, as required, to assemble eight-blanket strings.

[18] The interbay jumpers, jumper buses, and acquisition buses are automatically mounted on the 12.7-meter upper lateral beams as an integral part of the beam fabrication process.

[19] Before installation operations, solar array blankets will be inspected and checked out at storage locations.

[20] An unmanned transporter will be used to deliver the blanket containers to the appropriate installation locations.

[21] A pair of cherrypickers, performing coordinated activities, is required for the installation of a solar array blanket.

[22] A total of four cherrypickers is allocated for installing the blankets and assembling the blanket strings.

[23] A braking capability must be provided, which will allow the simultaneous longitudinal beam fabrication/solar array deployment to stop when required, without detrimental effects on the solar array blanket

[24] The satellite structure is to be divorced from the cumulative effect of the thermal variations of power distribution buses.

[25] The natural frequency of the power distribution buses is to be greater than that of the satellite.

[26] Major satellite elements are to be supported by the base during all phases of construction.

13

[27] The indexers should be located as far from each other as possible, to enhance stability.

[28] Indexer supports are to be attached to the satellite structure at nodal points (e.g., space frames on the continuous longitudinal beams at the bottom of the energy conversion system structure).

[29] The indexers can be independently operated while traveling about the GEO construction base, but during indexing operations, they will be operated under synchronized control.

[30] The SPS quality assurance activities are to be performed concurrent with SPS construction operations.

[31] Automated construction operations are to be continuously monitored and inspected. For example, mechanical attachments will be inspected for structural integrity and electrical connections will be subjected to continuity tests before acceptance.

[32] Satellite inspection will be performed at each level of system buildup to assure integrity of construction.

(d) Construction equipment - Typical construction equipment used by the major construction facilities of the GEO base is illustrated in figure III-12. The SPS construction equipment includes automatic machinery for fabricating large structural beams in space. These beam machines build three-sided open truss beams from tightly rolled strips of composite material to avoid the higher costs incurred in transporting low-density structures to GEO. General-purpose manned cherrypickers, provided with dextrous manipulators, are used to assemble these lightweight beams and install the required subsystem components in the energy conversion and power transmission systems. During construction, the major elements of the satellite are supported by indexers which can be moved across the base as needed. Additional equipment is also provided to facilitate the deployment of large sheet metal power buses, the anchoring of solar array blanket containers, and the installation of antenna systems. Table III-2 contains a summary listing of the major equipment types and use locations on the base. The solar collector beambuilder substations and the power bus dispenser station are discussed further in the following paragraphs.

[1] Energy conversion beambuilder requirements: Four different types of beambuilders are required to construct the energy conversion system as shown in table III-3. Two types of beambuilders are

14

synchronized for continuous longitudinal beam fabrication, whereas the
remaining two beambuilders are employed to fabricate lateral, vertical, and
diagonal bracing member·. The 7.5-meter synchronized and 12.7-meter autono-
mous beambuilders, which operate at the solar array level, are required to
install solar array maintenance track during beam fabrication. The longi-
tudinal beambuilders must also be capable of installing attachment frames for
joining other beams. All segmented beams, in turn, must be fabricated with
suitable end attachments.

The 7.5-meter synchronized substation il-
lustrated in figure III-13 includes a beam machine equipped with framemaking
features. Frame segment supply canisters are mounted at each beam face at
crossmember attaching stations. Since current maintenance track concepts
require supports at each crossmember, track attachment will occur after the
completed crossmembers emerge from the beam machine. This requirement dic-
tates the location of the track forming module as shown.

The 7.5-meter mobile substation illustrated
in the lower part of figure III-13 uses a beam machine provided with end-
fitting attachment features. A column-mounted end-fitting support fixture
with movable gripping fingers can rotate to place fittings on either end of
a beam. The column swings down as required to clear the emerging beam or to
pick up an end fitting from the supply canister. The grip is capable of ex-
tending to secure and withdraw a fitting from the supply canister. An auto-
matic arm attaches the end fittings to the beam on either end as required.
An accessory platform is equipped with holding devices which index the com-
pleted beam and position it for installation of the end fitting after it has
emerged from the beam machine. The entire platform with beam machine and
accessories is capable of 360° swiveling and can be rotated perpendicular
to the carriage to provide any required orientation.

The 12.7-meter beambuilder concept shown in
figure III-14 has multiple functions in addition to the basic beam fabrica-
tion.

[a] The entire substation platform can be
oriented to direct the fabricated beam
as required.

[b] Maintenance tracks are installed on the
top and side of the beam during fabri-
cation.

[c] An end-fitting fixture can take pre-
fabricated end fittings from a sup-
ply canister and install them on either
end of the beam with the aid of the
end-fitting installer.

[d] Acquisition and jumper buses are in-
stalled during beam fabrication as
needed.

15

[e] Catenary attach fittings and solar array (S/A) interbay jumpers are installed during beam fabrication.

[f] A support platform equipped with indexers holds the beam to maintain alinement during fabrication and end-fitting installation and aids in positioning the completed beam.

[2] Mobile power bus dispensing station: The power bus dispensing station, shown in figure III-15, dispenses both main and feeder buses and installs the bus support cables. Individual bus strips are supplied by specific supply canisters mounted at the back of the dispensing unit. The support cables are supplied by drums mounted on the top and bottom of the dispensing unit. The entire dispensing module pivots to dispense either feeder or main bus as required. The dispensing unit is supported on a base, which travels on the main carriage. The main carriage moves the entire assembly from one end of the construction base to the other during feeder bus dispensing.

Aided by a dedicated, mobile cherrypicker, the bus dispensing station installs and preloads the support cables on the array as part of the dispensing operation. The support strongbacks and intermediate stiffeners are installed while the bus array is still secured by the dispenser. The dispensing station provides the correct mix of bus array elements to meet main and feeder bus requirements in the correct sequence in the construction process. The dispensing station can cut and splice bus material as required. During main bus dispensing operations, the dispensing station is positioned at one end of the construction base.

(2) Energy Conversion System Assembly

A breakdown of the assembly operations for the energy conversion system is shown in abbreviated form in figure III-16. This assembly activity includes the fabrication and assembly of the structure for the first construction pass and the parallel installation and inspection of required subsystems (e.g., solar array blan'ets, power distribution). When the first half of the satellite energy conversion system has been constructed, the base will be indexed back along the side of the satellite structure to a position adjacent to the first frame. The second construction pass begins from that point and includes the fabrication and assembly of the remaining structure together with the parallel installation of other subsystems.

(a) Endbuilder assembly sequence - The endbuilder construction system is tailored to the structural cross section of the satellite and uses 10 dedicated semifixed beam machines to automatically fabricate continuous longitudinal members. Lateral and diagonal members of the structural assembly are fabricated by three mobile beam machines. The assembly sequence (fig. III-17) begins with step 1, the assembly of the first frame and its attachment to the longitudinal members. The structural members of the

16

frame are fabricated by three mobile beam machines that travel from one position to the next. The upper lateral beam is fabricated and then positioned for assembly. As this member is being joined, the mobile beam machines fabricate the other members of the frame needed to complete the assembly. In step 2, the frame for one bay length is indexed by fabricating the continuous longitudinal beams from the dedicated beam machines. In step 3, the next frame is built as in step 1. During these three steps, power buses and solar array blankets are installed in parallel. The solar array blankets are deployed in the direction of build, are attached to the upper lateral beams, and are fed out of canisters as the structure is indexed. Longitudinal buses are installed "on the fly" as the structure is indexed; lateral buses are installed before a bay is indexed. In step 4, the bay structure diagonal beams are fabricated and assembled to complete the bay. This bay is then indexed, as in step 2, and the entire sequence repeated until the energy conversion structure is built.

The endbuilder concept couples similar functions for installing each subsystem to related operations for assembling the energy conversion structure. As shown in figure III-18, the concept provides two avenues for attaining increased production performance: operate automated construction equipment faster or add equipment.

(b) SPS assembly operations - The rendering in figure III-5 depicts the construction activities at levels F, G, and H of the energy conversion construction facility. These levels are used in the construction of the upper surface of the energy conversion module. Shown nestled in the facility structure is the 7.5-meter longitudinal beam machine (semifixed), and operating from a horizontally mounted track system are two mobile beam machines. One beam machine is shown fabricating the 7.5-meter bracing beam and the other, a 12.7-meter lateral (solar array support) beam. Located overhead on the facility overhang and operating from a track system, cherrypickers are used to maneuver and attach the completed beams. The complex operations of these two cherrypickers in the maneuvering, handing-off, and installation of beam lengths of approximately 600 to 1000 meters require further study.

Solar array blanket deployment and installation is coupled with the endbuilder structural assembly sequence. Shown are the blanket installers operating from a track system mounted on the facility overhang. The solar array blankets are deployed from canisters mounted on the overhang. Replacement canisters are shown being moved into place and installed at their deployment station by a mobile flatbed cherrypicker.

The arrangement of major construction equipment at levels F, G, and H is also shown in figure III-19. The level G 7.5-meter longitudinal beambuilder substation is provided with 60 meters travel distance to permit on-line maintenance and repair for continuity of construction operations. This distance provides about 1 hour for the repair and replacement of beambuilder components while the shutdown beambuilder tracks along at the same rate as the indexing structure. The figure also shows the bus dispensing station in relation to the other beambuilders and the solar array

17

anchor at level H. The time line for assembling the first two rows of the energy conversion system is shown in figure III-20.

(c) **Fabricating and assembling structure** - The generic sequence used for the fabrication and assembly of the energy conversion system structure is shown in figure III-21. This structure provides support for the solar array blankets, the power distribution system, the attitude control system, and other subsystems that are part of the energy conversion system. It also interfaces with the antenna yoke.

As shown in figure III-22, the energy conversion system structure is designed with a hexahedral (box) truss arrangement 8 bays wide and 16 bays long, which includes two sizes of graphite composite tribeams. The heavier 12.7-meter beams are used at all other locations. In addition, 7.5-meter beams are used for structural support of the attitude control thrusters at each corner of the structure. The two types of beams are shown in figure III-23. Type A beams are fabricated by a 12.7-meter mobile beam machine and are used only on the upper level of the structure to support the solar arrays. Type B beams are used for the rest of the structure. Ten type B beams are fabricated by semistationary beam machines to provide the 16-bay-long continuous longitudinal beams. Type B beams with end fittings are fabricated for all other structural members by two 7.5-meter mobile beam machines.

In addition to the structural configuration previously described, the top surface of the energy conversion system structural framework includes a maintenance track to accommodate solar array annealing operations. This track imposes additional requirements on the energy conversion system structural arrangement and on the beam machines. The upper surface continuous longitudinal beams are required to be oriented with a flat side up, as shown in figure III-24, to provide for the mounting of the track system. The tracks are supported by the beam with fittings attached at each beam batten.

(d) <u>Installing solar array blanket strings</u> - The generic sequence used for the assembly of the solar array blanket strings for the energy conversion system of the SPS and their integration into the structural framework and the power distribution network are shown in figure III-25.

[1] Solar array blanket installation requirements: The solar energy collectors for the 5-gigawatt solar power satellite are glass-encapsulated single-crystal silicon cells, mounted in a 14- by 16-cell matrix to form the 1.059- by 1.069-meter solar array panels. These panels are joined together to form solar array blankets, 14 panels (14.9 meters) wide and 611 panels (656 meters) long, with catenary cables on each end for attachment to the 12.7-meter lateral beams of the energy conversion system structure. The 611 panels of each of the 14 separate strips of the solar array blanket are electrically interconnected but isolated from the adjacent strip. Each end of the 14 strips is connected to a number 12 aluminum wire, and the 14 wires at the ends of the blanket are intertwined to

18

form pigtails for electrical interface with other blankets or with acquisition buses.

The solar array blankets are manufactured on Earth, folded like an accordion, packaged in blanket containers, and installed in 22-blanket container magazines for transportation to GEO and subsequent installation on the solar power satellite. As shown in figure III-26, 44 blankets are installed within each bay of the energy conversion system and each blanket is preloaded to 61.5 newtons. The blankets are connected in series by interbay jumpers to form four-blanket strings, mounted between the first and fifth upper lateral beams of every four rows. Pairs of four-blanket strings are connected in series by jumper buses on the first, fifth, ninth, and thirteenth frames to form eight-blanket strings, which are connected to positive and negative acquisition buses on the fifth, ninth, thirteenth, and seventeenth frames.

[2] Solar array installation approach: The endbuilder concept uses a two-phase operations approach, which couples solar array blanket installation operations to related operations for the assembly of the energy conversion system structure. As shown in step 1 of figure III-27, while the structure is stationary and the lateral beam segments are being fabricated and installed, the solar array blanket containers are being mounted on the proximal anchors and the distal catenaries of the blankets are being attached to the N-th 12.7-meter upper lateral beam. In step 2, while the continuous longitudinal beams are being fabricated and the structure is being indexed outward, the solar array blankets are being deployed. When the longitudinal beam fabrication stops and the structure is again stationary in step 3, the proximal catenaries of the solar array blankets are removed from the anchor and attached to lateral support beam N + 1.

The operations required for mounting the blanket containers and attaching the catenaries are performed by two cherry-pickers. The initial operations for deploying the solar array blanket from the proximal anchor on level H of the construction base are shown in figure III-28. One 14.9-meter-wide blanket is shown deployed from level H and attached to the upper lateral beam of the satellite structure. Two carriage-mounted, mobile cherrypickers are also shown beginning to deploy the next solar array blanket. The cherrypickers, located at each end of the blanket, have removed a blanket container from the supply cart and attached it to the distal anchor posts. Working in unison, they remove the distal end of the blanket from the blanket container, deploy the array down to the 12.7-meter beam, and attach the catenary and electrical leads. Both cherrypickers will then move 15 meters laterally and repeat the operations for the next blanket.

In the dispenser box, panel segments are held in folded pairs by thin tapes from one end of the box to the other. The tapes, with a calibrated breaking strength, help reduce panel spillage. However, as construction proceeds, tension loads in the deployed portion of the panel increase until the load reaches the breaking point of the tape and a folded pair of panel segments is released, relieving the load. This repeated cycle causes periodic variations in panel tension. If planned or emergency factors require construction shutdown, braking loads may be sufficient to

19

cause spillage of the stowed panel even with restraining tape. Future studies should investigate alternative dispensing concepts; for example, reel- or drum-mounted panels which could be controlled using established methods of braking.

The current 12.7-meter lateral beam design was sized for an earlier solar array deployment concept, which was not coupled to the fabrication of continuous longitudinal beams. Each beam was allowed to rotate about its nodal end fitting to relieve solar blanket preload bending. The rotating beam concept is not compatible with the end-builder coupled solar array/structure deployment operations, since it makes solar array blanket tensioning very difficult. It is also not compatible with the installation of solar array maintenance track, particularly with respect to the lateral end members and the numerous track crossover connections. It is recommended that further study be devoted to alternate beam design concepts with different end fixities.

(e) Installing power distribution network - The generic sequence of operations for the assembly of the energy conversion system power distribution network is shown in figure III-29.

[1] Installation requirements: The power distribution network is composed of the main and feeder buses shown in figure III-30 and their interface with the power collection system together with the associated maintenance track system, shown in figure III-31.

The main and feeder buses are supported next to the satellite vertical beams beneath any intersecting diagonal or cross bracing structure. Support of the bus arrays is achieved using cables tensioned to compensate for thermal variations and provide preload to maintain the natural frequency of the bus array above that of the satellite.

The acquisition and jumper buses are attached to opposite sides of the lateral beams just below the cap members. The switchgear assemblies are supported on platforms attached to the lower cap member and braced with additional members from the upper cap members. Connections are made from the acquisition bus to the switchgear. Installation of the switchgear assemblies takes place after the beam is completed.

The maintenance concept shown provides a separate maintenance track beam underneath the solar arrays which parallels the main and feeder bus locations. This track provides a working base for bus maintenance equipment to travel upon. The requirement for a dedicated maintenance track can be satisfied by expanding the updated beambuilder substation concept, in which solar array maintenance track is installed during the beam fabrication process.

[2] Installation approach: Bus deployment operations are coupled to related operations for the assembly of the energy conversion system structure. The main bus is deployed while the continuous longitudinal beams are being fabricated for rows 5 to 16. The feeder buses are

20

deployed while the structure is stationary and the lateral, vertical, and diagonal beam segments are being fabricated and installed for rows 4, 8, 12, and 16.

Both main and feeder power buses are supported by nonmetallic cables attached to outrigger structure on the vertical beams, as shown in figure III-32. Placement of the cable attach points on the outriggers is planned to support the bus arrays in a plane parallel to the vertical beams at a point low enough to avoid interference with any overhead horizontal or diagonal structural members. The bus support cables are attached to strongbacks on the bus array, which serve to distribute the support cable tension loads across the bus array so that all the component bus strips share the tension load equally. The main and feeder buses also have stiffener members across the bus strips that maintain the correct bus-to-bus separation but do not provide structural support.

The feeder bus strips are supported so that an individual strip is alined at the same level as the corresponding strip in the main bus to which it is connected. As a result, the feeder bus arrays on one side of the main bus will have a different support geometry from that of the feeder bus array on the opposite side of the main bus. An examination of feeder bus electrical requirements indicates that not all bus strips are required for the entire length of the bus array; but for structural support, each bus strip must be continuous from one strongback to the next, regardless of whether or not it is required for electrical purposes. It may also prove necessary to increase bus strip width in some instances to carry the applied tension loads between strongbacks.

In the case of the feeder buses, where relatively few bus strips are arranged at widely separated intervals, bus installations are shown with strongback support limited to groups of bus strips rather than extending across the entire array. This approach simplifies strongback handling and fabrication and is more structurally efficient. Additional outrigger supports are required to support the resulting configuration. On the side of the vertical support beam farthest from the main bus, this configuration poses no problem as access to the beam is unrestricted. However, feeder bus access to the main bus side of the vertical member is obstructed by the main bus. In this case, access to support is provided by tension links passing from the vertical member through the main bus array in the space normally provided between bus strips. If the 0.5-meter space planned proves inadequate for this requirement, a larger space can be allowed in the bus array as needed with negligible impact on the design. Support cables run from the tension link to the feeder bus strongback.

(f) Installing attitude control system - The construction sequence for the SPS attitude control system is shown in figure III-33; also illustrated is its interface with the fabrication and assembly sequence for the energy conversion system structure. Figure III-33 also provides a detailed assembly flow for the number 1 reaction control system (RCS) unit, located on the first structural row.

The attitude control system includes all operational elements and software required to establish attitude control of the operational SPS on release from the GEO construction base and to maintain proper attitude and orbit stationkeeping during the operational life of the satellite. As shown in figure III-34, this equipment includes an ion thruster (with a chemical propulsion backup system for control during equinoctal occultation or unexpected loss of electrical power) at each corner of the satellite. Each thruster is mounted on a 500-meter outrigger that is positioned as an extension of a 12.7-meter lateral beam of the energy conversion system structure. The outrigger is supported by a 686-meter short brace from the lower continuous longitudinal beam and an 824-meter long brace located in the plane of the structure upper surface.

(3) Power Transmission System Assembly

The SPS microwave power transmission system (MPTS) is constructed on the antenna construction platform as a part of the construction base. The antenna construction approach is summarized in the following paragraphs as defined by Boeing during the Phase 1 study effort (ref. 2).

Figure III-35 is a side view looking into the antenna assembly facility. This picture illustrates the relative locations of the various construction equipment. The general construction sequence is illustrated in figure III-36. The antenna is indexed through the facility one bay at a time. When a full width of bays is completed, the antenna is indexed longitudinally out of the facility so that the next row of bays can be assembled. When the antenna is completed, it will be located at the proper position so that it can be mated to the yoke.

The integrated antenna construction time line is shown in figure III-37. Construction of the antenna entails the following suboperations: primary frame assembly, power distribution system installation, phase control system installation, subarray installation, and final test and checkout. These operations are described in the following subsections.

(a) Assembly structure – The configuration of the antenna primary structure is illustrated in figure III-38. The frame construction sequence, the beam machine and cherrypicker locations, and the time required are shown in figure III-39. Figure III-40 illustrates that both "tall" and "short" indexers are required during the frame assembly sequence. The beam end fittings and the battens are preassembled in the level K subassembly factory and are then delivered in sets or magazines to the antenna construction facility.

The antenna secondary structure is conceptually a preassembled deployable cubic structure. The structure is delivered as a collapsed and telescoped package. The construction task is to expand and lock the structure into a 104- by 104-meter square platform that can then be placed upon mounting points on the antenna primary structure.

The collapsed secondary structure package is delivered to the antenna deployment platform shown in figure III-35. This

22

platform is the most prominent assembly of equipment on the antenna con-
struction facility. Many pieces of equipment operate on this platform as
illustrated in figure III-41. The equipment platform is used to deploy the
secondary structure, to install phase control wiring, to install power distri-
bution wiring, and to install subarrays.

After each secondary structure package arrives at
the platform, it is placed onto the secondary structure detelescoper machine
mounted on one of the gantries. The phase control system installation cherry-
picker is employed to anchor one face of the secondary structure while the
detelescoper retracts to expand the structural package to its full 10-meter
depth. A lanyard is then pulled which allows the secondary structure to ex-
pand using spring-activated hinges on the structural struts. When the sec-
ondary structure is fully expanded and self-locked into a rigid structure,
the corners are attached to the secondary structure telescoping installa-
tion system. The structure is then ready to be wired. After the wiring is
completed and the primary structure correctly positioned, the secondary struc-
ture is raised into contact with the primary structure by the telescoping
actuators. Cherrypickers then make the necessary structural joints between
the primary and secondary structures.

(b) Installing power bus – After each bay of primary
structure is completed, it is time to install the power distribution system
on the surface opposite the subarrays. The first step is to install bus sup-
port subassemblies which have been preassembled in the level K subassembly
factory. A pair of cherrypickers is employed (the same ones used to install
the upper surface of the primary frame). At the nodal joints of the primary
structure, it is necessary to install a preassembled antenna switchgear sub-
assembly. After the support structures and the switchgear assemblies are
installed, a bus deployment machine moves into place and deploys the neces-
sary power busing for the bay.

It is necessary to install a power distribution
wiring harness on the secondary structures. This harness goes onto the face
of the secondary structure opposite the location at which the subarrays will
be installed. A gantry and a cherrypicker have been incorporated into the
deployment platform for this purpose.

After a secondary structure element has been
installed onto the primary structure, it is necessary to run power cables be-
tween the antenna switchgear subassemblies (on the primary structure) to the
power distribution wiring harness on the secondary structure. A 230-meter
cherrypicker is employed for this operation.

(c) Installing phase control – After the secondary
structure is deployed and attached to the installation telescopes, it is nec-
essary to install a phase control wiring harness (perhaps a fiber optics
harness) onto the face of the secondary structure adjacent to the subarray
installation locations. A gantry and a cherrypicker have been incorporated
into the deployment platform for this purpose. The phase control intercon-
nect operation between the subarrays and the harness installed on the second-
ary structure is accomplished as a part of subarray deployment.

23

(d) Installing subarrays - Before subarrays are delivered to the deployment area, the pallet of subarrays is delivered to a subarray test area, where each subarray will be tested for mechanical and electrical integrity (fig. III-42). The subarrays that require refurbishment would be taken to a nearby facility for repair. The tested subarrays are loaded onto a transporter for delivery to the deployment platform.

The method by which pallets of subarrays are transferred to and from the subarray deployer using an elevator is shown in figure III-43. The deployment machine traverses along the gantry, stopping every 10.4 meters. The deployment machine mechanisms extract each subarray panel from the pallet and raise it into position where the jackscrews can be attached to hard points on the secondary structure. The subarray is then leveled. The cherrypicker on the side of the deployer then makes the phase control and power distribution pigtail connections to the respective harnesses previously installed onto the secondary structure.

(4) Subassembly Factories

Subassembly factories are included on GEO base levels K and J, as shown in figure III-44, to support the main assembly operations for the antenna and solar array collector, respectively. The antenna subassembly factory on level K, for example, is equipped with component storage racks, manned cherrypickers, and various subassembly jigs. This factory preassembles beam end fittings, switchgear setups, and power bus support structures for the antenna and its rotary joint/yoke interface. The level J factory provides similar subassemblies which are tailored to be installed in the energy conversion system. The level J factory is also used to preassemble major components of the attitude control thrusters and major elements of required satellite maintenance equipment (e.g., solar array blanket annealing gantries).

(5) Interface Assembly and Systems Mating

A breakdown of the assembly operations for the interface system and of the mating operations for the assembled systems is shown in figure III-45. The assembly of the interface (block 3.3) includes the parallel fabrication and assembly of the yoke and rotary joint in blocks 3.3.1 and 3.3.2 and their subsequent integration by the block 3.3.3 operations. The completed interface system is then mated to the power transmission system in block 3.4.1 and to the energy conversion system in blocks 3.4.2 to 3.4.4, which include the fabrication and assembly of the yoke support structure and the concurrent lateral indexing operations.

(a) Installation requirements - The interface system construction includes the antenna yoke, the rotary joint, and the antenna support structure (figs. III-46 and III-47). The antenna yoke and the antenna support structure are assembled with the 7.5-meter beams baselined for SPS primary structure. The antenna support struts join to form a hexagonal interface that provides eight support points for the mechanical rotary joint circular beam. The mechanical rotary joint is composed of two segmented circular ring beams, as shown in figure III-48. The circular ring beams are

24

assembled with precut 1-meter beam segments. Roller ring drive assemblies provide the mechanical connection between each ring beam, and a central electrical rotary joint completes the interface.

(b) Interface assembly approach - The yoke/rotary joint assembly facility (fig. III-49) is used to construct the satellite interface system and support the mating of assembled systems. This facility moves across the back of the solar collector assembly facility; first, to support parallel yoke/antenna assembly operations (figs. III-50(a) and III-50(b)) and, second, to facilitate final systems mating (fig. III-50(c)).

Construction materials can be supplied to the yoke/rotary joint assembly facility directly from the top of the construction base. Required materials can be moved down the face of the facility to the construction equipment operating on its face. These operations are described further in subsequent paragraphs. Dedicated construction crews are not required for this facility operation since the interface assembly operations can be scheduled for periods when energy conversion and antenna assembly crews are idle.

(c) Yoke/rotary joint assembly - The antenna support yoke assembly sequence is shown in figures III-51(a) and III-51(b). The same construction facility used for the rotary joint is used to fabricate and position the support yoke. The entire yoke is fabricated at the final installed level using tall indexers to support the completed sections during the fabrication process. The yoke structure is fabricated using 7.5-meter beambuilder substations mounted on the face of the construction facility. The structure is composed of individual beam elements. The beam handling is accomplished using cherrypickers on the face of the construction facility and on the antenna construction levels as required.

The first view in figure III-51(a) shows the indexer supports moving the completed portion of the yoke along diagonal tracks as the first diagonal leg nears completion. The construction facility is indexed to the left and supports the yoke end where fabrication is in progress.

The second view shows the support indexers moving laterally as the construction facility moves to the right to position the completed yoke sections in their final location and as fabrication of the main crossmember proceeds. During this phase of fabrication, the main crossmember is supported on the construction facility.

The final stages of yoke/rotary joint construction are shown in figure III-51(b). In the first view, the yoke is shown completed and positioned ready to receive the antenna. The construction facility was positioned to the left to complete fabrication of the remaining yoke sections. In the second view, the antenna and yoke have been mated and the yoke, supported entirely by the indexer supports, has been separated from the construction facility. The facility is now free to begin fabrication of the rotary joint.

The second view in figure III-51(b) also shows the construction of the rotary joint to be well underway. Cherrypicker crane material transporters are used to assemble the rotary joint as they move along circular tracks on both sides of the circular ring beam. Equipment working inside the ring is removed before the last ring segments are installed. When the rotary joint is assembled, the yoke/rotary joint assembly facility is in position to also attach the rotary joint/yoke support struts.

(d) <u>Final system mating</u> – With the completion of both the antenna/yoke/rotary joint assembly and the solar collector assembly, the final mating of antenna and collector must be made. To accomplish this mating, the following operations have been established. First, the base is indexed to the solar collector antenna support strut pickups as shown in figure III-51(c). Next, the antenna assembly (antenna, yoke, rotary joint) is indexed to aline with the collector, and the yoke facility is positioned. Two mobile 7.5-meter beambuilder substations mounted on the yoke facility initiate the fabrication of the five outboard support struts. These stations aline the beam fabrication with the collector-pickup point areas, where cherrypickers mounted on the collector facility wait to capture and attach the fabricated struts to the collector attach fittings. The yoke facility mobile cherrypickers perform this same operation in attaching the strut end to the rotary joint pickup fitting. This procedure is repeated until all five outboard struts are installed. Next, the base is re-indexed and the yoke facility is repositioned to fabricate and install the four centerline struts. After the struts have been installed, the solar collector power buses are routed along and attached to these struts and final power bus hookup is made between antenna and collector. With the power bus installation completed, the base and yoke facility are again relocated to aline with the five remaining strut pickups and the operations are repeated for the fabrication and installation of these antenna support struts. The remaining operations are those for final satellite checkout.

(6) Final Test and Checkout

Once the assembled systems are mated, the GEO base flight control system will maneuver to expose the SPS solar arrays to full sunlight in the perpendicular to orbit plane (POP) flight attitude. Final test and checkout will be automatically performed on the major satellite systems (e.g., attitude control, direct-current (dc) power distribution, and radiofrequency (rf) phase control). At the conclusion of these tests, the base will be separated from the satellite and transferred to the next SPS construction site. Subsequent satellite power buildup operations will be controlled from the ground.

2. CONSTRUCTION BASE CONCEPT: ROCKWELL INTERNATIONAL

The Rockwell construction study emphasis was on the gallium arsenide solar cell design which uses reflectors to concentrate sunlight on the cells. The resulting base configuration is described in the following paragraphs.

a. Overall Scenario

The overall scenario leading to establishment of satellite construction support facilities and to satellite construction is shown in figure III-52. Initial operations entail use of the growth Shuttle and the Shuttle-derived heavy lift launch vehicle (HLLV) for transporting men and material to LEO for the precursor phase of the program. Subsequently, during the 30-year satellite construction phase, the HLLV will become the primary transportation element for delivering construction mass to LEO.

The initial step in satellite precursor operations is establishment of a LEO base as shown in the lower left of figure III-52. Crew and power modules are transported to LEO by Shuttle derivatives and assembled. When the base is fully operational, Shuttle external tanks are delivered and mated to form construction fixtures for satellite construction base (SCB) construction. The figure shows a completed SCB. Since the more economical HLLV will not be available during this phase of the program and since overall plans specify an EOTV test vehicle, it is probable that only the center section of the SCB would be constructed initially. This trough would be used to fabricate the pilot plant EOTV with an end-mounted antenna. After proof of concept and SPS go-ahead, the remainder of the SCB would be completed, sufficient EOTV's constructed to support initial satellite construction operations, and the SCB transferred to GEO, using one or more EOTV's for propulsion and attitude control. Upon reaching GEO, satellite construction would commence, with the logistics support as shown at the right of figure III-52.

b. LEO Base Description

After completion of the satellite precursor operations, the function of the LEO base includes EOTV maintenance, payload transfer from HLLV to EOTV and vice versa, personnel orbital transfer vehicle (POTV) stage mating, intraorbit transfer vehicle (IOTV) fueling, crew transfer, and base maintenance. The base (fig. III-53) nominally consists of crew habitat modules, a power module, an EVA airlock and crew support module, and a LEO operations control and staging module. With the exception of the power package, each module is 29.5 meters long and 5.7 meters in diameter and is compatible with the payload capacity and volume of the Shuttle-derived HLLV. The base can be expanded as required by adding additional docking adapters and modules.

It is estimated that LEO support operations will require a permanent crew of 30. The LEO base personnel provide supervisory activities for transfer of up and down payloads between the HLLV and the EOTV's and perform the scheduled maintenance required by the EOTV (changeout of thruster grids and propellant tanks). Direct transfer of crew and equipment between the HLLV and EOTV's is planned; however, multiple docking ports and excess subsystems capacity and power are provided for emergency staging support. It is noted that the additional crew required for EOTV construction, originally in LEO and subsequently in GEO, will be housed aboard the satellite construction base.

27

The 30-man crew is believed to be adequate for LEO functions as currently conceived; however, individual crewmember functions have not been defined in detail. As the program matures and more data are available, adjustments to the crew size may be warranted.

c. **GEO Base Description**

The satellites are constructed in GEO; each satellite is constructed at its designated longitudinal location. All construction activities are supported by a single integrated construction base (SCB). The SCB supports construction of two satellites per year during the mature portion of the program. Upon completion of a satellite, the SCB is moved to the operational location of the next satellite for construction of that satellite.

The SCB (fig. III-54), constructed of composites, consists of the construction fixture, construction equipment, and base support facilities. The construction fixture is in the form of three troughs, corresponding to the satellite configuration, which permits simultaneous construction of the three satellite troughs. Additional structural members are located in the middle trough and are used as fixtures for constructing the rotary joint and supporting structure.

The location of the major construction equipment items is identified in figure III-54. Twenty-seven 50-meter tribeam fabricators for both longerons and crossbeams are required. The solar blanket dispensers (items 34 to 36) are installed at the bottom of each trough, whereas the reflector dispensing areas (items 28 to 33) are located on the inner side of each trough diagonal.

The central habitat, including docking and warehouse facilities (item 37) is located on the top deck girder of the middle trough. Auxiliary habitats and facilities (items 38 to 40) are installed at the bottom of each trough to reduce the time required for crew rotation at the end of each shift.

Figure III-55 is a perspective view of the SCB. Details of the primary installation equipment are described subsequently. Table III-4 contains the SCB mass statement.

Current program ground rules specify a satellite construction rate of two per year over a 30-year period, or 180 days per satellite. The time line in figure III-56 conforms to that schedule.

Table III-5 contains the crew size required to support the construction schedule. The time phasing of the crew size reflects the major events on the time line (fig. III-56). The operation is based on four shifts; three shifts per day with 2 days off per week. Although construction of the troughs could be started as soon as the slipring structure is complete, it is not a pacing item and its deferral results in minor crew size reduction.

d. Construction Operations

The satellite structure and solar converter is constructed
in a single pass, using the integrated SCB described in Section III.C.2.c.
Initially, construction of longitudinal members of the slipring interface
structure is initiated, and the members are fabricated to a length permitting
attachment to the triangular frame (fig. III-57). The first satellite frame
is then constructed as shown in figure III-58, followed by additional fabri-
cation of slipring longitudinal members until the first triangular frame is
positioned properly away from the SCB so that the second triangle can be
completed. The SCB then proceeds to fabricate/install the remainder of the
satellite structure and solar converter. Concurrently, construction of the
sliprings (rotary joint) takes place, using free-flying fabrication facili-
ties (fig. III-59). In the figure, the second satellite frame has been con-
structed and the slipring structure has been completed.

Mobile free-flying tribeam fabricators are used to con-
struct the slipring structure, the antenna yoke base, and the arms. The con-
figuration of the fabricator and the structural elements to be fabricated are
displayed in figure III-60.

A layout of the sliprings, yoke, and antenna structure is
contained in figure III-61. The right of the upper illustration shows one
800-meter bay of the satellite, which contains the supporting structure for
the sliprings and the sliprings themselves. The yoke is attached to the
left-hand portion of the slipring assembly. The antenna trunnion mountings
are contained in the yoke arms as shown. Side elevations of the antenna, the
antenna yoke, and the slipring are in the lower part of the figure.

The assembly operation described previously is shown in se-
quence in figure III-62, starting with the configuration in the upper left,
where the slipring supporting structure has been completed. In the next
view, the slipring has been fabricated in its position and the yoke interface
has been constructed. The last two views show the partially and fully com-
pleted yoke structure. The next step in the process consists of fabricating
a movable beam, which traverses both sides of the yoke arms in tracks and pro-
vides a platform for the equipment needed to construct the antenna and in-
stall the rf elements.

e. Assembly Equipment and Operations

(1) Primary Structure Fabrication

The overall satellite structural configuration is
16 000 meters in length, divided into twenty 800-meter bays separated by
twenty-one transverse frames. The satellite primary structure is constructed
of 50-meter tribeam girders which use the basic 2-meter triangular beam ele-
ments for the longitudinal elements at the three corners and for the trans-
verse ties, which occur at 50-meter intervals (fig. III-63). The basic struc-
tural 2-meter triangular beam is constructed as a continuous element by a single

beam machine, which is fed by three cassettes containing prepunched composite ribbons. (Shear stabilization of both the tribeams and the satellite structure is achieved by use of the X-tension cables.)

The 50-meter tribeams are also fabricated a_ continuous elements. The tribeam fabricator (fig. III-64) is one concept for a unitized 50-meter tribeam builder. The concept uses six beam machines to construct each girder, one for each of the three longitudinal members and one for each of the three sides to fabricate the transverse ties.

A side and end elevation of the facility is shown in figure III-65. Referring to this figure, facilities are provided at the right of the structure for transferring and attaching the 2-meter crossbeams without shutting down the 2-meter longeron beam machines. Other necessary attach fittings also are installed at this station. After beam attachment, the 50-meter beam advances to the next two stations, where tensioning cables are installed and beam alinement is completed. The 50-meter longeron is attached to the 50-meter crossbeam at the final station, using manned manipulator modules (MMM's) with a 50- to 65-meter reach.

Additional detail of this process is illustrated in figure III-66, which shows installation of a 50-meter crossbeam at the bottom of a trough section. Movable tribeam facilities (A) construct the 50-meter crossbeams, the completed beam advancing to the right in each case. When the beam has advanced to the longeron to which it will be attached, the movable facilities are translated downward to make room for installation of the beam closeout section. Fixed facilities (B) then fabricate the closeout section, which is translated downward into the proper position for attachment. In figure III-67, the cross tribeam and longeron are shown in the process of construction; in figure III-68, the crossbeam has been completed and the closeout section installed.

An alternative concept eliminates the need for the extra movable facility shown in figure III-66. In this concept (fig. III-69(a)), the movable facility has been replaced by relocating the crossbeam fabricator from inside the longitudinal tribeam pod to an adjacent site as shown at the left of the figure. A parking spur for the crossbeam fabricator is provided to permit translation of the fabricator in a downward direction as indicated in view A-A at the bottom of the figure. In addition to the beam machines which construct the basic 50-meter crossbeam, additional beam machines are mounted external to the fabricator as shown.

Initially, the crossbeam is fabricated, progressing across the bottom element of the SCB as it advances. When the beam reaches the longitudinal tribeam fabricator, or pod, at the right of the trough bottom (fig. III-69(b)), the crossbeam fabricator is translated downward (view A-A) to position the external beam machines. The closeout elements, which consist of 2-meter beam sections, are then fabricated by the external beam machines and translated into position by manned manipulator modules for attachment using the attach concept described in the next section.

30

(2) Solar Blanket Installation Facilities

Solar blankets are deployed along the bottom of each of the three troughs. The general arrangement of the deployment facilities is shown in figure III-70(a) for one trough and is described in more detail later. The blanket dispensers are located on the lower deck (side elevation) and to the left of the blanket attach plane.

Figure III-70(b) is an elevation view of the solar blanket deployment facility. This facility provides for the installation of tension cables, switchgears, distribution feeders, and other equipment associated with the solar blankets. An auxiliary base (15), including a crew habitat (17), a docking and service module (16), and a power module (shown to the left of the crew habitat), has been established at each of the three deployment facilities. Previously, all such modules were located at the central habitat/warehousing area on the top of the SCB main deck girder. An evaluation of time lines and the estimated rate of travel of personnel vehicles traversing tracks from the central base to the various deployment areas indicated that considerable time over the nominal 8-hour shift would be required for crew rotation. Therefore, the central base size was reduced and the three auxiliary bases were added to the concept. Capability has been retained, however, for movement of logistics and personnel to and from the central base to the auxiliary bases, since more extensive warehousing and servicing facilities exist at the central location, and arriving payloads will be a mix.

The top deck of the facility contains a cargo loading deck, which can receive cargo either from the central base or from an EOTV by way of transfer tugs (IOTV's). A warehousing area is provided on the next lower deck (23). Means of transferring material from this area to the main deck are provided by the interdeck elevator (24) and the material transit system (22). Supply elevators (3 and 9) are used for deliveries of material or manned manipulator modules to the lower deck. A POTV arriving from LEO can dock as indicated at the right of the figure (20 and 21).

The overall installation concept is similar to that described in reference 3 in that cables and blankets are deployed as the crossbeams to which they are attached advance in the course of main structure fabrication. The satellite (and SCB) configuration has changed since submission of the final report; that factor plus concept update has resulted in the current facility.

The first step in solar blanket deployment is to load the blanket rolls in the 24 dispensers (5) installed in each of the 3 facilities. This loading is accomplished by a logistics vehicle (4) which traverses the entire trough width, loading each dispenser as it progresses. It is estimated that the vehicle can load the 24 dispensers in 6 hours (15 minutes per dispenser). The dispensers must be loaded before the fabrication of each bay, a six-shift operation, so that additional time is available if required by contingencies.

31

The blankets are attached to the tension cables, which are strung at either side of the blanket strip by an attachment machine (7). Other stations for attaching side and end catenaries and electrical components are also shown as indicated in the number index at the left. The triangular section at the bottom right of figure III-70(b) represents the 50-meter crossbeam in position for attachment of solar blankets, cables, etc., and for installation of switchgears and other electrical components.

A perspective of the solar blanket deployment facility (fig. III-70(c)) shows the location of certain stations relative to the bottom of the SCB trough. The numbers are keyed to the numbering index in figure III-70(b).

Figure III-70(d) is a plan view of the facility, looking upward at the lower deck. The apex of the 50-meter crossbeam (fig. III-70(b)) is indicated as the blanket attach station. The guide/attach cable deployment reels (1) are located at the left of the figure. The track-mounted cable reel servicing unit (2) can traverse the entire width of the SCB trough bottom to load the reels and perform any required maintenance. The blanket supply truck (4) is shown adjacent to the blanket dispensers (5). A solar blanket roll (25 meters wide) to the left of the truck is being delivered by the elevator.

The end catenaries are 50 meters wide; each catenary is attached to two blanket strips. Each blanket roll has half of the catenary attached. These catenaries are attached to form a 50-meter-wide assembly on the platform (6) which extends across the trough. The side catenaries are assembled on a platform (8) and attached to the two outboard solar blanket strips as they deploy.

The guide cable alinement tower (12) has the capability of moving on tracks in the longitudinal direction (fig. III-70(b)). The tower is used to fasten the leading and trailing edge catenary cables to the crossbeam. Additionally, as the cables deploy with the advancing crossbeam, the towers restrain the cables from a direct line to the crossbeam by depressing them so that they are deployed in the proper plane.

A mobile gantry (10) traverses laterally and is used to install the switchgears, sending feeders, and other ancillary electrical equipment on the crossbeams at the bottom of the trough. Additional details of this operation are described later.

Figure III-70(e), a perspective of the preceding figure, shows the location of the numbered items relative to the overall facility structure. The crossbeam upon which the installations are being made is shaded and is to the right center of the figure.

(3) Installation Operations at Crossbeams

Upon completion of crossbeam structure fabrication, the saddle clamps, the switch assemblies, and the distribution, monitoring,

and control (DM&C) equipment are installed. Figure III-71 represents the general arrangement of the installation. Secondary feeders and their insulation mounts are included in this installation for alternate crossbeams. The solar blanket trailing edge catenaries and longitudinal cable tensioning ties are then attached, followed by tensioning and clamping of the transverse catenaries and longitudinal cables. Following this operation, the leading edges of the solar blanket transverse catenaries are attached to the trailing edge of the crossbeam by means of brackets installed on the saddle. The operation at each station is completed by attaching the blanket connectors to the switch assemblies, connecting the DM&C bus, and connecting the switchgears to secondary feeders (alternate crossbeams). Construction of the longerons and crossbeams for the next bay is then initiated.

A time line encompassing the operations incident to construction of one bay is contained in figure III-72. Two days or six shifts have been allocated for the operation.

One of the satellite construction guidelines entailed no planned EVA. Accordingly, construction and installation operations concepts have leaned heavily on automated activities, assisted by manned manipulator modules. A typical manipulator module is shown in figure III-73. Its primary elements are the control cab, the support base, and the bilateral manipulator. The base rotates around the centerline of the boom attach wrist, and the control cab rotates 360° around the vertical axis of its base. The cab provides a shirt-sleeve environment and can be operated by one man but has sufficient space to accommodate two suited astronauts. The life support system is sized to support three persons for short periods (e.g., a rescue operation). One docking port is located at the top of the cab and one at the bottom of the base, providing dual exits. Facility power is provided through the boom. The boom operation is controlled from the cab with secondary control capability at the platform. The MMM contains provisions for lights and TV cameras.

A crew transport module is depicted to the right of the MMM (fig. III-73). Its life support capabilities are less than for the MMM. Its primary purpose is to rotate MMM crews for operations requiring more than one shift (e.g., solar blanket electrical installation) without having to remove the MMM and replace it with a similar unit.

A traveling gantry, or platform, installs and connects the electrical components, and attaches and tensions the various cables. The gantry (fig. III-74) is equipped with two MMM's and a switchgear assembly dispenser. The saddle clamp already has been installed on the crossbeam (this operation taking place in the tribeam fabrication facility) and the cables have been attached. The MMM to the right has a tensioning tool used to apply the correct tension to the cables and then clamp them. Another view of the tensioning tool is shown in figure III-75. The tensioning yokes are attached to the brackets with the clamp already attached. The MMM's apply the tensioning screwjack at the left of the figure until the longitudinal cable is tensioned to the proper value. The end of the tool pushes against the clamp mounted on the yoke to maintain tautness. The cable clamp is then secured to the longitudinal cable.

In figure III-76, which shows additional detail, the magazine has been indexed to the proper position for installing the switchgear assembly, which is automatically inserted into the keyway on the saddle clamp and locked into position. An electrical connector attached to wiring from the solar array is automatically inserted into its mating receptacle as the assembly advances into position.

After the cables have been attached and tensioned and the switchgear assembly has been installed, secondary feeders must be secured to alternate crossbeams. This process (fig. III-77) uses the same gantry previously described. The aluminum feeder roll is mounted on the brackets, which are attached to the magazine. As the gantry traverses laterally from one installation point to the next, the feeder is unrolled and welded to insulation mounts which have been installed at the tribeam fabrication facility.

TABLE III-1.- EQUIPMENT OPERATING TIMES AND RATES

Operation	Value
Beambuilder substations	
Beam machine aiming,[a] min	5
Average beam fabrication rate, m/min	
Longitudinal beams	0.5
Lateral, vertical, or diagonal beams	5
Installation of end fittings, min	10
Handoff, min	5
Travel, m/min	20
Cherrypickers	
Beam installation, min	10
Travel, m/min	50
Indexer/support	
Attachment, m/min	10
Index/travel, m/min	10
Support/travel, m/min	(b)
Bus dispensing station	
Travel, m/min	(b)
Bus dispensing rate, m/min	[c]5

[a]Rotate in yaw 90°, elevate 45° or 90°.
[b]As required.
[c]Minimum.

TABLE III-2.- CONSTRUCTION EQUIPMENT SUMMARY

Item	Quantity				Mass, t	
	SA[a]	A[b]	Y[c]	Total	Each	Subtotal
Beam machines						
7.5-m synchronized travel	10	--	--	10	11	110
7.5-m gimbaled mobile, manned	2	2	2	6	15	90
12.7-m gimbaled mobile, manned	1	--	--	1	21	21
Cherrypickers						
30-m	8	--	2	10	2.5	25
90-m	4	2	--	6	5	30
120-m	--	2	1	3	7	21
250-m	--	1	--	1	9	9
Indexers						
15- to 45-m	5	--	--	5	1.3	6.5
130-m	--	6	8	14	3.0	42
230-m	--	2	--	2	5.5	11
Bus deployer - 90-m (also 80-m)	1	1	1	3	8.0	24
Solar array deployment equipment - proximal anchors	176	--	--	176	(d)	(d)
Antenna deployment platform	--	1	--	1	28	28
10-percent allowance for undefined equipment	--	--	--	--	--	42

[a]Used on solar array system.
[b]Used on antenna.
[c]Used on yoke and rotary joint.
[d]To be determined.

TABLE III-3.- ENERGY CONVERSION BEAMBUILDER SUBSTATION REQUIREMENTS

Type machine	Use	Functions	Quantity	Fabrication rate, m/min	Beam material capacity, m	Gimbal capacity, deg	Travel, m/min
7.5-m synchronized							
With track	Upper (SA) longitudinals	Fabricate 7.5-m continuous beam with frames and track; nominal fixed; remote control	5	3.5	10 800	(a)	3.5
Without track	Lower long beams	Fabricate 7.5-m continuous beam with frames; nominal fixed; remote control	5	3.5	10 800	(a)	3.5
12.7-m autonomous with track	Upper (SA) laterals	Fabricate 12.7-m beam with end fittings and tracks; attach acquisition bus and jumpers; mobile and gimbaled; onboard operation	1	5	10 700	b±90	20
7.5-m autonomous without track	All other beams	Fabricate 7.5-m beam (various lengths) with end fittings; mobile and gimbaled; onboard operation	2	5	10 200	b±90 c90	20

aTo be determined.
bYaw.
cPitch.

TABLE III-4.- SCB MASS SUMMARY

[3-trough, single-pass]

Equipment	Mass, kg
Tribeam fabricators	166 000
Reflector installation equipment	120 000
Solar blanket dispensers (including cables and catenaries)	187 000
Subtotal	473 000
Microwave antenna	409 000
Fabrication fixture	1 499 000
Logistics vehicles and manned manipulators	252 000
Subtotal	2 160 000
Habitat and power supply	1 617 000
Total	4 250 000
Total including 25 percent growth	5 312 000

TABLE III-5.- CREW SIZE (REFERENCE CONCEPT)

Activity	Crew size for day -		
	1 to 80	81 to 140	141 to 180
Construction			
Solar converter construction	60	--	--
Antenna rf assembly and installation	24	24	24
Construction support	12	5	5
Maintenance	10	5	5
Base management	8	4	4
Crew support	12	4	4
Total per shift	126	42	42
Total for 4 shifts	504	168	168
Operational maintenance	--	--	30
Total onboard	504	168	198
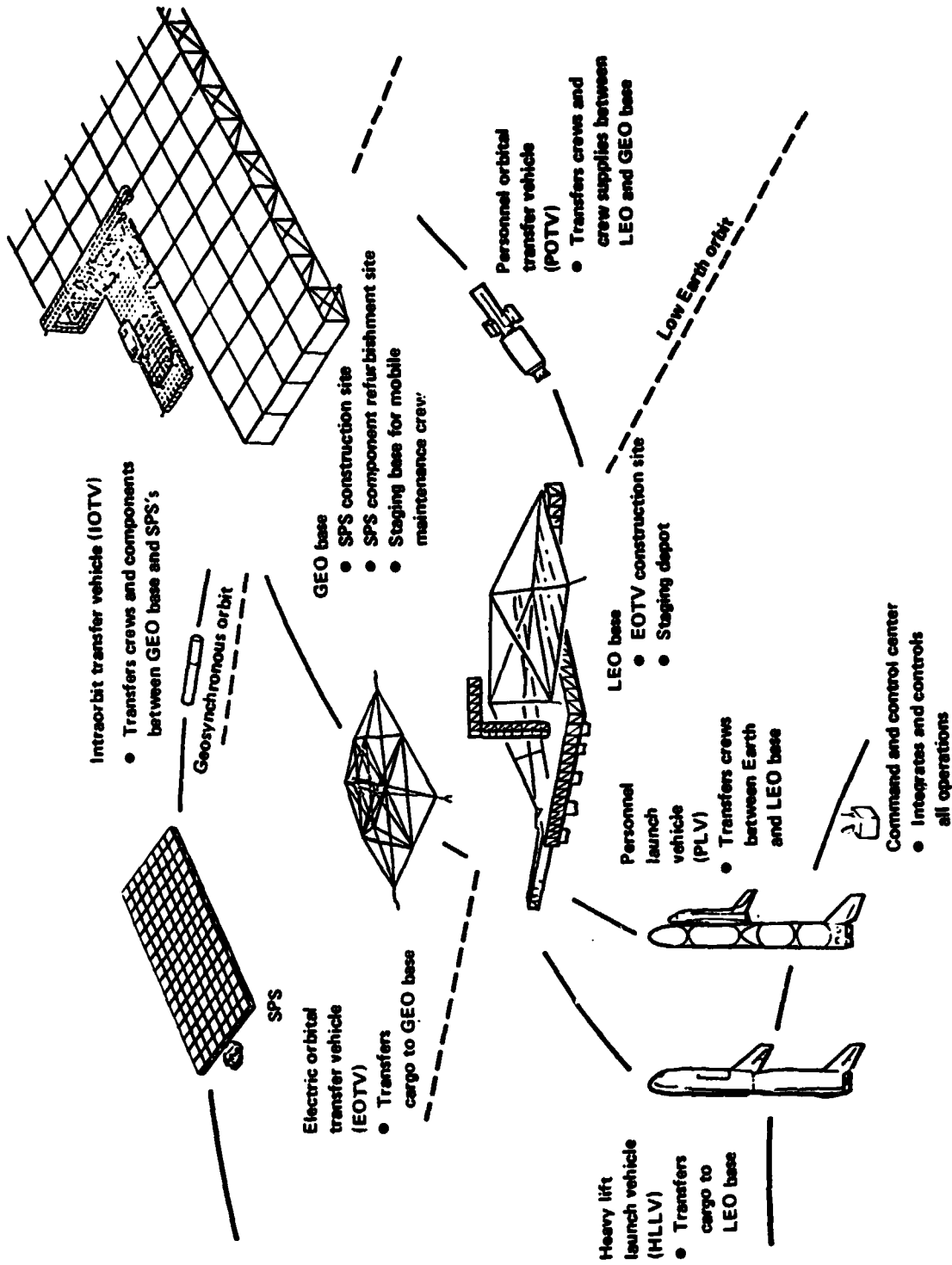
Figure III-1.- SPS operational elements.

Personnel orbital transfer vehicle (POTV)
• Transfers crews and crew supplies between LEO and GEO base

Low Earth orbit

Intraorbit transfer vehicle (IOTV)
• Transfers crews and components between GEO base and SPS's

GEO base
• SPS construction site
• SPS component refurbishment site
• Staging base for mobile maintenance crew

Geosynchronous orbit

LEO base
• EOTV construction site
• Staging depot

Command and control center
• Integrates and controls all operations

SPS

Electric orbital transfer vehicle (EOTV)
• Transfers cargo to GEO base

Personnel launch vehicle (PLV)
• Transfers crews between Earth and LEO base

Heavy lift launch vehicle (HLLV)
• Transfers cargo to LEO base

Figure III-2.- Grumman SPS system definition study for Boeing/JSC.
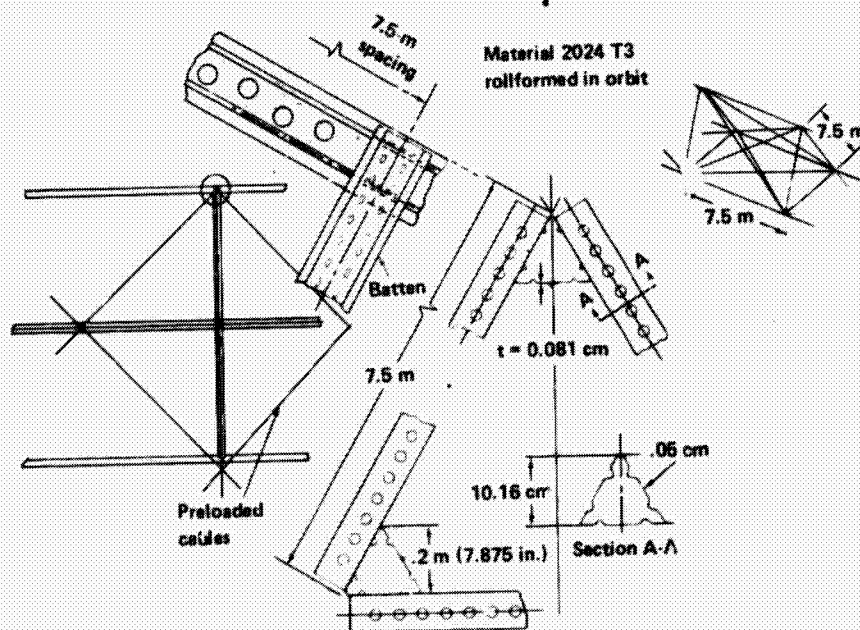
Figure III-3.- 7.5-meter aluminum beam design.
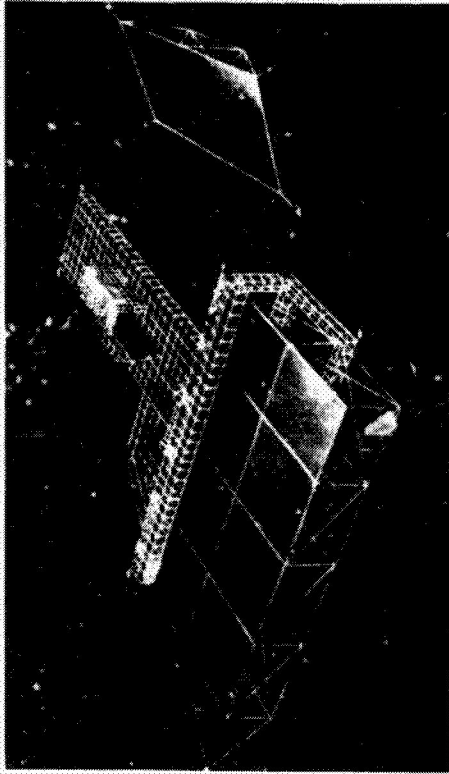
(b) First construction pass.
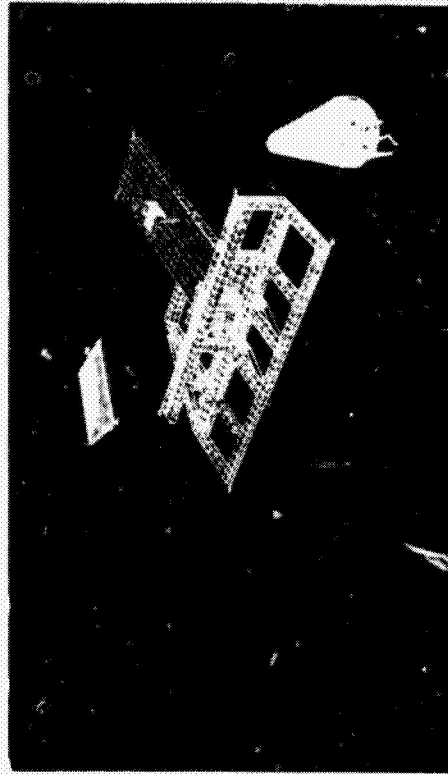
(d) Checkout of SPS and transfer of base.
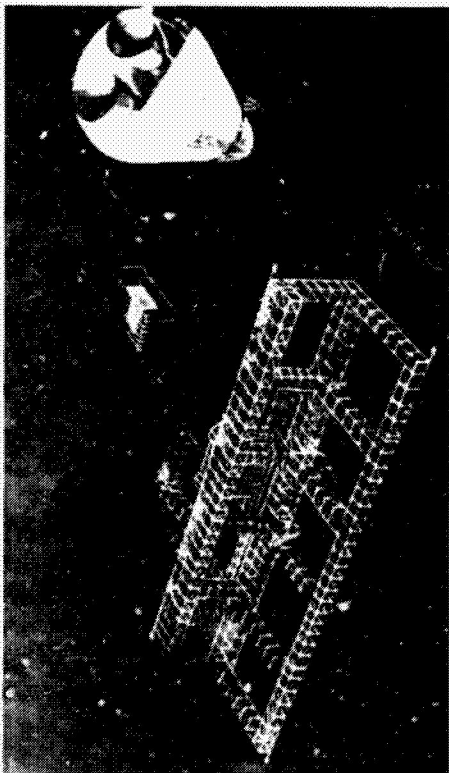
(a) Activation of GEO base.
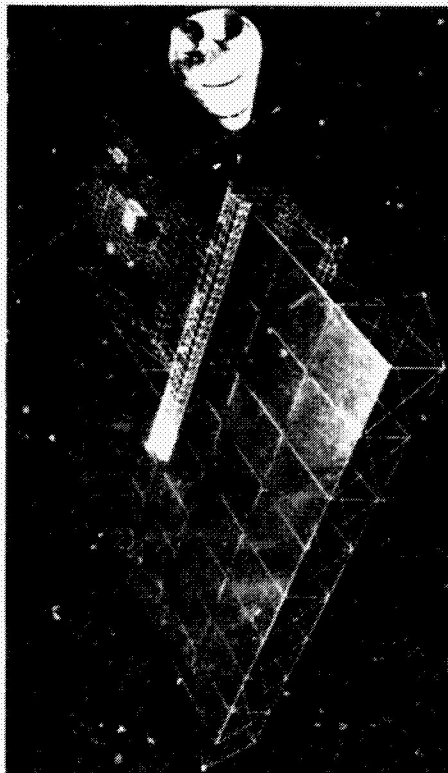
(c) Second construction pass.

Figure III-4.- Four-bay endbuilder construction.
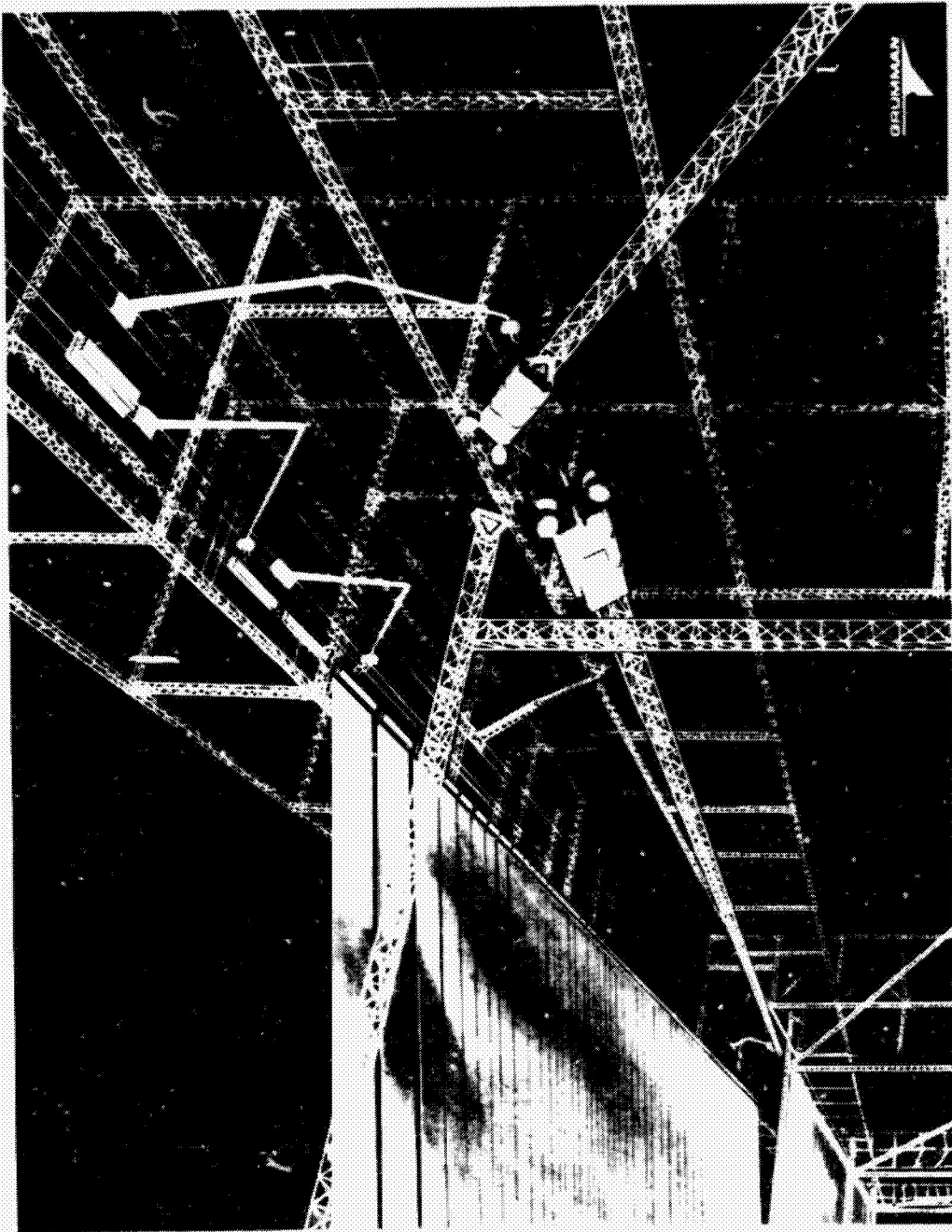
Figure III-5.- SPS assembly operations.

43

Solar collector
assembly facility

Yoke/rotary joint
assembly facility

Antenna
assembly
facility
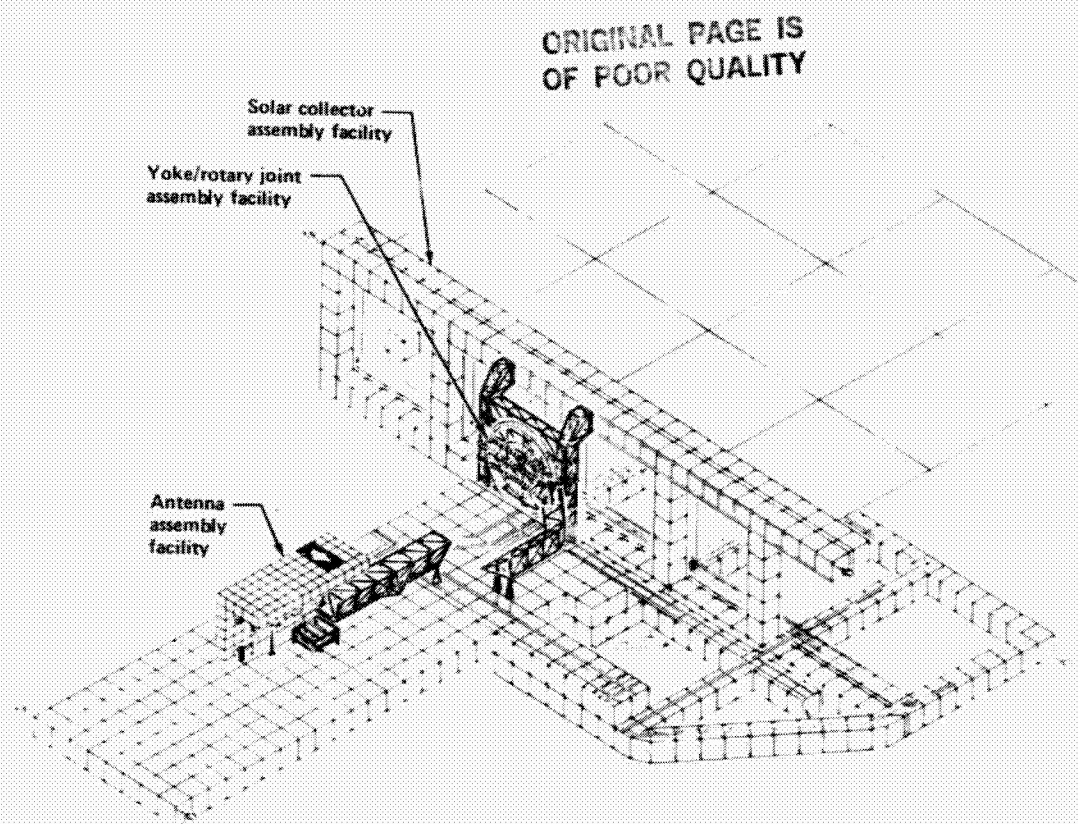
Figure III-6.- Initial satellite construction using four-bay endbuilder.

Rotary joint/yoke assembly
facility

Antenna assembly
facility

Solar collector
assembly facility

3438 m

700 m

3652 m

913 m
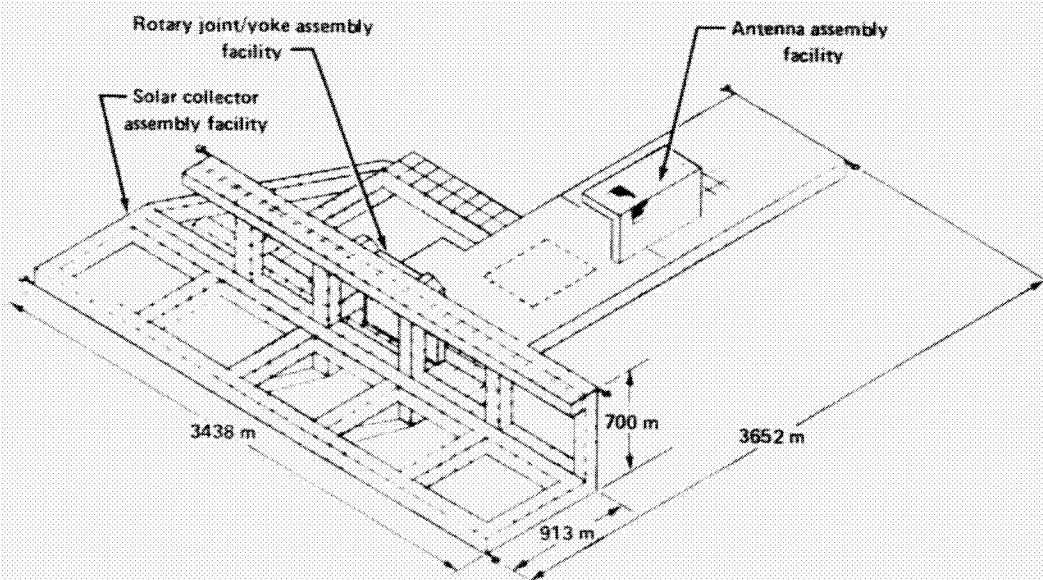
Figure III-7.- Four-bay endbuilder construction base update.

- Assemble baseline 5-GW satellite in 6 months

8 by 16 bays

Main bus

SA jumper

SA blankets

667.5 m
672.7 m
470 m

- 4-bay endbuilder (ref 2)
  - 2-pass long. energy conversion assy
  - 11-row lateral antenna assy
- IVA assembly methods - EVA emergency limited
- SPS construction issues
  - Satellite construction approach
  - Structural assembly methods
  - Subsystem installation techniques
  - Construction equipment requirements
  - Satellite support and base interactions
  - Handling and mating large system elements
  - In-process inspection and repair
  - Final test and checkout

Figure III-8.- SPS Phase 2 construction requirements and issues.

| 1.0 Build GEO base | 2.0 Operate GEO base | 3.0 Construct 5-GW SPS | 4.0 Support SPS maintenance | 5.0 Reposition GEO base |

| 3.0 Construct 5-GW satellite | 3.1 Assemble energy conversion | 3.4 Mate systems | 3.5 Final test and C/O |

Assemble power transmission

Assemble interface
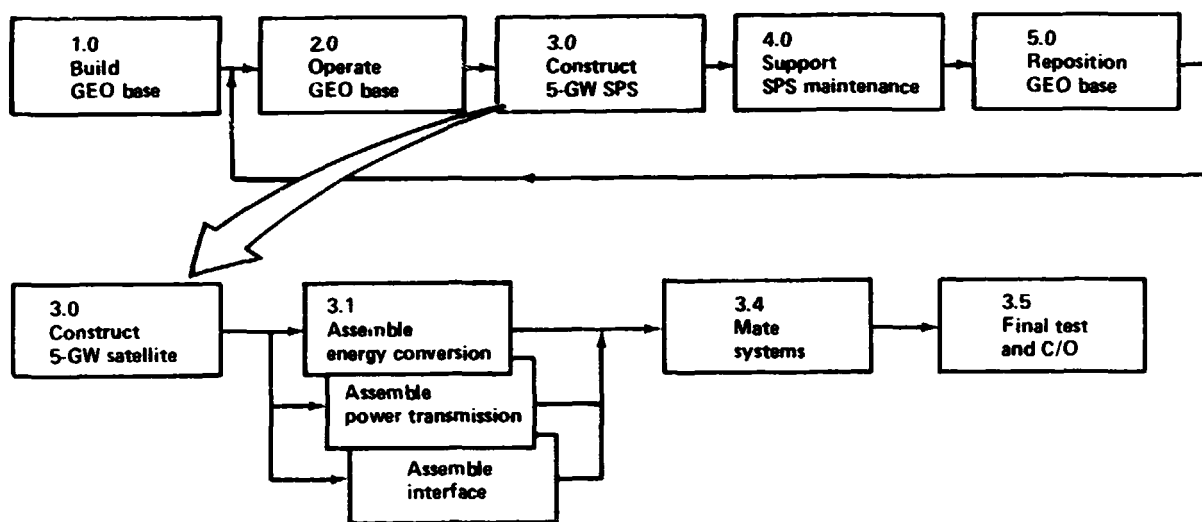
Figure III-9.- Four-bay endbuilder operations flow.

45
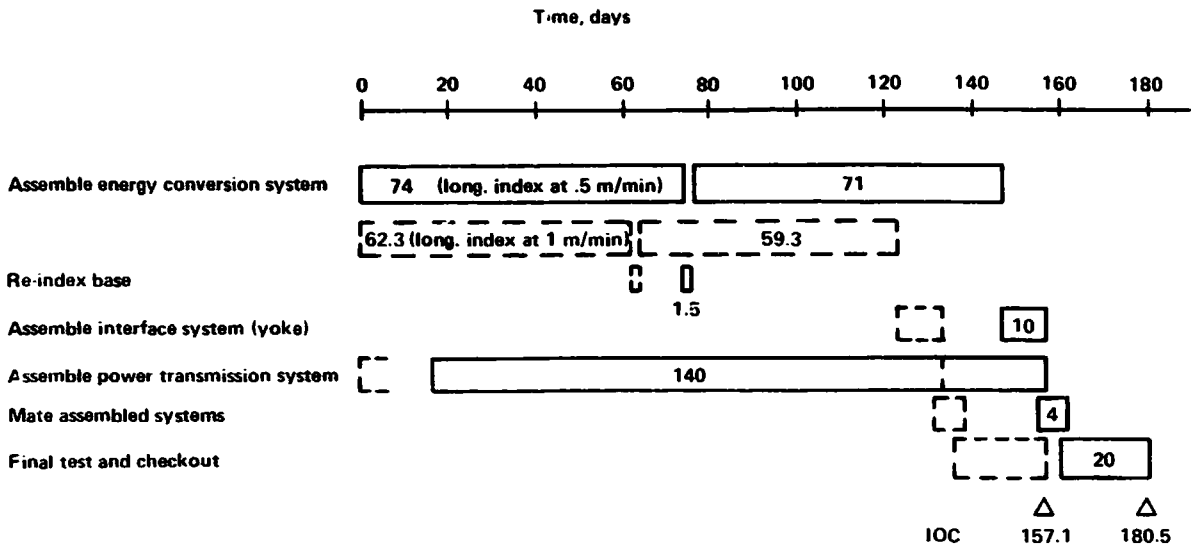
Figure III-10.- Four-bay endbuilder time line; IOC is initial operational
configuration.
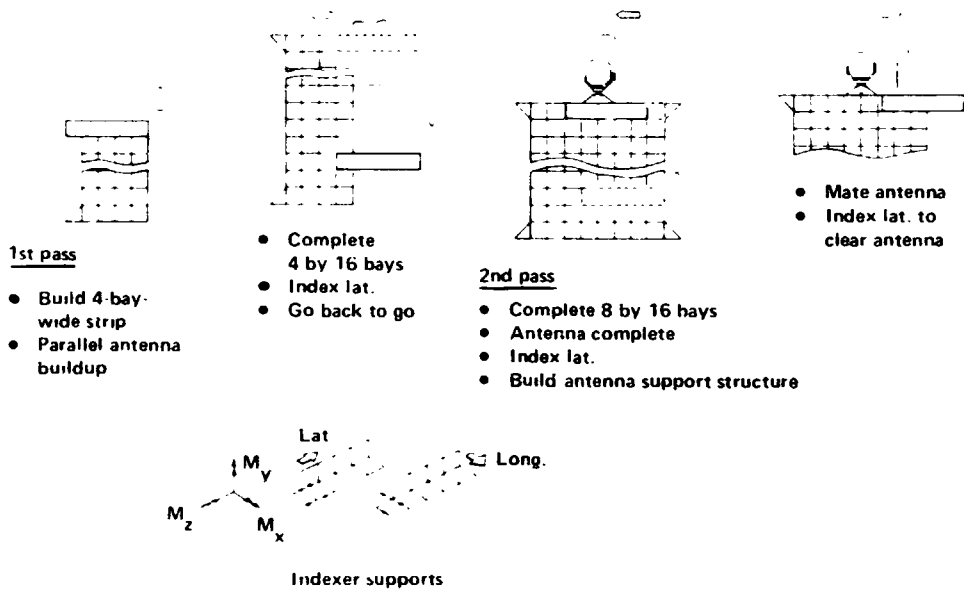
Figure III-11.- Four-bay endbuilder construction sequence.

46
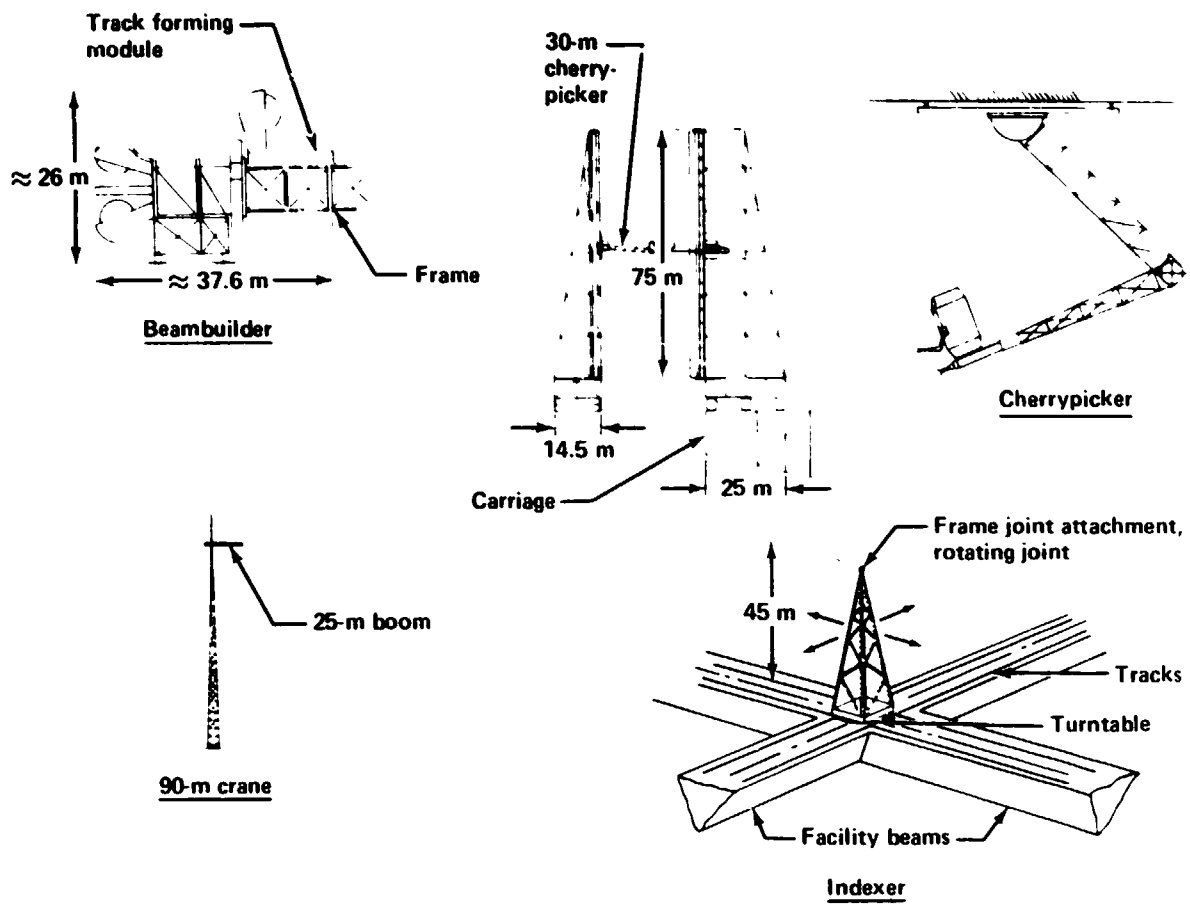
Figure III-12.- Typical construction equipment.
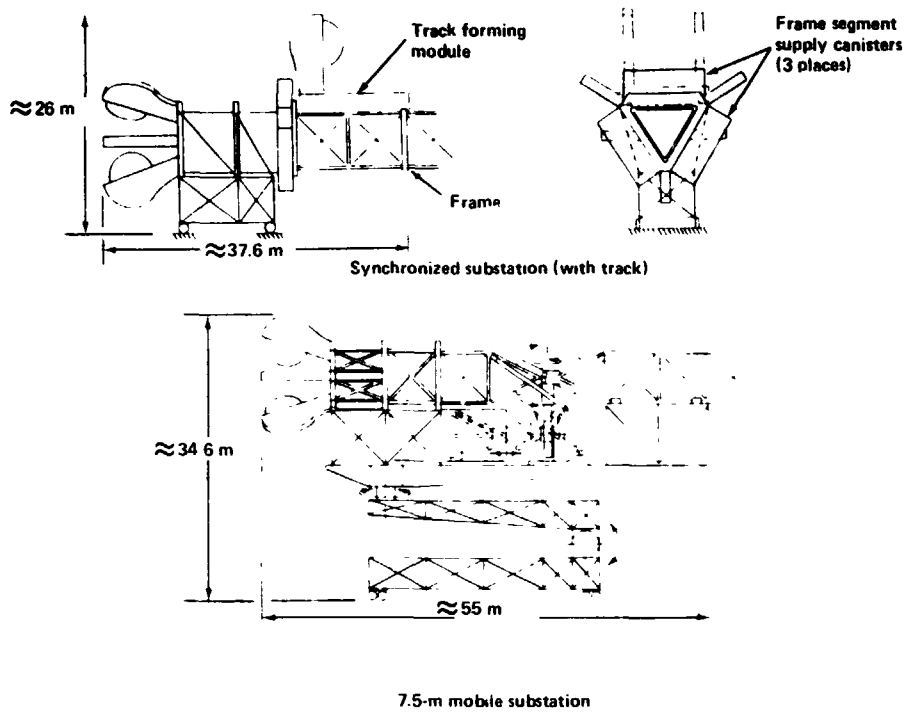
Figure III-13.- 7.5-meter beambuilder substations.
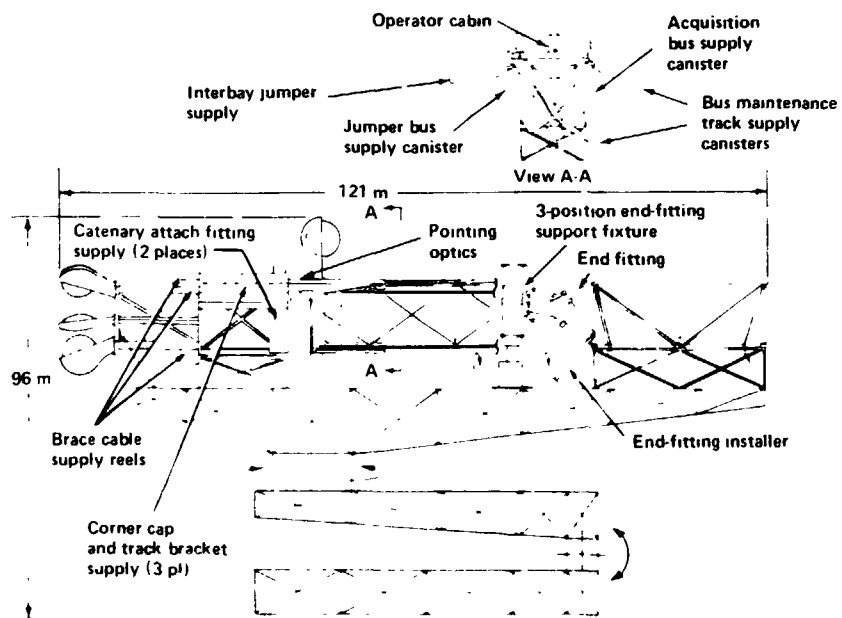
Figure III-14.- 12.7-meter beambuilder/acquisition bus substation.

Requirements

- Dispense main and feeder buses in sequence
- Cut and splice bus material
- Install stiffeners and strongbacks
- Install and preload cables
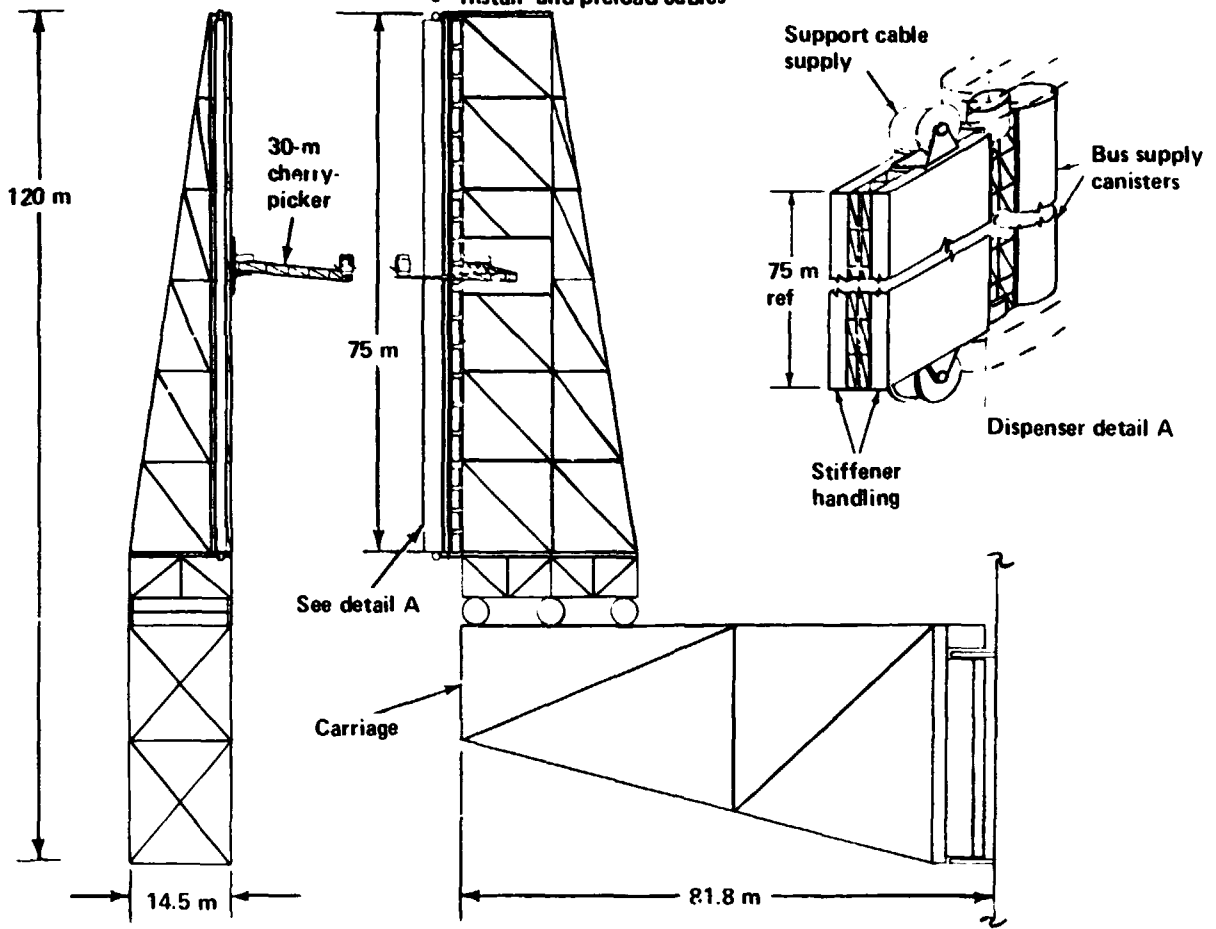
Figure III-15.- Mobile power bus dispensing station.

49
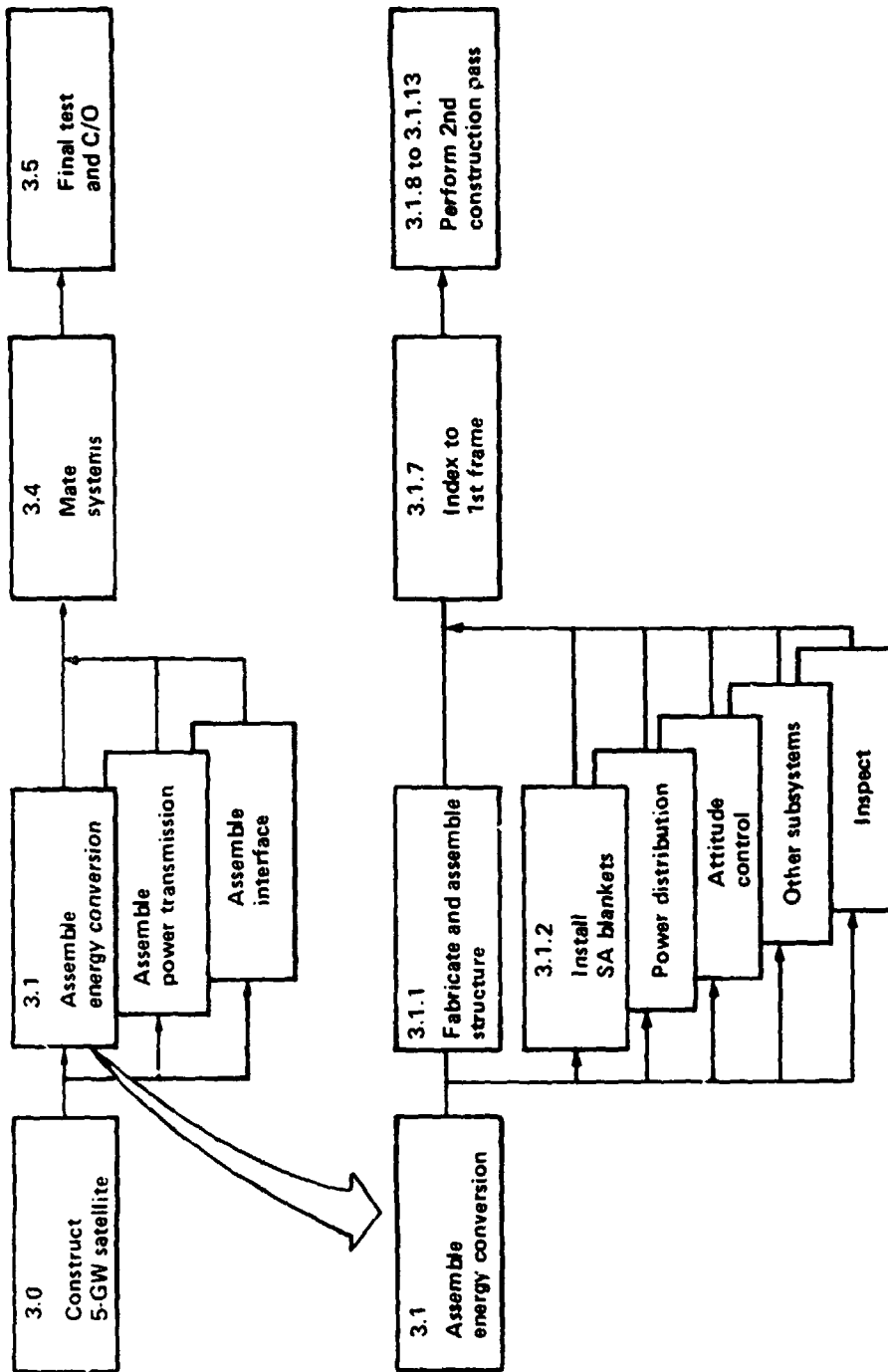
Figure III-16.— Satellite construction operations analysis.

50
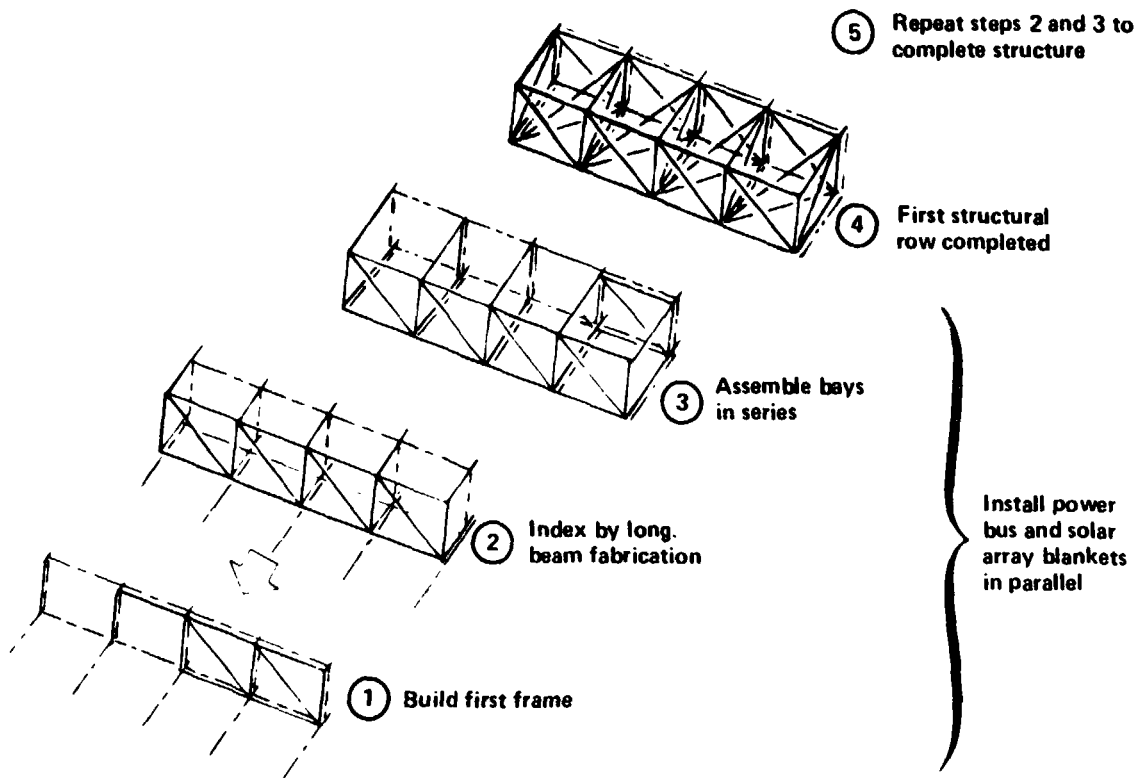
Figure III-17.- Endbuilder structural assembly sequence.
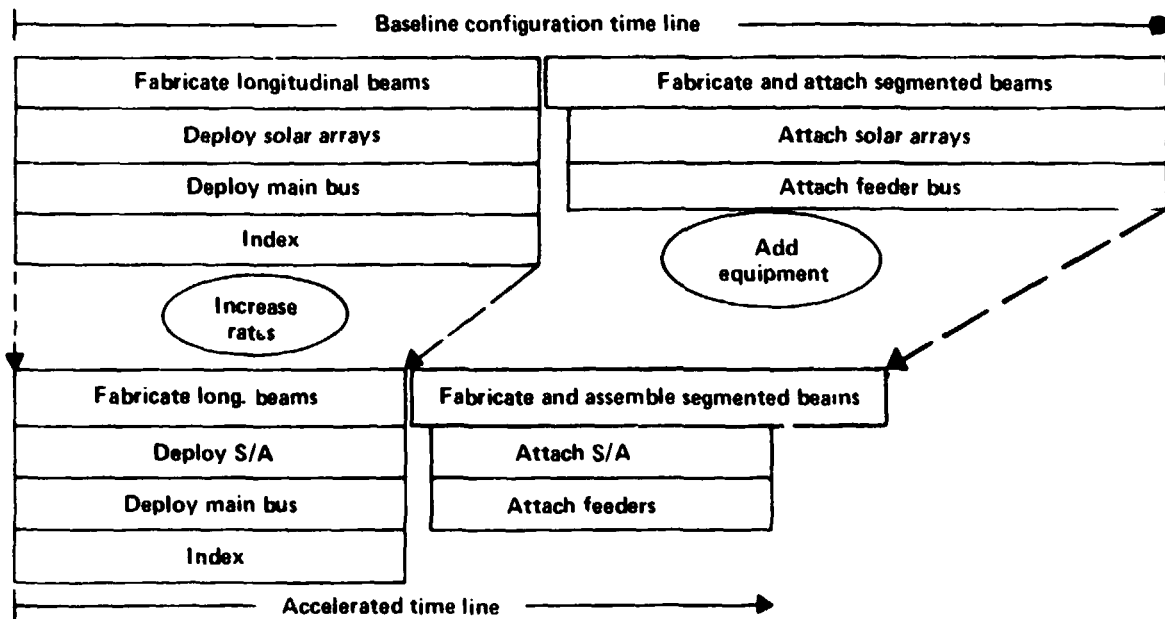
Figure III-18.- Endbuilder coupled assembly operations.

51
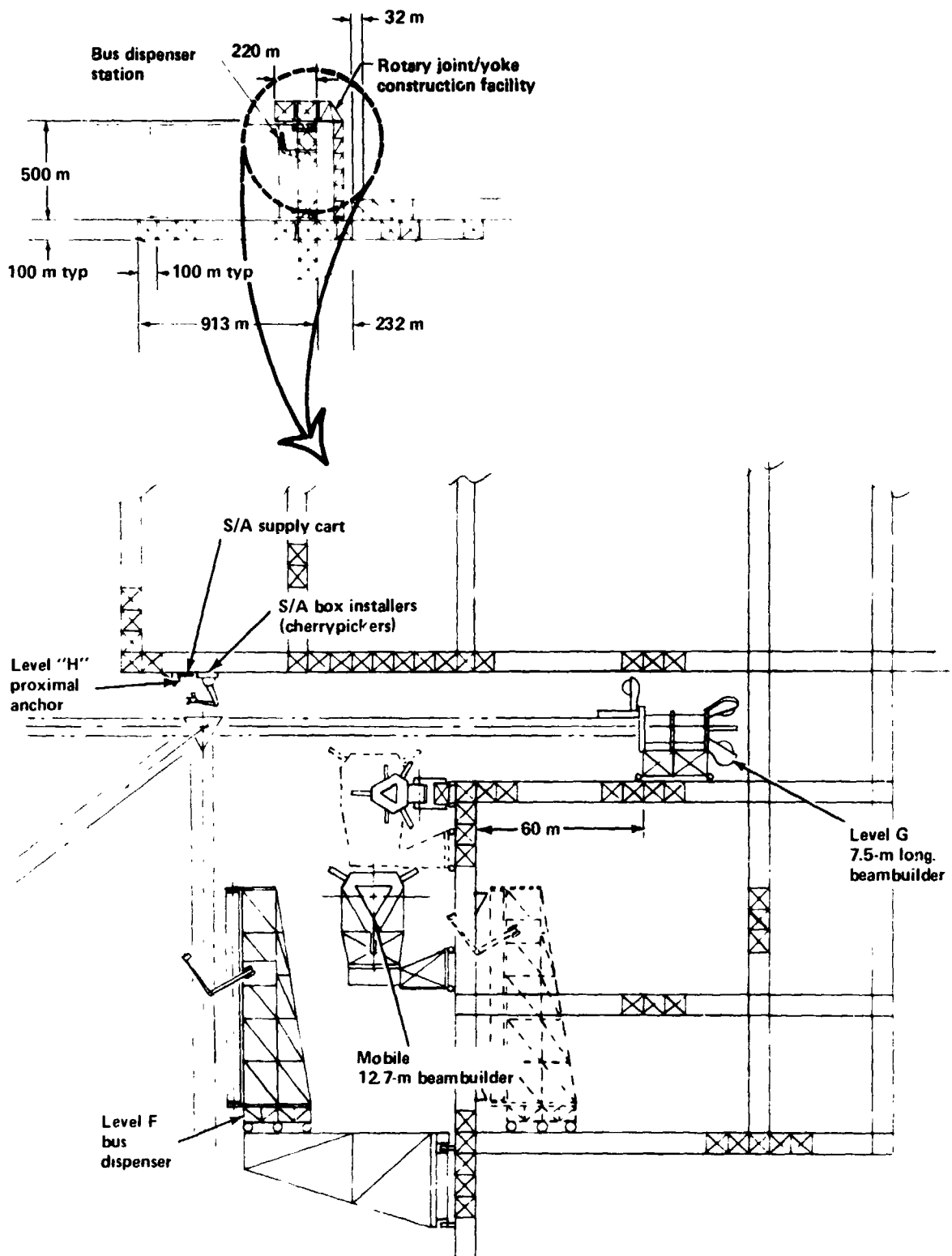
Figure III-19.- Construction system for solar collector facility.
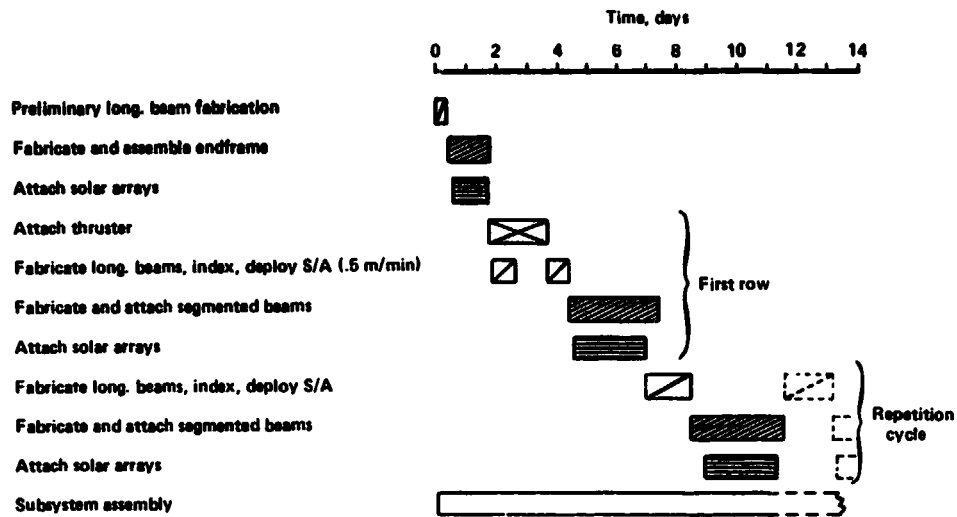
Figure III-20.- Energy conversion system assembly time-line update.
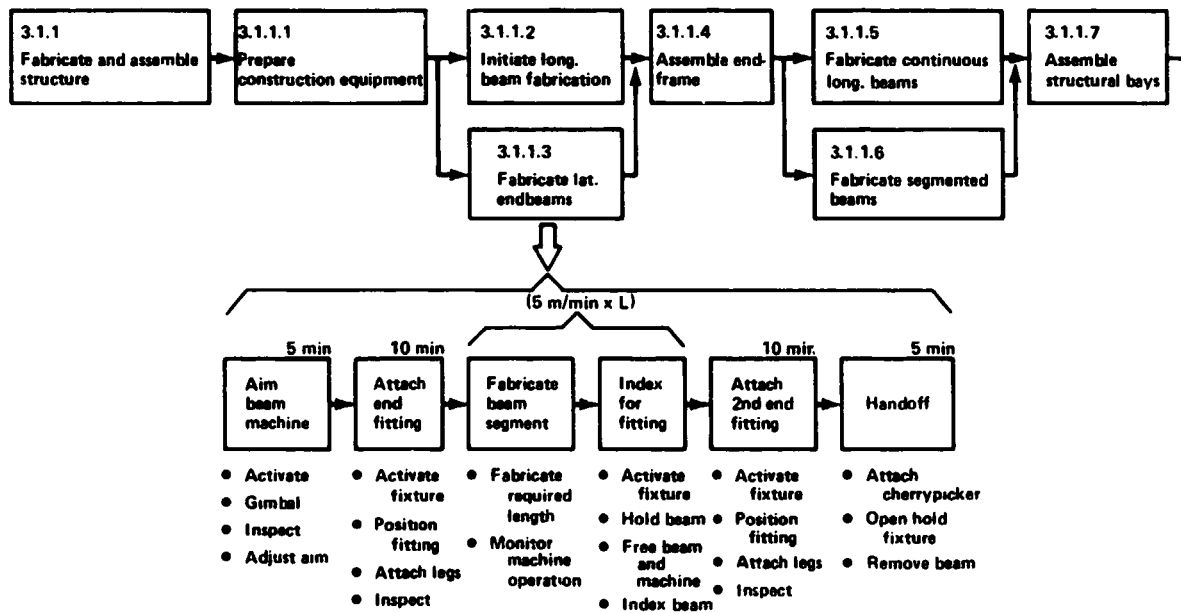
Figure III-21.- Energy conversion structure fabrication and assembly flow.

53
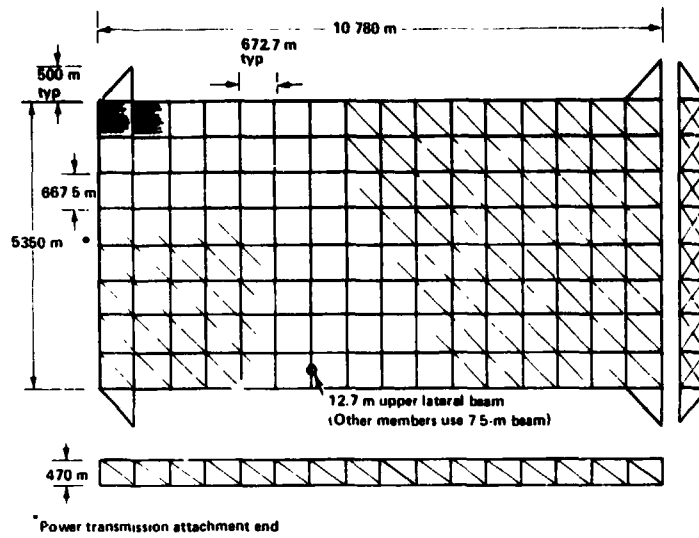
Figure III-22.- 5-gigawatt SPS energy conversion system structure.
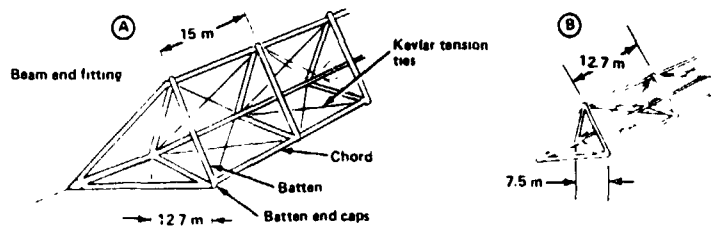
Item	Type A upper surface lateral beam	Type B beam used in all other locations
Section (chord)	①	②
Material thickness (t)	0 86 mm	0 71 mm
EI_x	3.39×10^8 N/cm²	1.80×10^8 N/cm²
Batten	②	②
Batten spacing	15 0 m	12 7 m
Beam width	12.7 m	7 5 m
Mass/length	7.48 kg/m	4 11 kg/m
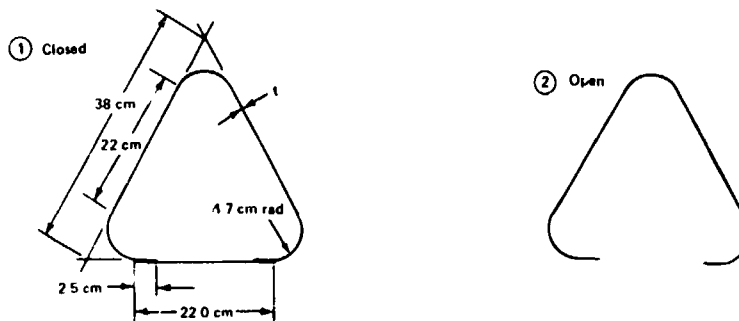
Figure III-23.- Energy conversion structural configurations. The symbol E is modulus of elasticity; I_x is moment of inertia.

54
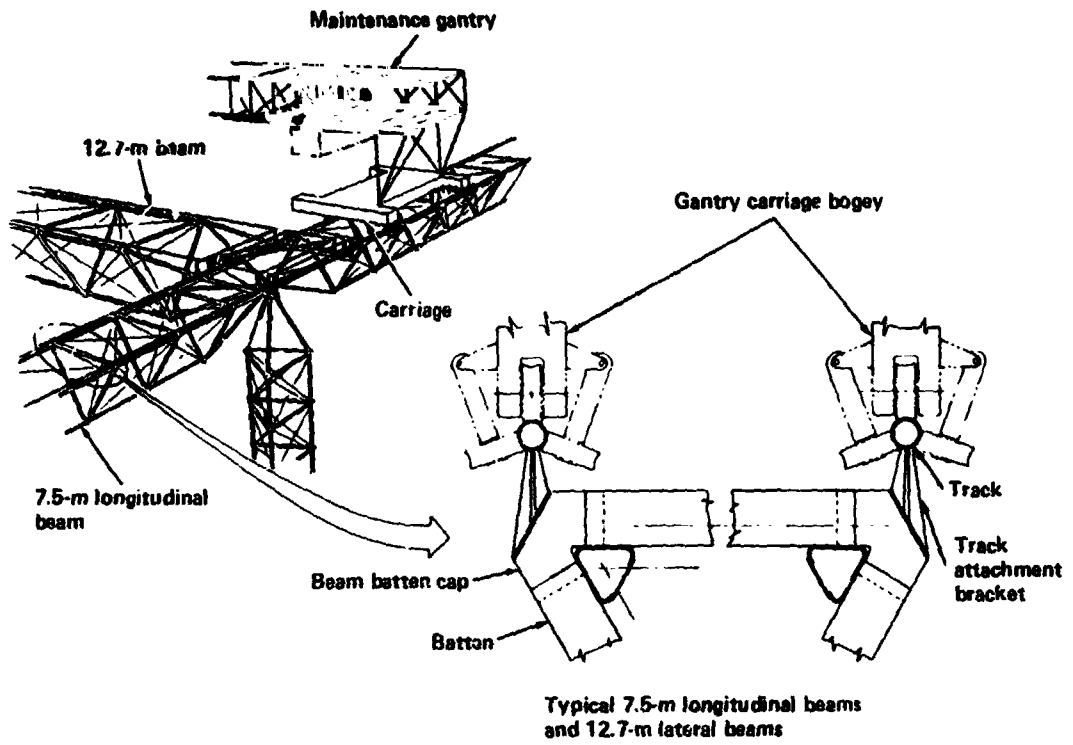
Figure III-24.- Satellite maintenance track requirements.
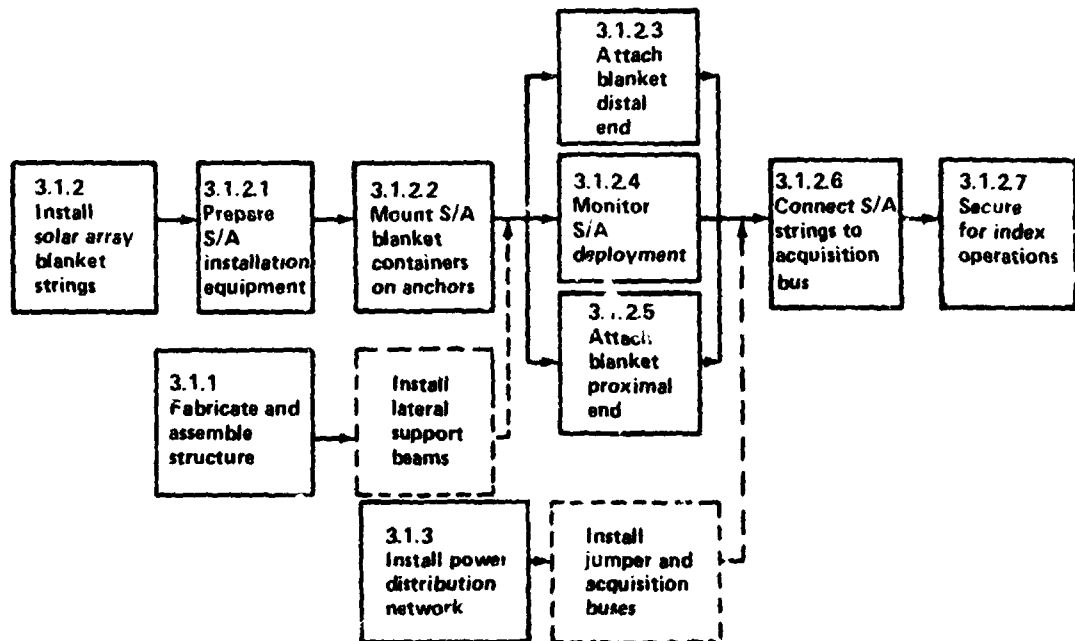
Figure III-25.- Energy conversion system solar array installation flow.
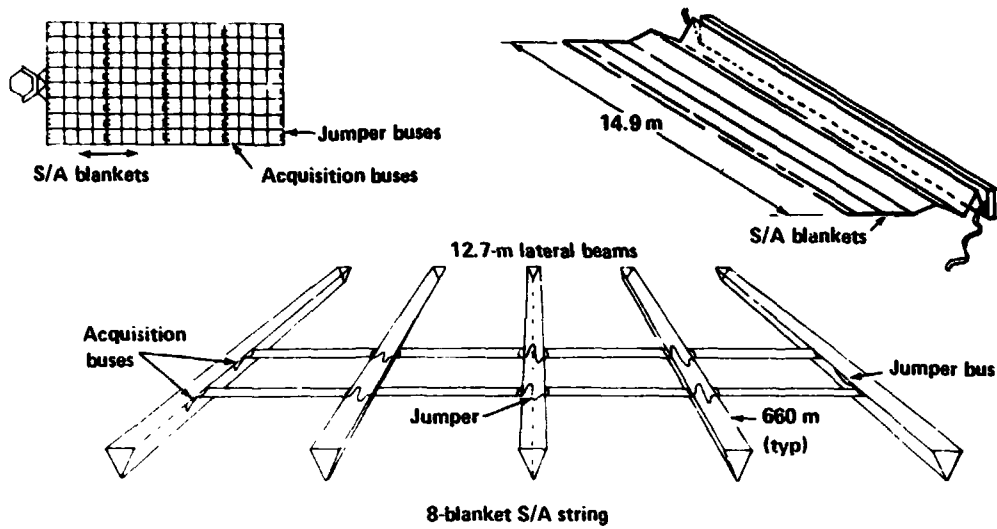
- Accordion-folded solar array blankets
  - Attached concurrent with segmented beam fabrication
  - Deployed concurrent with long. beam fabrication
- 44 blankets/bay, each tensioned at 61.5 N
- Blankets joined by jumpers and jumper buses
- 8-blanket strings connected to acquistion buses

Figure III-26.- Solar array installation requirements.
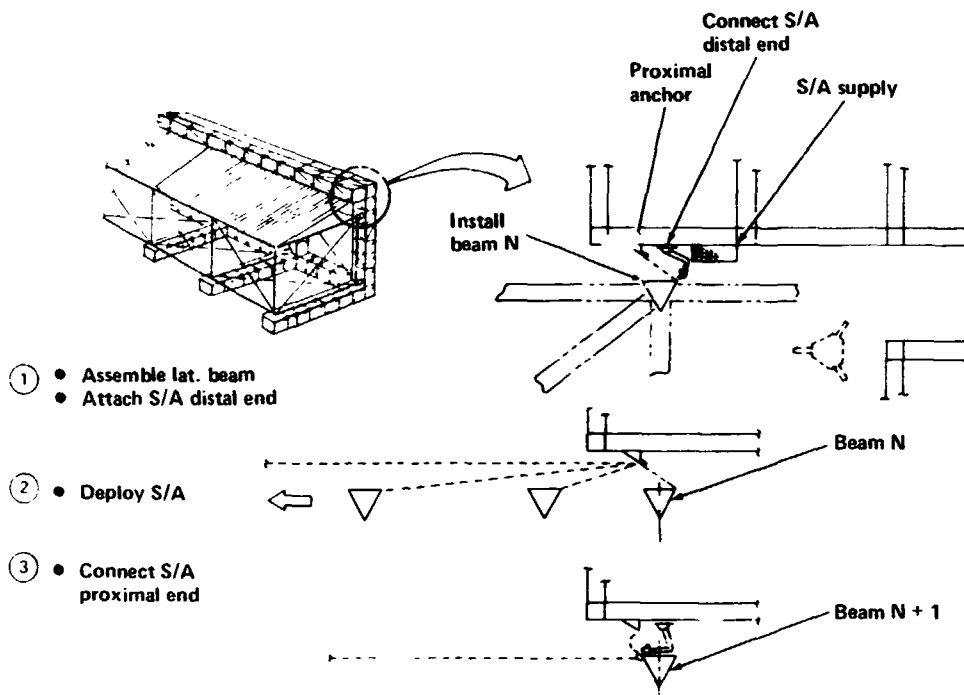
Figure III-27.- Coupled frame assembly/solar array deployment.
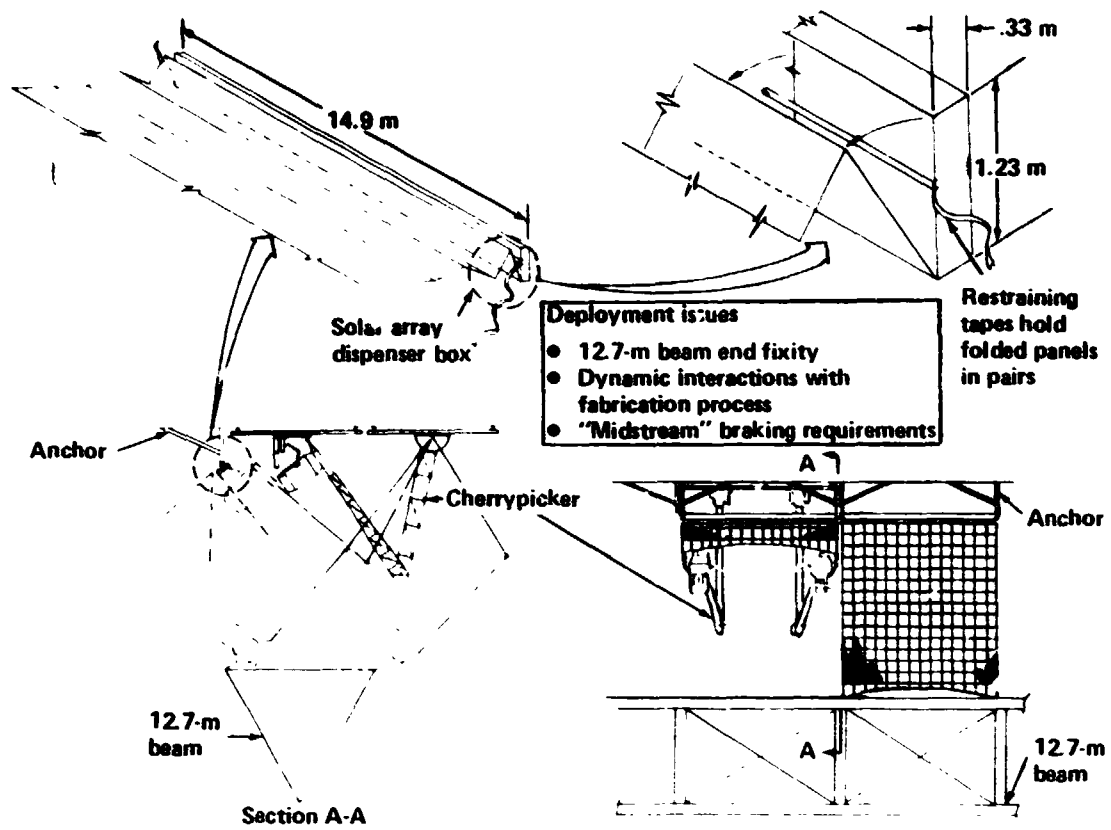
Figure III-28.- Solar array handling and deployment.
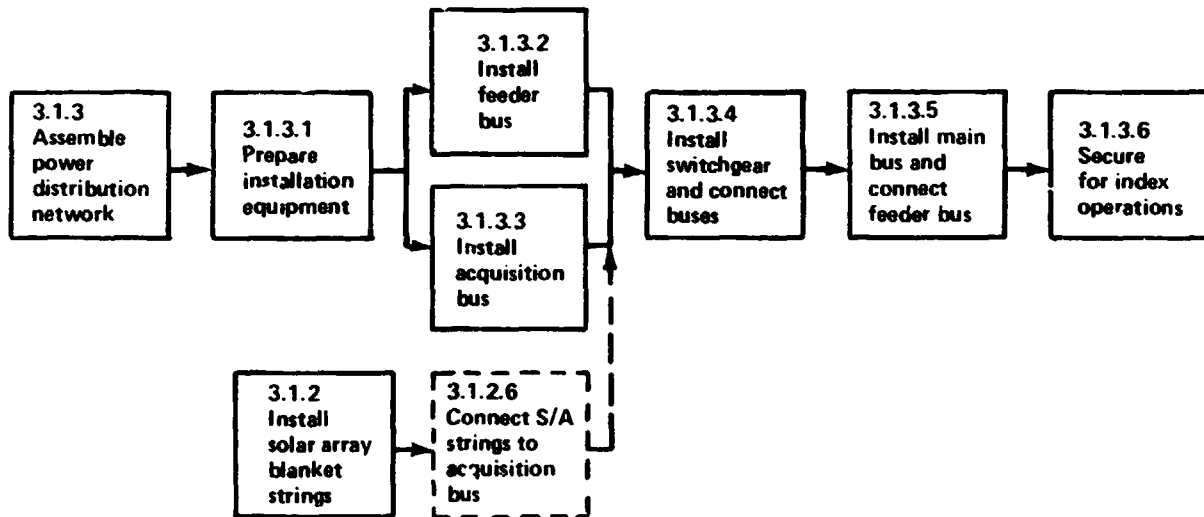
Figure III-29.- Energy conversion system power distribution network assembly
flow.

57
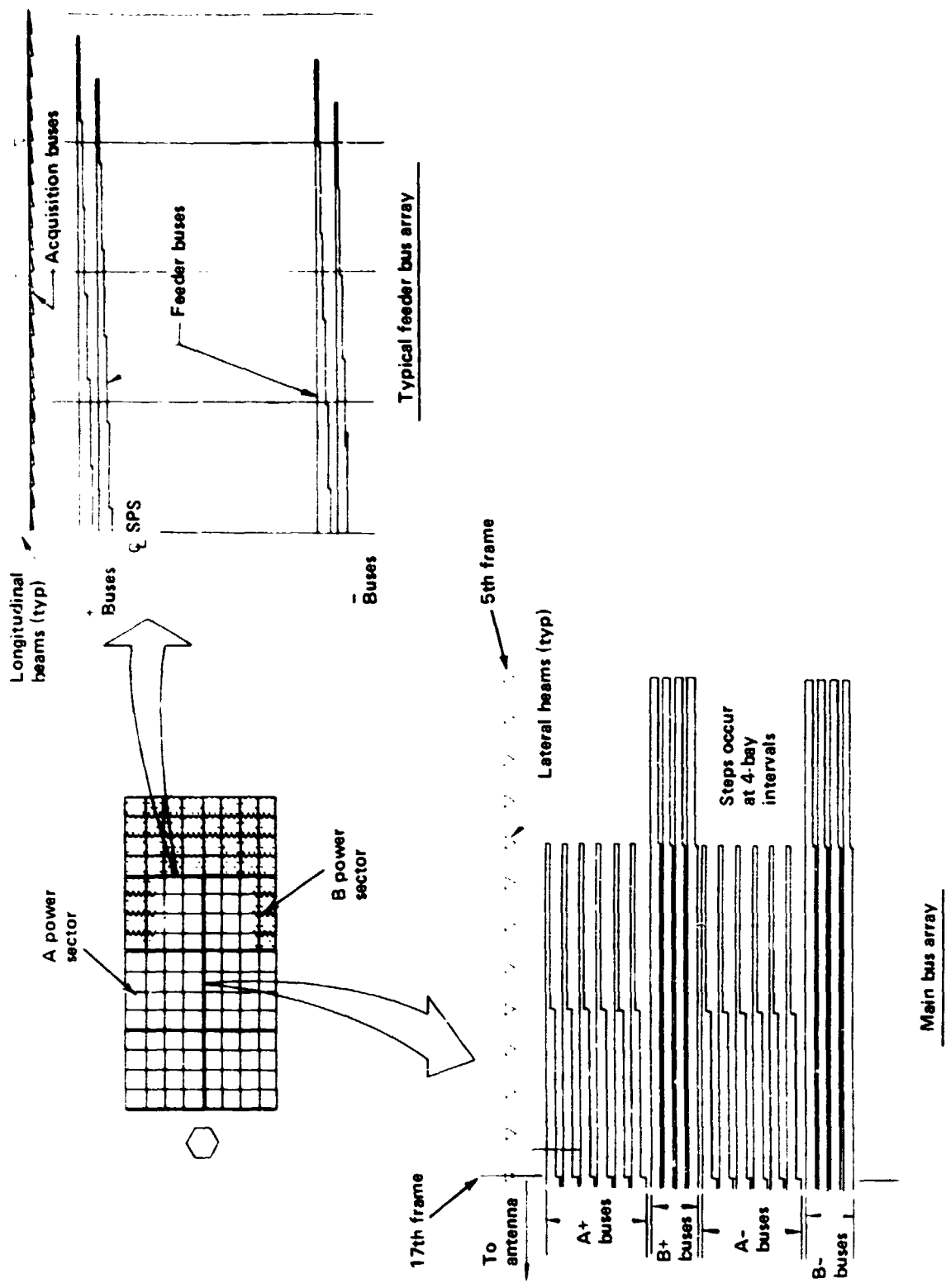
Figure III-30.- Power distribution system.
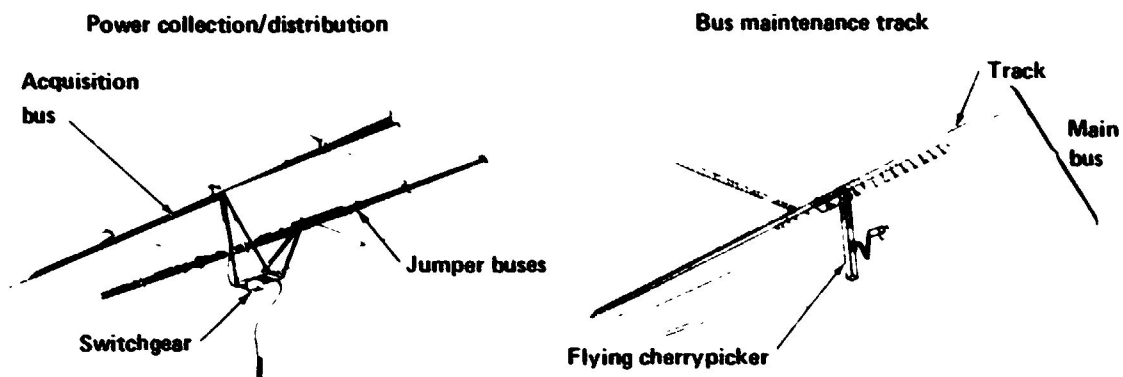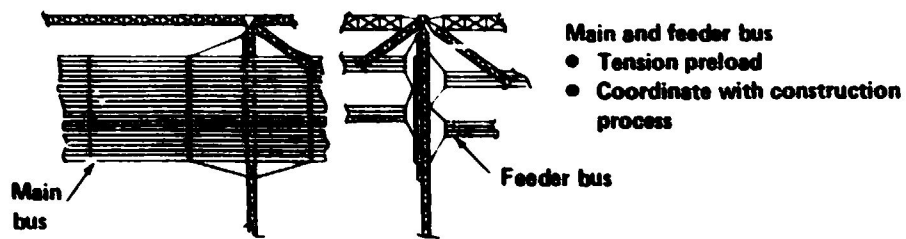
Figure III-31.- Power distribution system installation requirements.
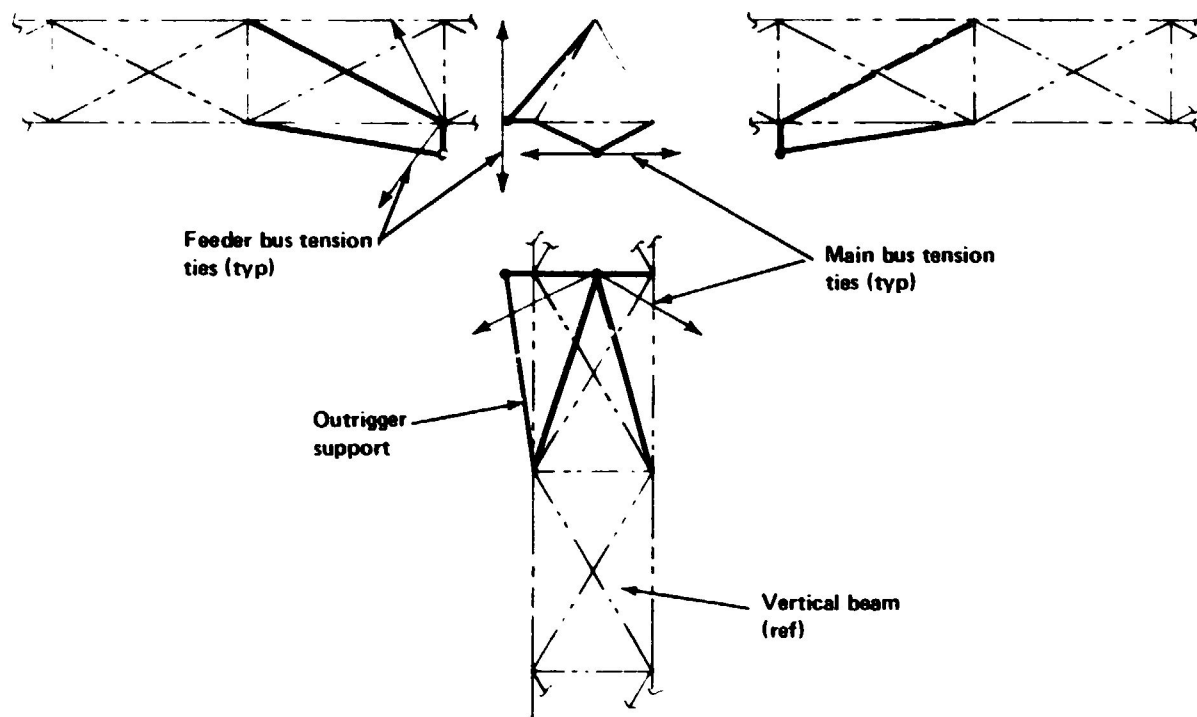
Figure III-32.- Vertical beam with main and feeder bus supports.
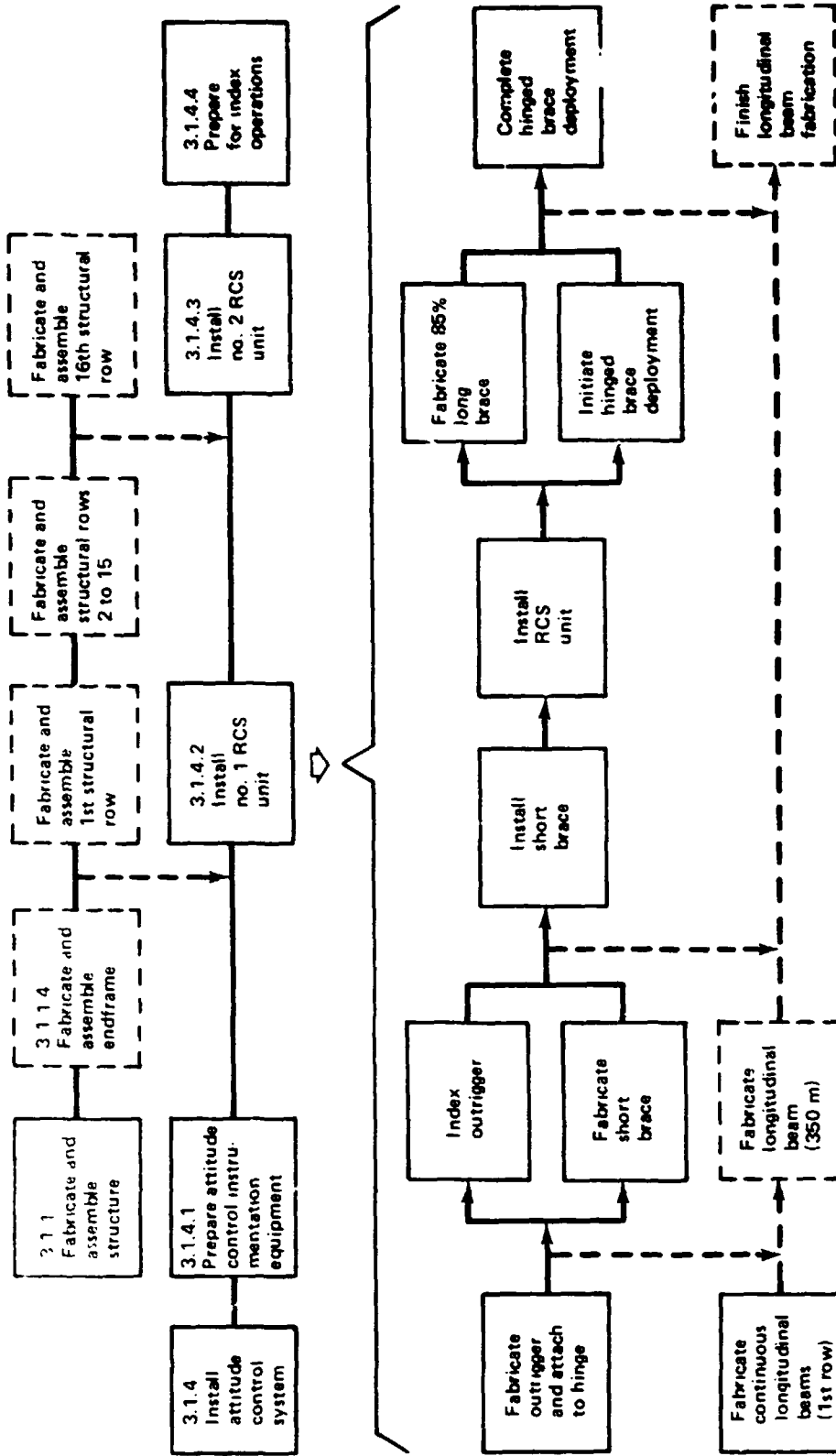
Figure III-33.- SPS attitude control system assembly flow.
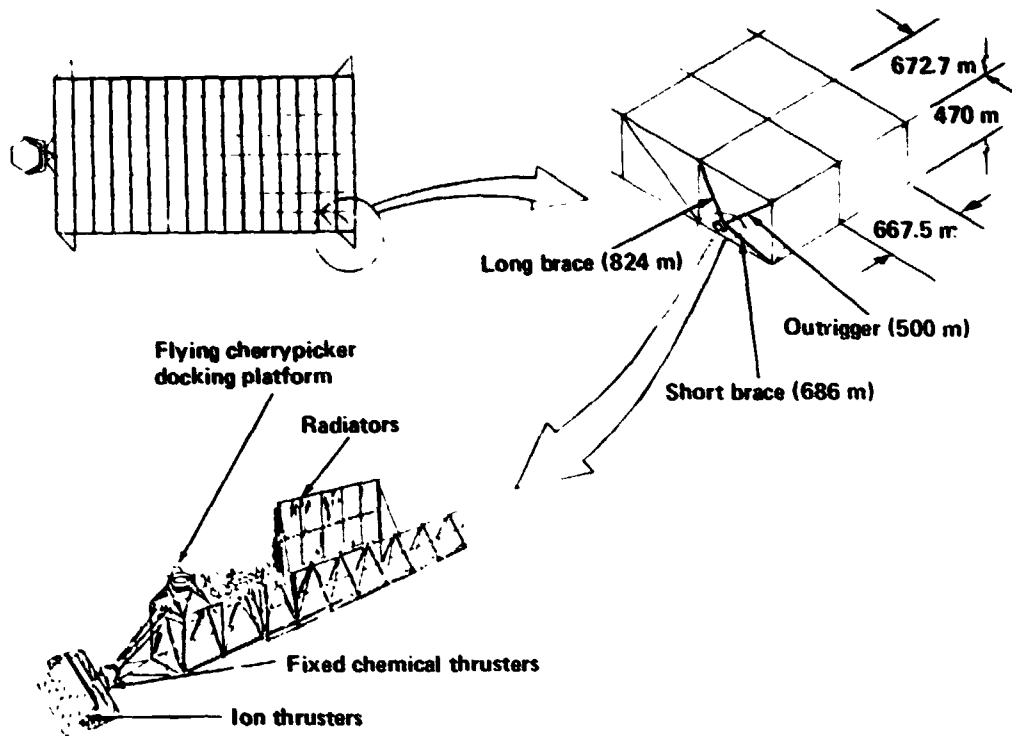
Figure III-34.- SPS attitude control support requirements.
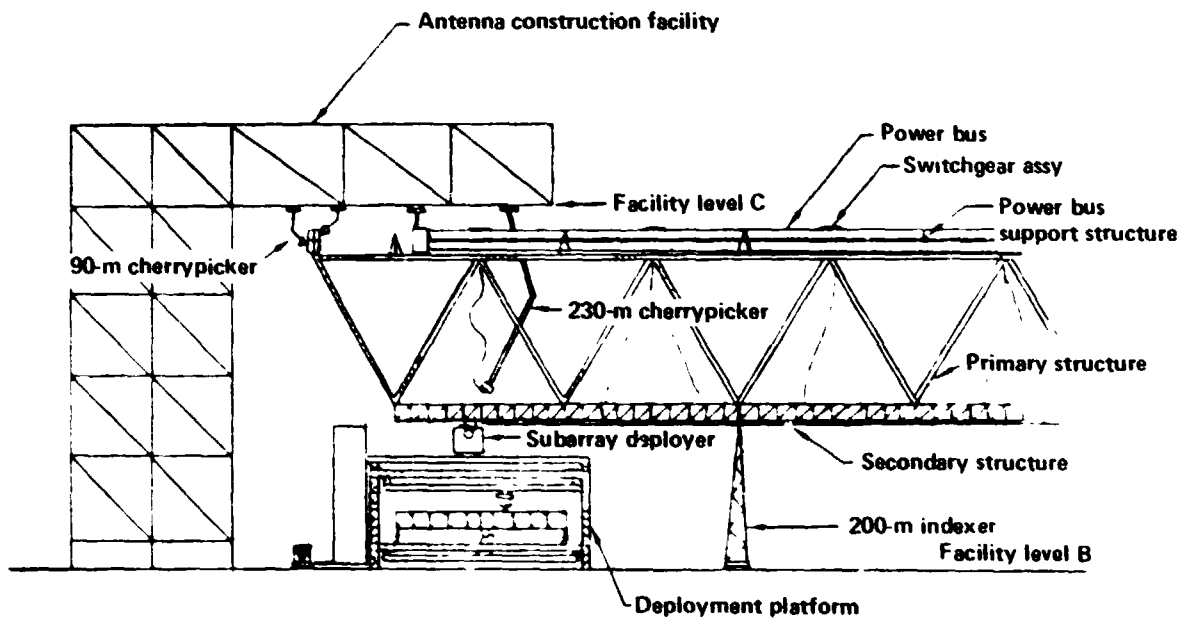
Figure III-35.- Antenna construction facility.

61

Primary structure

Subarrays

Secondary structure

Ridge beam

Primary beam

Location of frame assy equipment

Facility

(1) Assemble primary frame strip 1

Strip 1

(2) ● Index strip 1 out of facility

(3) ● Assemble frame for strip 2
● Install secondary structure
● Install subarrays
● Install other components

Strip 1

Strip 2

(4) Index antenna through facility

(5) ● Index antenna out of facility
● Move frame assy equipment to opposite end of facility
● Assemble strip 3 frame

Strip 1

Strip 2

Strip 3

(6) ● Complete strip 3
● Index antenna out of facility
● Continue

Figure III-36.- Antenna assembly sequence.

62
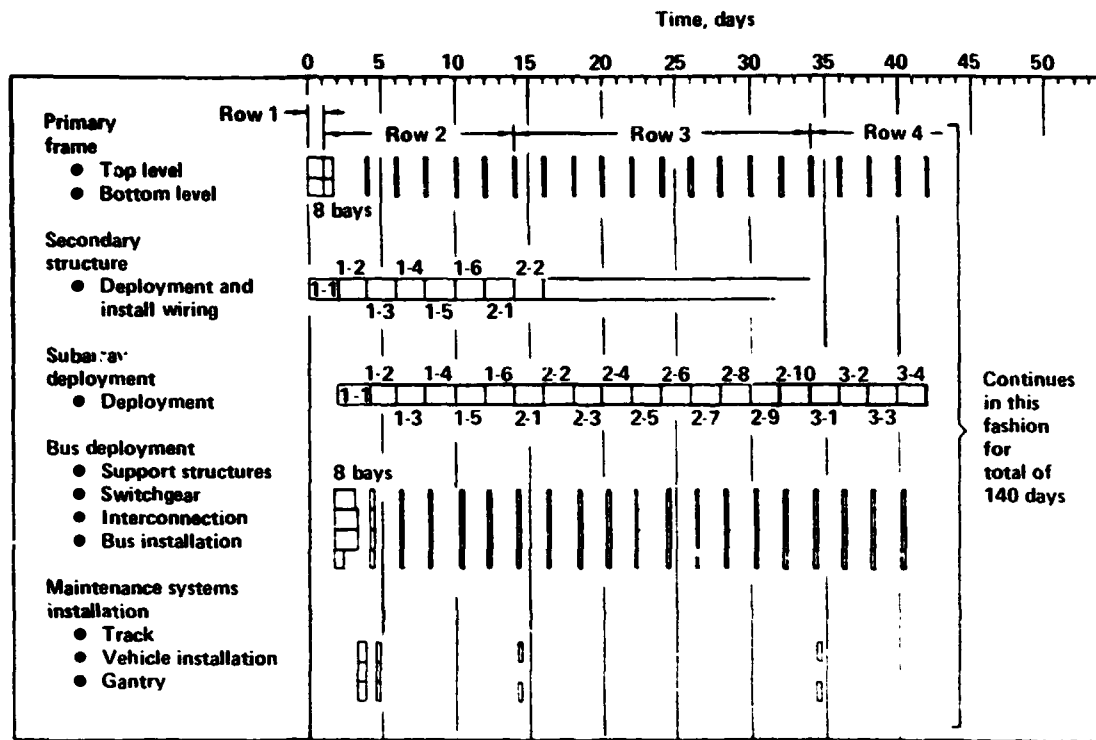
Figure III-37.- Antenna construction time line.
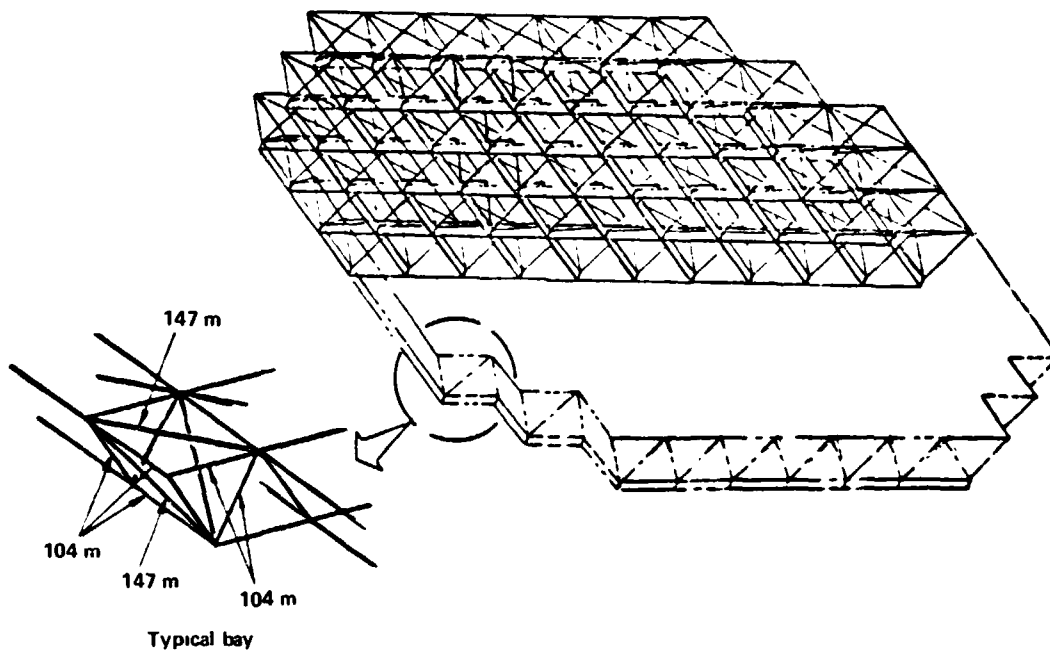
Figure III-38.- MPTS primary structure.

63
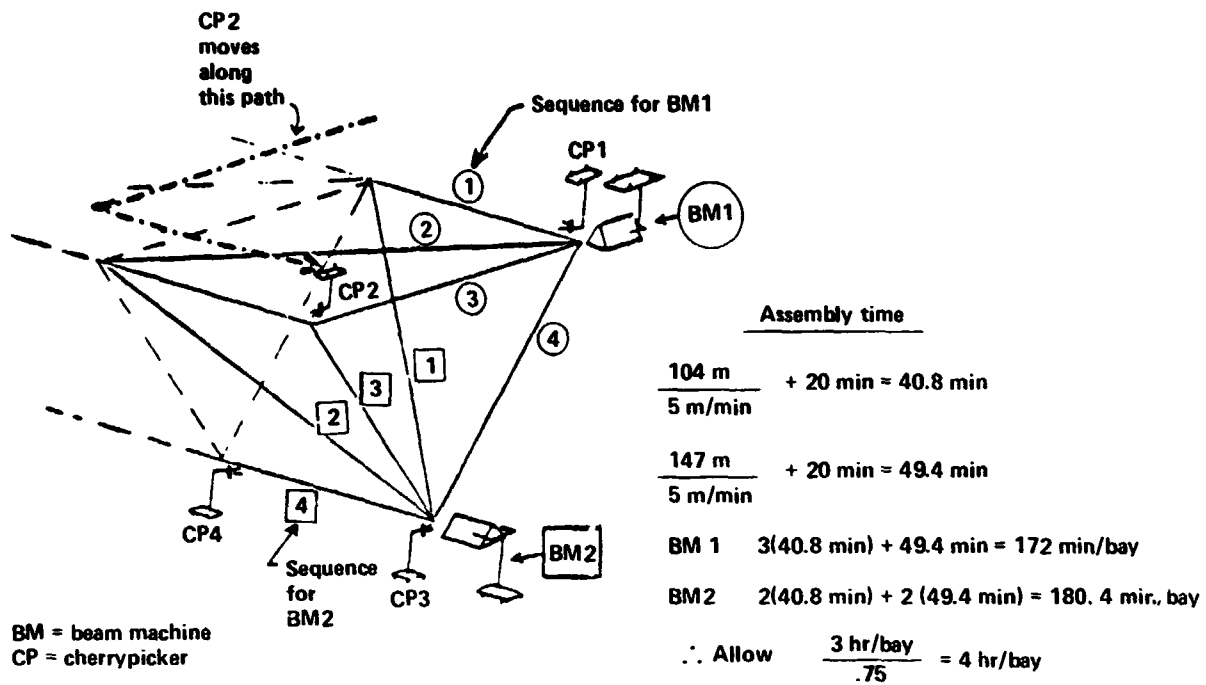
Figure III-39.- MPTS primary frame assembly equipment, sequence, ana time line.

Figure III-40.- Antenna indexers.

Figure III-41.- Antenna deployment platform.

- Load subarrays
  onto transporter

- Test subarrays

- Stack subarrays
  onto transporter

To
deployment
machine

Figure III-42.- Subarray preparation process.

② Transfer stack
of subarrays
off transporter
onto elevator

Subarray transporter

Pallet of 28 subarrays
(enough for 2 passes along gantry)

③
Transfer stack of
subarrays to
deployment
machine
loading position

① Park subarray transporter
adjacent to elevator

Subarray elevator

Subarray deployment gantry

⑤ Move deployment machine
along gantry

Subarray deployer

④ Transfer stack of
subarrays onto
deployment machine

⑥ Install subarray onto
secondary structure

⑦ Connect subarray wiring to
secondary structure wiring

Figure III-43. Subarray deployment sequence.

66

Level J (900 m)

Level K (400 m)

Level A (0 m)

Antenna/yoke
bus support
structure
subassy

Tool
storage
busbar
forming
area

Antenna
switchgear
subassy

Strut
subassy

200 m

60 m

Component
storage
rack

Tracks

To ramp

Level K subassembly factory

Frame
assy
area

Strut
assy
machine
(6 pl)

Thruster
component
storage
rack

Thruster
component
storage
rack

Component
storage rack

Welder

90 m

Rod
bender

225 m

Busbar
storage
rack

Level J subassembly factory

Transporter

Figure III-44.- Subassembly factories.

67

3.0 Construct 5-GW satellite

3.1 Assemble energy conversion system

3.2 Assemble power transmission system

3.3 Assemble interface

3.4 Mate systems

3.5 Final test and C/O

3.4 Mate systems

3.4.1 Mate power transmission and interface

3.4.2 Fabricate and install support structure

3.4.3 Mate interface to energy conversion system

3.4.4 Index

3.3 Assemble interface

3.3.1 Fabricate and assemble yoke

3.3.2 Fabricate and assemble rotary joint

3.3.3 Connect yoke and rotary joint

Figure III-45.- Interface assembly and systems mating flow.

68
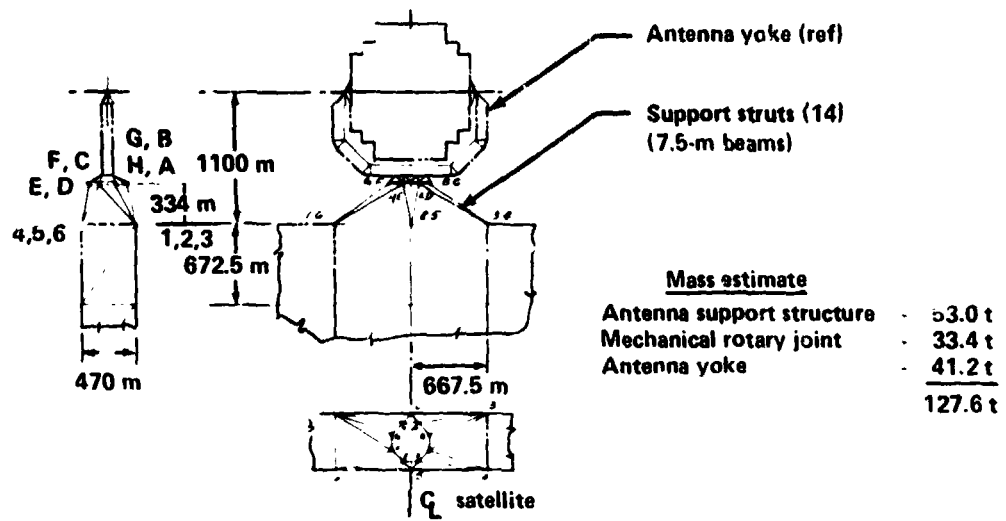
Figure III-46.- Interface structure.
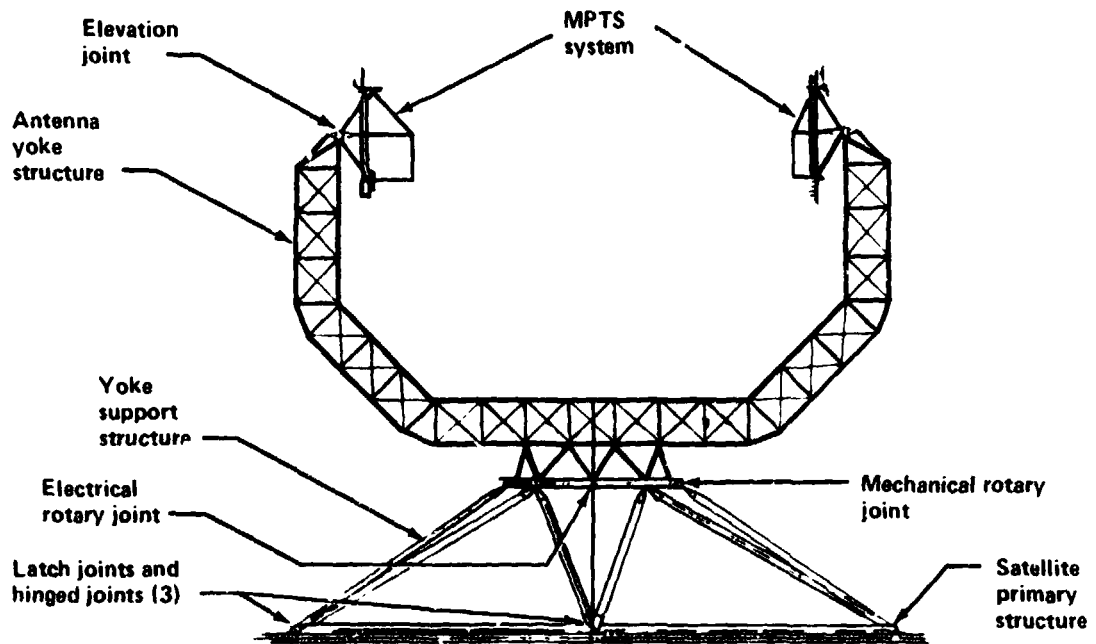
Figure III-47.- Antenna interface.

OUTER BASE
CHORD

APEX
CHORD

20 m

INNER BASE
CHORD

SECTION A-A

19 36 m

A

A

20 m

17 27 m

6°

175 m

170 m

185 m

RADIAL STRUT
(EVERY 30°)
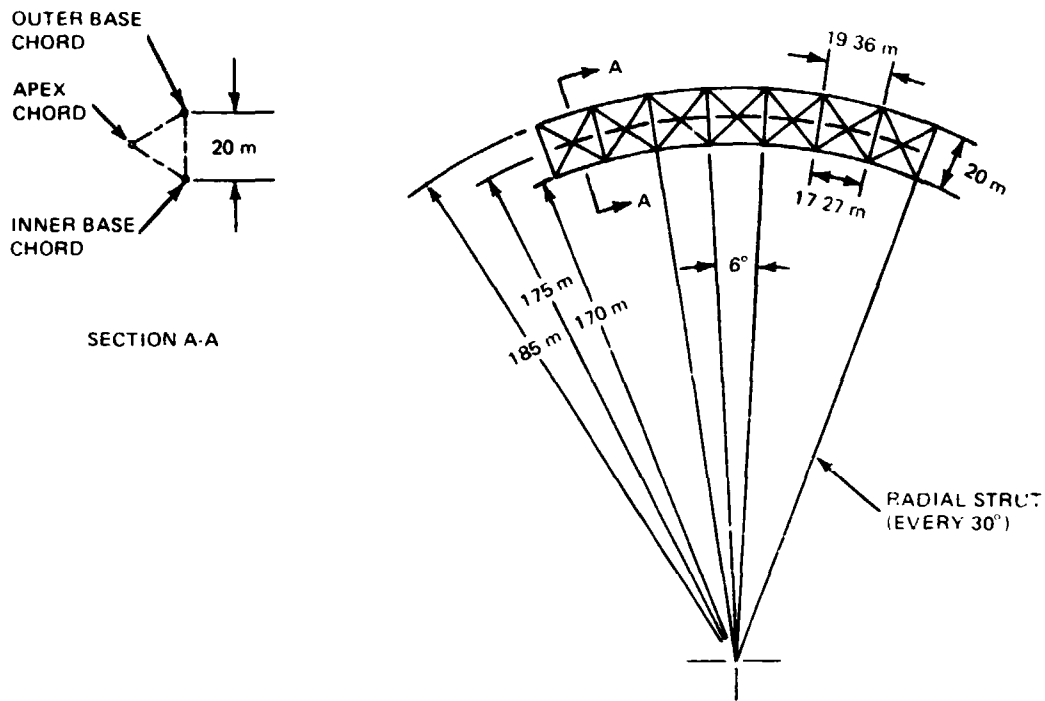
Figure III-48.- Circular ring beam geometry.

Collector construction
facility

Rotary joint

Cherrypicker crane and material
transporter 2

Solar collector

B

Support struts
(16) (7.5-m beams)

Yoke

Track system

7.5-m
mobile beam
station (2)

Rotary joint
construction facility

B

Circular beam
construction

Hub support beams

View B-B

Fi   III-49.- Yoke/rotary joint assembly facility.

70

- First construction pass
- Locate yoke facility for initial construction
- Construct antenna and yoke in parallel

- Second construction pass
- Relocate yoke facility for continued use
- Antenna and yoke construction near midpoint

(a)   First and second construction passes.

- Second pass complete
- Yoke assembly complete
- Antenna assembly complete

- Join yoke and antenna
- Center yoke/rotary joint assembly facility to fabricate rotary joint
- Fabricate and attach yoke/rotary joint struts

(b)   Mating of yoke and antenna.

Figure III-50.- Antenna/interface construction sequence.

71

- Index base to solar collector pickup
- Index antenna to aline with collector
- Position yoke facility to fabricate and install support struts

- Re-index base and reposition yoke facility to fabricate and install remaining (9) support struts
- Prepare for C/O

(c) Final systems mating operation.

Figure III-50.- Concluded.

- Start antenna fabrication
- Fabricate yoke in parallel
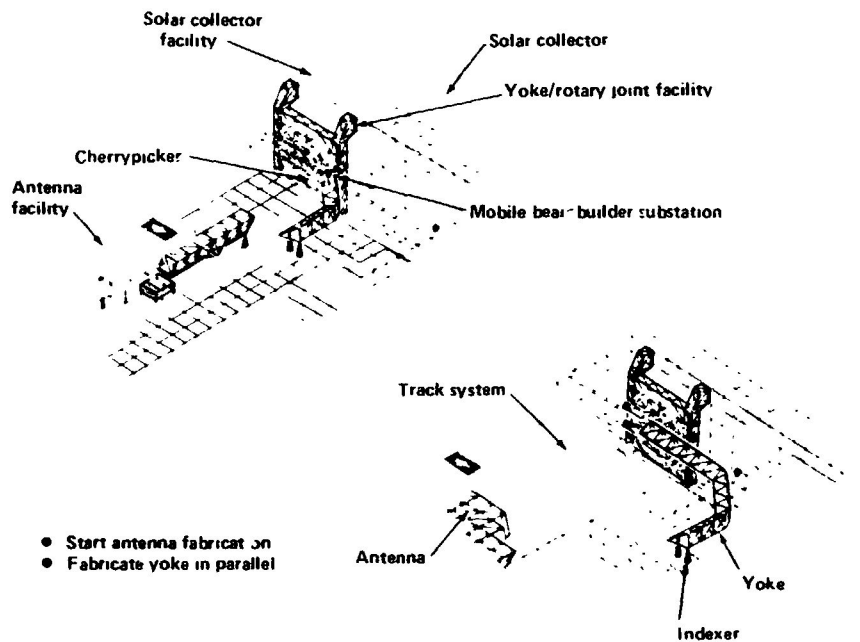
(a) Fabrication of antenna and yoke.

Figure III-51.- Yoke/rotary joint assembly.

Yoke completed
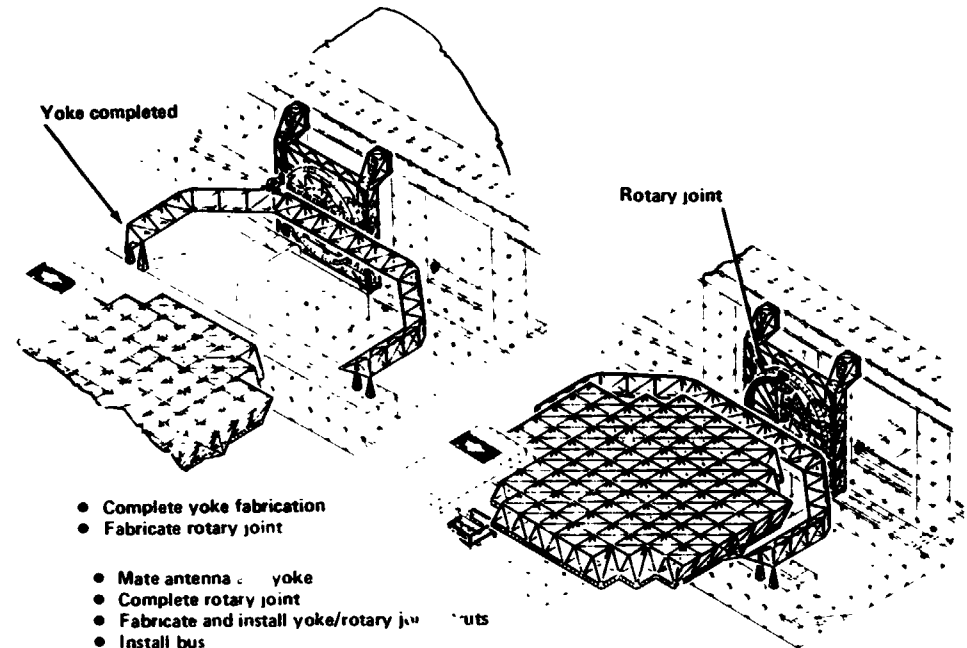
Rotary joint

- Complete yoke fabrication
- Fabricate rotary joint

- Mate antenna & yoke
- Complete rotary joint
- Fabricate and install yoke/rotary joint struts
- Install bus

(b) Joining of antenna and yoke.
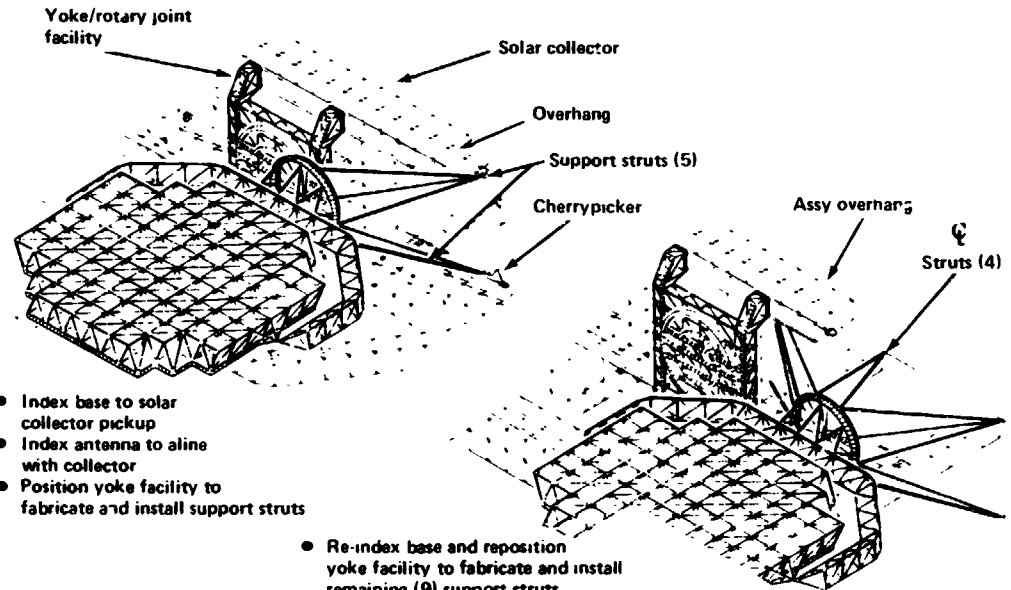
Yoke/rotary joint facility

Solar collector

Overhang

Support struts (5)

Cherrypicker

Assy overhang

₵

Struts (4)

- Index base to solar collector pickup
- Index antenna to aline with collector
- Position yoke facility to fabricate and install support struts

- Re-index base and reposition yoke facility to fabricate and install remaining (9) support struts
- Install power bus
- Prepare final C/O

(c) Final systems mating.

Figure III-51.- Concluded.

73

IOTV operations

IOTV operations

HLLV

EOTV

POTV

EOTV construction

SCB

Orbiter-delivered external tank

Satellite construction

Construction fixture

SCB transit to GEO

GEO

LEO

Initial LEO base
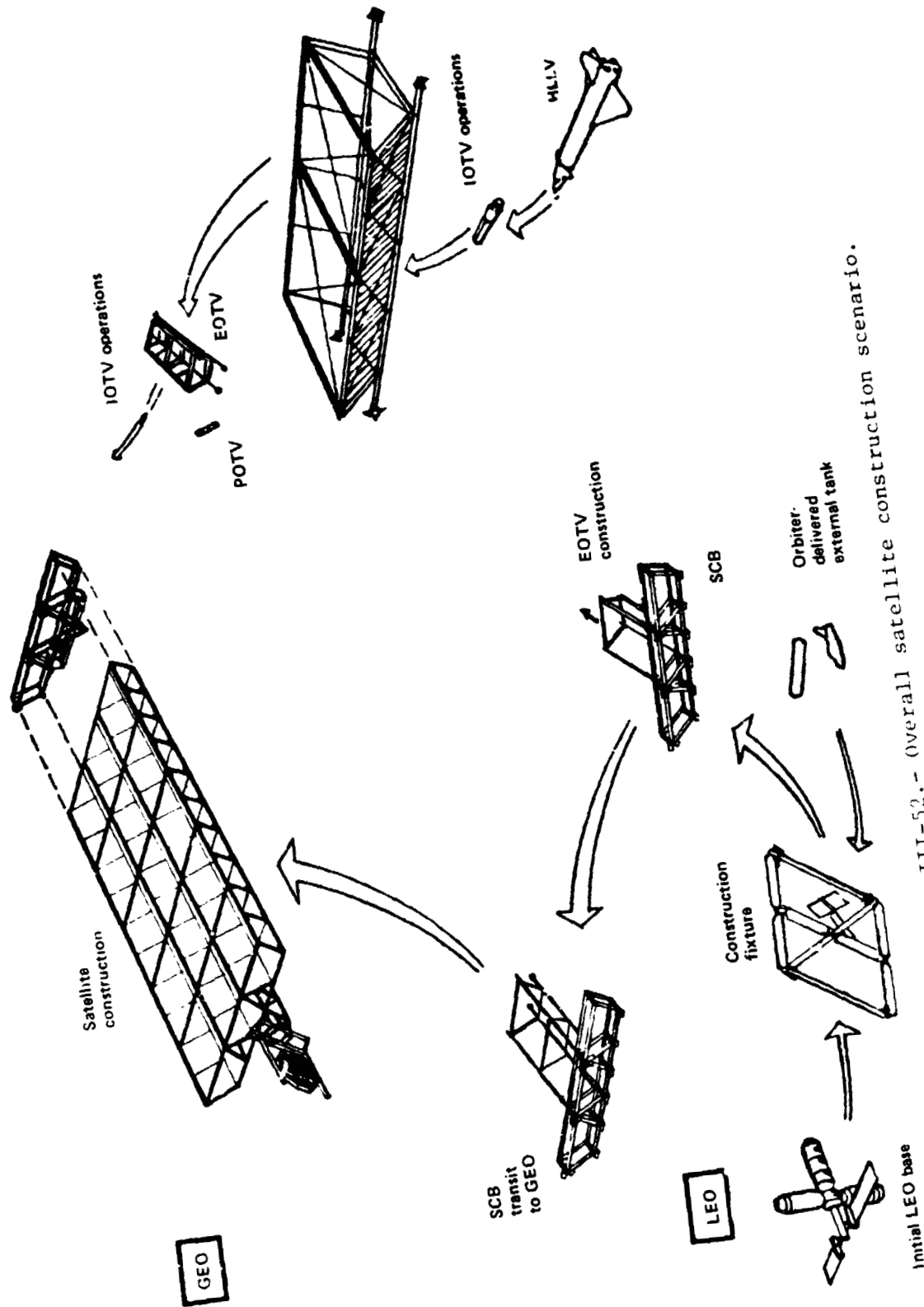
Figure III-52.- Overall satellite construction scenario.

74

Figure III-53.- LEO base.

75

Equipment and location descriptions

① to ⑪	Longitudinal tribeam fabrication pods	
⑫ to ㉗	Crossbeam fabrication pods	
㉘ 'o �33	Reflector dispensing areas	
�34 to 36	Solar blanket dispensing areas	
㊲	Central habitat, landing and warehousing	
㊳ to 40	Auxiliary habitat/complex blanket facilities	

View A-A

View B-B
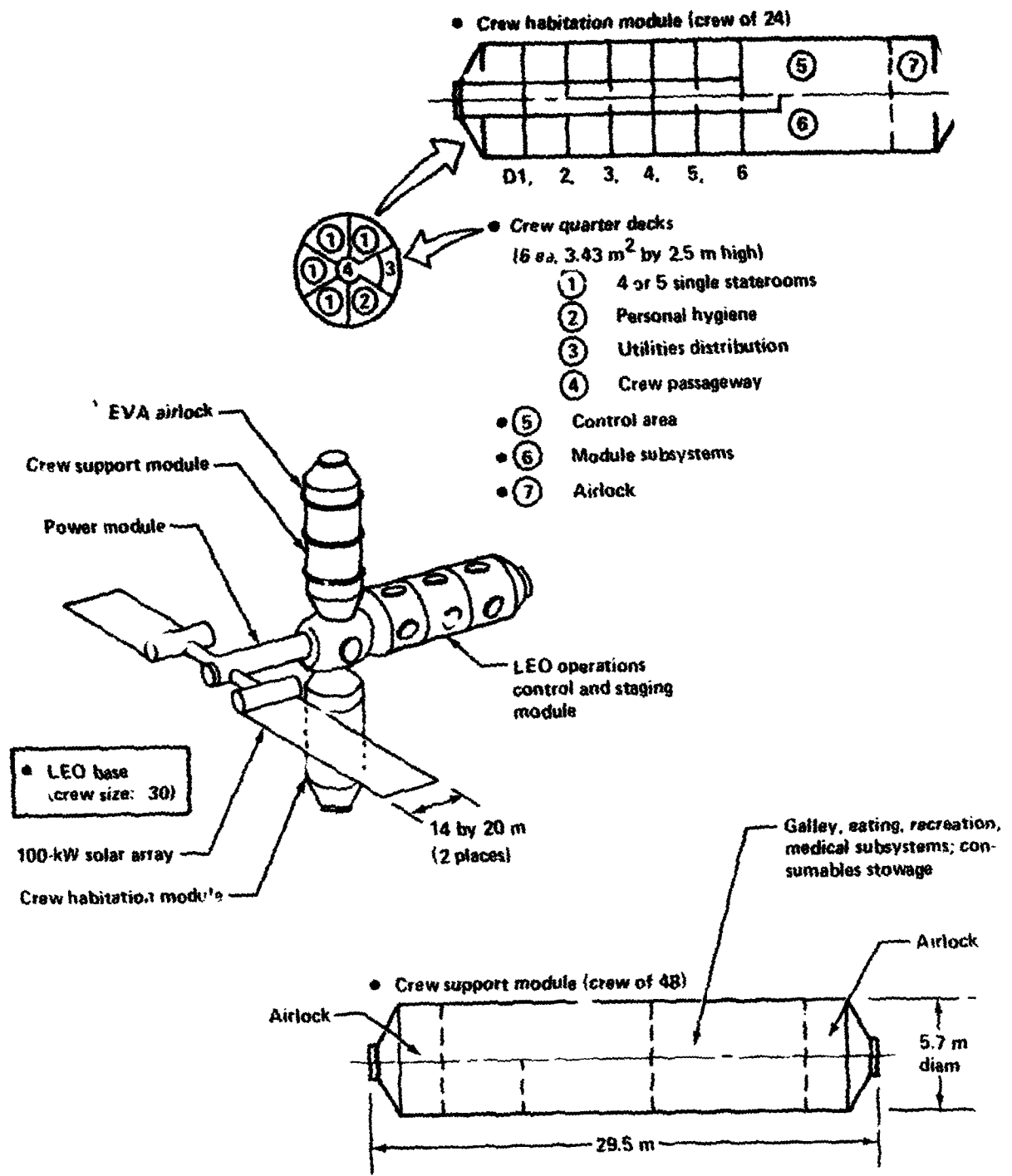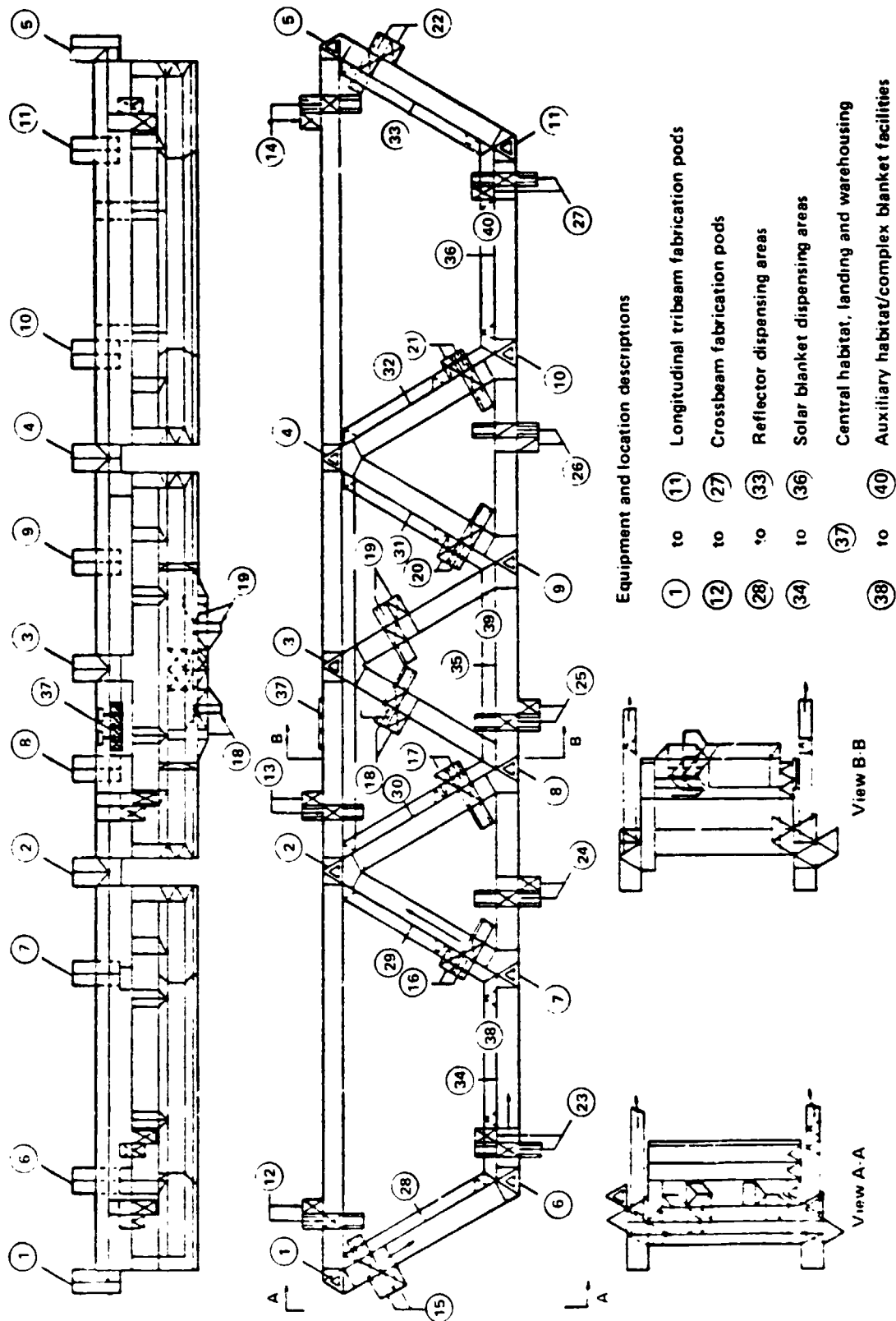
Figure III-54.- Satellite construction base.

76
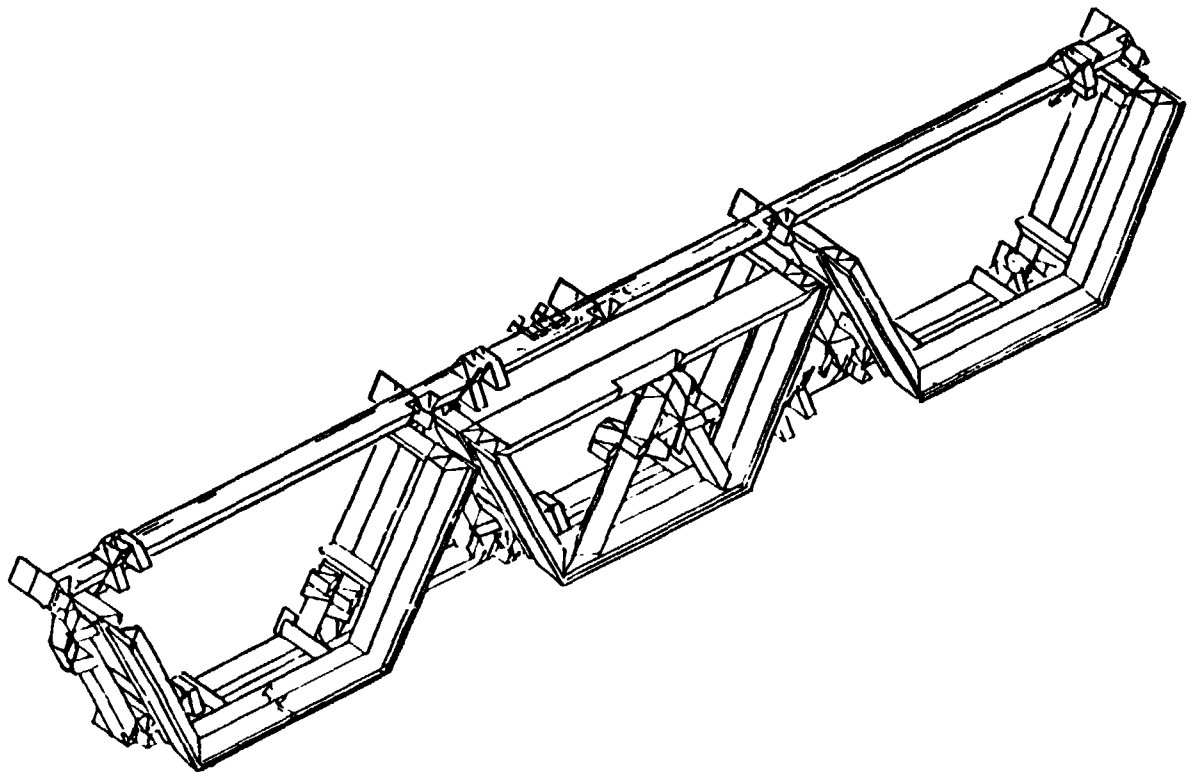
Figure III-55.- Integrated satellite construction base.
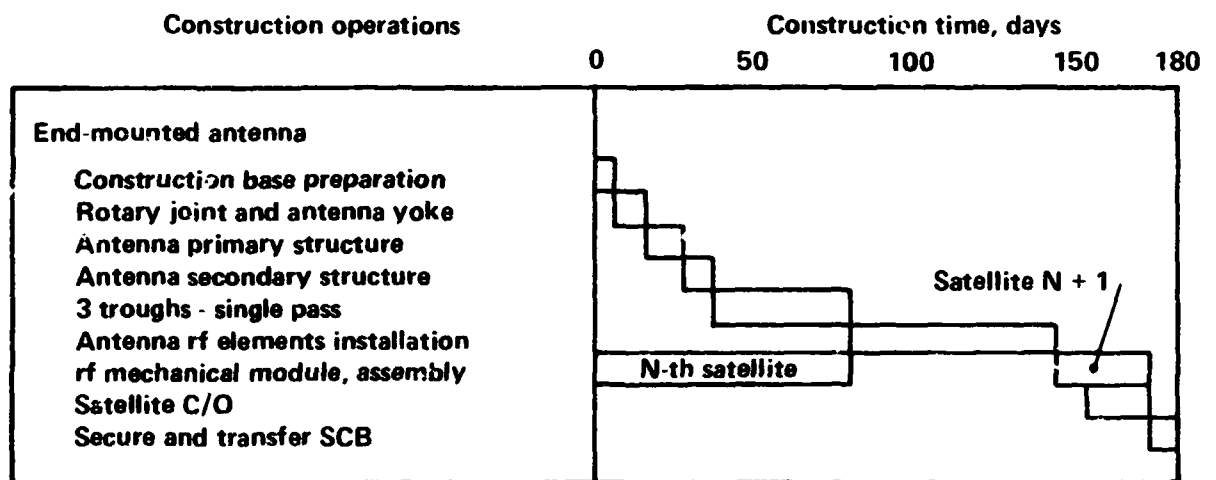
Figure III-56.- Satellite construction time line.
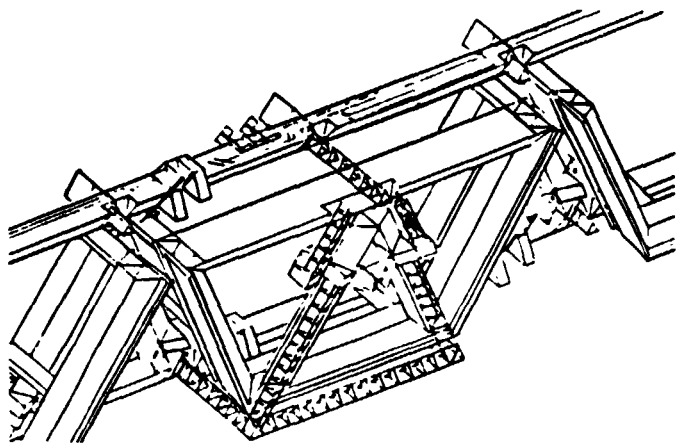
Figure III-57.- Slipring interface structure.
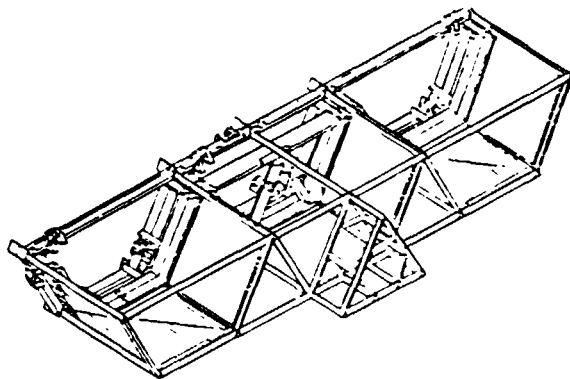
Figure III-58.- Solar array first frame and slipring interface structure.
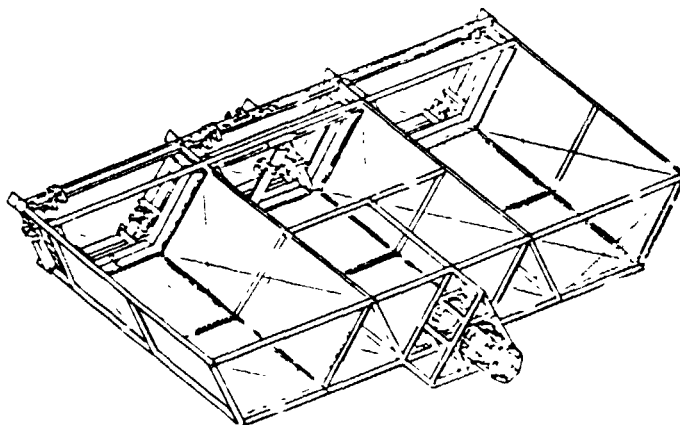
Figure III-59.- Slipring structure independent fabrication.

SCB 80-m facilities modified to fabricate 50-m tribeams regrouped to form independent fabrication facilities

Antenna hex frame

Yoke base/arms

Slipring structure
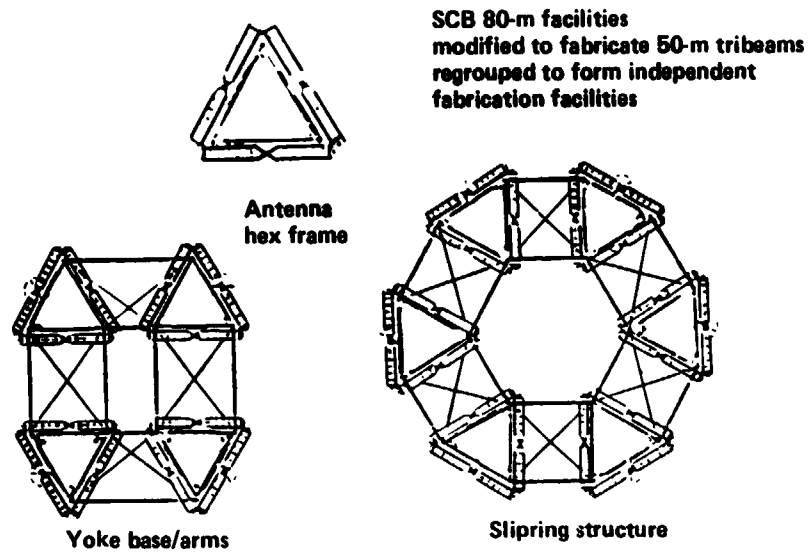
Figure III-60.- 50-meter tribeam facility for fabricating antenna and supporting structure.

Mechanical module rf elements

₵ SPS

←— 800 m —→
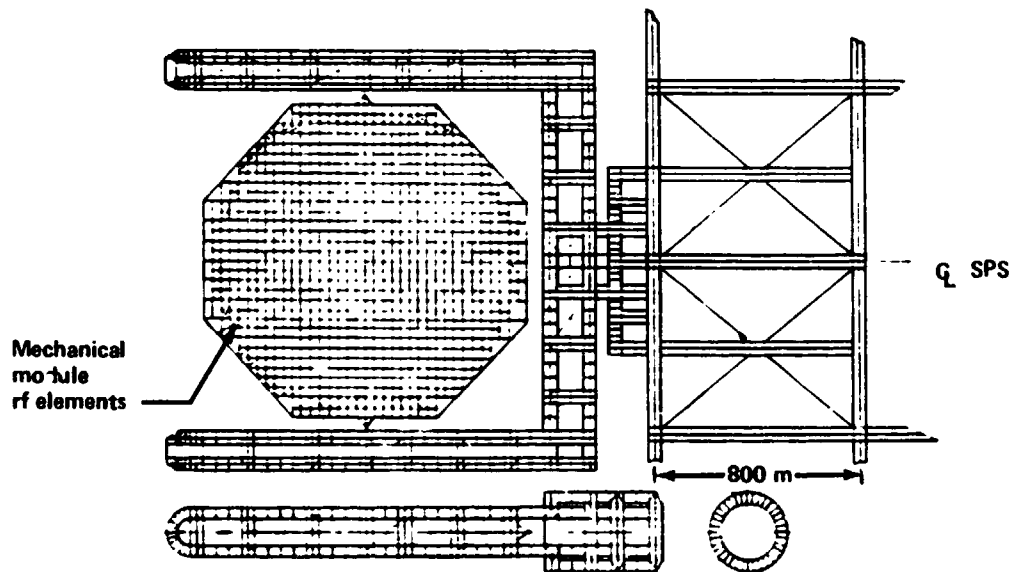
Figure III-61.- Slipring/yoke/antenna structural layout of space-frame antenna.
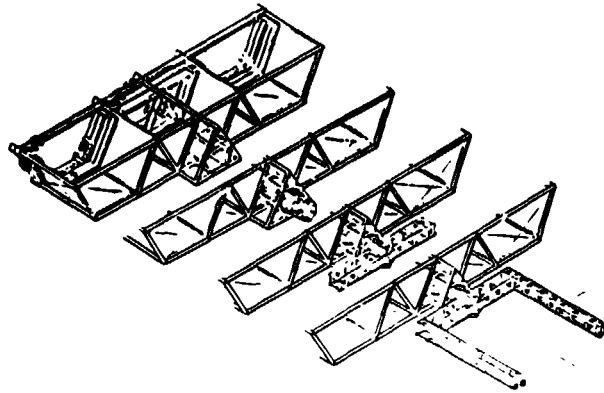
Figure III-62.- Antenna supporting structure assembly sequence.
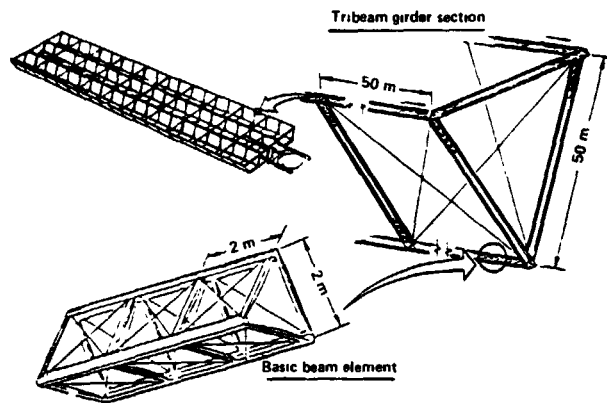
Figure III-63.- Primary structure evolution.
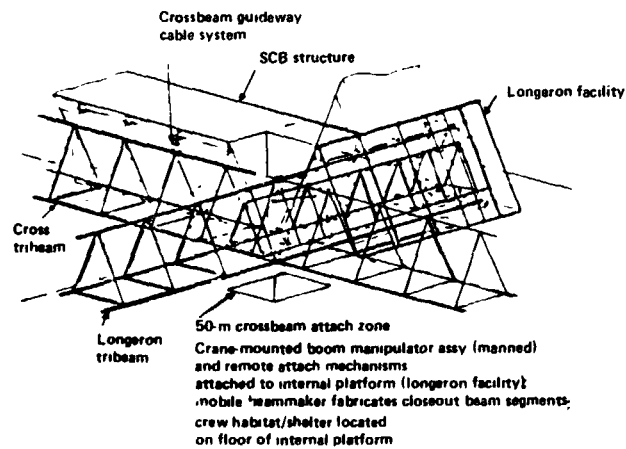
Figure III-64.- Typical longeron facility.

80
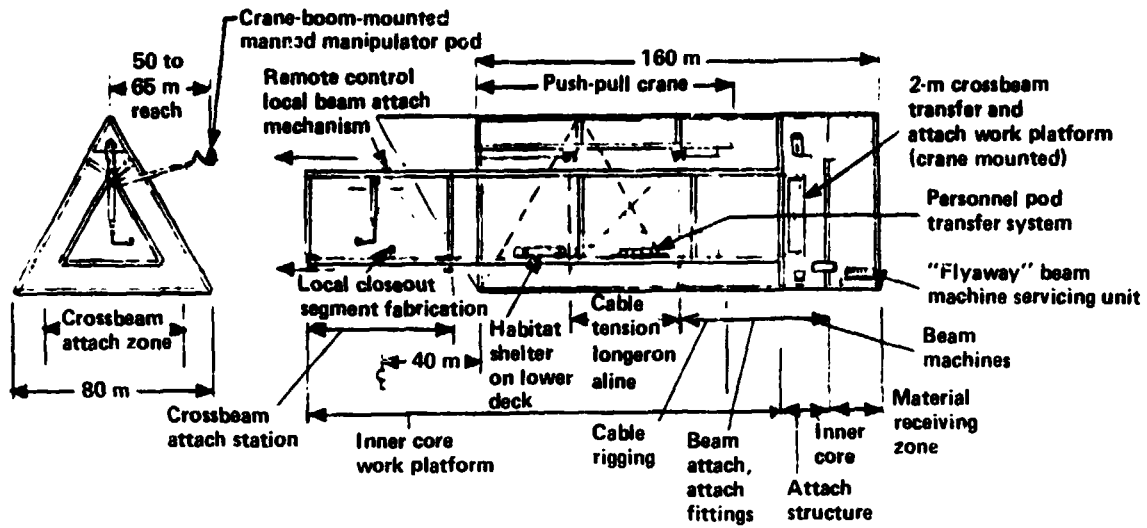
Figure III-65.- Longeron fabrication facility.
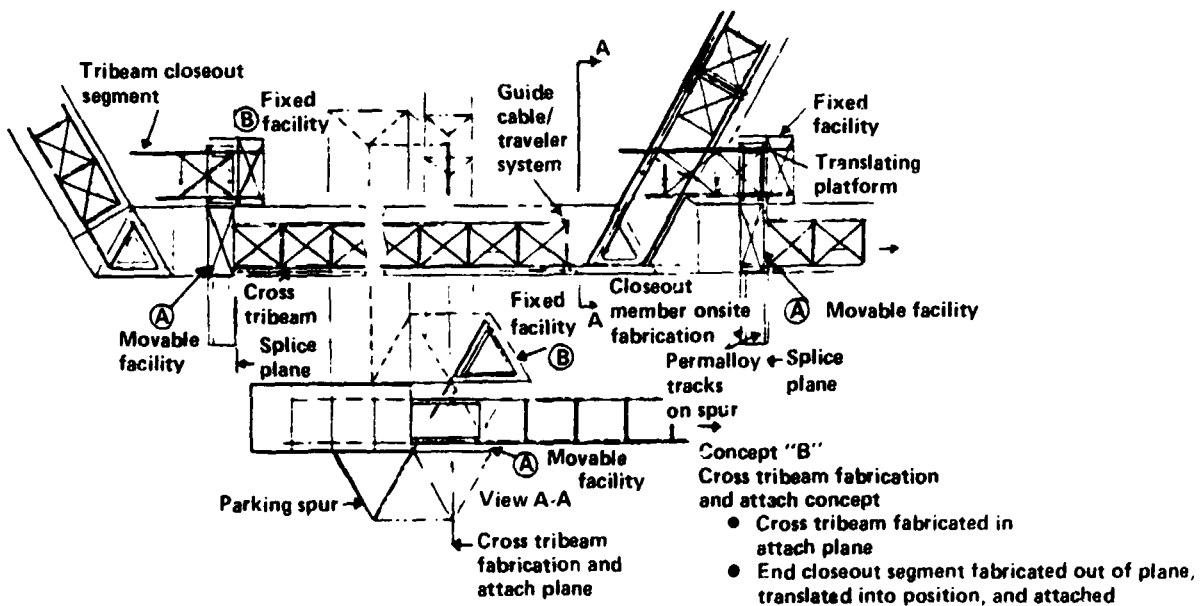
Figure III-66.- 50-meter crossbeam installation.

81
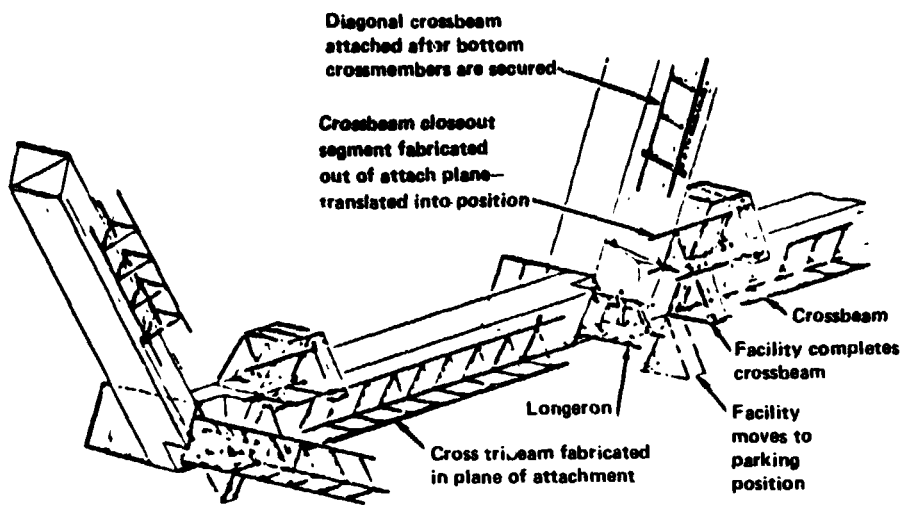
Figure III-67.- Typical three-way intersection with longeron.
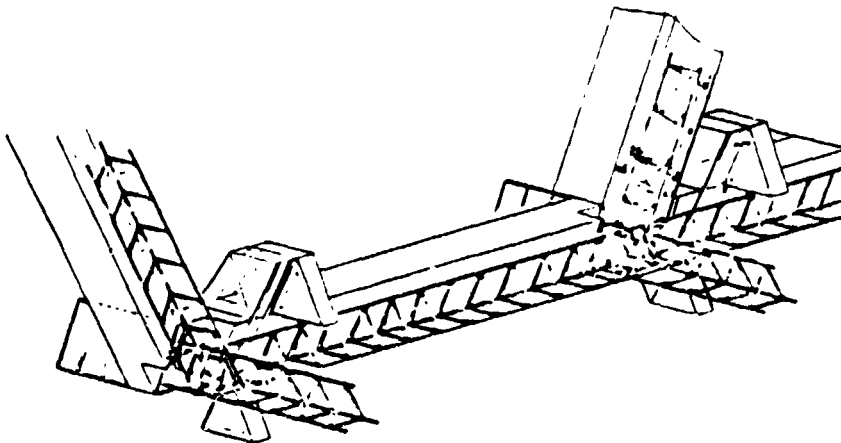
Figure III-68.- Crossbeam attachment configuration.

1. Crossbeam fabrication attach concept:
beam machines mounted
external to tribeam pod

Cable/traveler guide system

Crossbeam facility fabricates crossbeam "in place"

Beam machines mounted external to pod fabricate closeout members

Parking spur

Cross tribeam fabrication pod

View A-A

(a) Sequence 1.

2. Crossbeam closeout element fabrication and attachment

External beam machines fabricate closeout elements adjacent to closeout location. Mobile manipulator translates beam into position and secures Marmon-type connectors

End attach by manipulators located on inner core work platform of longeron facilities

Longeron facility (typ)

Crossbeam pod moves down on spur to position external beam machines

View A-A

(b) Sequence 2.

Figure III-69.- Construction concept for crossbeam fabrication and attachment.

83

1300 m

650 m

650 m

15-m clearance
main structure

5-m clearance
lower deck

170 m

Blanket attach
plane (all stop)

Crossbeam attach
plane (all stop)
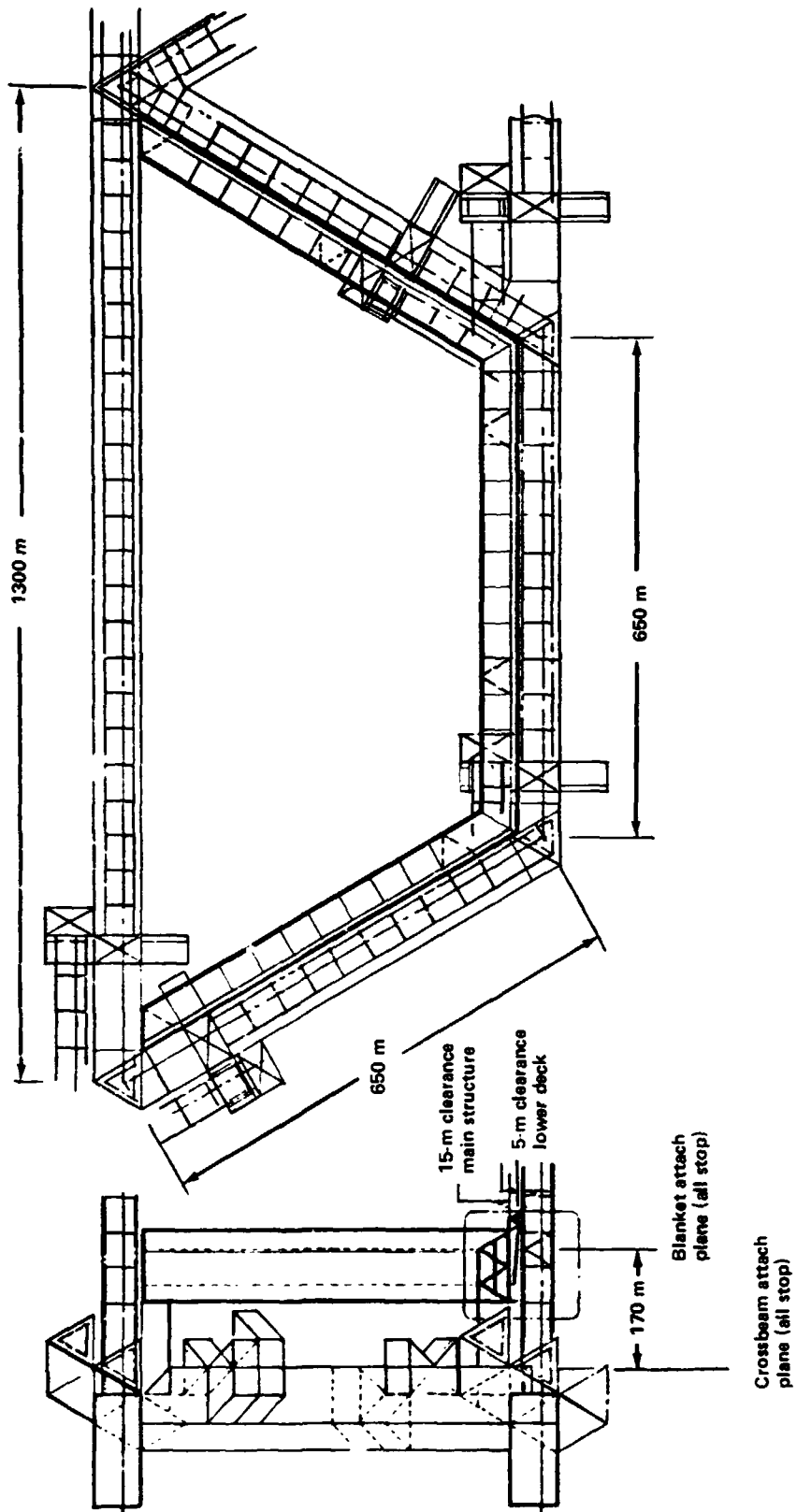
(a) General arrangement.

Figure III-70.- Solar blanket deployment facility.

84

C-2

Blanket installation facility

1 Guide/attach cable deployment reel
2 Cable reel servicing unit
3 Material delivery elevator
4 Blanket supply truck (Permalloy tracks)
5 Blanket dispenser
6 End catenary layout-fabrication-attachment platform (50 m)
7 Blanket to cable attachment machine
8 Edge catenary layout-fabrication-attachment platform (2)
9 Electrical material supply elevator
10 Crossbeam electrical gear/cable installation mobile gantry
11 Side catenary attachment unit (2)
12 Guide cable alinement/"sefing" tower (every 50 m) and electrical cable
   attachment
13 Switchgear/electrical unit inspection/servicing/maintenance area
14 Crew transporter/MMM storage and maintenance area
15 Auxiliary base - crew habitat and support
16 Docking and service module
17 Crew habitat
18 Transportation module
19 Personnel transporter to main SCB area
20 POTV landing area
21 POTV
22 Material transit system
23 Material warehousing area
24 Interdeck elevator system
25 Cargo-OTV landing deck
26 Cargo canister
27 OTV to SCB cargo transfer tug

(b) Elevation view.

Figure III-70.- Continued.

85

Reflector facility (similar to solar blanket facility)

Solar blanket facility, main deck

Reflector facility

Main SCB structure

Longeron fabrication facility

Crossbeam attachment station

170 m

Blanket attachment station

Longeron

(c) Isometric view.

Figure III-70.- Continued.

(d) Plan view looking up at lower deck.

Figure III-70.- Continued.

87

(e) Isometric view looking up at lower deck.

Figure III-70.– Concluded.

① Switchgear	⑦	Longitudinal solar blanket restraining cables
② Installation saddle	⑧	Catenary/solar blanket cable attachment fittings
③ Multiattachment bracket	⑨	Solar blanket cable tensioning yoke
④ 50-m transverse catenary assembly	⑩	Crossbeam (50-m tribeam girder)
⑤ Catenary	⑪	Top cap (2-m basic beam element)
⑥ Catenary to solar blanket tension ties	⑫	Side beam members (50 m long)

Figure III-71.- Installation operations at crossbeams.

Figure III-72.- Solar converter construction sequence for typical bay.

89
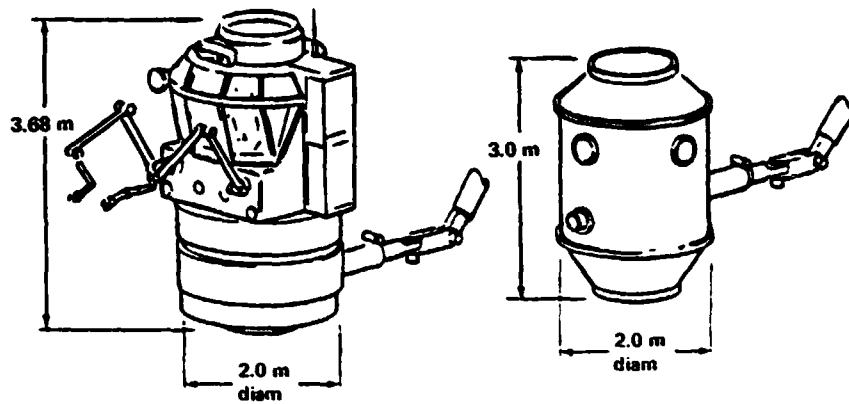
Figure III-73.- Manned manipulator module (left) and crew transport module (right).
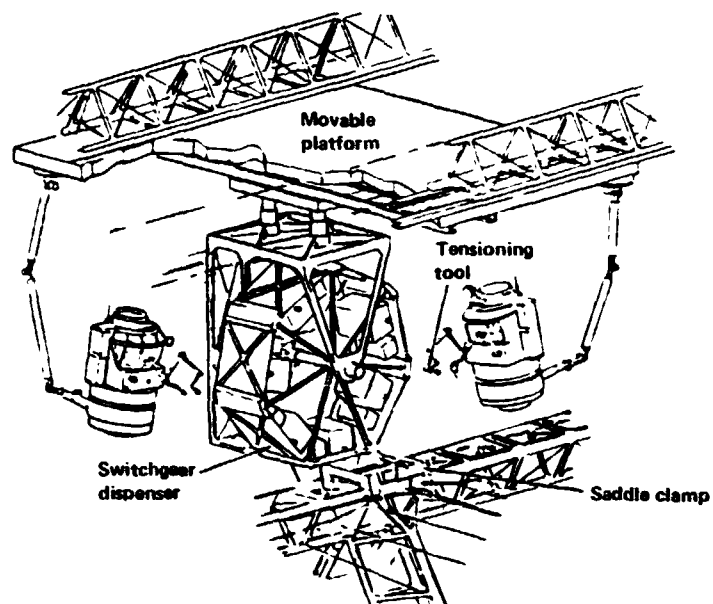
Figure III-74.- Switchgear installation.
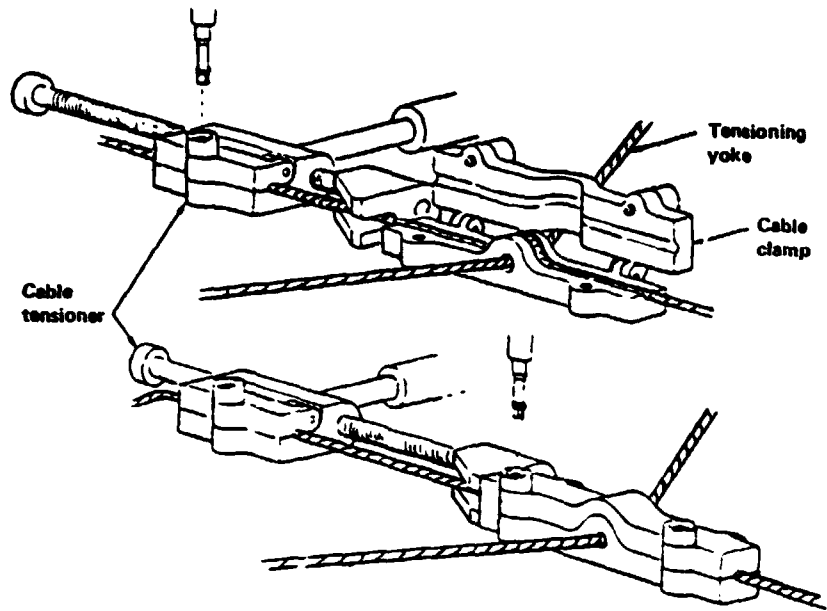
Figure III-75.- Cable tensioning device.
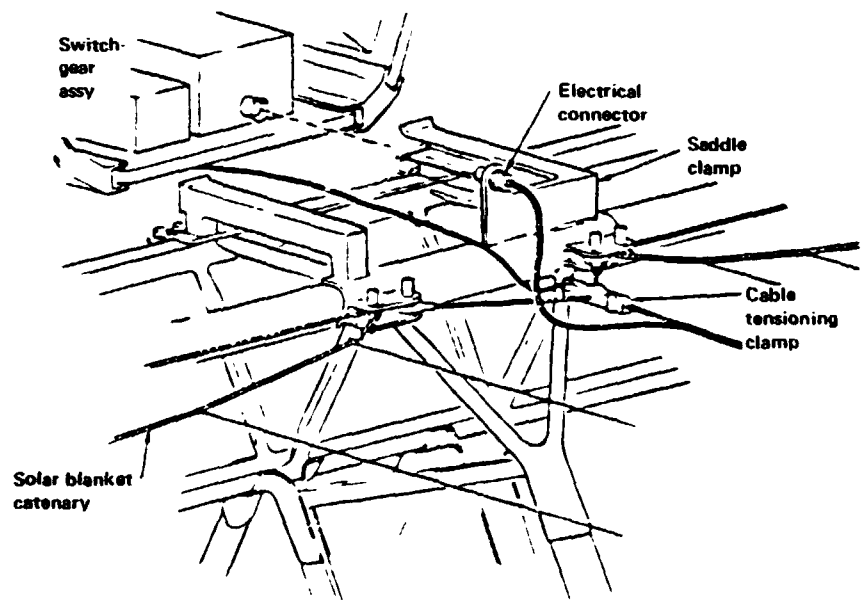
Figure III-76.- Switchgear installation detail.
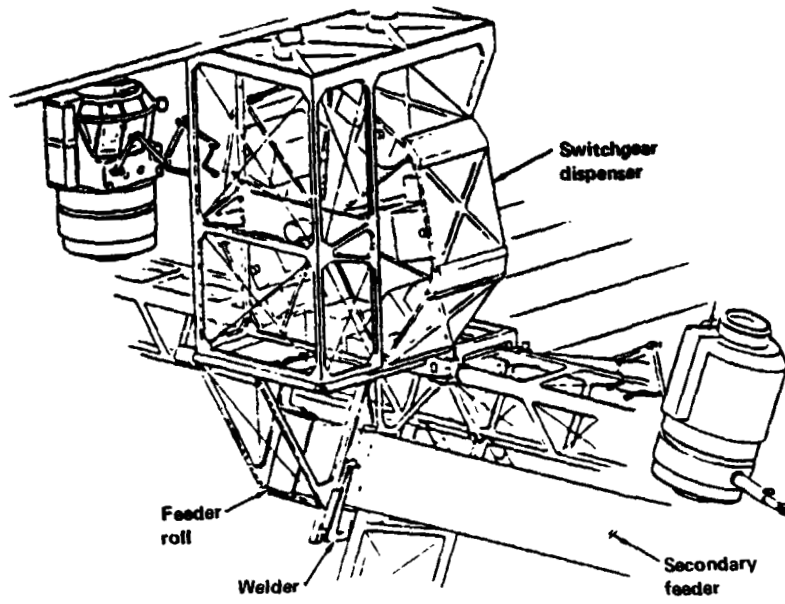
Figure III-77.- Secondary feeder installation.

IV. RECTENNA CONSTRUCTION

The rectenna is the ground-based unit of the SPS which receives micro-wave energy and converts it to grid-compatible electrical power (fig. IV-1). Recent analysis favors a concept using individual antenna elements with dedicated rectifiers and filters for rf to dc conversion. These elements are mounted on flat panels arranged to be perpendicular to the incoming rf beam. A steel mesh is used behind these elements as an electrical ground plane. Elements are connected in parallel and series groups, as required, to produce voltage levels compatible with dc to alternating current (ac) conversion. The rectenna ground area varies with location and is ellipti-cal because of its position relative to the equatorial orbit plane of the SPS antenna.

Rectenna site locations and alternative structural designs were inves-tigated. The rectenna structure selected as a reference is constructed of steel with aluminum electrical conductors. Aluminum, wood, and concrete have also been examined for structural use. Several studies have been con-ducted on availability of suitable sites.

A. SITE LOCATION STUDIES

1. UTILITY INTERFACE, SITE AVAILABILITY

A siting analysis was conducted to develop information on siting criteria and to make a preliminary assessment of siting problems. Three areas were surveyed: (a) Pacific Northwest, (b) north-central region, and (c) southern California. Information was informally exchanged with power companies in these areas. The analysis was conducted manually using aeronautical charts, contour plots, and roadmaps. From this study, it was concluded that the number of potential sites available exceeds the estimated requirements.

2. OFFSHORE RECTENNAS

A preliminary feasibility and cost study was performed on the concept of an offshore rectenna to serve the upper east coast. A candidate site was selected and several types of support structures were analyzed. Results indicate that a rectenna could be built offshore but that the practicality of this system is undemonstrated.

3. SITE REQUIREMENTS

A number of studies have focused on site layout for typical locations. Maintenance facilities, access roads, converter stations, dis-tribution towers, control buildings, and other similar factors were exam-ined in the construction analysis.

93

4. SITE LOCATION STUDY: BOEING

a. Approach

A siting analysis was conducted to develop information on siting criteria and make a preliminary assessment of siting problems. Related to this task, an informal information exchange agreement was made with three utility regions.

(1) Bonneville Power Administration (BPA) (Pacific Northwest)

(2) Mid-Continent Area Power Pool (MAPP) (north-central United States)

(3) Southern California Edison

Additional ground rules employed in the siting investigation are as follows. Most of these can be regarded as candidate site selection criteria.

(1) Two "beam plus buffer" region width (east-west dimension)

(a) 13.18 kilometers (corresponds to 5000 megawatts output)

(b) 9.32 kilometers (corresponds to 2500 megawatts output)

(2) SPS on the longitude of the site

(3) North-south dimension a function of latitude; e.g.

(a) 48° latitude, 23.05 kilometers

(b) 35° latitude, 17.37 kilometers

(4) No encroachment upon

(a) Game preserves

(b) Bird refuges

(c) National Monuments

(d) National and State parks

(e) Indian Reservations

(5) Maximum and minimum elevations in site to be within 305 meters (1000 feet) of each other

      (6)   Minimum displacement of persons and property

      (7)   National Forest and existing farmland use acceptable

      In the siting analysis, a manual map search using aeronautical charts, contour plots, and roadmaps was employed. Population counts were derived from the "Atlas of the United States." The approach was composed of five steps.

      (1)   Identification of promising areas

      (2)   Check for agreement with ground rules

      (3)   Check for fit of 5000-megawatt rectenna

      (4)   If fit acceptable, 5000 megawatts assigned

      (5)   If 5000 megawatts did not fit, 2500 megawatts was tried

      The relative sizes of 5000-megawatt and 2500-megawatt sites are illustrated in figure IV-2.

    b.   Results

      Preliminary studies of rectenna siting have indicated that the number of potential sites is considerably greater than presently estimated requirements. Specific sites were identified in the three areas indicated with total numbers of sites as summarized in table IV-1.

      It was found beneficial to have available in the inventory two sizes of receiving antenna. The two sizes used correspond to the power transmission link capacities (2500 and 5000 megawatts). If both 2500- and 5000-megawatt receiving sites could be employed, the total amount of power that could be sited was much greater than that for either size of receiving antenna alone.

      Specifically, if only 2500-megawatt rectennas were sited, 385 gigawatts of capacity could be installed. If only 5000-megawatt rectennas were sited, 420 gigawatts of capacity could be installed (9 percent more than with 2500 megawatts alone). However, if both 2500- and 5000-megawatt rectennas are available, 595 gigawatts could be sited (42 percent more than with 5000 megawatts alone). This preliminary analysis indicates that potential sites exist for at least four times the 2000 A.D. requirements. Siting in the energy-intensive Northeast was not investigated, but demands for that area might be met by modest interties from rectennas in the north-central United States. Alternatively, offshore rectennas may be possible and are discussed later.

      A number of sites in each utility region were selected at random for closer investigation of slope and other features that might presumably cause rejection. In general, most of the sites were quite flat.

That is, the average slopes were less than 5 parts in 100; however, most sites had small regions of local slope that might be considered to be excessive (slopes of 30° or more).

As shown in figure IV-3, the microwave beam from space ultimately falls on some ground area. It is possible in this concept to locate rectenna panels so as to receive all of the beam area even in regions of very extreme slope, but diffraction effects may cause some loss of performance for panels positioned far downbeam from adjacent panels as a result of steep slopes. Consequently, it appears that rejection of sites on the basis of slope must be decided individually, with economics as the criterion.

In investigation of specific individual sites, it might be decided to merely reject any site with localized slope. Alternatively, large-scale landscaping would be used. Also, it might be desirable, in some cases, to allow holes in the rectenna. That is, in the area of either excessive slope or some other terrain features, it might be desirable merely to not construct panels and to allow the microwave beam to fall (wasted) directly on the natural or somewhat modified terrain. The consequences of reflection of the microwave power from such unused area need closer examination.

c. Conclusions

This siting effort indicated that, in the three utility areas investigated, "potential" sites exist to more than fill the requirements for electrical power for those regions in the year 2000. Because of the potential of excess sites, it might be possible to feed energy to the Northeast from rectenna sites in the north-central area, using modest interties. The benefits of having two rectenna and SPS sizes (in this case, 5000 and 2500 megawatts) were obvious. Far more "energy from space" can be sited by having two sizes rather than with either size alone. Further, the siting of SPS rectennas will obviously require individual site investigation. Each site selected will be a compromise. That is, no site can be expected to be perfectly flat, with the most desired terrain, type of soil, drainage, etc. No site will be immediately adjacent to the required energy use point. Thus, each siting will be an engineering and economic compromise.

B. CONSTRUCTION CONCEPTS

Current reference system concepts for rectenna structure and construction techniques are based on standard methods of implementation. Because of the large projected costs for these methods, automatic rectenna panel fabrication methods are desirable. Several studies have examined potential construction scenarios, various types of specialized heavy equipment, and manpower for rectenna fabrication. Specialized machines for rectenna fabrication are expected to provide significant cost-reduction benefits.

1. RECTENNA CONSTRUCTION STUDY: ROCKWELL

a. Site Requirements

A rectenna site requires approximately 140 square kilometers (35 000 acres). Figure IV-1 shows a layout of a typical site. The inner ellipse containing the rectenna panels, 10 by 13 kilometers, is about 100 square kilometers (25 200 acres) or 72 percent of the total area. The area surrounding the inner ellipse is used for maintenance facilities, access roads, converter stations, and the two peripheral rows of towers which support the 40-kilovolt dc and 500-kilovolt ac cables. The outer perimeter of the area is fenced for security reasons. The towers which support the 500-kilovolt ac cables are constructed of steel girders footed in concrete and are approximately 70 meters (230 feet) high. Each inner tower is composed of four tapered steel columns 18.3 meters (60 feet) tall. Fifty-four of the larger towers and 401 of the smaller towers are required; the latter figure translates into 1604 tubular members because of the configuration.

b. Panel Installation

The panels are 9.33 by 14.69 meters and are attached to continuous concrete footings at eight points as shown in figure IV-4. A trade-off which considered eight individual footings versus continuous footings was made. A maximum wind force of 40 m/sec (90 mph) was assumed. It was determined that the amount of concrete required for either approach was essentially the same but that the continuous footing concept was easier to install.

Threaded inserts are placed in the concrete during the pouring process and provide the means for mounting the panel attach fittings, which are capable of longitudinal and lateral adjustment. Screwjacks are installed at each of the four rear attach points to allow for panel adjustment and alinement.

Details of panel construction are shown in figure IV-5. Four standard size 20.3-centimeter (8 inch) I-beams, to which the attach fittings are secured, are spaced in the lateral (14.69 meters) direction. Galvanized steel hat sections (thin sheet, 0.051 centimeter (0.020 inch) thickness) of the dimensions as shown are mounted in the longitudinal direction (14.69 meters) and provide the mounting for the substrate containing the electronic components. The substrate (with components) is delivered to the onsite assembly plant in strips of 9.33 by 0.74 meters. The panels are supported in the inclined position by tubular steel members which provide an angle from the horizontal of 40° for this example (latitude, 34° N). Each panel weighs 2080 kilograms, of which approximately 85 percent is steel.

c. Construction Sequence

The sequence of the nine primary operations attendant to construction of a rectenna site is shown in figure IV-6. It is assumed

that land acquisition has been completed and that the environmental impact report and other necessary permits have been approved.

Initially, site survey and engineering activities must take place. When these are completed, the first step is to install utilities (water, power, etc.), access roads, and railroad spurs. Facilities must then be provided for equipment maintenance and servicing, logistics (material receiving and distribution), concrete production, panel assembly, crew support, and an operations center which coordinates all site construction activity.

Upon completion of support facilities installation, reference coordinates for the clearing and grading of the 10- by 13-kilometer ellipse must be established. This operation is followed by site clearing and panel pad grading.

The panel installation operations, the next series of events in the overall sequence, entail establishment of string lines (although use of lasers with multiple reflectors is a viable alternative), footing excavation, concrete pouring, panel fabrication and installation, and electrical hookup of the panels. Two periphery cable runs around the perimeter of the panel ellipse must be installed. The 40-kilovolt dc row will be located approximately 50 meters outside the ellipse; the 500-kilovolt ac lines, about 500 meters outside. These two rows of cabling will be separated by converter stations. Although iustallation of this equipment is shown as the last steps in the complete operation, installation of the towers and stations could be started earlier on a noninterference basis with panel installation. The operational activities required for construction of the rectenna are summarized as follows.

    (1) Site survey and engineering

    (2) Support facilities installation

        (a) Utilities, road, and rail spur

        (b) Equipment maintenance and servicing

        (c) Materials distribution center

        (d) Concrete plant

        (e) Panel assembly factory

        (f) Construction control center

        (g) Crew support

    (3) Reference coordinates clearing and grading

    (4) Site clearing

(5) Panel pad grading

(6) Panel installation operations

    (a) Setting of string lines

    (b) Excavation for footings

    (c) Pouring of footings and setting and alining of attach fittings

    (d) Fabrication and transport of panels

    (e) Installing and alining of panels

    (f) Distributing and installing of switches and feeders

    (g) Electrical connection and closeout of panels, switches, and feeders

(7) 40-kilovolt dc bus installation

    (a) Distributing and installing of poles, switches, and buses

    (b) Electrical connection and closeout of poles, switches, and buses

(8) Converter station installation

(9) 500-kilovolt ac bus installation

d. Construction Schedule

The time allocated for construction of a rectenna site, exclusive of land acquisition and permits, is between 14 and 15 months. Figure IV-7 is a schedule for the major activities discussed in the preceding section. The equipment and crew requirements for each task which are developed in subsequent sections are predicated on this schedule. It is noted that approximately 270 days each are allocated for the major activities. The schedule is based on a site location featuring relatively benign characteristics relative to timber and slope. Selection of a site featuring more extreme slopes or extensive timber would affect either the time line or the manpower and equipment requirements.

e. Construction Operations

(1) Industry Contacts

A number of industry contacts were made to acquire more insight into procedures involved in clearing large land areas and

99

in large-scale equipment installation. These contacts, summarized in table IV-2, included organizations that produce heavy, earthmoving equipment, that pour concrete for freeways, that supervise construction of installations such as the Sandia Thermal Test Facility (STTF), or that are involved in other activities having a bearing on the SPS Program. The data derived from these contacts are reflected in the types of equipment, equipment capabilities, and supporting manpower described in subsequent sections.

(2) Support Facilities

Approximately 3 months have been allocated for installation of the facilities required to support construction of the rectenna panel farm. Initially, provisions must be made for availability of utilities, primarily water and electrical power. Existing roads and railroads must be supplemented by access roads and railroad spurs to provide immediate access to selected portions of the overall site.

Because of the large concrete requirements, it has been determined that the most practical method for satisfying these requirements is to establish a concrete mixing facility on the site. This facility would require some 100 000 square meters (25 acres), which would provide space for the concrete factory, a concrete truck loading area with multiple loading hoppers, and a storage area for the concrete ingredients. This latter area would be equipped with largely automated conveyor systems, which would transport the material to the mixing facility. This procedure and supporting equipment is inherent in modern large concrete producing facilities.

Since the rectenna panels are excessively large for delivery in the assembled configuration, a panel assembly facility also must be provided. Details of a facility concept are contained in a subsequent section.

In addition to these specific facilities, provisions must be made for maintaining the extensive rolling stock inventory and for receiving and storing the large amounts of material that will be required. Figure IV-8 is a typical site layout with facilities that must be installed to support the construction of the rectenna panel farm and peripheral electrical feeder installation.

(3) Clearing and Leveling Operations

Figure IV-9 is a representation of activities incident to site preparation; included are bulldozing, grading, and dirt removal. The equipment pictured is based on current inventories of large, earthmoving equipment available on today's market.

The clearing and leveling operations will occur at a number of locations within the panel farm perimeter. These operations consist of tree removal (if required), grading and leveling the terrain

to acceptable slope angles, and removing excess dirt. Sixteen areas of the ellipse would be cleared and leveled simultaneously.

Table IV-3 is a summary of the equipment and crew size required to complete the clearing and leveling operations in 9 months. Based on information obtained from industry sources, a 13-man crew equipped as indicated in the table can clear 32 375 m^2/day (8 acres/day). This factor was used to project the total requirements. It is noted that this operation has been restricted to one daily shift, or essentially daylight hours.

(4) Footing Excavations

Conventional trenchers are used to excavate the 0.31- by 0.43-meter trenches, which will be filled with concrete to form the panel footings. A typical operation with two sets of trenchers in operation is shown in figure IV-10. Each set of trenchers excavates the front and rear trench simultaneously and feeds the removed dirt into trucks that are stationed between the trenchers and that move at the same pace. When the truck is filled, it proceeds to the dumping area and another truck moves into position.

Approximately 17×10^6 meters of trench must be excavated in 278 days. An excavation rate of 90 meters per hour per trencher has been established as a figure representative of the capabilities of current equipment. At this excavation rate, 38 trenchers and the dump trucks will be required. A round trip time of 1 hour was assumed for the dump trucks. These requirements are predicated on a 20-hour day, 7 days a week.

Personnel requirements for this operation include trencher and truck operations, maintenance crews, and supervision, totaling 324 men for 4 shifts (3 shifts per day, 7 days per week, 2 days off per shift week). Table IV-4 is a summary of both equipment and crew requirements.

(5) Concrete Installation

Concrete formers such as are used in freeway or road curb installation are used to pour the concrete in the trenches. In figure IV-11, a concrete former is shown in operation. The formers, fed by concrete trucks, extrude a shaped ribbon at rates as high as 6 m/min, including the 0.15-meter extension above ground level. No forms are required. The concrete is poured into a hopper as shown, where it is transported upward by an auger to a second hopper which feeds the mules. Within the mules, the concrete is hydraulically vibrated to remove air pockets and to consolidate the concrete into a homogeneous solid mass before extrusion. Reinforcing steel bars are fed into the mule and inserted into the concrete during the extrusion process. Additionally, the attach points (e.g., threaded inserts) for the panel attach fittings are inserted into the concrete before extrusion. Guideline sensors are provided as shown so that the rig can accurately follow a line or wire, although laser control is a viable alternative.

101

Ten of these machines, including one spare, are required to install concrete in the 17×10^6 meters of trenches. Two days have been allocated for concrete curing after installation. Table IV-5 is a summary of equipment and manpower requirements for completing the concrete installation in 270 days on a 3-shift, 20-hr/day, 7-day/week basis.

After the concrete has cured, 8 attach fittings per panel, or a total of 4.6×10^6 fittings, must be secured to the attach inserts embedded in the concrete. The equipment and crew required to deliver and install these attach fittings are shown in the lower portion of table IV-5.

(6) Panel Fabrication and Installation

Because of the panel dimensions, shipping completed panels from an offsite manufacturing facility to the rectenna site is not practical. The alternatives are to ship the prefabricated materials to the rectenna site and assemble the panels either at a centralized factory or on a mobile fabricator. The former concept has the advantages of centralized material receiving and a protected environment but requires delivery of completed panels to the point of installation. The mobile concept requires delivery of materials to many locations, which complicates logistics, and provides no environmental protection during the assembly process. However, double handling of the finished panels is not required. The centralized facility was selected for this study. A concept for such a facility is shown in figure IV-12. The factory has multiple assembly lines; each line consists of a materials feed station, a panel assembly, electrical hookup of the 14.69- by 0.74-meter substrates containing the electronics, and, finally, checkout. It was assumed that one line using automated procedures could assemble and check out a panel in 40 minutes. On this basis, 72 assembly lines operating 20 hr/day, 7 days/week are required to produce 580 500 panels in the allocated 270 days. Eight additional assembly lines have been specified as spares.

After the panels have been checked, they are placed on an overhead conveying system and transported to loading stalls, where they are assembled into nine-panel magazines and loaded on specially designed trucks for delivery to the point of installation. Production rates and crew requirements are summarized in figure IV-12.

Specialized equipment is required to deliver the panels from the factory to the installation point and to install them because of their large dimensions. Use of cranes for lifting the panels from a delivery vehicle and lowering them to the attach position was considered but discarded because of potential difficulties involving windloads on a suspended object with a large surface area. After consultation with industry sources, a concept for a specialized machine was developed (fig. IV-13). The machine can carry as many as nine panels. The front and rear wheel pairs are each steerable as a unit and have provisions for height adjustment. Although dual wheels are shown at each corner, the bearing load could result in substitution of caterpillar track units. Power packages for

vehicle movement and hydraulic power are located on either side of the central stations located at both ends of the vehicle. The panels (not shown) can be translated laterally and longitudinally for final positioning before attachment to the footings.

In figure IV-14, a concept is shown for a panel magazine delivery truck which loads magazines of as many as nine panels each at the panel factory and transports them to the panel installation site. There, they are transferred to the panel installation machine. The delivery truck can be driven directly beneath the installation machine in order to transfer the panels. The panels are secured in the magazines by means of fixtures mounted in a vertical assembly which attach to the panel I-beams as shown in figure IV-15. When the truck is positioned beneath the installer machine, the vertical fixture assembly holding the panels is secured to the hoist as shown in the middle illustration of the figure and elevated sufficiently to permit departure by the truck. At the right of the figure are shown movable L-shaped arms which attach to the bottom panel retention fixture and lower it to the proper position and angle for attachment to the footings. The retention fixtures of the vertical fixture assembly are uncoupled when the panel has been secured to the movable L-shaped arms.

The sequence of events just described is shown in figure IV-16. Commencing at the upper left, the delivery truck approaches the installer machine and then is positioned for magazine transfer. The installer machine is then elevated (lower left), the magazine is transferred and hoisted clear, and the truck departs. In the lower right of the figure, the bottom panel has been lowered into position for attachment. Panel installation operations are shown in figure IV-17. The installer machine is straddling the two rows of footings. A panel has just been installed and the machine advanced into position for installing the next panel.

The equipment and personnel requirements to assemble and install the panels in a 9-month period are summarized in table IV-6. The panel assembly requirements were discussed previously. An installation rate of 20 minutes per panel has been established. On this basis, 36 panel installation machines with 4 spares are required. Twelve panel delivery trucks (plus 2 spares) with a round trip time of 1 hour maintain the panel flow to the installers, using a total of 66 magazines. Approximately 900 men (4 shifts) are required to operate the vehicles, attach the panels, and conduct checkout operations. This, when added to the assembly factory crew of 1872, results in a total of 2772 men required to assemble, install, and check the panels.

f. Key Issues

Five key issues which can affect rectenna constructability have been identified.

(1) Site Selection

The characteristics of a proposed rectenna site can have significant impact on schedule, manpower, and equipment require-

103

ments. Important factors in site selection include overall topography, drainage, type of soil, prevailing weather, and location relative to industry and transportation.

(2) Environmental Impact

Considerable advance planning will be required to assure that the environmental impact report and other necessary permits are prepared and submitted well ahead of planned construction go-ahead. In some instances, as many as 5 years have been required for approval of these documents.

(3) Site Operational Control

A site operational control plan is vital to effective construction operations of this magnitude. The plan must provide for communications, disposition of incoming material, traffic control of the many vehicles involved, and a detailed operational sequence of events.

(4) Lightning Protection

Studies conducted at Rice University under contract to the NASA George C. Marshall Space Flight Center indicate a high probability of multiple lightning strikes in an area the size of the panel farm. Lightning could result in both localized physical damage to panels and propagating damage to circuitry. The effects on rectenna reception of erecting a protecting rod on each panel have not been determined. The amount of copper required for grounding would be significant for this type of approach. This overall area requires additional study relevant to effects and feasible preventive measures.

(5) Resource Availability

Material, manpower, and equipment requirements for construction of one rectenna site are considerable. Additional facilities, particularly for steel, may be required. The equipment requirements reflect, for the most part, vehicles which are produced currently; however, ample leadtime for acquiring them in these numbers would be necessary. Sixty sites would be constructed in a 30-year period. Although the equipment could be transferred to the next site and reused, the current postulated schedule would require that several sites be under construction at any one time.

Availability of manpower reflecting the required skills and in the required quantity constitutes a potential problem area, particularly in some areas, where the local labor market is inadequate.

104

2. RECTENNA CONSTRUCTION ANALYSIS: GENERAL ELECTRIC

General Electric conducted an analysis of rectenna structure and construction processes. This section is a synopsis of their results.

a. Task Description

For purposes of analysis, the overall project is divided into tasks, which are completed in serial fashion; i.e., task 1 must be complete before task 2 can be started, etc. Within each task, all jobs are conducted in parallel, paced by the "slowest machine" in the task. This is a simple artifice to assure that no attempt is made to place superstructure into footings not yet dug or to make panel assemblies without enough parts yet made. Task allocations are given in table IV-7.

A preliminary concept for a 10- by 12-kilometer rectenna site is shown in figure IV-18. The east-west road is about 7 kilometers long, from staging area to the west lateral. The east and west lateral (north-south) roads are taken to be 6 kilometers long, and the center lateral is 9 kilometers long. Based on these distances, the following average travel distances for all construction "move" tasks have been used: an onroad distance of 10 kilometers and an offroad move distance of 1 kilometer. This estimate is almost certainly high, and the total hauling cost for the construction task is only $24 million.

Figure IV-19 is a simple illustration of a rectenna "module," which will be repeated 1 238 350 times. It contains the equivalent of six of the 3.3- by 3-meter panels.

The concept used is based on minimum site preparation. The trees on the site will have to be cut down, and the logs will be moved back to the staging area, where they are sold. Stumps will be left in place, unless they happen to occupy the location chosen for a footing hole. In that case, assumed to happen once every 50 modules, the stump is removed with a bulldozer. The bulldozer also backfills the cavity and compacts it to enable drilling of a footing hole.

Except for grading and graveling roads, and removing trees and underbrush, nothing is done to the site. A rectenna can be built wherever a bulldozer can be driven.

The main active rf configurations considered are shown in figure IV-20. At the midterm briefing, the "printed honeycomb" and the "low drag" configuration concepts were discussed. However, when the time came to start doing actual construction and manufacturing cost analysis, it was concluded that the design basis was insufficient to support a costing exercise. The low-drag version of the baseline was considered briefly, until it was noticed that the rf shield effectively blocks the lower dipole from receiving microwave radiation. This problem caused a return to the original baseline configuration. It should be noted that all three concepts impose substantial lifting forces on their supporting structures.

The baseline structure is shown in figure IV-21. On the assumption that tons of materials will be needed to avoid upward loads on the footings, the cheapest choice is concrete, reinforced or prestressed as necessary to support the applied loads. Using an automated factory (fig. IV-22), these piers can be made for about $26 assumed for reinforcing bar. No stress analysis has yet been done to support these estimates.

b. Dipole Machine

The operation of a multistation transfer machine simultaneously making the baseline dipole/diode assembly is shown in figure IV-23. The machine illustrated is part of a complex of three machines making foreplane assemblies. Each set of machines is assumed to cost $1.0 million and to be capable of manufacturing 150 10-meter foreplane strips every hour. The total cost for the 120 sets of machines, not including material, is $161.6 million. The cost of material, which will be examined more closely later, is the driving factor in total rectenna cost.

The flow needed to assemble a 3- by 10-meter rectenna panel from all the component parts is illustrated in figure IV-24. The process is assumed to be highly automated, with only two machine tenders for each panel assembly machine. The cost of this assembly machine is $3.3 million.

Figure IV-22 is an artist's concept of an automated plant to produce the concrete support structure for the rectenna panels. The sketch shows only two conveyor belts carrying forms past the pouring chutes, but in the overall concept, each machine would have five such belts, each casting an arch every minute, for a total of 250 arches produced every hour. Each machine costs about $2 million and has four operators. Ten such machines are used to produce the 3 750 000 arches needed in 9 months. The equipment amortization for this equipment is $3.3 million, and the total cost to make all of the arches for one rectenna is $177 million, of which $139 million is materials, including $100 million for reinforcing bar.

This is a good place to mention that two kinds of arches are used: "regular" and "special." The regular arch is shown in figure IV-21. It supports the rectenna panels with the lower edge 2 meters above the ground. This is not high enough to permit trucks to pass under the rectenna on the north-south roads; therefore, special arches are used over north-south roads to increase the clearance to 4 meters.

Several specialized construction machine concepts were developed. These machines incorporate a design philosophy generally similar to that used for roadbuilding equipment but are tailored for the rectenna construction task. An example is the concept shown in figure IV-25 for a machine to drill footings. This concept implies work on soils that are reasonably cohesive and do not have much rock near the surface. Small rocks are broken by the jackhammer action of the tip (when needed) so that boring is not interrupted often. Another machine is used to handle large rocks, assumed to occur once for every hundred modules constructed. The

machine shown here is assumed to cost $250 000 and is capable of drilling 10 pairs of holes in an hour. The capital cost charged to one rectenna for this machine is $10.4 million. The total cost to drill all of the footings with this machine is $23.7 million.

Figure IV-26 shows the rectenna panels being delivered to the field and installed.

c. Five-Gigawatt Rectenna Construction Concept

Figure IV-27 is an artist's concept of the entire rectenna construction approach, using automated equipment for field erection of the many rectenna modules. Each "module" has three prestressed concrete "piers" or "arches" supporting two rectenna panels 3 meters wide and 10 meters long. This panel size was selected as being the largest panel that could be conveniently moved over offsite roads. Initial panels built at an onsite staging and manufacturing area, as in this concept, could be made larger. However, panels needed to replace any damaged by accident would have to be moved by highway to the damaged rectenna.

The 6-meter width of these panels was derived by using a double-width version of the design described in the final briefing. This width is adequate to provide a roadway between rectenna rows about 4 meters (13.12 feet) wide and a clearance of 5 meters (16.4 feet).

A "grassroots" (detailed estimating) computer cost model was developed for the cost analysis. At the onset, the distinction between major and minor cost elements was not apparent. Therefore, it seemed that the best approach would be to divide the whole job into a number of pieces small enough to be amenable to analysis, and for which an opinion could be developed about the cost of doing that job, and then to estimate all of the kinds of costs involved in doing each small job thousands or millions of times.

The input data are stored in several data files. More than 1675 pieces of input data are needed to run the program, and they must be in order, formatted exactly, and so on. However, using a text editor, any piece of data can be quickly changed.

The model flow is shown in figure IV-28. The cost matrix has 12 375 cost bins to hold intermediate results. Most of the bins are empty, since only a few jobs are active at any time, and not every task generates every category of cost. This matrix is printed, so that detail data are available to permit trade-offs to be done at any level of cost accumulation.

Cost results are summarized in table IV-8 and figure IV-29. The total SPS ground system cost is about $2 billion. This cost excludes land and development of the rectenna and associated special-purpose equipment. About one-third of the ground system cost is in the ground power distribution and transmission. The other two-thirds of the cost are in the rectenna itself; this includes the cost from the dipole elements up to the

wiring of the converter stations. The bulk of the rectenna cost, $1014 million, is in three materials: (1) diodes, $298 million; (2) steel, $449 million; and (3) aluminum, $267 million. Labor and capital costs are very low by comparison.

3. OFFSHORE RECTENNA FEASIBILITY: RICE UNIVERSITY

Rice University, with subcontracts to Brown and Root Development Inc. and Arthur D. Little Inc., has performed a preliminary study of the feasibility and cost of an offshore rectenna to serve the upper metropolitan east coast. The study was begun by first locating a candidate site at which to build a 5-gigawatt rectenna. The site was selected on the basis of proximity to load centers, avoidance of shipping lanes, sea floor terrain and conditions, etc. Several types of support structures were selected for study based initially on the reference system rectenna concept of a wire mesh ground screen and dipoles, each with its own rectifier and filter circuits. Possible secondary uses of an offshore rectenna also were studied. The principal results of this study are as follows.

a. Suitable candidate sites exist off the northeast coast and probably all along the east coast and Gulf of Mexico.

b. Hurricane and winter storm conditions were examined for this area and a set of environmental criteria was established.

c. The winter storm criteria plus tests done at Rice University under icing conditions lead to the conclusion that a protective radome will be required over the active elements of the rectenna including a portion of the ground plane. This conclusion probably also holds for land rectennas located everywhere except perhaps in the desert southwest.

d. For the reference system rectenna (using a wire mesh ground plane and individual dipoles), a double-pendulum, two-level rectenna panel which can swing freely is suitable (fig. IV-30).

e. Approximately 25 000 support towers would be required for a 5-gigawatt antenna using the reference system rectenna.

f. Four different types of support tower structures were studied and costed. The least expensive of these was the piled guyed tower (fig. IV-31).

g. For the 49.4-meter (162 foot) water depth site examined. the total cost of a 5-gigawatt rectenna using the piled guyed tower and reference rectenna panel is estimated at $36 billion. This concept was considered excessively expensive for serious consideration.

h. The water depth, wind loading, and soil condition cost
   sensitivities were examined. None of these factors could
   be altered sufficiently to significantly reduce the cost.

i. Based on the foregoing, the only substantial way to reduce
   the cost of the offshore rectenna is to reduce the number
   of support towers or to use a fully surface floating sys-
   tem. Reducing the number of support towers requires a
   change in the type and mass of the rectenna panels.

j. The number of support towers can be reduced from 25 000
   to 3000 by eliminating the ground screen and adopting an
   image dipole reflector antenna (fig. IV-32) wherein each
   dipole plus reflector element is supported individually
   by cables which also carry the power from the dipoles
   (figs. IV-33 and IV-34). This is called the clothesline
   concept. Each dipole plus reflector is individually
   encapsulated to protect it from the weather.

k. The cost of the clothesline concept for the 49.4-meter
   water depth site is estimated at $5.7 billion.

l. The cost-reduction potential possible with new rectenna
   concepts was demonstrated. The clothesline concept is
   only one of several possible concepts. Time and fiscal
   constraints have prevented examination of other concepts
   such as a surface floating rectenna. However, Peter
   Collins in Great Britain has very roughly estimated the
   cost of a North Sea floating rectenna at about $6 billion.

m. Secondary uses, in particular mariculture, appear to be
   promising adjuncts to the offshore rectenna. The possi-
   bility of wave energy extraction has also been examined
   briefly. Such secondary uses do not appear to constrain
   the basic rectenna design significantly.

n. A major problem identified with the reference rectenna
   offshore version is the sea birds which will be attracted
   to the vicinity of the rectenna and will land and roost on
   it. This problem requires further study, but it appears
   that the more open structure of the clothesline concept
   will reduce the bird problem somewhat.

The following issues remain.

a. The optimum design from the standpoint of cost and reli-
   ability has not been determined. Specifically, a surface
   floating system has not yet been studied. Because of the
   different cost per unit area for a sea antenna, the optimum
   size may not be 10 kilometers.

109

b. A great deal of research needs to be done on the efficiency of various types of receiving elements. For example, whether the dipole without a ground plane has an adequate conversion efficiency is not known. Results of a Rensselaer Polytechnic Institute study of higher gain antennas suggested that they might have substantial advantages for land rectennas. These need to be examined for offshore rectennas as well.

c. The reradiation of harmonics and noise is a major problem area requiring investigation.

d. Much remains to be done in the area of survivability and environmental protection of the rectenna, particularly against birds and corrosion.

e. Little is known about secondary use potential.

f. A careful study should be performed on the feasibility of combining the rectenna with a hydrogen generation plant. The electricity from the rectenna could be used to generate hydrogen by way of electrolysis. The wave energy extraction adjunct needs further study. Also, mineral extraction from seawater should be examined.

In summary, the feasibility of an offshore rectenna near east coast load centers has been demonstrated. The practicality of such a system has not been demonstrated, nor has the design been optimized for cost, efficiency, or minimal harmonic reradiation. The secondary and fuel generation uses remain to be fully explored. Even at this early stage, it is apparent that the offshore rectenna feasibility is sufficiently great that, with the significant advantages of no land requirements and removal of the radiation from populated areas which may offset any additional costs, further investigation should be pursued.

TABLE IV-1.- POTENTIAL RECTENNA SITES IDENTIFIED

Utility region	Number of sites for rectenna size of -	
	5000 MW (a)	2500 MW
Bonneville Power Administration	25	27
Mid-Continent Area Power Pool	51	34
Southern California Edison	8	9
	—	—
Total	84	70

[a]Also suitable for 2500-megawatt rectenna.

TABLE IV-2.- INDUSTRY CONTACTS

Organization consulted	Purpose
Society of Manufacturing Engineers	To obtain technical data on roboticals and technology status
Riverside Cement Co.	To determine rectenna cement and concrete requirements and processes
Modern Alloys, Inc.	To discover methods and equipment for continuous placement of rectenna panel concrete footings
Sandia Solar Thermal	To compare STTF construction and handling approach with SPS rectenna requirements
Townsend and Bottum, construction managers, 10-MW solar plant in Barstow, Calif.	To obtain information on site preparation and construction operations
American Bridge Div., United States Steel	To determine steel requirements and construction approach for installation of rectenna panels
Alpha-Beta Distribution Center	To analyze materials handling systems
Caterpillar Tractor Co.	To study earthmoving and grading equipment
International Harvester	To study earthmoving and grading equipment
Southern California Edison	To obtain information on dc and ac power distribution lines and towers

TABLE IV-3.- REQUIREMENTS FOR CLEARING AND
LEVELING OPERATIONS

Shifts   1
Maximum average grade 1:30
Land type . . . .   Nonforested
Schedule, months   9
Area, km^2 (acres) 141.6 (35 000)
Rate, m^2/day (acres/day) 526 091 (130)
Crew requirements
  Composition
    Road grader operators   4
    Bulldozer operators   3
    Dump truck operators   3
    Crane operators   2
    Backhoe operators   1
        Total . . . .   [a]13
  Number of crews   16
  Total operators   208
  Support personnel . . . .   [b]72
  Total onsite crew . . . .   [c]280
Major equipment requirements[d]
  Road graders   67
  Bulldozers   50
  Dump trucks   50
  Cranes   34
  Backhoes   17

[a]Based on 32 375 m^2/day (8 acres/day).

[b]15 percent maintenance, 10 percent servicing, and
10 percent supervision, based on number of operators.

[c]Based on three crews per row, greater than five
rows per day.

[d]For 16 crews plus 5 percent standby.

TABLE IV-4.- REQUIREMENTS FOR FOOTING EXCAVATION

```
Shifts . . . . . . . . . . . . . . . . . . .                    3
Operation time, hr/day . . . . . . . . . .                     20
Schedule, months  . . . . . . . . . . . . .                     9
Total trench length, m  . . . . . . . . . .             $^a17 \times 10^6$
Trenching rate, m/hr  . . . . . . . . . . .                  3140
Trench section, m³/m length . . . . . . . .                 $^b0.1$
Excavation volume rate, m³/day  . . . . . .                   302
Equipment requirements$^c$
  Unit
    Composition
      Trenchers . . . . . . . . . . . . . . .               $^d2$
        Dump trucks . . . . . . . . . . . . .                  1
      Number  . . . . . . . . . . . . . . . .                 18
    Total
      Trenchers$^e$  . . . . . . . . . . . . .                38
      Dump trucks$^f$  . . . . . . . . . . . .                26
Crew requirements
  Trencher operators  . . . . . . . . . . . .                38
  Dump truck operators  . . . . . . . . . . .                26
    Total . . . . . . . . . . . . . . . . . .                64
  Supervision$^g$  . . . . . . . . . . . . . .                 7
  Servicing/maintenance$^h$  . . . . . . . . .                10
    Total per shift . . . . . . . . . . . . .                81
    Total for 4 shifts  . . . . . . . . . . .               324
```

---

^{a}8.5 × 10⁶ meters of double footings.

^{b}0.31 by 0.31 meter.

^{c}Includes 5 percent standby.

^{d}One front footing; one rear footing.

^{e}Approximately 90 linear meters per hour and
8.5 m³/hr each machine.

^{f}52-cubic-meter capacity; 1 hour round trip dump time.

^{g}10 percent of number of operators.

^{h}15 percent of number of operators.

TABLE IV-5.- REQUIREMENTS FOR FOOTING INSTALLATION (CONCRETE AND ATTACH FITTINGS)

Item	Value
Concrete pouring	

Item	Value
Requirement	
Total footing, m	17×10^6
Volume, m^3 (yd^3)	
Total	3.06×10^6 (4×10^6)
Per panel	5.2 (6.8)
Per day	11 178 (14 620)
Reinforcing steel, kg	
Total	139×10^6
Per day	0.5×10^6
Equipment	
Concrete delivery trucks	
Quantity	190
Capacity, m^3 (yd^3)	7.6 (10)
Concrete forming machines	
Quantity	10
Forming rate, m/min	6
Crew	
Per shift	289
Per 4 shifts[a]	1156

Item	Value
Panel attach fitting installation and alinement	

Item	Value
Requirement	
Total quantity	4.6×10^6
Per day	17 200
Equipment – Tractor-trailers	40
Crew	
Per shift[a]	80
Per 4 shifts[a]	320

[a]Including support personnel.

115

TABLE IV-6.- PANEL ASSEMBLY AND INSTALLATION REQUIREMENTS

(a) Equipment

Panel assembly factory	1
Assembly lines[a]	
On-line	72
Standby[b]	8
Total	80
Panel installation machines[c]	
On-line	36
Standby[b]	4
Total	40
Magazine delivery trucks[d]	
On-line	12
Standby[b]	2
Total	14
9-panel magazines	
On installers	36
On trucks	12
On loading dock at factory	12
Spares	6
Total	66

[a]Assembly time: 40 minutes per panel; production
capability of 72 lines: 108 panels per hour.

[b]For servicing, maintenance, and downtime.

[c]Installation time: 20 minutes per panel; production
capability: 60 panels per 20-hour day each.

[d]Delivery rate: 9 panels per delivery each, 108
panels per hour for 12 trucks; delivery time: 1 hour
round trip.

TABLE IV-6.- Concluded

(b) Crew

Panel assembly factory
    Assembly   216
    Electrical and checkout   144
    Loading   12
    Materials distribution   18
    Servicing and maintenance   36
    Supervision   42
      Total per shift   468
      Total for 4 shifts   1872
Magazine delivery truck
    Drivers   12
    Servicing and maintenance   2
    Supervision   1
      Total per shift   15
      Total for 4 shifts   60
Panel installation
    Riggers . . . .   [e]144
    Machine operators . . . .   [f]36
      Total per shift   180
      Total for 4 shifts   720
    Machine servicing and maintenance . . .   20
    Supervision   100
      Total   840

[e]Four riggers per crew; 36 crews.
[f]One machine operator per crew; 36 crews.

TABLE IV-7.- TASK DESCRIPTION

Task	Description	Time, months	No. of workers
1	Initial site preparation	3	239
2	Complete site preparation	5	306
3	Structure construction	8	706
4	Rectenna panel manufacture and installation	9	327

117

TABLE IV-8.- SPS GROUND SYSTEM COST

Type	Sensitivity	Total cost, 1977 dollars
Rectenna		
Material		
Diodes	4¢/diode	298×10^6
Steel in panels	15.8 kg/m^3	349
Aluminum busbars (0.05 by 1.27 cm (0.02 by 0.5 in.))	165 000 t	267
Structure		
Concrete (6- by 10-m module)	9 t/module	81
Steel (reinforcing)	300 kg/module[a]	100
Labor		50
Capital cost	Typical machine life is 5 yr; cost to project only during use	40
Miscellaneous		175
Total		1360
Ground power distribution and transmission[b]		630
Total[c]		1990

[a]100 kilograms per arch; three arches per module.
[b]Per SPS Phase III final review.
[c]Excluding land and development cost.
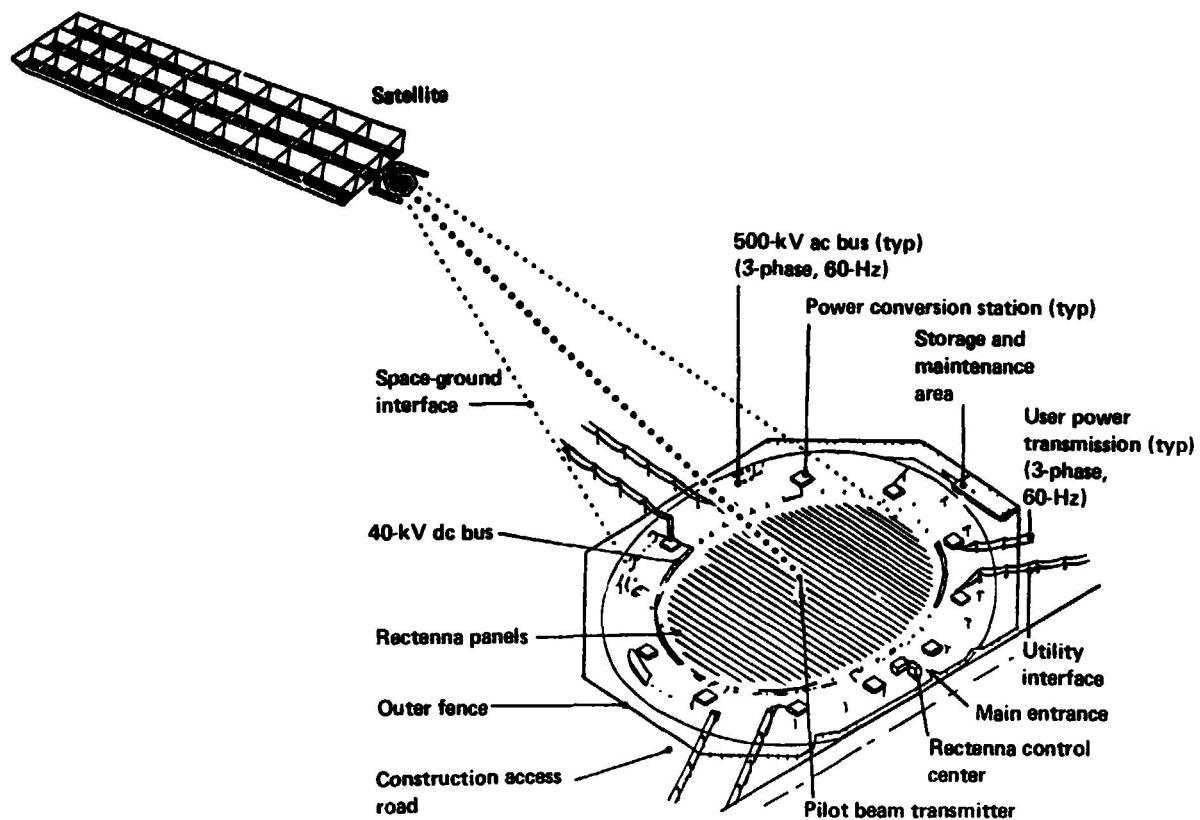
Not to scale (panel area 10 by 13 km)

Figure IV-1.- SPS system showing rectenna details.
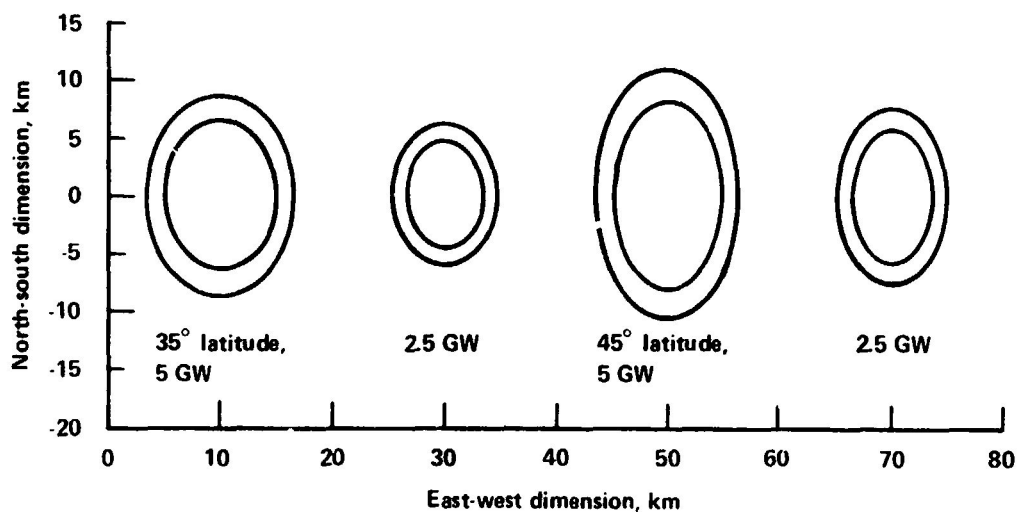
Figure IV-2.- Rectenna dimensions.

119
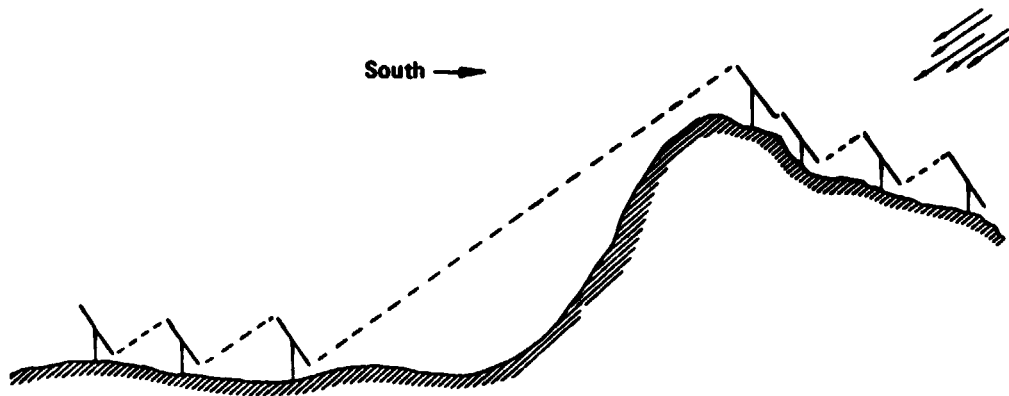
Figure IV-3.- Illustration of the manner in which rectenna elements can be located to ensure reception of the SPS power beam under conditions of extreme slope. Rejection of rectenna sites on the basis of slope will be a function of construction economics.
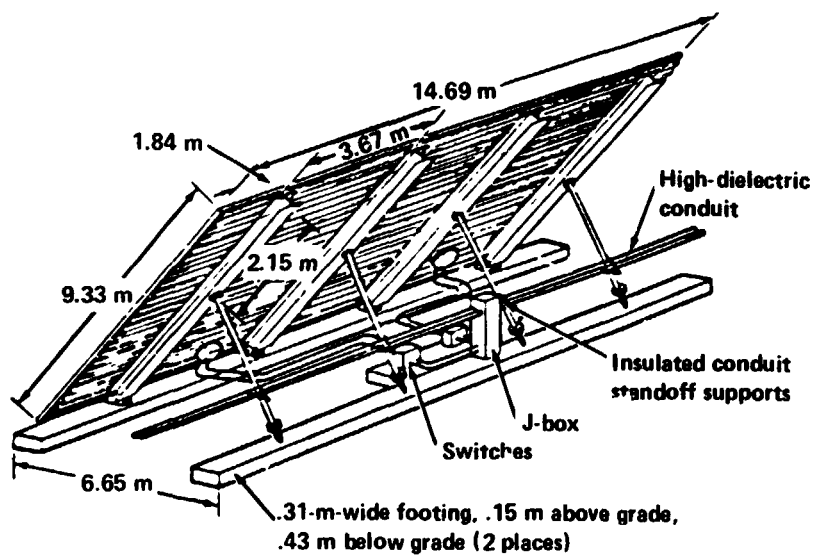
Figure IV-4.- Rectenna panel installation.

120
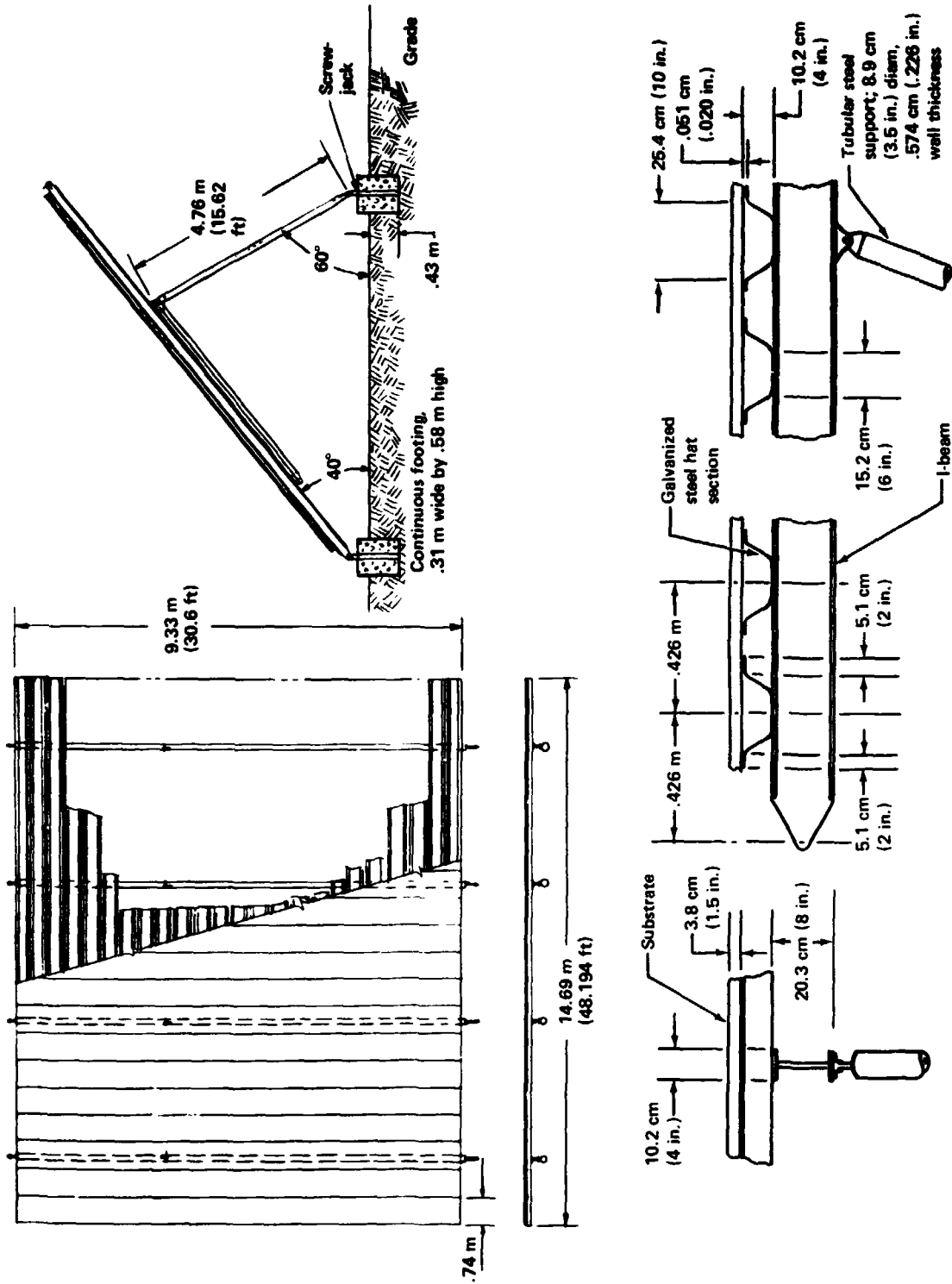
Figure IV-5.- Rectenna array support structure.

Site survey engineering	Support facilities installation	Reference coordinates
Site clearing	Panel pad grading	Panel installation operations
40-kV dc bus installation	Converter station installation	500-kV ac bus installation
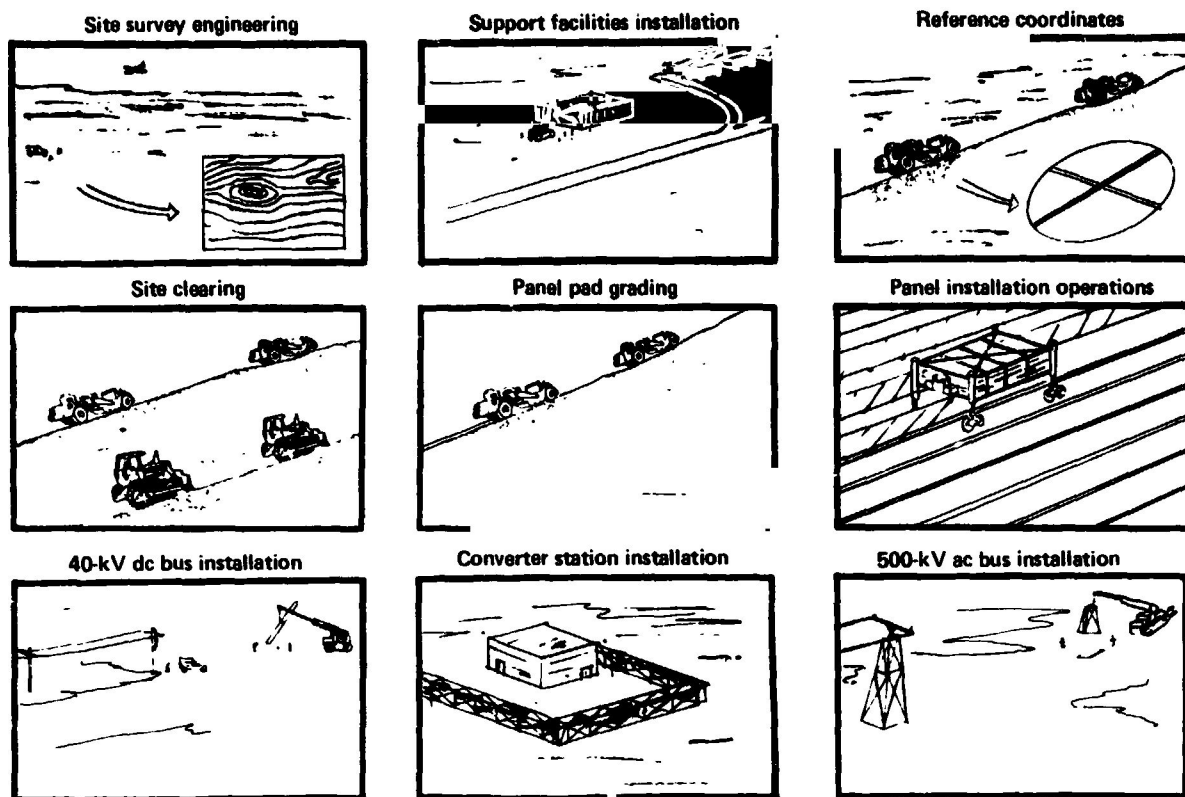
Figure IV-6.- Rectenna construction sequence.

Time, months

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |

Site preparation

- Site survey, architectural and engineering planning
- Utilities and facilities
- Reference grid
- Clearing and grubbing
- Grading
- Rail and road installation

Rectenna construction

- Concrete footings
- Panel assembly
- Panel installation
- Control center construction
- Electrical hookup and checkout
- 40-kV ac bus installation
- Converter stations
- 500-kV ac bus installation

Figure IV-7.- Rectenna site construction schedule.

122
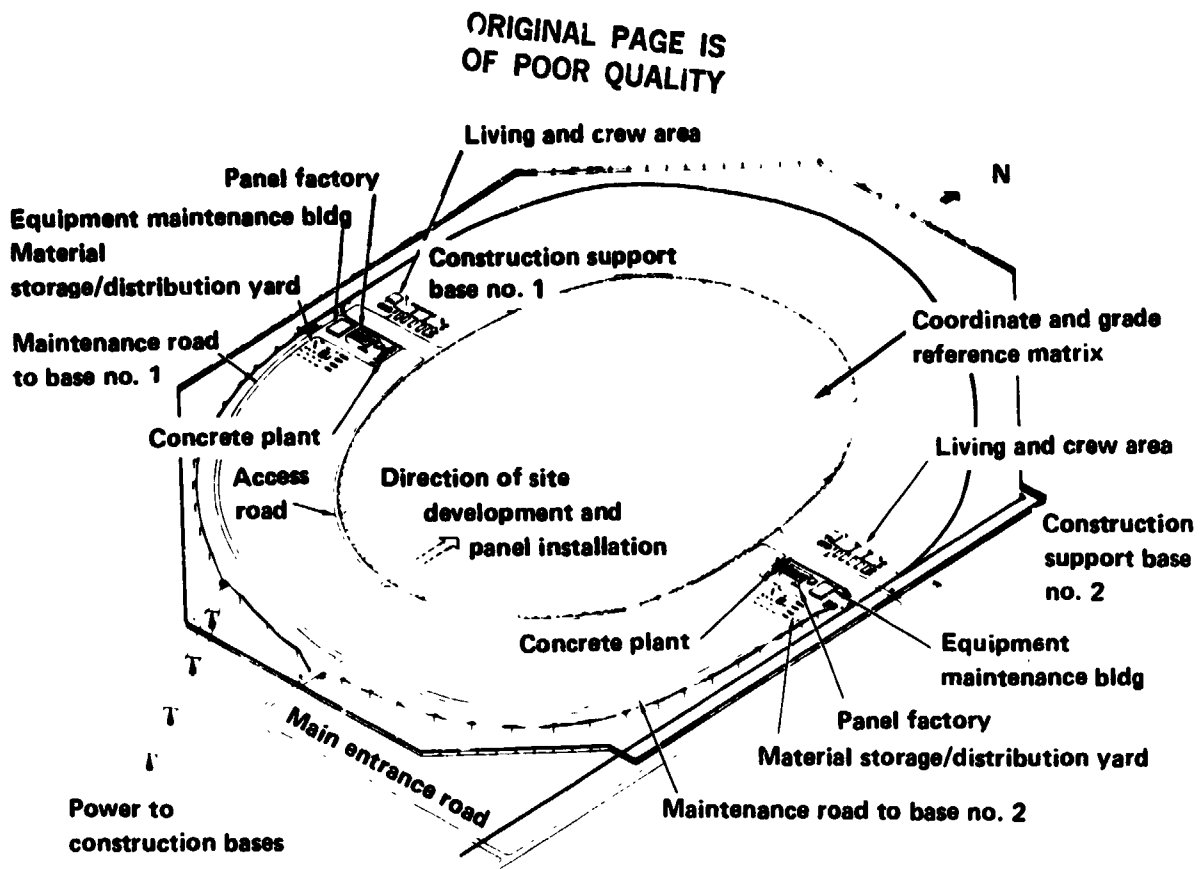
Figure IV-8.- Support facilities.
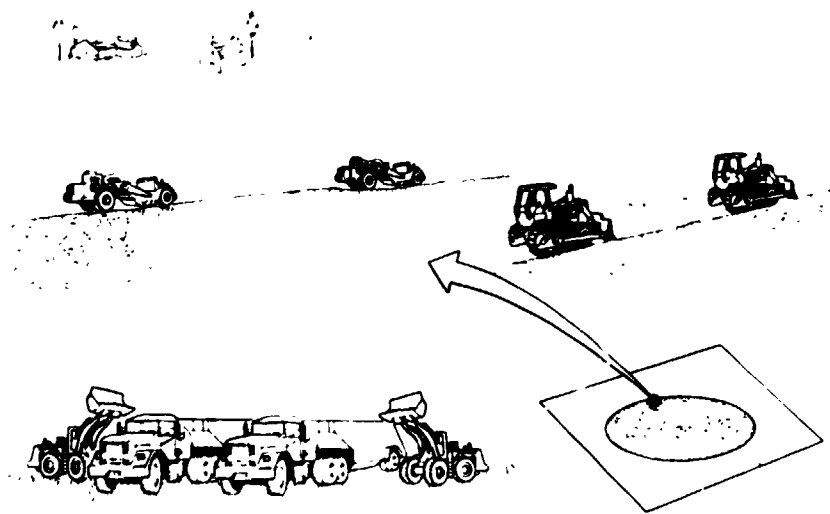
Figure IV-9.- Clearing and leveling operations.

123
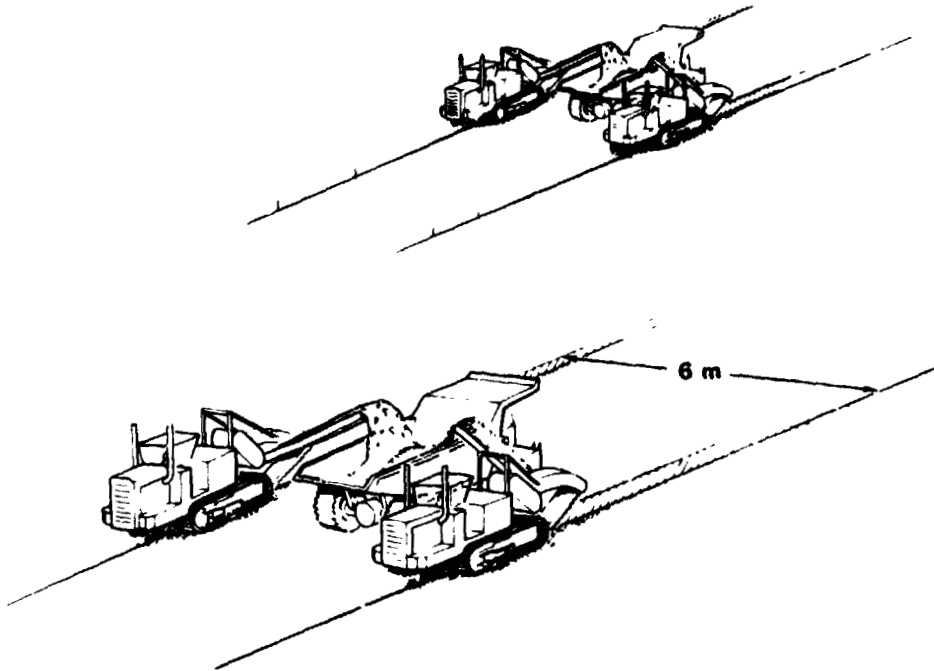
Figure IV-10.- Footing excavation.
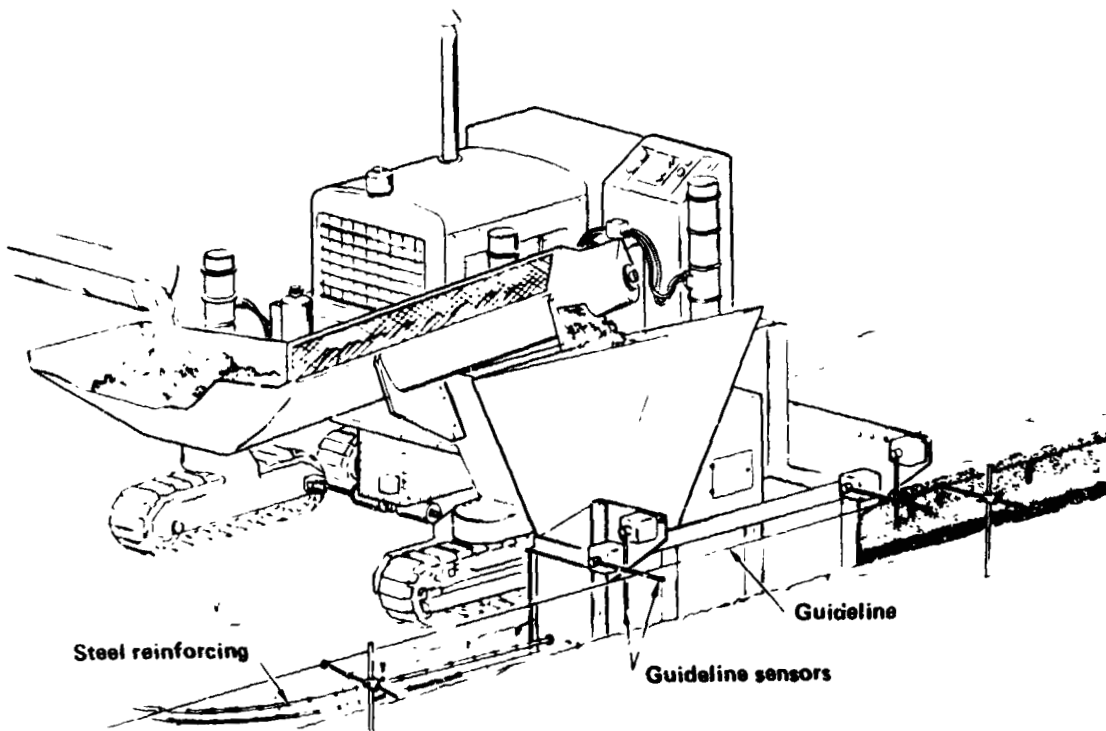
Figure IV-11.- Concrete installation.

124
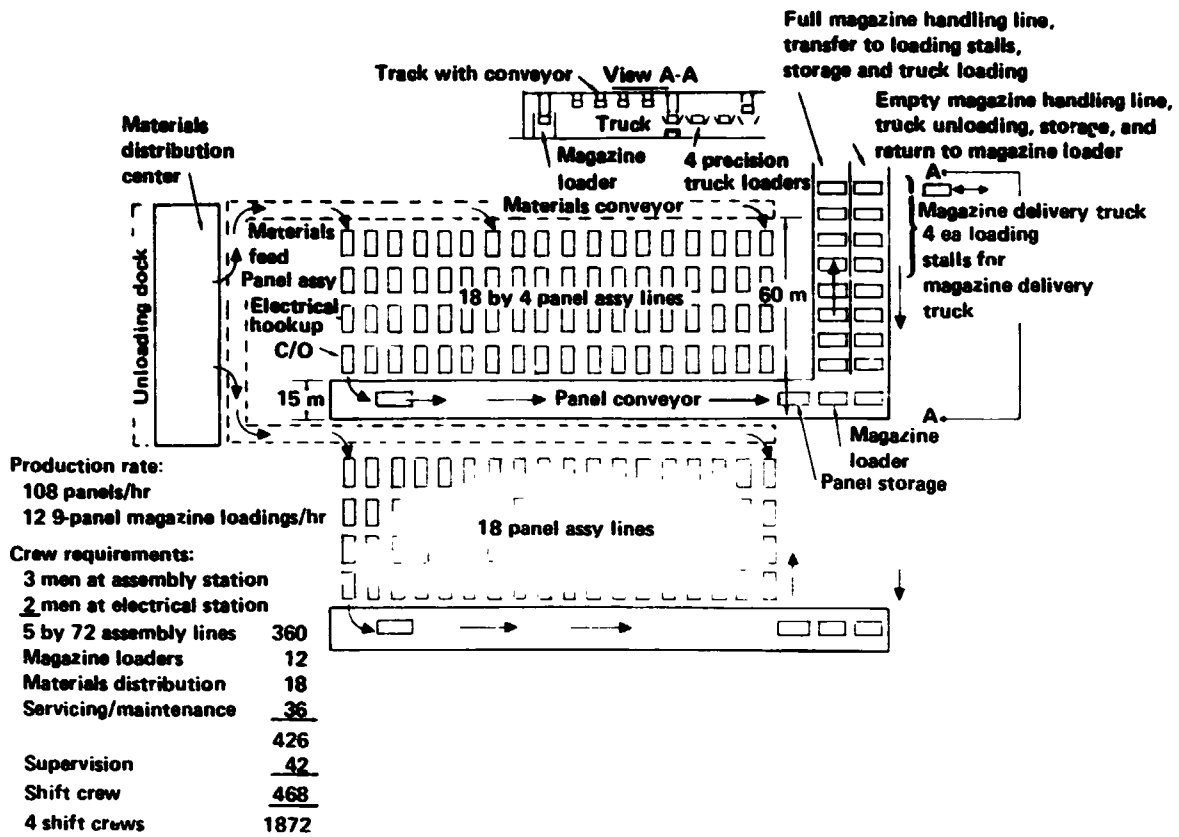
Figure IV-12.- Central panel factory.

Production rate:
108 panels/hr
12 9-panel magazine loadings/hr

Crew requirements:

3 men at assembly station	
2 men at electrical station	
5 by 72 assembly lines	360
Magazine loaders	12
Materials distribution	18
Servicing/maintenance	36
	426
Supervision	42
Shift crew	468
4 shift crews	1872
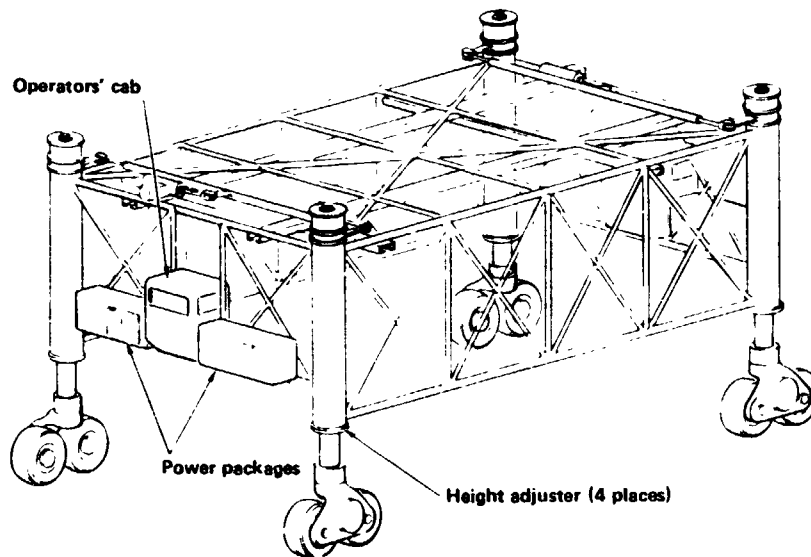
Figure IV-13.- Panel installation machine.
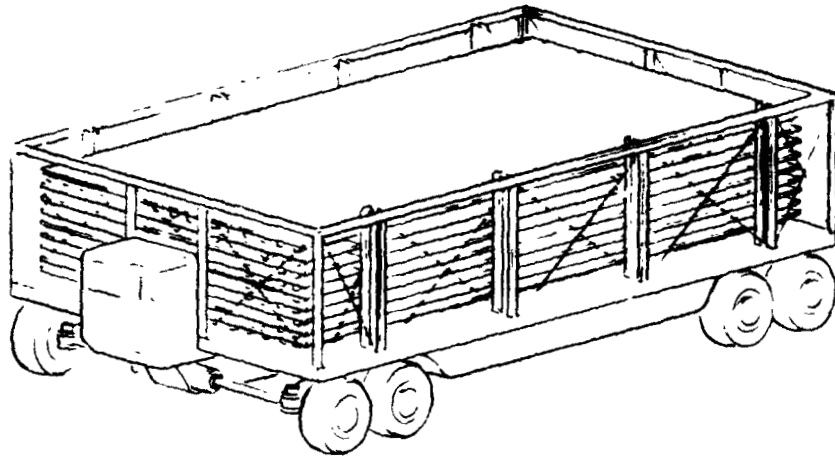
Figure IV-14.- Magazine delivery truck.
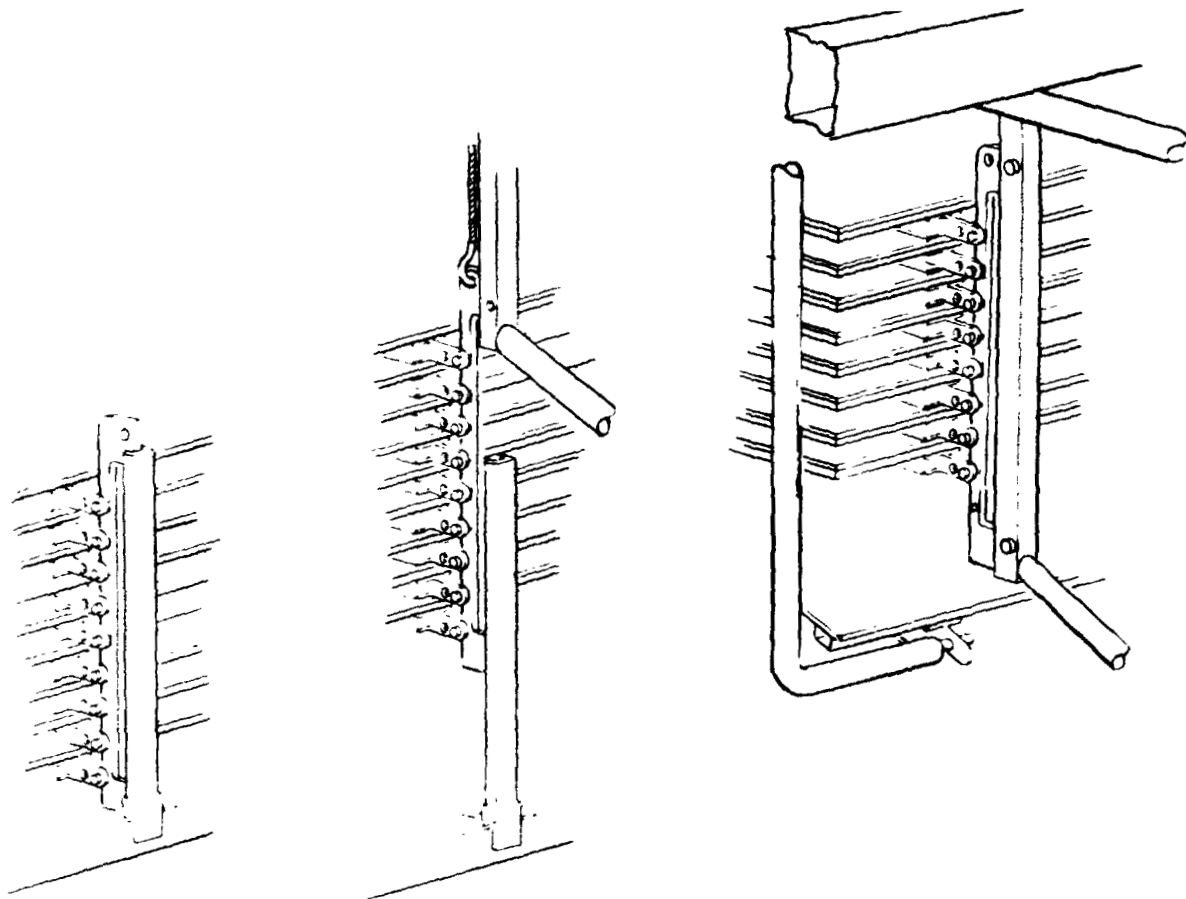
Figure IV-15.- Panel magazine transfer.
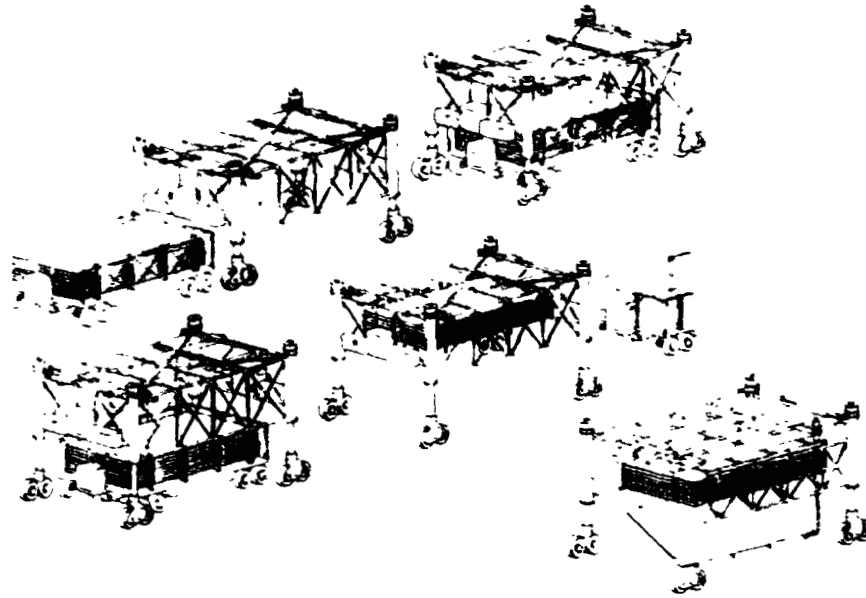
Figure IV-16.- Panel loading sequence.
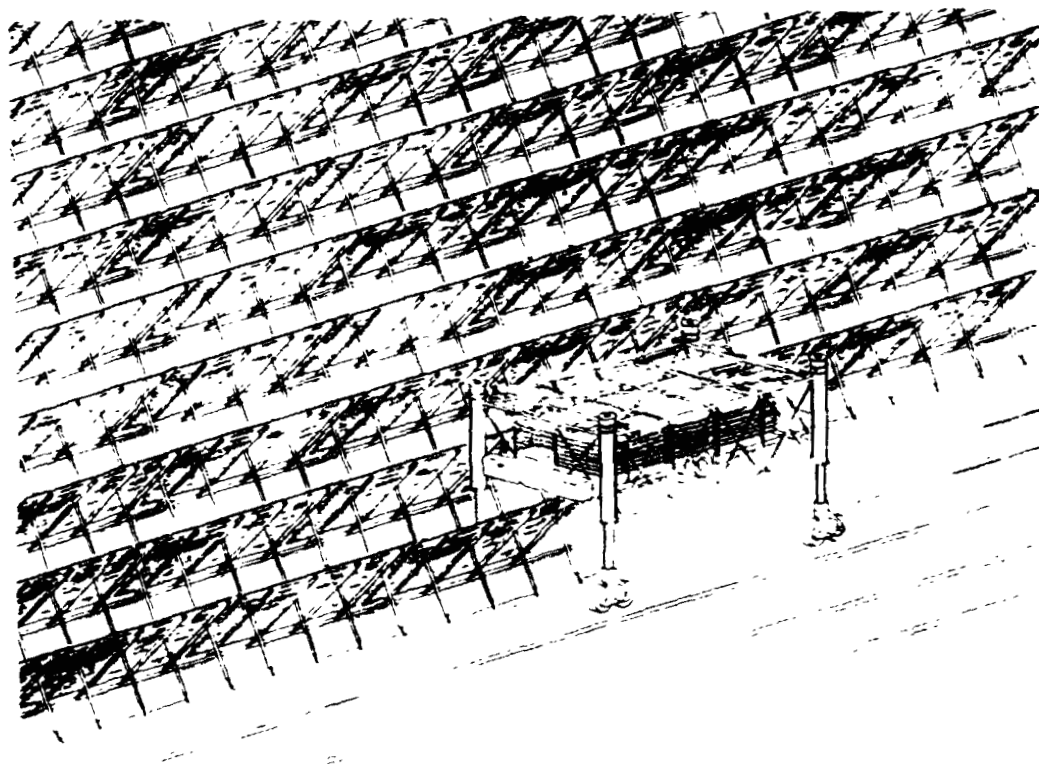
Figure IV-17.- Panel installation operations.

127
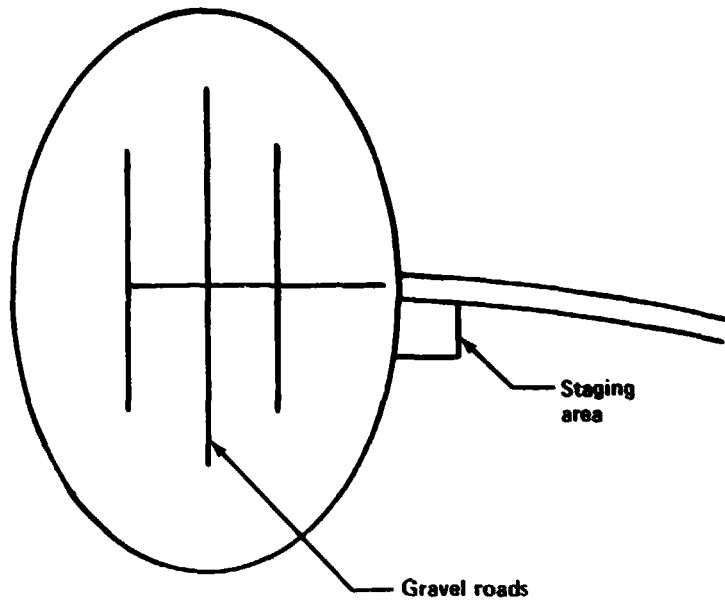
Figure IV-18.- Site plan.
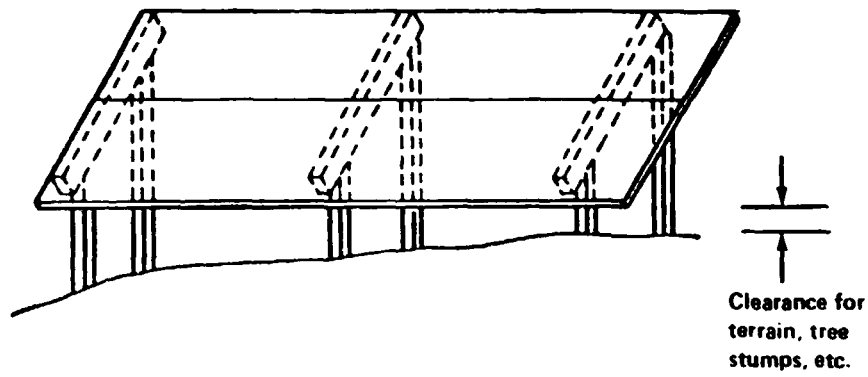
Figure IV-19.- Rectenna module.

128

Printed solid panel   **Low-drag airfoil**   **The baseline**
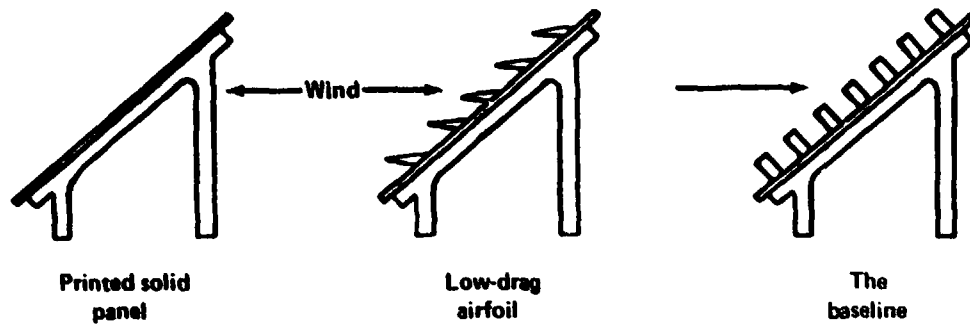
All three concepts wave lift for ∿ 44.7 m/sec (∿ 100 mph)

Lift = 51 000 N   Lift = 34 000 N   Lift = 48 500 N

Figure IV-20.- Three panel concepts.

6 m

6.2 m

2 m

Typical 3 715 050 places
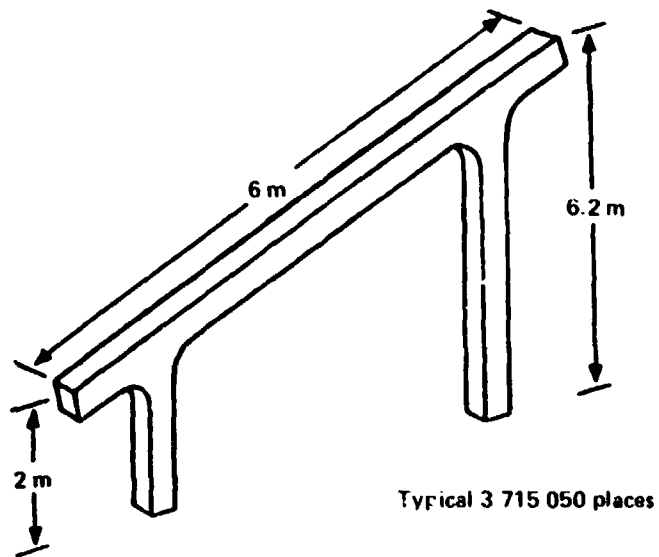
Figure IV-21.- Prestressed concrete arch used in baseline structure.
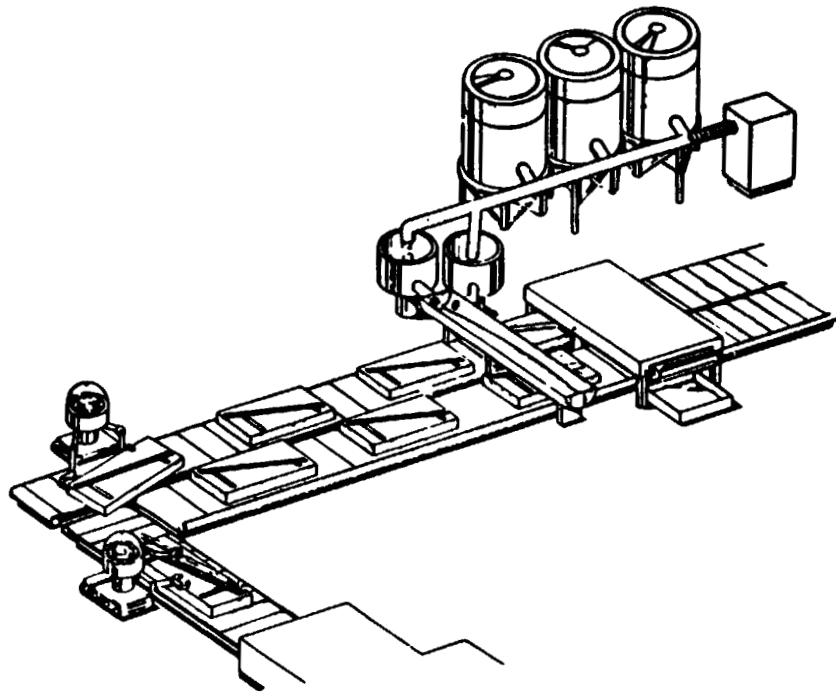
Figure IV-22.- Arch casting factory.
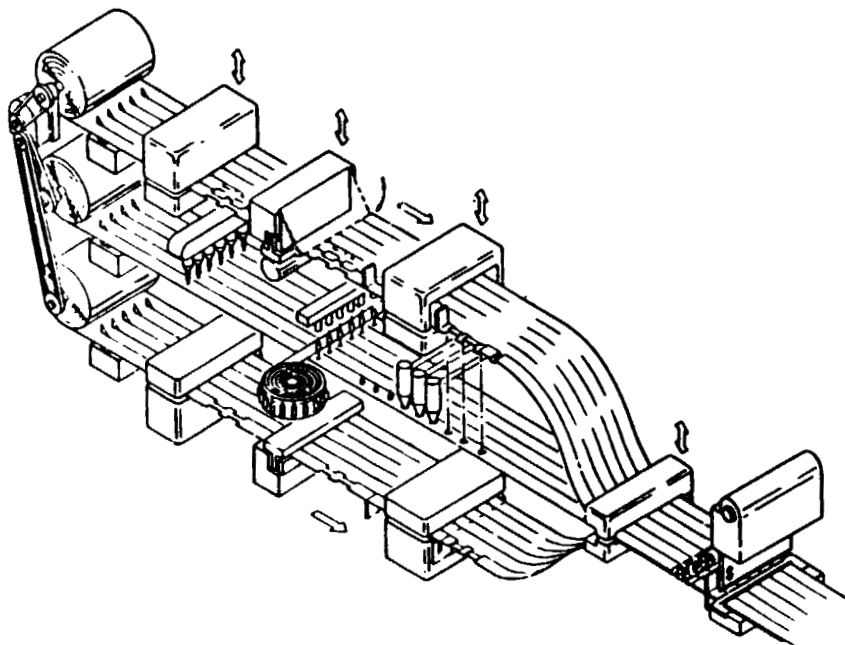
Figure IV-23.- Dipole machine.
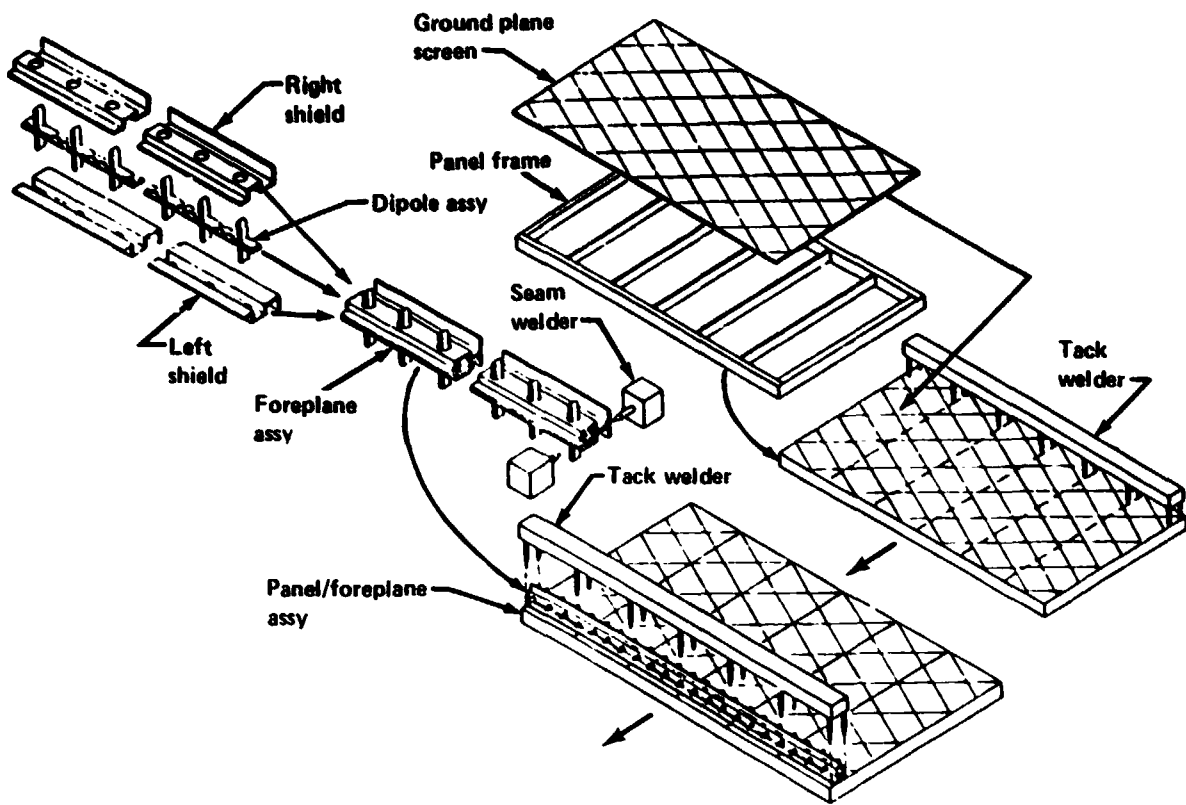
Figure IV-24.- Rectenna panel fabrication sequence.
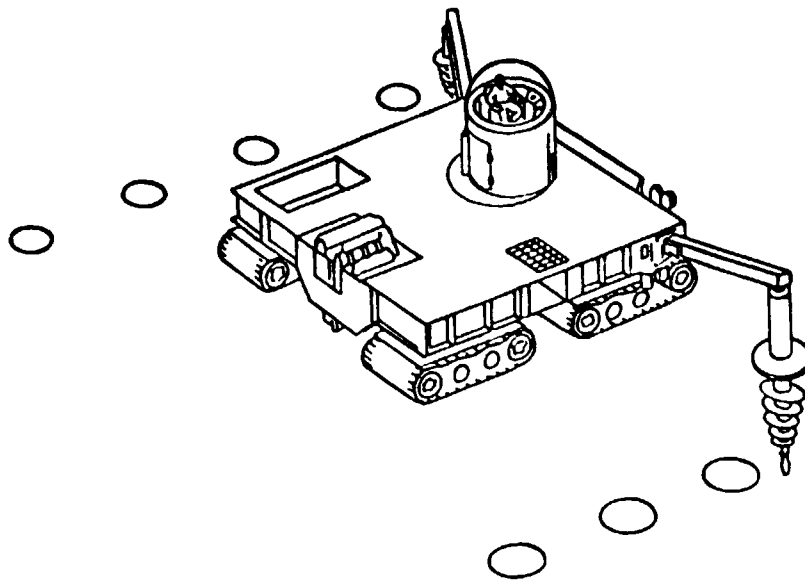
Figure IV-25.- Foundation machine.
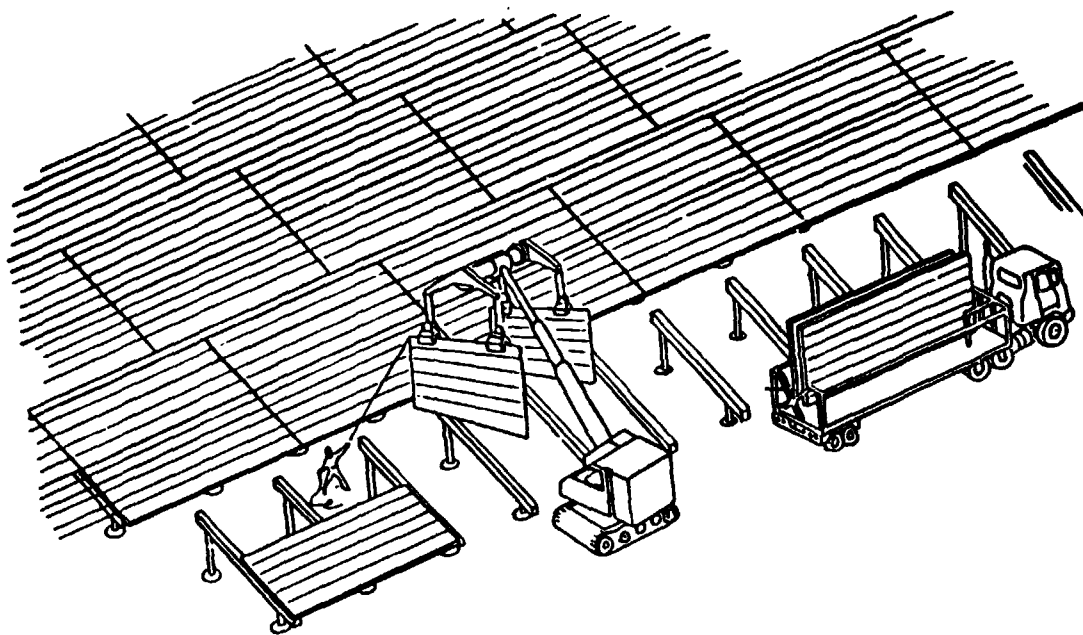
Figure IV-26.- Panel installer.
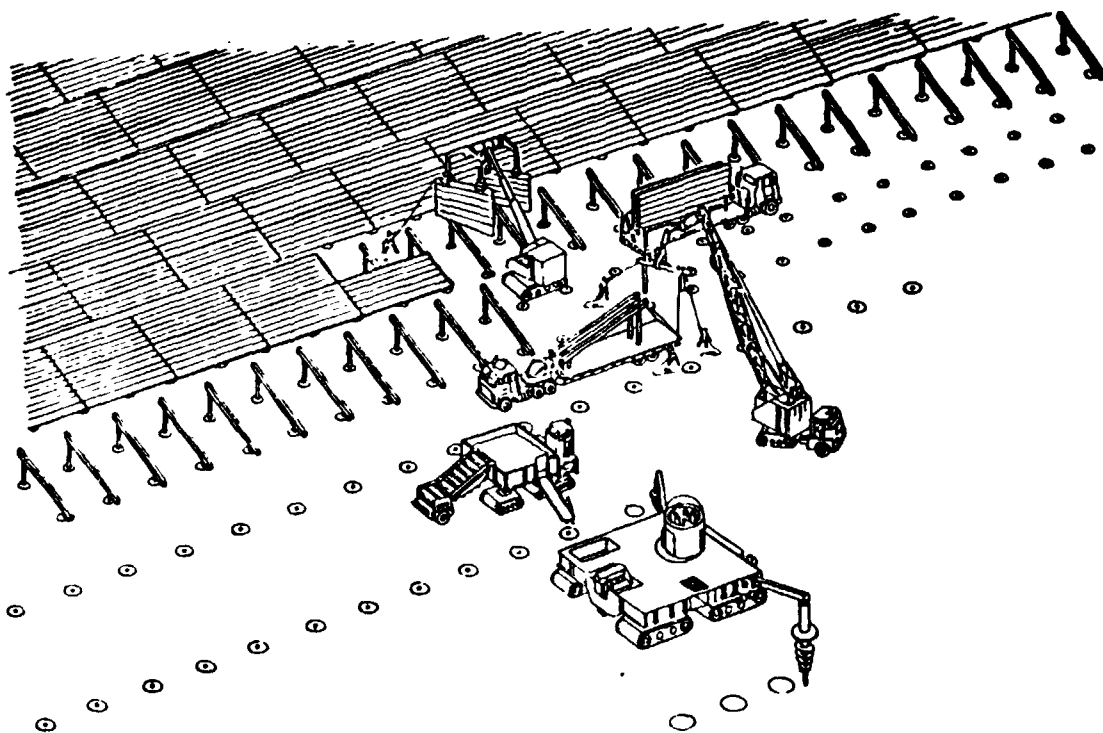
Figure IV-27.- 5-gigawatt rectenna construction concept.
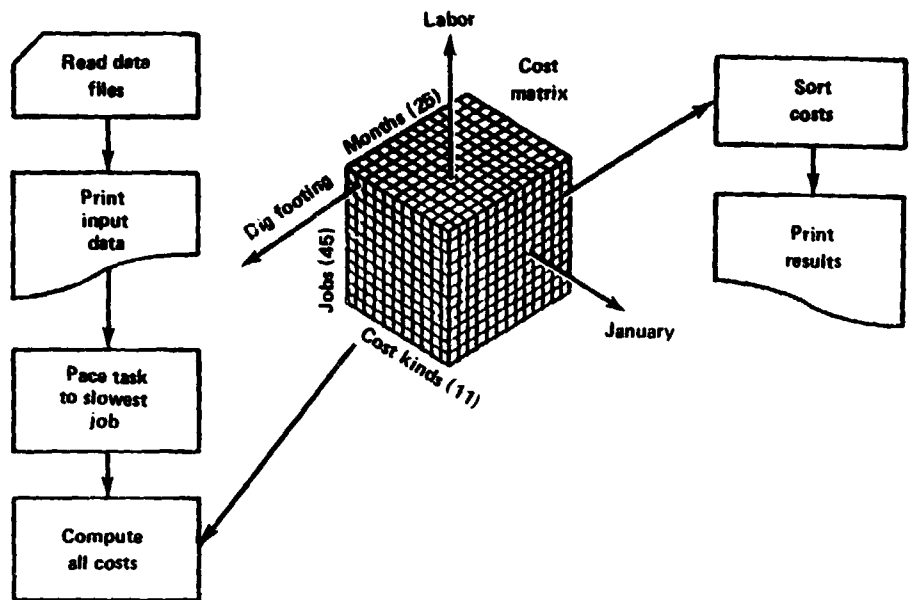
Figure IV-28.- Operation of the cost model.
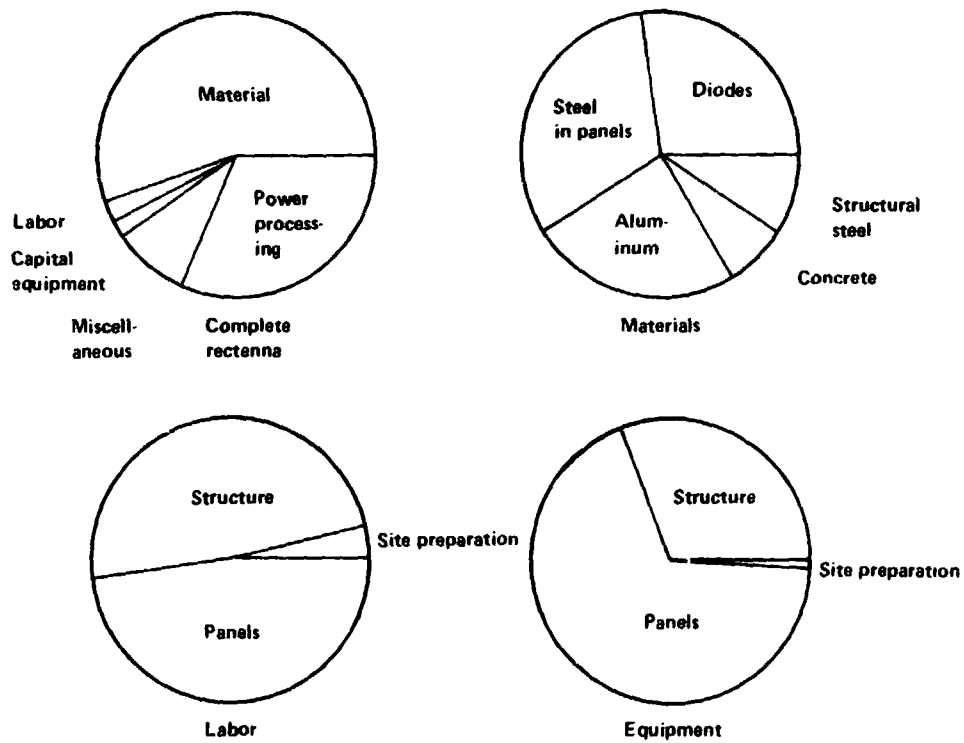
Figure IV-29.- Rectenna cost distribution.

133
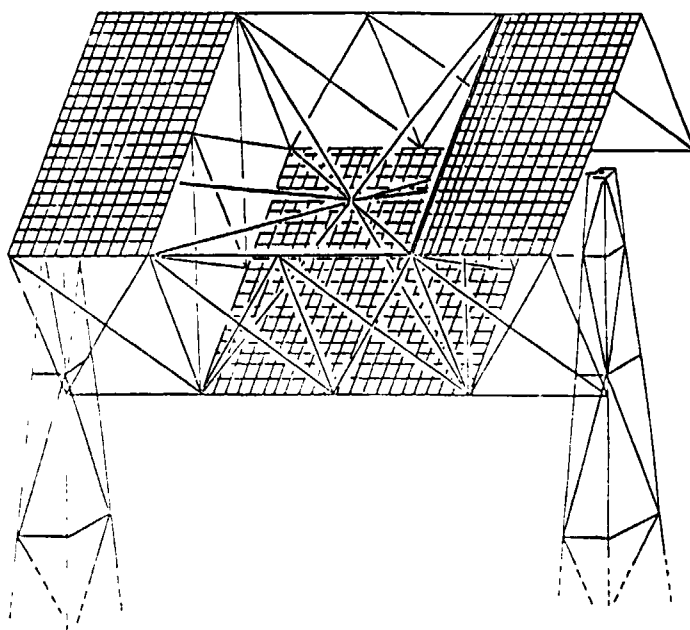
Figure IV-30.- Two-level rectenna panel.
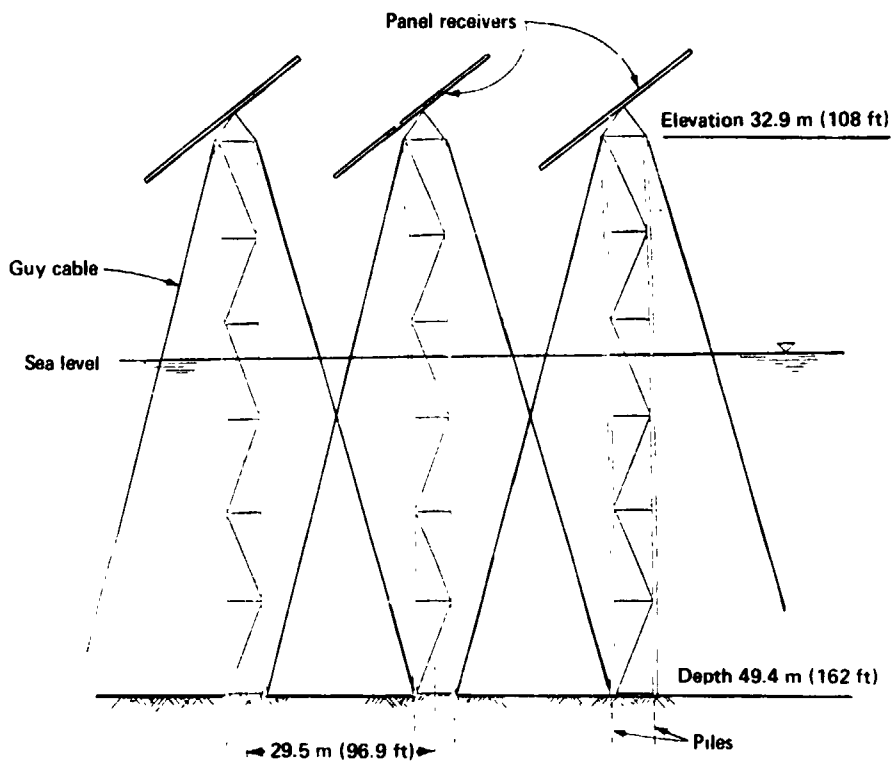
Figure IV-31.- Piled guyed tower structure with panel receivers.

134
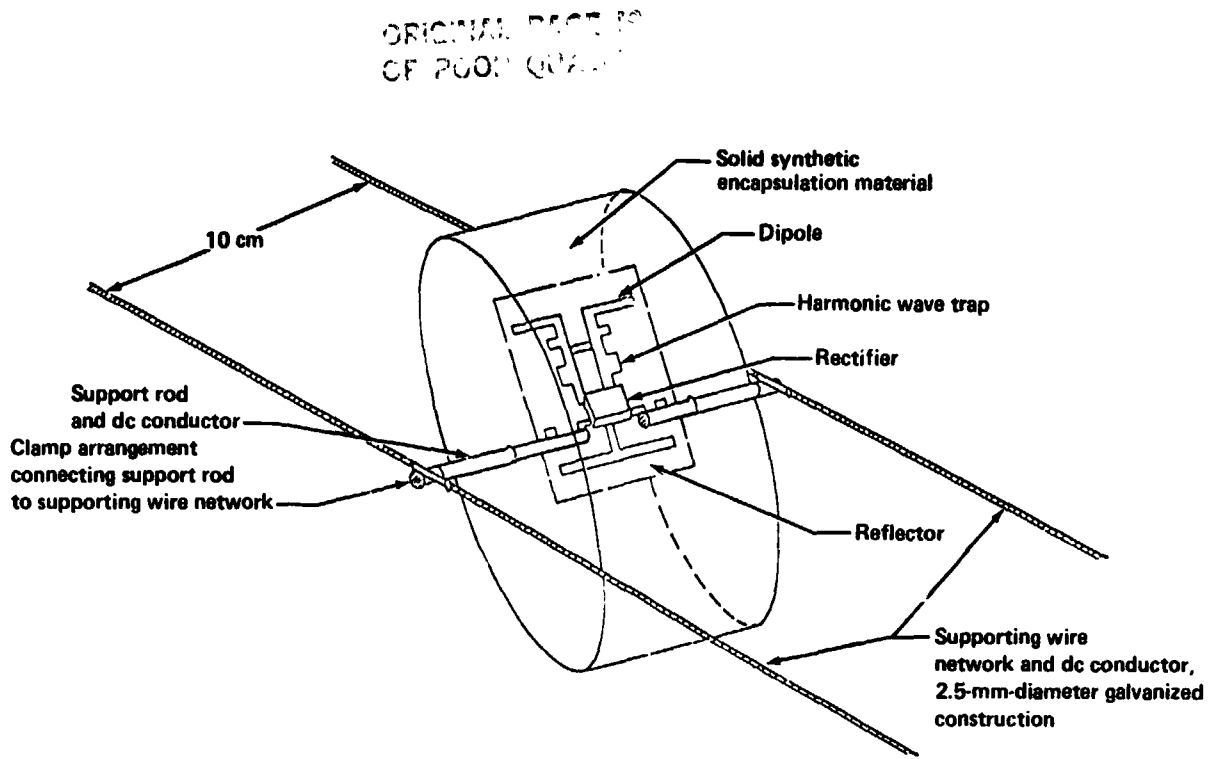
Figure IV-32.- Diagram showing encapsulated non-ground-plane diode and
detailing electronics and supporting arrangement.
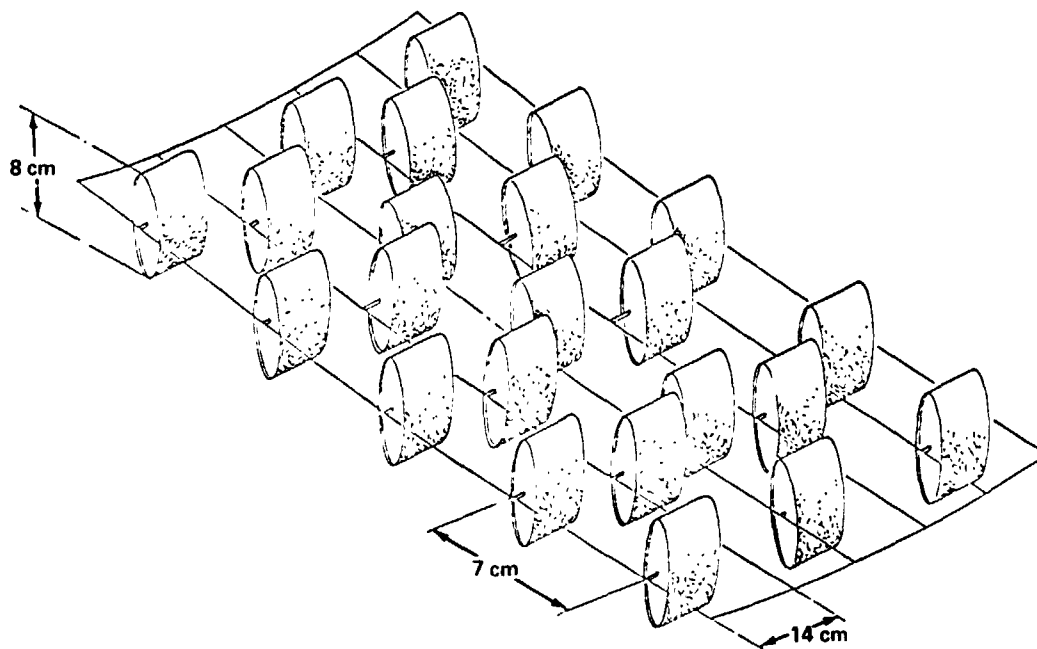
Figure IV-33.- Diagram showing section of 30.5- by 30.5-meter (100 by
100 foot) non-ground-plane dipole microwave receiving arrangement.

135

1.3-cm (.5 in.) φ steel cable
crisscross wires

At intervals of
914 m (3000 ft), towers will be
double spaced and
guyed as shown

30.5 m
(100 ft)

7.6-cm (3 in.) φ
perimeter cable

Piled platform

Distance between platforms, 305 m (1000 ft)

12.7-cm (5 in.) φ permanent wire cables,
guys, and guy anchors on out-
side perimeter of rectenna
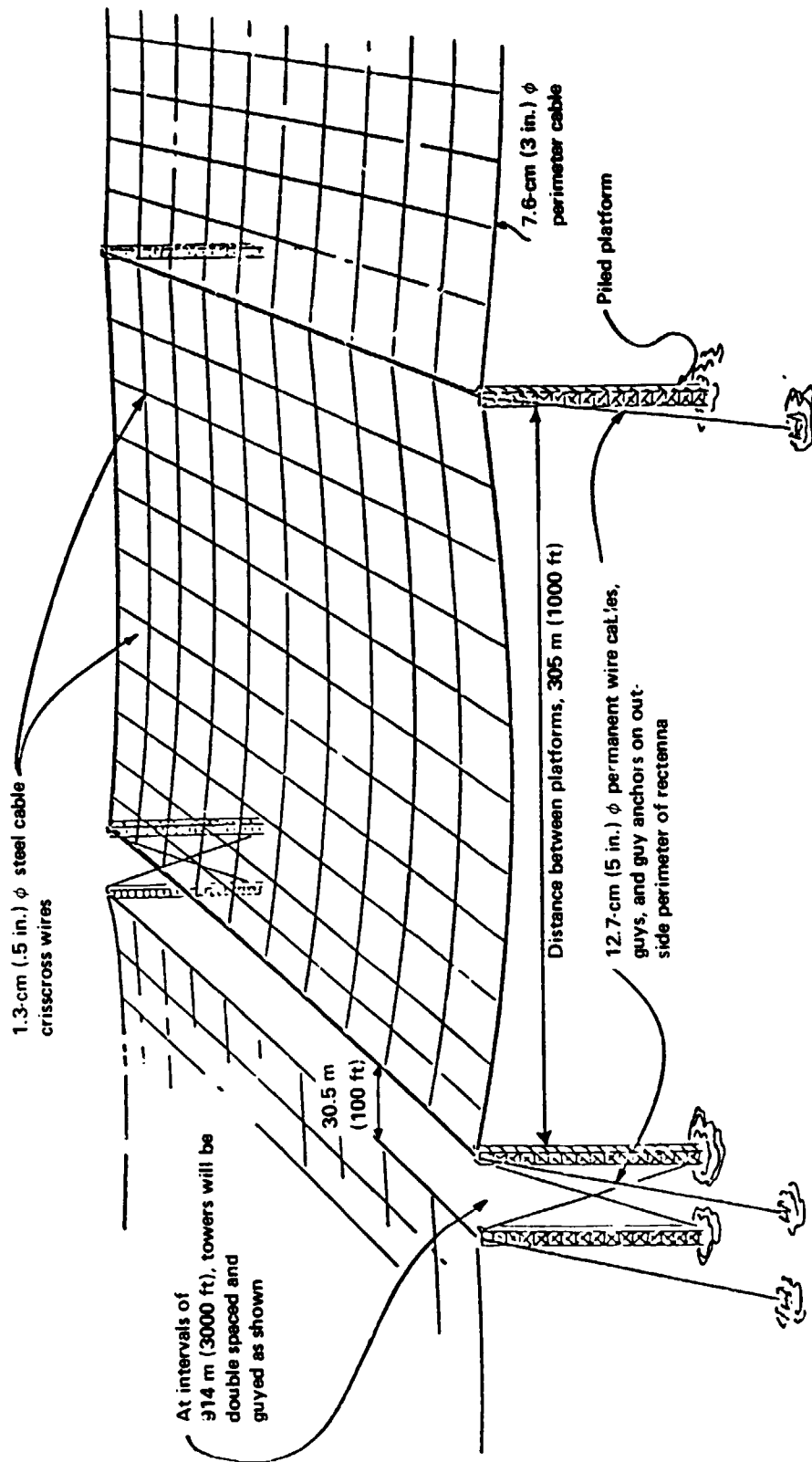
Figure IV-34.- Diagram showing platform and taut-wire support arrangement
for flexible non-ground-plane dipoles.

136

V. OPERATIONS AND MAINTENANCE

A. SATELLITE

The bulk of the SPS components are highly reliable, redundant, or relatively inert. Most satellite maintenance will involve periodic replacement or refurbishment of microwave antenna elements. Even though the reliability is fairly high, cumulative failures of these active elements over the SPS lifetime would result in an unacceptable degradation in performance. Alternative concepts for maintenance are a permanent maintenance base and crew at each satellite or mobile maintenance crews who return to one of the GEO construction bases with components to be refurbished. The latter concept is illustrated in figure V-1.

At the GEO base, maintenance workers board a mobile crew habitat. Along with maintenance equipment and replacement components, they travel to an operational SPS, which has been shut down before their arrival, and dock to the satellite's antenna. Using built-in equipment (e.g., cranes and cherrypickers), over a 3.5-day period, they remove defective components and replace them with new or rebuilt parts. Defective components are returned to the GEO base. The crew, mobile maintenance equipment, and replacement parts then move on to the next satellite, visiting as many as 20 satellites in a 90-day period, which is consistent with crew rotation time.

At the GEO base, other crewmen diagnose defective components, repair or replace them as appropriate, reassemble, and test. When possible, the refurbished components can then be reused on other SPS's.

For 20 satellites, a mobile maintenance crew requires about 80 people with about another 300 needed for the refurbishment work. The crew size varies with the number of satellites in service.

The primary components on the reference satellite which require maintenance are the klystron tubes and the dc-dc converters. These parts are removed from the satellite and transported to the GEO construction base, where they are refurbished. Because of the circuit redundancy inherent in the design, maintenance of the solar cell blankets is not considered cost effective. If degradation of the output of the silicon cells due to radiation becomes a factor in SPS output, the cells must be annealed or the array oversized. A concept for annealing the damage by heating the cells with a laser system was defined for the silicon system. On the gallium cell satellite, the cells are annealed by operating at a temperature high enough to cause self-annealing.

1. SATELLITE MAINTENANCE CONCEPT: ROCKWELL

The permanent satellite maintenance base is located on the first frame adjacent to the rotary joint since the bulk of the maintenance activity is anticipated to be on antenna components. (For a center-mounted antenna configuration, the base would be located on one of the two center frames.)

137

a. Antenna

Klystron maintenance is anticipated to be a major portion of
the overall maintenance effort. The population of approximately 136 000
klystrons is life limited and also can be expected to encounter a high number
of random failures. Currently, mean times to failure (MTTF's) of more than
150 000 hours are being projected for traveling-wave tubes (TWT's), which are
somewhat similar to klystrons. The primary life-limiting factor is the
cathodes. Even if klystrons reflecting SPS requirements can be developed
with similar MTTF's, a virtually total replacement would be required over a
30-year period. An alternative would be to develop a klystron design which
would permit changing the cathodes without removing the klystron.

Because of the thermal interface between the klystrons and
the heat pipes, definition of a line replacement unit (LRU) is not clear at
present. Preferably, an LRU would consist of a klystron cathode or a klys-
tron but could be a power module or higher assembly. Regardless of LRU defi-
nition, means for removal and replacement will be provided by the gantries or
cable-mounted platforms (i.e., see Sec. III.C.2), which provide access to
both sides of the antenna. These platforms will be equipped with the special
equipment needed to perform maintenance on both the face and the underside
of the antenna. Since shutdown will be required during maintenance, it is
anticipated that degradation to a predetermined point would be tolerated
and that a nonoperating period of some days might be required for complete
restoration of functions.

b. Power Distribution

The components comprising the power distribution system
(PDS) (e.g., switchgears) generally are more reliable and fewer than the
klystrons, but random failures can be expected. (PDS elements on the back
side of the antenna are accessible to the antenna gantry.) Because of the lo-
cations of these components in the bottom crossbeams of the troughs, the dis-
tance of a disabled component from the maintenance base could approach 16 000
meters for an end-mounted antenna configuration. Removal and replacement
of PDS components, then, will require either an extensive track system or a
free-flying facility with the capability of an MMM plus space for components.
Since maintenance operations would be sporadic and would occur at various
locations, a free-flying concept appears to be preferable to an extensive
track system, which would have to provide access to every crossbeam through-
out the length of the satellite as well as to other areas.

A version of the free-flying concept could consist of an
arrangement similar to the vehicle shown in figure III-73, but somewhat
smaller. The MMM would be equipped with special grabber arms for attaching
to a 2-meter beam (fig. V-2) and providing a measure of stability during the
operation. Sections of the solar array will be deactivated during mainte-
nance periods. However, temperatures of 398 K (125° C) or higher may be en-
countered at the bottom of the trough. Dependent on detailed design charac-
teristics and the type of materials used in MMM construction relating to ther-
mal control, it may be necessary to work from the underside of the crossbeam

138

rather than the top. This approach would slightly restrict the access, but the operations still could be accomplished.

c. Solar Blanket/Reflector

The design and the sizing of the solar blanket/reflector are predicated on the degradation expected over 30 years, including meteoroid penetration. To effectively immobilize a large section of solar blanket would require some kind of catastrophic event (e.g., large meteor, collision). The isolation, removal, and replacement of small solar blanket sections with the many interconnects does not appear feasible at this time. Replacement of an entire 25- by 750-meter strip by use of free flyers also does not appear practical. The alternative of using permanently installed equipment mounted on tracks or cables would require an installation in each bay of each trough, totaling 60 sets; most of these installations probably would not be used during the satellite life because of the low probability of catastrophic events. Therefore, the current design is based on acceptance of the predicted degradation and includes no provision for blanket strip replacement.

The same rationale applies in general to the reflector sheets, which are considerably larger. However, in the event of a large perforation or tear in the reflector, it may be possible, by use of free flyers, to treat the edges of the perforation in some manner to avoid propagation.

d. Attitude Control

Servicing and maintenance of the reaction control system, including thruster replacement, will be accomplished by the same type of vehicle (beam-grabbing MMM) used for the PDS.

e. Conclusions

With the exception of solar blanket and reflector replacement, maintenance of the satellite subsystems is feasible. Partial or complete satellite shutdown will be required for conducting maintenance in some areas. More detailed design information for both satellite subsystem installations and manned manipulators will be required before maintenance operations can be defined in any great detail, time lines established, and satellite downtime assessed.

2. OPERATIONS CONTROL CONCEPT: BOEING/TRW

a. Introduction

A concept has been developed for the integration and coordination of SPS Program operating activities which will assure that all program requirements are satisfied, that the program is accomplished in a timely fashion, and that a mechanism exists for solving problems that require essentially real-time solution (e.g., orbital anomalies). This concept embraces the activities of all operating elements of the SPS system, including those illustrated in figure V-3, plus the industrial complex and the surface transportation system.

139

The concept was developed by defining, at a summary level, the tasks that must be performed to assure proper execution of the program. To make this definition, the program was divided into major activity groups and the tasks performed by each group were defined. The tasks thus defined were expanded and regrouped, and additional major activity groups were defined. After several iterations, it was established that the program can be divided into 12 groups, or "local operations," each of which will coordinate and integrate all of the activities and tasks performed within that group. The activities of these 12 local groups or operations will in turn be coordinated and integrated by a central group called "Integrated Operations." Thus, Integrated Operations will be the top-level planning and technical organization, which will be responsible for the execution of the program. The total coordinating and integrating concept consisting of the 12 local operations, plus Integrated Operations, comprises the "Operations Control Concept."

The results of this analysis also indicated that it would be desirable to place 11 of the 12 local operations in a central location together with Integrated Operations. This arrangement provides ease of communication and makes possible the use of common computing and space communication equipment.

For costing purposes, an estimate was made of the manpower required in each of the local operations as well as in Integrated Operations. The ground rules used in developing the concept and the manpower estimates are as follows.

(1) The period in the program to which the concept applies is the time at which 20 SPS's have been completed and are in operation with their associated rectennas.

(2) Two additional SPS's and rectennas are being completed and becoming operational each year.

(3) To the extent possible, authority will be delegated to the local operations which are responsible for performance of the tasks. Thus, there will be as much local autonomy as possible.

b. Integrated Operations

The function of Integrated Operations, the central organization, is to coordinate and integrate the activities of the 12 local operations to assure that all program requirements are satisfied and that the program is accomplished in a timely fashion. It is the central authority which will monitor the day-to-day progress of the program, determine the solution to any problems which develop, and implement the action to correct these problems, including problems that must be solved in real time or as near real time as possible (such as orbital anomalies).

140

To develop the organization required to accomplish the described objectives, an analysis was made of the specific activities involved. The existence of certain common functions which Integrated Operations will perform with respect to the activities of each local operation rapidly became apparent. These tasks are listed and described in table V-1.

c. Maintenance Access Systems

The fundamental premise in the maintenance access systems analysis was that every SPS component (except structural members) must have a maintenance equipment access provision (even components that have a negligible failure rate). It was deemed prudent to force this requirement so that unexpected failures could be attended to. Ten general maintenance access requirements were identified (table V-2). The alternative maintenance access systems for each of these locations are given in table V-2. These 10 access requirements can be satisfied by combinations of built-in tracks, a flying cherrypicker, a rotary boom, and some gantries (fig. V-4).

The configuration of some of the components to be serviced from the top surface of the solar collector is illustrated in figure V-5. The baseline satellite has a requirement for some solar array annealing machines, which would be mounted on gantries that can traverse over the top surface of the solar collector. Four gantries operate on a built-in track network on the satellite. These gantries and tracks provide a readymade maintenance access system for reaching the entire upper surface of the solar collector. It will be necessary to get a maintenance cherrypicker onto the gantries to perform maintenance on the solar array components (tensioning devices, catenary cables, and cell string blocking diodes).

A flying cherrypicker would rendezvous with a gantry to which a flying cherrypicker carriage is attached. This carriage has a docking interface to which the cherrypicker would mate. This carriage would then traverse across the gantry as required. A flying cherrypicker was employed because there are not enough maintenance tasks to warrant the expense of a permanent cherrypicker installed on each gantry.

d. GEO Base Maintenance Support Systems and Operations

The objectives of the GEO base maintenance analysis subtask were the following: (1) to define the klystron tube module refurbishment systems and operations, (2) to define the systems and operations required to refurbish the other components, and (3) to create an integrated GEO base maintenance support systems and operations concept. The general guidelines for this analysis are as follows.

(1) Refurbishment crew is stationed at the GEO base for 90-day stay times.

(2) SPS maintenance crews return to the GEO base after 90 days on Earth to repeat the 90-day maintenance visit cycle.

141

(3) Replacement components are delivered to GEO on the EOTV.

.4) Defective components are delivered to the GEO base by OTV's.

(5) The traveling maintenance crew and their equipment and vehicles must have docking provisions at the GEO base.

(6) Crew duty cycle is the same as that of construction and base operations crew.

(a) 6 days on/1 day off

(b) 10-hour work shift

(c) Two shifts per day

(d) 0.75 productivity factor

(7) Refurbishment operations are conducted within pressurized work modules (no EVA).

e. Integrated SPS Maintenance Operations Plan

The integrated SPS maintenance operations concept is depicted in figure V-1. The top-level time line, shown in figure V-6, reveals two types of operations: (1) maintenance operations at the satellite and (2) refurbishment of defective components at the GEO base.

The at-satellite maintenance occurs over a 90-day period when each satellite is visited by a mobile maintenance crew and equipment for a 3.5-day stay time. Twenty operational 5-gigawatt SPS's are assumed in the mission model. At the end of the 90-day period, the traveling maintenance crews are returned to Earth. They return to orbit after 90 days on Earth and repeat the maintenance visit routine. Hence, each satellite is visited twice a year for maintenance. The refurbishment operations are conducted continuously with a crew changeout every 90 days.

There are 260 GEO base maintenance crewmembers plus 40 support personnel that must be rotated every 90 days. These crewmembers will be delivered to LEO by way of personnel launch vehicles, along with the other SPS space workers. They will, in turn, be transported to the GEO base in the personnel orbital transfer vehicles.

B. RECTENNA

The rectenna provide the interfaces between the SPS and the electrical utility grid. Power generated in space must be transferred through the rectenna to the user in a controlled and orderly fashion. Operation includes, therefore, startup, shutdown, and steady-state control under normal and emergency conditions. Extensive use of computer hardware will be required because of the extreme complexity involved in interfacing large

142

amounts of power at very high speeds. All communications and telemetry will be interfaced through the rectenna control center. Rectenna operation under various conditions and maintenance have been addressed in Rockwell and General Electric studies.

1. GROUND RECEIVING STATION/UTILITY INTERFACE CONCEPT: ROCKWELL INTERNATIONAL

The ground receiving station (GRS) and utility interfaces are designed to effectively emulate existing power generation sources, such as hydroelectric, thermal, or nuclear plants. The fact that the electrical power is first converted from solar sources in space is irrelevant to the utility companies. The rectenna receiving panels, which cover 77.7 to 103.6 square kilometers (30 to 40 square statute miles), are treated as if they are merely another type of power source.

Redundancy of operation and flexibility in power distribution interconnections are the keynotes of the concept shown in figure V-7. More than 1000 rectenna "voltage strings" may be connected to each of the feeder lines. These may be selected in groups of as many as 55 feeder lines with as many as 16 groups of these lines. A number of groups may be interconnected as in the illustrated concept. Each panel is connected by motor-operated disconnects, which must accommodate 10 to 20 kilowatts each at high voltage; e.g., 40 000 volts dc. Thus, a large number of motor-operated disconnects may be required on the feeder lines alone; e.g., perhaps several hundred thousand or more.

Each feeder of each group may be connected to a dual redundant dc bus, which consists of main and transfer buses. The feeders connect to the dc buses by way of dual 40 000-volt dc breakers, which may have to conduct several hundred amperes each. The buses, in turn, are connected together by 40-kilovolt dc breakers, which must handle current loads of 10 000 amperes or more. Each group of power panels is protected by dual 40-kilovolt dc, sectionalizing breakers.

The dc buses feed into dc-to-ac (or dc-to-dc) converter stations. Each input line is provided breaker protection. For the dc feeder groups, an identical number of converter stations are provided. Each station converts several million watts of electrical power to 60-hertz ac and from 40 kilovolts dc to 500 kilovolts ac or dc. Each station will probably consist of a large building, perhaps one to two stories high by several hundred feet on a side. Advanced technology may allow application of solid-state conversion techniques, which would reduce both building size and system complexity. An advanced technology converter station presently operational at Newhall, California, may provide some insight as to station sizes, problems, and concepts.

In this SPS concept, a dual ac output bus is provided. The groups of feeder lines essentially emulate a multigenerator power station. The groups may be isolated to provide dedicated service to special customers whose applications may impose unique load surges or line noises. In this

event, each converter station could supply hundreds of megawatts of electricity at 500 000 volts ac. If dc power is required for the using utility, the converter stations would incorporate the additional rectification needed.

It is evident from this brief description that the size and complexity of the GRS imposes instrumentation and control demands similar to those of the satellite (table V-3). More than 390 000 rectenna panels are to be installed. A like number of motorized disconnects are needed. Temperature, voltage, and current measurements are anticipated on the panels to monitor conditions and outputs.

The hundreds of thousands of motor-operated disconnects will require computer control. In turn, the instrumentation and measurements subsystem (IMCS) must provide necessary command verification, switch position, and perhaps other information; e.g., temperature.

Thousands of switchgears are also needed to provide the breaker and contingency isolation protection needed to achieve a reliable consumer power system. Position, temperature, and reset controls must be provided. Although maintenance disconnects may be manual or motorized, the IMCS may be required to monitor conditions in either case to automatically establish system status and reserve capacity and to provide configuration and safety protection.

Finally, the converter stations are expected to be complex, advanced technology, high-power-level facilities. The resulting IMCS requirements are anticipated to be sufficiently extensive that the ground-based IMCS should be of the same order of magnitude as that used on the satellites. The spaceborne electronics technology approach may be transferable to the ground systems to meet the instrumentation and control challenges. Reduced unit costs may result because space qualification will be unnecessary, but this reduction could be offset by unique terrestrial environmental requirements of humidity, dust, windloads, rain, snow, ice, or lightning.

a. Ground Control Facility

The ground control center at the GRS site will control the uplink pilot beams, provide status and control of the GRS power distribution network and utility interfaces, and provide primary satellite control support. It is anticipated that it will be located at the GRS site in a separate building, which also would house administrative personnel, management and maintenance workers, and displays, computers, and controls.

The computer architecture concept shown in figure V-8 projects the use of multiprocessing units, which interface to the satellite through communications processors and to control/status operations through a common bus and terminal equipment. Real-time displays and related keyboard control/entry equipment would be incorporated into the design.

The center's functions and their allocations are beyond the scope of this introductory study. Some of the basic functions anticipated include the following.

(1) Operating system

(2) Data base control

(3) Data logging/storage

(4) Pilot beam control

(5) Satellite status monitoring

(6) Satellite control

(7) Power beam monitoring

(8) Rectenna site safety

(9) Intrusion control

(10) Telemetry control

(11) Rectenna power distribution

(12) Converter station status/control

(13) Emergency shutdown

    (a) Satellite

    (b) Rectenna

(14) Utility interface control/monitoring

b. Ground Operations

Operations begin with status confirmation and proceed to startup and steady-state phases. The satellite and ground systems are assumed to have been completely assembled, integrated, manned, checked out, and placed in standby status.

(1) Display and Control Thermal/Human Interface

The SPS ground system requires a high degree of adaptability in its ground operations center to meet the varying demands of the system. The operating scenario discussed herein has been oriented toward providing a basic representational understanding of the operator-machine interfaces.

In the initial system startup, man will interface with the system primarily to validate or stop system operations. The basic information that will be presented to the human will involve status and operational checks of all ground subsystems and a countdown to system startup. In addition, status summaries of all satellite subsystems will also be presented. The system initiation sequence will involve the use of both voice and displayed messages. These will be properly validated and authenticated.

The focal point of human decisionmaking and control is the display and control terminal. Augmenting this interface are the following.

(a) Communications

[1] Voice

[2] Teletype

[3] Computer-to-computer

[4] Written with manual transmission

(b) Management

[1] Organization

[2] Operating policies and rules

(c) Manual operations - space/ground onsite

Before startup of the satellite or the GRS, the configuration and status of the local control center must be determined by operations personnel. Displays will be assigned to various functions; e.g., communications, computer operations, satellite, and rectenna. Each of these consoles might be sequenced through various types of display formats and information content to assess the status of the following.

(a) Display electronics

(b) Keyboard functions

(c) Related data buses and external communications

(d) Supporting computers and software

(e) Data files

(f) Operating modes

Upon system startup, all power levels, beam focusing, beam dispersion, etc., will be monitored and checked to ensure that they are within predetermined levels. For elements of the system that will require

146

switching or shutdown faster than human reaction time, the system will operate in an automated mode to prevent damage tc any system elements and to maintain safety requirements. When time and policy permit, human intervention will be able to start, stop, validate, override, or branch any machine function.

Upon receipt of a requirements schedule and startup command from a higher echelon of authority (i.e., regional control center director), the aforementioned make-ready status assessment would be performed. Next, the GRS control center is ready to extend its information input and command authority to other interfaces; i.e., GRS and satellite.

(2) Sateilite Interfaces

Communications, telemetry, command, and pilot beam control interfaces to the satellite must now be exercised to ensure control integrity. Voice, telefax, and teletype links to and from the satellite are exercised with test messages to ensure functional readiness. Satellite computer (and backup primary instrumentation) data telemetry streams would be sampled to confirm high-speed downlink digital data functions as well as reported subsystem status. Ground-based pilot beam transmitter status is next checked. This scenario assumes that a spaceborne crew has completed satellite assembly and checkout and placed the satellite into a standby systems mode; i.e., only computer controls, communications, and environmental systems activated.

The GRS pilot transmitters are now activated and radiated power and pointing angles are verified. On the satellite, pilot receivers are turned on in response to enabling commands from the GRS control center. Downlink telemetry further verifies reception of the pilot beam signals and boresite.

Those elements of the detailed schedule of required operations, logistical support, and power demands that are needed by the spaceborne control center are transmitted by high-speed uplinks. These data are assumed to be prepared in the regional control center on a generalized basis and are refined to a detailed schedule at the ground control facility.

(3) GRS/Utility Interfaces

The GRS and its utility interfaces must be configured to receive the power which is converted and transmitted from the satellite. Rectenna panel status must be checked through instrumentation inputs related to temperature, mechanical integrity, and electrical continuity. Maintenance status must be reviewed to ascertain which panels are inoperative and to reroute any affected interconnections. Personnel must be notified and cleared from exposed areas within the rectenna site.

Power distribution to the utility interface is next configured. Feeder lines and bus switches are configured to route the scheduled power to the proper customer interfaces. The various groups of panels are appropriately interconnected on the dc buses to provide the required degree of

147

isolation. All bus connections, including backups, and breakers are checked. Orders are automatically issued to yard crews to establish correct switch positions for manual maintenance disconnect switches.

Status and control is next sequenced to dc-to-ac converter subsystems. The huge size, redundancy needs, and system complexity of the converter stations dictate that they incorporate their own dedicated computerized controls. Within this assumption, it is also presumed that digital data buses connect converter and rectenna control centers so that converter station readiness is automatically determined. Status is, of course, displayed to rectenna center control personnel, who may sequence their displays to examine in increased depth any specific areas of concern.

Converter stations are sent enabling commands to allow local control to turn on electronics to standby mode. Automatic sequencers and input power detectors are assumed to switch each converter station to operating mode as power is received from the satellite.

Finally, the ac bus switches are monitored for their status and appropriate commands are issued to establish the required distribution configuration. At this point, the ground systems are checked out and placed in standby or operating mode as appropriate.

Next, the regional control center and the utility distribution network control centers are sent standby status signals. Similarly, the satellite is also sent prestart "make ready" warning signals and appropriate enabling commands. Encryption is used for communications and command to ensure security against intrusions or takeover.

(4) Satellite Prestart "Make Ready"

The ground control facility is assumed to control the satellite through the master control center, which is located on the satellite. Control is effected through the satellite's distributed computer control and information management system. This configuration results in a higher level of control on the ground; i.e., enabling and scheduling of spaceborne activities in contrast to direct telemetered control. Only in contingency situations involving critical subsystems would direct preemptive control links be provided to the ground center.

Nevertheless, the spaceborne computerized control system must be polled to determine subsystem status. The ground center would also be expected to issue enabling commands, adjustments to performance levels, requests for specific pointing angles, system configurations, etc. Status polling would include structure, attitude control, solar panel conditions, power distribution, environmental control, and the spaceborne information management and control system. The latter would include operating modes of the various distributed computers, data bus ready condition, terminal equipment, software configuration, and data base contents. Any updates to the data bases would be provided from the ground control center. Such updates might include maintenance schedules, logistics planning, control system parameters, ephemeris updates, etc.

148

Status prestart operations would also include providing to the satellite systems various ground-based systems status data. This information might include pilot beam status and pointing parameters to facilitate acquisition and boresight.

Status checking would include issuance of enabling commands to the satellite IMCS to begin automatic sequencing checks. These would also bring nonoperating segments on line to achieve the required configuration of the various subsystems. When checkout is complete, a formal data logging command would be issued to record a sequential subsystems summary of satellite status into the ground center logs.

Where questionable status exists in various areas, the ground center might command prestored limited control actions on the satellite to test, debug, or verify system conditions. Prestart status and configuration operations involve hundreds of thousands of control and data points, requiring significant processing time even with automatic seque.icing. Satellite attitude refinement may involve long time delays, and the integration of space-ground prestart operations may amplify any such time delays. Special studies are needed to quantify these potential impacts on SPS operations.

(5) Satellite Startup

Startup control functions for s&tellite power production and transmission are automatically sequenced by the spaceborne compuLers. The ground control center does not play a direct role unless the onboard control system fails. In this event, direct ground control would be limited to performing emergency shutdown using separate control links in critical sysLems areas. Whether this control would be implemented through separate, direct telemetry command links, which bypass the onboard IMCS, is undetermined. Special operations impact and design feasibility studies are needed in this area to clarify this situation.

The ground control center would monitor startup sequencing to provide any necessary ground support to the satellite. This support includes antenna boresighting, pilot beam control, and initiation of power reception, conversion, and distribution to the utility customer interfaces. Special coordination functions may be needed from the ground center to avoid power surges and to provide load leveling. Emergency shutdown of satellite operations may also be required if a major ground system failure occurs.

Ground center support to satellite startup will generally parallel satellite systems sequencing, which begins with attitude control. The satellite may have drifted in attitude or geographical position. Ground center support to boresight and ephemeris updates based on precision observations are major elements of this type of ground support. This support may include revised satellite antenna gimbal angles to be inputted into the spaceborne data base. Attitude, stationkeeping, and boresight functions are expected to be long-term, repetitive operations which extend into steady-state operations.

149

Once boresight is achieved, the solar panels can be brought on line. This is a complicated operation, which is automatically sequenced by onboard computers. Ground center personnel would merely issue enabling commands once prerequisite spaceborne functional modes and system configurations are achieved and verified. Similarly, power distribution from the solar panels to the antenna is automatically implemented by onboard computers. This is also true of the voltage regulation process. Operations are only monitored on the ground. Preemptive ground support is required only if the onboard IMCS fails.

Antenna operations do require additional ground support because of boresight, alinement, and pilot beam functions. The mechanical pointing status of the antenna is verified during the earlier status checking phase. However, this status must be continuously rechecked during start-up to ensure safety and efficiency of power transmission.

Following boresight confirmation, enabling commands are sent to the satellite to turn on the reference phase frequency generator and related retrodirective control electronics. This procedure enables processing of the received pilot signals and initiation of power transmission. Earlier data base updates ensure insertion of the correct data to the beam programers.

Power beam monitors are located throughout the GRS site to provide an independent assessment of power beam pointing. Outputs of these monitors are computer polled and processed. Any residual pointing errors are translated into phase angle corrections and telemetered to the satellite for use by the beam programers within the retrodirective electronic control system. Beam location and drift rate are monitored for possible emergency shutdown of satellite operations if error boundaries are exceeded.

If the satellite startup coincides with termination of a solar eclipse, the ground center must confirm that battery recharging operations are initiated. If the satellite is projected to enter an eclipse, battery status must be verified. Use of klystrons for power transmission requires ample power for thermal stabilization (i.e., cathode heating) during eclipse periods.

Two operational considerations which relate to klystron activation must be investigated. If all klystrons are powered up simultaneously, power surges may be injected into the utility network. Simultaneous klystron energization is assumed to begin at low levels with power output gradually raised so that the ground power station can gradually come on line to full power output to the utility network. Coordination between the rectenna, regional, and utility network control centers is needed to ensure smooth load time history changes.

If klystrons are activated to full power with a given number of klystrons activated at a time, the impact on rectenna power output must be ascertained. Problems may result in coordination of panel grouping, conversion, and distribution. Unstable beam patterns, if resulting, could

150

cause power output transients to utility customers, distribution surges with undesired bus breaker activations, and unstable dc-to-ac conversion processes.

In any event, power startup operations between space and ground systems must be closely coordinated to ensure smooth power delivery. Excessive transients in the satellite and rectenna/utility interfaces must be avoided. The rectenna control center will automatically monitor the thousands of power conversion, distribution, and control points to effect adjustments or emergency shutdown as needed. Any unusual situations will be displayed to rectenna center operations in real time. Emergency conditions must be relayed to any regional and utility network command centers.

(6) Nominal Operations

(a) Satellite - At this point, the satellite has reached stabilized power production and transmission of that power to the rectenna. Power demands are constantly monitored at the GRS and transmitted to the satellite so that system surges can be mitigated and scheduled maintenance can be planned. For example, as midnight is reached at the users' locations, power demands reduce. Solar blankets, antenna components, or other related power production elements are removed from the line for replacement or repair on a progressive basis to avoid future unscheduled shutdowns.

Satellite and GRS status is constantly monitored so that any unscheduled power production or distribution changes can be accommodated. Constant communications - voice, data, and commands - are required between the satellite and the ground control center to achieve effective coordination.

Progressive maintenance inspections are performed on the satellite to ensure reliable operation. The IMCS is constantly monitoring the status of components. As out-of-tolerance conditions are noted, the affected element is scheduled for repair or replacement before failure. As a statistical basis is developed for predicting problem conditions, inspections and replacements are prescheduled at convenient times before the problem occurs. The ground control center is expected to provide some support through logistical scheduling and data base maintenance.

Scheduled outages occur during solar eclipses. These time periods can be used for minor repairs and replacements. Before each eclipse, coordinated planning occurs between the satellite and ground control center crews to develop a master maintenance schedule. Since an eclipse may last for a maximum of 1.2 hours, careful planning is needed to capitalize on this time for component replacements. Once replacement parts are installed and safe conditions are verified, selective activation of the affected subsystems is implemented to check out replaced parts in preparation for startup after the eclipse.

(b) Ground - In the ground operations phase, the satellite and GRS have reached stabilized power conversion and transmission to the utility network. The ground center will receive periodic updates

151

of scheduled power requirements from the utility network control center. These load schedules are translated by the ground center into satellite power output schedules, in which rf transmission, rectenna conversion, dc-to-dc conversion efficiencies, and related factors are considered. This scheduling facilitates matching of generated power to load levels.

If for some reason the entire utility network or a dedicated customer drops off the line, the SPS power output may be shut down, adjusted, or switched to other loads. The ground center must accommodate these and other contingencies such as problems in rectenna dc-to-ac conversion and distribution. Emergency shutdowns or load adjustments require transmission of authenticated commands, rather than enabling messages, to the satellite.

Progressive maintenance schedules and procedures are prepared by the ground center for rectenna, converter, and distribution maintenance. Similar schedules and procedures are prepared for the satellite. However, those related to the GRS will be detailed, whereas those for the satellite would be at a higher level. The onboard system and control center personnel would convert such inputs from the GRS center into the required detailed form.

Satellite tracking and ephemeris refinement functions are performed by the supporting rectenna satellite tracking subsystem. Eclipse and related systems schedules are then prepared based on these schedules, which include space-ground system startup, shutdown, and logistical support.

Several other safety, security, and environmental monitoring functions are performed during startup and steady-state operations. Safety will be of continuous concern. Before startup, maintenance and other types of workers must be evacuated from exposed radiation or high-power switching areas. Equipment must be properly configured and adjusted to avoid or investigate accidents or incidents. Particularly close monitoring must be maintained and safety shutdown possibilities must be preserved during startup because of the presence of rapid and large power transients. Required safety functions must be defined along with supporting caution and warning instrumentation and controls.

Security perimeters must be defined so that the GRS site, control center, and switching yards are protected from personal, command, and other forms of physical intrusion. Accidental or intentional intrusion of people must be presented by automatic detector, entry controls, and guard personnel. Command links must be encrypted and physically protected from accidental or intentional interference or takeover. Arrangements must be made with appropriate authorities to avoid beam interruption by overflights which might cause power transients in various portions of the rectenna, confuse beam location monitoring equipment, or interrupt the pilot beam.

Environmental monitoring will also take place during all phases of system operation. For example, radio receivers located within the neighborhood of the GRS (e.g., 48 kilometers (30 statute miles) radius)

will scan the radio spectrum for possible interference with radio or television bands and for other forms of radiofrequency interference (RFI). Inputs to the GRS control center may allow identification of malfunctioning SPS equipment to resolve any RFI problems. The SPS system design must minimize environmental im.acts to acceptable community levels. Electromagnetic interference (EMI) must also be monitored.

2. UTILITY SYSTEM REQUIREMENTS CONCEPT: GENERAL ELECTRIC

a. Utility System Operating Requirements

Currently accepted response characteristics for utility system generating plants have been the basis for establishing the integration of the SPS system with the existing utility systems. These requirements are defined and described in this subsection.

(1) Powerplant Operation on a Utility Network

The operating environment of a power generating plant is characterized by the following.

(a) Fluctuating and changing levels of connected load, aggravated by unusual loads or weather

(b) Changing powerplant status, both planned and unplanned, resulting in varying levels of available generation

(c) Network disturbances due to unplanned loss of generation or change in network configuration due to line switching

(d) Necessity to overgenerate or undergenerate to correct system time or adjust for inadvertent energy exchange on the lines

Random load changes (i.e., small in magnitude and occurring over relatively short time intervals) cause small deviations in generation load balance and result in small frequency deviations (from +0.02 to -0.04 hertz in the United States). Hence, one requirement for plant response is the necessity of frequency regulation.

Over longer timespans (i.e., days, weeks, years), variation in load occurs within larger tolerance; this variation is predictable as a function of time of day, day of week, and time of year. The necessity to maintain a match of generation with load over these larger variations requires that at least some plants have load-following capability.

The variability in connected load together with the economics of plant and system operation create the need to take units fully out of service, either daily or for more extended periods. Maintenance of the plant also creates a need to shut down and start up plants on a planned

basis. Hence, plant characteristics in startup and shutdown are an important operating consideration.

A mild emergency in a power system results from the un-expected loss of generation within a control area. The sudden inflow of power over tielines from adjacent control areas may exceed the thermal capacity of transmission line conductors. A small drop in frequency on the entire inter-connection also results. To restore the tieline loadings to normal and elim-inate the frequency deviation, the remaining generation in the area must be increased by the amount lost. Industry standard practices specify that this increase shall be accomplished within 10 minutes, and, in most utilities, this additional power must be provided by units already synchronized to the system. This requirement is referred to as tieline backup.

Major system emergencies may result in a loss of all ties to the remainder of the power system, leading to the isolation of a part of the system; i.e., the formation of an island. The isolated segment may be generation-rich (with a rise in frequency and a need to reduce generation) or generation-deficient (with a need for an increase in generation, load shedding, or a combination to restore frequency and permit resynchronization with the interconnection). A special case of islanding, referred to as load rejection, is the sudden disconnection of a unit or plant from the rest of the system, leaving the unit with no connected load. The unit is usually shut down by its overspeed protection. However, it is desirable (where possible) to cut back on unit power output to the level of the plant auxiliaries' load. It is usually desirable to resynchronize and reload the unit as quickly as possible if the load rejection has been caused by a malfunction outside the plant.

(2) Desirable Plant Response Characteristics

Operation of an interconnected power system places cer-tain control and maneuverability requirements on the aggregate generation in the interconnection; these requirements must be imposed ultimately on the individual units. Since individual units vary in their relative capability to maneuver and perform different functions in the overall economics of day-to-day operation, it is not possible to unequivocally define absolute response requirements. However, there are some general guidelines which can be used in the design of powerplants for use on electric utility networks. General guidelines which are desirable objectives in the design of a new plant con-cept are as follows.

(a) Each generating unit and its controls should be inherently stable under all combinations of pos-sible manual and automatic control while connected to the system. That is, under no circumstances should the stable operation of any unit depend on the characteristics of other units.

(b) It is highly desirable that each unit, if needed, be capable of assuming its proportionate share of load regulating and/or frequency regulating duty.

154

(c) Generating unit controls, in responding to external stimuli (such as frequency deviation or automatic generation control signals), should not impose on the unit an excursion which would cause the unit to lose control or to trip off the line. That is, control action should be limited to the amount of control to which the unit can respond without exceeding limits on process variables (such as water level, pressures, or temperatures).

Based on these guidelines, it is possible to specify quantitative goals for the control of individual generating units from an analysis of the aggregate system needs. In the following paragraphs, the aggregate system needs are quantified and the resulting requirements for response of individual units are stated.

(a) **Frequency regulation** - The requirements for frequency regulation are essentially those for speed governing of the prime mover. They are defined in industry standards and may be summarized as follows.

[1] A prompt stable response in change of power output of +1.3 percent or -0.7 percent of megawatt rating, with at least 30 percent of total change within the first 2 seconds

[2] A maximum deadband of 0.06 percent frequency (0.036 hertz on a 60-hertz system)

[3] A steady-state regulation of 5 percent (i.e., 20 percent change in power output for each 1-percent decrease in frequency)

These specifications apply only to the speed control and are based on the assumption that the energy supply is capable of meeting the demands made upon it as defined previously. In plants characterized by a complex energy supply, the overall plant control will respond to frequency deviation and will exercise a coordinated control over both prime mover and energy supply to meet the speed/load demand.

(b) **Load following** - For generating units that must adjust output to follow long-term load variations, a typical expectation is the capability to go from 100 percent power to 50 percent power at rates of 1 to 2 percent per minute over much of this range, and to make the total excursion over a 2-hour period and return in the same elapsed time. Peaking units (normally combustion turbines) are expected to load and unload over a range of 70 percent of rating in periods of 10 to 20 minutes.

(c) **Tieline backup** - Increase in generation for tieline backup is generally provided for spinning reserve (units already synchronized to the system). The 1- to 2-percent/min response rate cited for load-following duty is generally adequate for tieline backup.

155

(d) **Startup/shutdown of plant** - Just as different re-
quirements for load following exist for different types of units, a distinc-
tion is made for startup and shutdown rates. Peaking units, most likely com-
bustion turbines, are often used for nonspinning reserve to meet unexpected
sudden load increases; as such, these units should be capable of start to
full-load operation in 30 minutes or less. For intermediate-range steam
units, start to full-load operation in 1 to 2 hours is desirable. Baseload
units could take from 2 to 4 hours for a start following a brief shutdown and
6 to 10 hours following a more extended shutdown. Shutdown rates comparable
to startup rates would be permissible.

A plot of response rate in percent megawatts per
minute as a function of the number of minutes at which this rate can be
sustained, plotted on log-log coordinates, contributes to comprehension of
the preceding description. The transition from excursion-limited response
to rate limits over the range of normal operation conditions is illustrated
in figure V-9. Typical system emergency requirements are also shown.

(3) Operation of the SPS System

It is probable that the SPS system will operate at or
near full output as a baseload plant with a minimum of need for load follow-
ing. However, as the penetration of SPS on a power system increases, some or
all of the SPS plants would be required to have some load-following flexibil-
ity.

b. Utility System Reliability/Availability Characteristics

Historically, utility system planners measured generatio.. .ys-
tem reliability with a percent reserve index. This planning criterion simply
measured the ratio of total installed generating capacity to the annual peak-
load demand. However, this approach proved to be a relatively insensitive in-
dicator of system reliability, particularly when comparing alternative units
with varying size and forced outage rate.

Today, reliability of electric utility systems is commonly
measured by using probability mathematics. The most prevalent method is
called the "loss of load probability" (LOLP) method. The LOLP calculations
are relatively simple to perform using digital computers and allow different
generation expansions to be designed and compared on the basis of a common
level of reliability.

Generation system reliability is affected by several factors.
Among these factors are unit size, forced outage rate, and planned outage
rate. Although LOLP is concerned with the capability of the system to meet
the demand, utility system reliability is the net result of the individual
generating units and their reliability.

The LOLP calculation is performed by using a chronological
daily peakload forecast including measures of load forecasting uncertainty.
Each generating unit is represented by its rating, its probability of outage,

156

and its maintenance requirements. Conventional generating units are typically represented by a two-state reliability model. The two states are full output and no output, respectively, and the probability of full outage is defined according to the Edison Electrical Institute.

$$\text{Forced outage rate} = \frac{\text{Service hours}}{\text{Service hours} + \text{forced outage hours}}$$

The only conventional generating unit for which a multistate reliability model is normally required is a combined cycle unit made up from several gas and steam turbine units. The combined cycle unit, therefore, has the capability of producing power while parts of the plant are down for maintenance. Typically, a five-state model has been found sufficient to approximate the reliability model for a combined cycle unit.

The maintenance requirement is measured by a planned outage rate equal to the ratio of scheduled maintenance hours and the 8760 hours of the year. Since scheduled maintenance is a deterministic quantity, it is common practice to attempt to plan each individual generating unit's maintenance schedule in order to minimize the annual LOLP. This practice would result in scheduling of maintenance for the largest units on the system during low-load periods of the year. As the number of large units on a system increases, it is conceivable that additional reserve capacity would be needed because of some of the large units being scheduled down during periods of high risk.

3. INVERTER CONTROL AND OPERATION

    a. Power Conditioning System

        The power conditioning system that has previously been recommended for the SPS is the current-fed, line-commutated inverter. This type of system is in common use in high-voltage direct-current (HVDC) power transmission. The largest system presently in use supplies 3.4 gigawatts to the Winnipeg area in Canada. A larger system supplying 6.3 gigawatts is to be built in Brazil. Each of these large systems employs eight inverter circuits feeding . parallel into the ac systems. Although the individual converters are much larger and operate at much higher dc side voltage than the converters for an SPS system, they are quite similar in function and are completely compatible with the ac utility systems.

        These HVDC systems employ synchronous condensers for the same purpose as those recommended for the SPS system, namely the control of ac voltage and the supply of reactive power. Filters are employed to absorb the harmonic currents generated by the converters. The dc load presented to the rectenna assembly by such a converter is under control of electronic circuits. On the ac side, the converter appears as a constant-current negative load, which has proved to be completely compatible with the ac system.

157

b. Steady-State Control Mode

It has been recommended that the SPS should operate at full available output. To achieve this objective, the power conditioning unit must present to the rectenna the optimum load impedance. For a conventional antenna, this impedance is usually resistive in nature and is unique to the design of that antenna. It is assumed that the rectenna is basically no different and that there is an optimum dc load resistance for maximum power transfer. This relationship is shown graphically in figure V-10.

The current-fed, line-commutated inverter is controllable in a constant-resistance mode as shown in figure V-11. The dc voltage of the rectenna unit is sensed and divided by the current that is flowing, and the resultant resistance value is compared to a reference. The difference between reference and measured resistance is an error signal, which is fed to the firing angle control of the inverter. The load impedance reference can be adjusted for maximum power out of the rectenna. This adjustment should be independent of load level, as suggested in figure V-10.

Normally, the system would be operated at optimum resistance so that the rectenna would reflect a minimum of power. The power level would be adjusted at the satellite as indicated in the block diagram and would usually be set at maximum available power. If power reduction should be required by overall utility considerations and it could not be accomplished at the satellite, the converter power is readily adjusted by means of the impedance reference input. Of course, rf power would be reradiated, but that might be acceptable under the circumstances.

The converter module requires reactive power from the ac bus in approximate proportion to the active power being delivered to the utility network. This reactive power is supplied by static capacitors, harmonic filters, and synchronous condensers as indicated in figure V-11. Such compensation is state of the art in HVDC power transmission.

c. Normal Startup/Shutdown

(1) Synchronou, Condenser Start

Synchronous condensers, being large machines, require a starting procedure. If ac power from the transmission line is available, the condensers are started automatically using static frequency changing equipment. Auxiliary power, such as diesel engines, can be supplied for starting in the event that ac power is not available. In any case, when the machines are up to speed, they are connected to the ac system by means of their circuit breakers. If the ac system was previously energized, the synchronous condensers must be synchronized before breakers are closed. This is a state-of-the-art automatic process.

(2) Setting of rf Power to Start Level

The rf power should be set to a start level by one of the means at hand, any of which is acceptable to the converters.

158

(3) Sequential Energization of Converter Modules

The converter modules will be energized automatically according to a predetermined pattern. The rate at which they are energized will be determined by the capability of the ac system to absorb the generation without overspeed. The individual energization sequences will begin with closing of the ac breaker and will end with operation at maximum available power. The individual sequences will be controlled by computer subroutines.

(4) Increase of Power to Desired Level

When all converter modules have been energized and are operating at maximum available power level or some other level as directed by the central dispatch system the rf power can be increased to the desired operating level by any of the means available.

(5) Normal Stop

Any converter module can be deenergized by opening its dc circuit breaker. This action should be accompanied by a short-circuiting or crowbar action at the rectenna. It is understood that such action is to be provided on an automatic basis.

If the entire SPS is to be shut down, ac system considerations will dictate that it be done gradually, either by sequential and spaced shutdown of the modules from their operating level or first by reduction of rf level and then by module shutdown at a more rapid rate. In any case, the final condition will be that the synchronous condensers and filters alone are connected to the ac system.

d. Operation During Faults or Eclipse

(1) Faults

Faults can be divided into three categories: rf-rectenna faults, dc collection and converter faults, and ac system faults. Faults in the satellite systems will result in decreased rf power level, which will be reflected in decreased ac output of the converter. There will be no other disturbance. When rf level is restored, the converters will automatically respond.

For best protection, the dc breaker will be located as near the rectenna as possible. Any fault in the dc bus work between the dc breaker and the converter or in the converter itself will result in tripping of the dc breaker, which will cause short circuiting of the rectenna system. The converter will be arranged so that its ac breakers are opened as a result of any such dc fault. These dc faults result in permanent shutdown of the module pending determination of cause of fault and manual reset and restart.

An ac system fault, usually from lightning flashover somewhere in the ac system, will sometimes result in a temporary inverter

159

functional disorder known as a commutation failure. The inverter appears as a temporary short circuit to the dc source with complete loss of power to the ac system. These commutation failures are temporary and do not involve any arcing or current in other than normal paths. Automatic sequences will restore the converter to normal operating conditions when the fault has been cleared.

(2) Semiannual Eclipse

Performance during the semiannual eclipse periods can be made largely automatic. As rf power decreases during the partial eclipse period, the converter, through its constant-resistance load characteristics, will track the rectenna output and provide available power. Before totality occurs, it will probably be advisable to go through a normal shutdown sequence. As available power level again increases, restart sequences can be initiated with power level returning to normal automatically.

The principal problem during these eclipse periods will be power dispatch in the ac system to preserve load and frequency. A mitigating factor will be that the power loss occurs at night when the ac system is most capable of responding to it.

4. SPS/UTILITY SYSTEM INTEGRATION

a. SPS Operating Characteristics

The power control methods for the SPS were examined in relationship to the desired response and in terms of impact on SPS operations. Two were deemed both practicable and acceptable by these criteria: the introduction of a quadratic phase error to the antenna aperture and the tilt of the antenna phase. Both provide a satisfactory range of power control and an acceptable time response.

For comparison with the response of current generating plants, the SPS response for both methods has been plotted in figure V-9. The plot is reproduced in figure V-12. It is seen that the SPS response for either method of power control is better than that for conventional generation. No evaluation has been made of other environmental impacts from either of these two control modes.

b. Utility System Integration

(1) SPS Impact on System Design and Integration

Power generating units connected into a large power system become an integral part of that system and are affected by a number of conditions and controlling influences to which they would not be subject if they were simply serving an isolated load. The SPS system will be similarly affected when connected to a utility system.

A power system never operates at a point of true steady state and thus is always characterized by dynamic behavior. This state has

160

a primary impact on the operation and design of controls for both generation and distribution. Whenever a change in operating condition or a disturbing event occurs in a power system, there is a nearly instantaneous change in the state of the electric and magnetic fields of the system, followed in seconds and minutes by the longer term electromechanical response of the rotating elements of generating sources and loads.

The SPS is unlike conventional generation in that it has no mechanical inertia and hence appears as a negative load to the system. Furthermore, the rectenna-inverter control proposed will act to transmit to the utility system all the power incident on the rectenna. Control of the incident power will be at the satellite antenna by way of the space communications link as indicated in figure V-11. This control loop, involving transmission of control signals through space, is the nearest analog of governor control of a conventional generation source.

It is assumed that the SPS system will be operated at the maximum level of available power most of the time. In the baseline design, there is no control of power level responsive to frequency variation and therefore the SPS will not contribute to the regulation of system frequency. It should be pointed out that additional control functions could be included to provide that contribution, either by control of the antenna in space or by control of the rectenna-inverter combination on the ground, to vary power output. This provision would require operation at a power level ~1 to 2 percent below maximum available in order to provide a margin for increased power with decreasing frequency. Either approach results in increased radiation around the rectenna, either from the broadened beam width or from reradiation at the ground. If this condition is acceptable, it should be considered. Without contribution by the SPS to frequency regulation, additional duty will be imposed on the other generating units on the utility system, with a corresponding requirement for even higher response from those units. In either event, it appears that the other units on the network must have the capability to respond to load-following requirements and must provide the capacity for tieline backup.

Finally, the operating characteristics of the SPS system, especially the control of output power from the rectenna, require a high reliability of transmission connections to the load areas. Utilities will have to perform more extensive transmission planning studies and to provide increased transmission facilities to ensure the integrity of power absorption from the SPS.

(2) SPS/Utility System Interface and Power Transfer

The interface between the SPS as a source of generation and the utility system is uniquely different from conventional generating plants because of the absence of a prime mover. This difference will become more apparent through the following simplified analysis.

In the analysis of ac electrical systems, the angular relationships or phase angles among the voltages and currents are required.

The use of phasors for graphical representation assists in understanding the analysis.

Consider the simple ac circuit in figure V-13(a), with the relationship between the two voltages and the current expressed in the adjacent phasor equation. If $\widetilde{E}_1 = \widetilde{E}_2$ (magnitude equal and coincident in phase), no current will flow ($\widetilde{I}_L = 0$) and the equation is satisfied.

If $|\widetilde{E}_1| > |\widetilde{E}_2|$ (magnitudes different but still coincident in phase, as shown in fig. V-13(b)), a current I_L will flow through the reactance X_L. The phase angle of $\widetilde{I}_L$ will lag the voltage drop across the reactance X_L ($\widetilde{E}_1 - \widetilde{E}_2$) by 90°. Note that with current and voltage in quadrature, no real power flows, only volt-ampere-reactive (var) power.

To transfer real power (watts) across the reactance requires an angular difference between the voltages $\widetilde{E}_1$ and $\widetilde{E}_2$ as shown in figure V-13(c). Now, the current I_L has a component in phase with the voltage and there is real power flow.

The interface between the SPS ground system and an electric utility may be represented by the simple one-line diagram of figure V-14(a). Power is transmitted across a transmission line to the system, which is represented by an infinite bus. The synchronous condenser (SC) is operated with a field regulator to control the voltage on its bus and therefore the flow of reactive power Q (var) in the system.

For a particular real power flow, determined by the inverter firing angle control, the relationships among the voltages and currents is illustrated by the phasor diagram of figure V-14(b). This is a graphical representation of the phasor equations shown.

If the energy capture by the rectenna increases, the inverter will be controlled to transfer greater power to the utility system over the transmission tie. An increase in the ac current from the inverter I_A causes changes in the magnitudes and angular relationships of currents and voltages (except where constrained). This state is shown in the new phasor diagram of figure V-15, here superimposed on the prior diagram from figure V-14(b). Note that the magnitude and phase of an infinite bus are fixed and that the synchronous condenser bus voltage V_B is unchanged in magnitude. Notice also that there is no change in mechanical power level involved here; there are no finite rotating masses to accelerate or decelerate. The change is solely an electromagnetic transient measured in milliseconds; hence, the characterization of an SPS as a negative load on the utility system.

(3) Utility System Controls

Individual utilities have found it advantageous to interconnect their systems by means of transmission tielines. This procedure provides flexibility in terms of sharing generation capacities and increased reliability of operation. When tnis procedure is followed, systems that form

162

an interconnection will be locked in synchronism, and, aside from occasional short-lived local oscillations, the frequency will everywhere be the same.

Multiple control areas within an interconnection are operated to continually control generation to meet loads and regulate the flow of power across the tielines into or out of adjacent control areas. The geographic boundaries of control areas usually follow corporate lines.

Automatic generation control (AGC) with the economic dispatch function shown schematically in figure V-16 is used to augment the system operator's capabilities to assure satisfactory operation of the power system in each control area. The AGC acts to regulate the power output of the electric generators within the control area in response to system frequency and tieline power flows so as to maintain the scheduled system frequency and the established net power interchanges within prescribed limits.

The economic dispatch function acts through the AGC function to adjust the output levels of individual generating units to achieve maximum economy of system operation, taking into account the cost of unit operation, transmission system losses, and current operating constraints. The action of AGC is illustated in figure V-17 by simulation in a hypothetical utility control area of 4 gigawatts generation capacity (1.25 gigawatts in group A, which is controlled by the AGC; 2.75 gigawatts in group B with no AGC).

At time equals zero, load is increased by 50 megawatts (or 50 megawatts of generation is lost). The line flow from adjacent area 2 into area 1 increases to almost 50 megawatts. The system frequency dips, because of a generation deficiency, and governor action on both groups of generators results in an increase in power output. This increase, together with the tieline flow, supplies the load demand.

The AGC action (on unit group A only) raises its output over a 5-minute period to restore the tieline flow to zero and the system frequency to 60 hertz. Note that unit group B, not under AGC, returns to its original output level with the restoration of system frequency.

If group B was a solar power satellite, its output would be totally unaffected by this sequence of events. This condition would result in an initial tieline flow of 50 megawatts and hence increased regulating duty on the units in group A.

Generating plants in a utility network are operated under the direction of a company dispatcher, who in most instances is provided direction from a power pool center, and with the assistance of an automatic generation control system. Telemetering of power flows and voltages provides system dispatchers and pool operators a current picture of conditions on the network. As loads and power flows change, generating levels are changed (a) to maintain system frequency, (b) to load generating units within ratings and according to the most favorable economic considerations, and (c) to limit line flows to meet rating or stability considerations. The solar

power satellite, representing a significant block of generation in any operating utility or power pool, would be under the direction of such operations, as shown in figure V-18.

It is estimated that there will be 12 operators and 50 maintenance people on duty at all times. This estimate results in a total of 333 (108 operators and 225 maintenance) people at each rectenna site. It is also estimated that there will be 165 people required in the rectenna/ground operations group and 240 people in the SPS operations group when 20 satellites are operational.

c. SPS/Rectenna/Utility System Reliability Impacts

To study the impact of adding SPS generation to utility systems in the future, several assumptions had to be made. The first assumption is to use the probability of available power curves from the SPS system developed in Phase I as the starting point for the utility investigations. The curves developed in Phase I are shown in figure V-19, and the circles marked indicate the "breakpoints" for adapting the curve to available utility models.

To enable relating to utility system size, a study was made of the growth projections found in reports from the various National Electric Reliability Council (NERC) regions. Figure V-20 is a map indicating NERC region boundaries. In the first column of table V-4, the 1998 capacity forecast in each region is shown. By using the growth projections from 1989 to 1998, the second column was calculated as a year 2020 estimate. The last column indicates as a benchmark the number of SPS rectennas that would be in each region with a 20-percent penetration.

To study the SPS reliability impact, the smallest region size in year 2020 was chosen, and the assumed generation mix in the study system is shown in table V-5. It should be noted that this mix is not relating to the Mid-Atlantic (MAAC) projections for the future. The mix would be more indicative of an average U.S. mix. The forced outage rates shown are assumed to be for mature units and are representative of current technology levels.

The five-state reliability model for the SPS based on figure V-19 is shown in table V-6. This model may be regarded as the most optimistic interpretation of figure V-19 and gives an impact on the utility system reliability as shown in figure V-21 marked "Midterm." To evaluate the SPS reliability model on a parametric basis, the data in table V-7 were developed. The first line in the table consists of the table V-6 values, and the rest of table V-7 shows a more conservative approach to modeling figure V-19, particularly in the areas of full outage.

It is obvious that the estimates for the probability of full outage will have the most effect on the utility system reserve levels. Only a modest estimate of 1-percent probability of 5000 megawatts output will cause a deterioration of utility system reliability, as indicated by increasing reserve levels with penetration. Several causes for power outages are not explicitly included in figure V-19, and further work should be performed in

the area of utility system reliability impacts as the SPS design and operational characteristics are further refined and developed.

d.   SPS/Rectenna/Utility System Maintenance Impacts

Generating unit maintenance is performed in an attempt to match the available maintenance personnel with the need for leveling risk (LOLP). Since the SPS output will be affected by the eclipse period in March and September, one first approximation would be to attempt to maintain all the SPS powerplants during these 2 months. To investigate whether this procedure would be feasible from a utility system point of view, the NERC regional data were used as a study base. The monthly peakloads in September and March as a percentage of the yearly peakloads are shown in table V-8. In view of the data, September appears to be of a greater concern than March.

The margins between maximum available generation with all SPS (25 percent penetration) on maintenance are indicated in table V-9. In all but a few regions, September has negative margins, whereas March indicates no particular trouble. If feasible from a space maintenance point of view, March would be acceptable and September would need extra reserve installed to take all SPS down on maintenance. One additional factor to keep in mind is that maintaining all SPS's in these 2 months would force all other generation maintenance into the remaining 10 months.

Monthly peakloads may also vary significantly from one utility to the next. This fact is illustrated in figure V-22, where two regions, Energy Reliability Council of Texas (ERCOT) and East Central Region (ECAR), are plotted. It is obvious that ECAR with perhaps 14 SPS's would have a significantly harder time scheduling maintenance without adding to their reserve margin than would ERCOT. From an operational integrity point of view, it would be important to make sure that there always would be adequate conventional generation connected to perform the regulating duty. On the whole, however, with the SPS maintenance spread uniformly over the year, it does not appear from these investigations that maintenance scheduling would adversely impact utility system reliability or operational integrity.

165

TABLE V-1.- GENERAL TASKS PERFORMED BY INTEGRATED OPERATIONS

General task	Description
Identifying, defining, and allocating overall program requirements	Based on study and test results in combination with national needs, identify overall program requirements.
	Analyze requirements and allocate to local operations.
	Prepare program-level documentation (system specifications, program requirements documents, program directives).
	Allocate responsibilities for preparation of lower tier documentation among local operations.
	Review and approve lower tier documentation as necessary.
Preparing master program plans and schedules; monitoring program performance against these	Prepare, coordinate, and implement master plans and schedules of program activities which will assure a program that meets all requirements in a timely fashion.
	Obtain detailed plans and schedules that comply with masters from each local operation.
	Set up system for feedback of plan and schedule performance from each local operation.
	Set up system for monitoring plan and schedule performance which will flag problems.
	Resolve programmatic problems and/or problems which involve interfacing local operations.
	Assure coordination among operations.
Assuring satisfactory technical performance	Monitor technical performance at program level.
	Review studies, analyses, test results, orbital performance.
	Conduct periodic technical reviews.
	Resolve technical concerns.
	Apply additional technical resources.
	Reallocate requirements among program elements.
	Review and modify requirements.
Preparing master logistics plan for program	Obtain logistics requirements from local operations which they must have to comply with program requirements.
	Prepare, coordinate, and implement master logistics plan and schedule.
	Obtain complying detailed plans and schedules from each local operation.
	Set up logistics status reporting system for local operations.
	Monitor, logistics status with respect to plans and schedules.
	Materials, equipment, propellant flow
	Inventories
	Spares
	Use rates
	Resolve program-level problems and/or problems which involve interfacing local operations
Preparing and maintaining master power generation plan and schedule	Prepare master plan and schedule for satellite-rectenna/grid combinations and operations. Plan must consider
	Rectenna/grid power loading schedules
	Eclipse seasons
	Rectenna maintenance schedules
	Satellite maintenance schedules
	Contingencies

TABLE V-2.- MAINTENANCE ACCESS PROVISIONS

Location	Maintenance operations	Alternative access systems
1. Main power buses	Main bus repair	Flying cherrypickers mounted on annealing machine gantries
	Switchgear replacement	Track-mounted flying cherrypickers
	Blocking diode replacement	
2. Solar collector nonmidline bay ends including outside edges)	Blanket tensioning device replacement	Cherrypickers mounted on annealing machine gantries
	Blanket mechanical attachment replacement	Track-mounted cherrypickers
	Jumper bus repair	
3. Attitude control system	Electric thruster system repair	Track-mounted cherrypickers
	Chemical thruster system repair	Long-boom (500 m) cherrypicker
		Free flyer
		Platform-mounted flying cherrypicker
4. Interface structure upper surface	Main bus repair	Track-mounted cherrypicker
		Free flyer
5. Mechanical rotary joint decimeter	Drive mechanism repair	Hub-mounted boom with flying cherry-picker
	Drive motor repair	

167

TABLE V-2.- Concluded

Location	Maintenance operation	Alternative access systems
6. Slipring assembly	Slipring shoe replacement	High-mounted boom with flying cherrypicker
	Mechanical drive replacement	
	Drive motor replacement	
	Bus repair	
7. Yoke (power bus side)	Power bus repair	Track-mounted flying cherrypickers
	Elevation joint mechanism repair	Free flyer
8. Antenna back face	Power bus repair	Gantries with flying cherrypickers
	Switchgear repair	
9. Antenna primary structure interior	Power conductor replacement	Free flyer
		Gantries with flying cherrypickers
10. Antenna front face	Klystron tube module	Maintenance gantries defined in the earlier study
	Phase control system repair	

168

TABLE V-3.- PRELIMINARY INSTRUMENTATION AND CONTROL REQUIREMENTS

Device	Function	Rating		Quantity
		Voltage, kV	Current, A	
Rectenna panels	Measurement of temperature, voltage, and current	--	--	>390 000
Motor-operated disconnects	Verification of commands and switch positions; measurement of temperature	40 dc	0.3	>390 000
Switchgears	Control of switch position, current, temperature, etc.	40 dc	400	1 760
			10 000	16
		500 ac	700	32
			800	16
			10 000	(a)
Converters	Conversion of current; trans-forming of voltage	40 dc to 500 ac	800	16
		40 dc to low voltage	--	(a)

[a]To be determined.

TABLE V-4.- NERC FORECAST OF BULK POWER SYSTEM CAPABILITIES

Regional reliability council	1998 forecast, GW	2020 estimate, GW	No. of satellites at 20-percent penetration
Northeast (NPCC)[a]	83	130	5
Southeast (SERC)[a]	258	550	22
Southwest (SPP)	138	380	16
East Central (ECAR)[a]	194	365	14
Mid-Atlantic (MAAC)	69	100	4
Mid-America (MAIN)	94	210	8
Mid-Continent (MARCA)	55	125	5
Texas (ERCOT)	87	200	8
Western (WSCC)	222	440	18
Total	1200	2500	100

[a]Winter peak.

TABLE V-5.- SAMPLE ELECTRIC UTILITY SYSTEM

No. of units	Generation type	Unit capacity, MW	Forced outage rate	Total output,[a] MW
100	Peaking	100	0.05	10 000
20	Hyd-oelectric	500	.01	10 000
20	Midrange	500	.04	10 000
45	Base fossil	1000	.13	45 000
25	Base nuclear	1000	.09	25 000

[a]Total system output: 100 000 megawatts.

TABLE V-6.- UTILITY SYSTEM RELIABILITY[a]

Outage level MW	Probability of megawatt output
0	0.1
250	.56
610	.33
1440	.01
5000	0

[a]SPS reliability model, five state representation.

TABLE V-7.- SPS RELIABILITY MODEL

Case	Probability of megawatt output for outage level, MW, of -				
	5000	1500	700	200	0
Mid-term	0	0.01	0.33	0.56	0.1
1	0	.30	.40	.20	.1
2	0.01	.29	.40	.20	.1
3	.02	.28	.40	.20	.1
4	.03	.27	.40	.20	.1

TABLE V-8.- NERC PEAKLOAD REQUIREMENTS

Regional reliability council	Fraction of annual peakload, percent	
	March	September
Northeast (NPCC)	85.4	90.7
Southeast (SERc)	84.1	94.6
Southwest (SPP)	62.8	93.3
East Central (ECAR)	89.7	93.4
Mid-Atlantic (MAAC)	78.2	90.2
Mid-America (MAIN)	70.6	89.3
Mid-Continent (MARCA)	75.8	84.9
Texas (ERCOT)	63.0	94.5
Western (WSCC)	88.2	96.3

TABLE V-9.- SPS SCHEDULED MAINTENANCE: IMPACT
ON RESERVE LEVELS FROM SPS SHUTDOWN IN MARCH
AND SEPTEMBER[a]

Region	"Maximum peak," percent	Margin, percent	
		March	September
Northeast	90.5	5.1	-0.2
Southeast	90.5	6.4	-4.1
Southwest	90.5	27.7	-2.8
East Central	90.5	.8	-2.9
Mid-Atlantic	90.5	12.3	.3
Mid-America	90.5	19.9	1.2
Mid-Continent	90.5	14.7	5.6
Texas	90.5	27.5	-4.0
Western	90.5	2.3	-5.8

[a]Assumptions: 25 percent SPS penetration;
15.5 percent generation reserve.

173

Figure V-1.- Integrated maintenance mission concept.

- Transfer crew and mobile maintenance equipment to next SPS

- Transfer replacement components to SPS

- Transfer crew and mobile maintenance equipment to SPS

- 3-1/2 days maintenance visit each SPS

- Return defective components to GEO base

- 1 day transfer and setup

- Transfer components to SPS and return defective components to GEO base

- Transfer replacement components to GEO base with EOTV's along with construction components

- Return crew and mobile maintenance equipment to GEO base

- 20th SPS

- Deliver maintenance crews to LEO with PLV

- Deliver replacement components to LEO with HLLV

GEO base
- Refurbish defective SPS components
- Staging base for mobile maintenance crew and equipment
- Staging depot for OTV's transferring components to/from SPS's

- Return EOTV to LEO base for reuse

- Return maintenance crew to LEO base

- Deliver maintenance crews and supplies with liquid oxygen/liquid hydrogen OTV

- Return crews and reusable equipment to Earth

LEO base
- Transfer replacement components to EOTV
- Transfer crew to POTV

174

Figure V-2.- Manned work module, free flying or stationary.

Docking ring (2 places)

Attitude control quads (RCS)

Lights and TV camera module

Bilateral manipulator arms

Docking/grabber arms

Very high frequency antenna

Modular fuel cells

Component supply platform

175
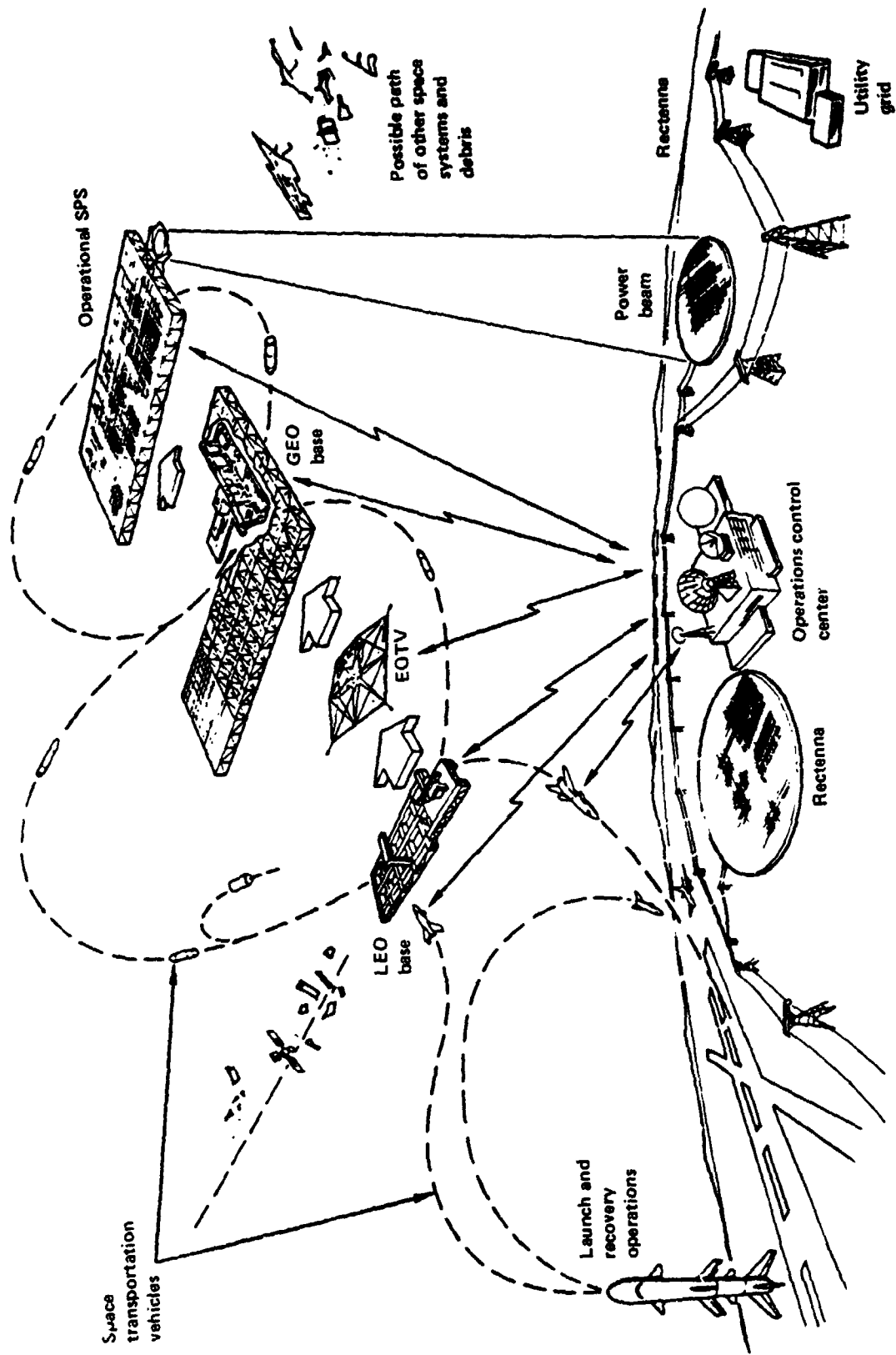
Figure V-3.- SPS operational system.

176
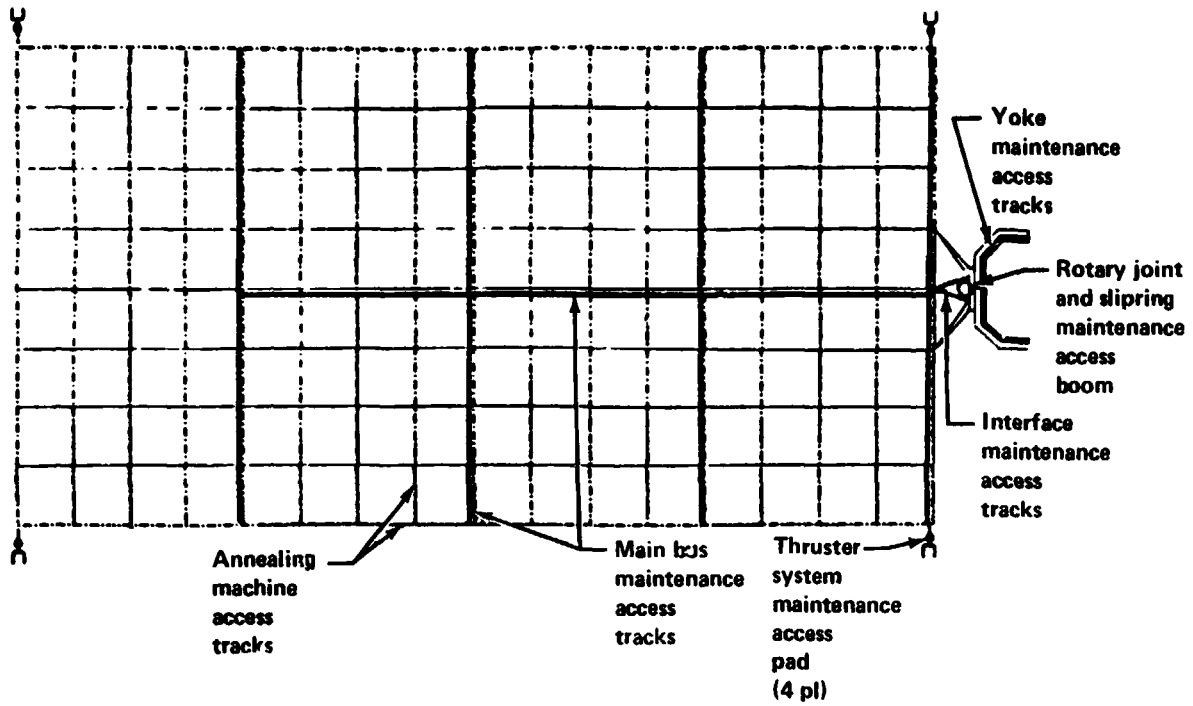
Figure V-4.- SPS maintenance access systems.
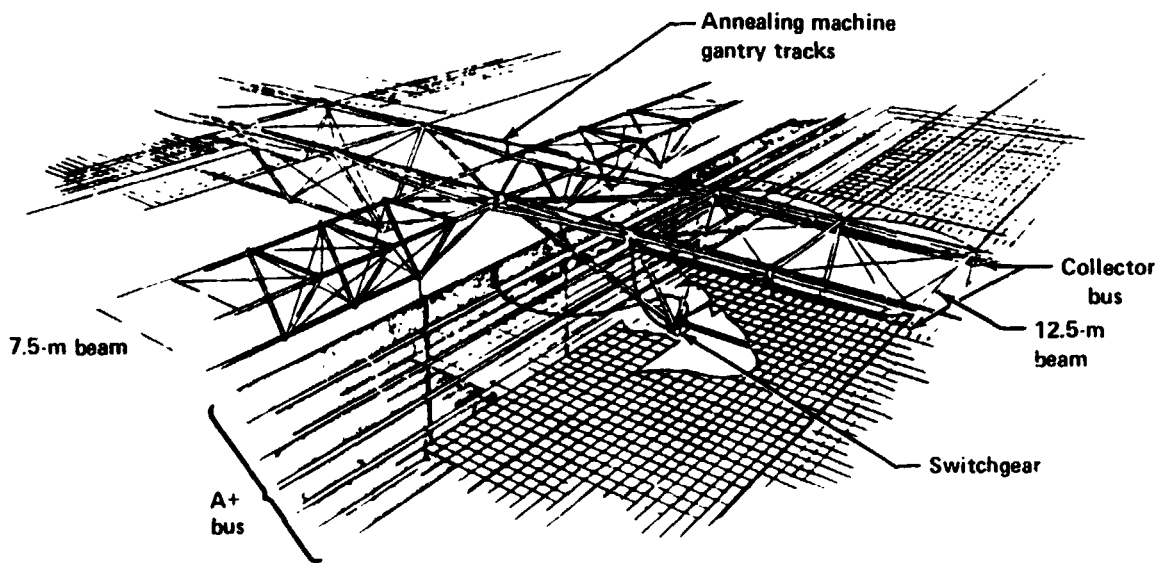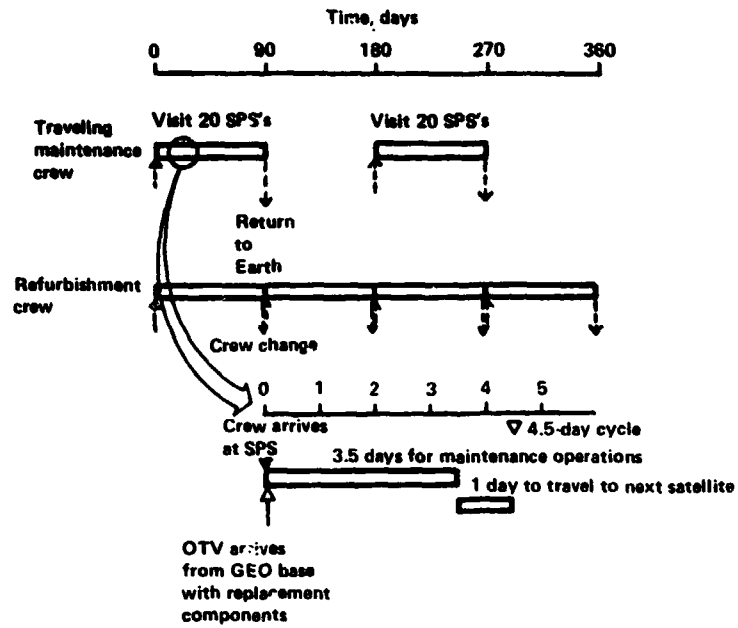

Figure V-5.- Power collector configuration.
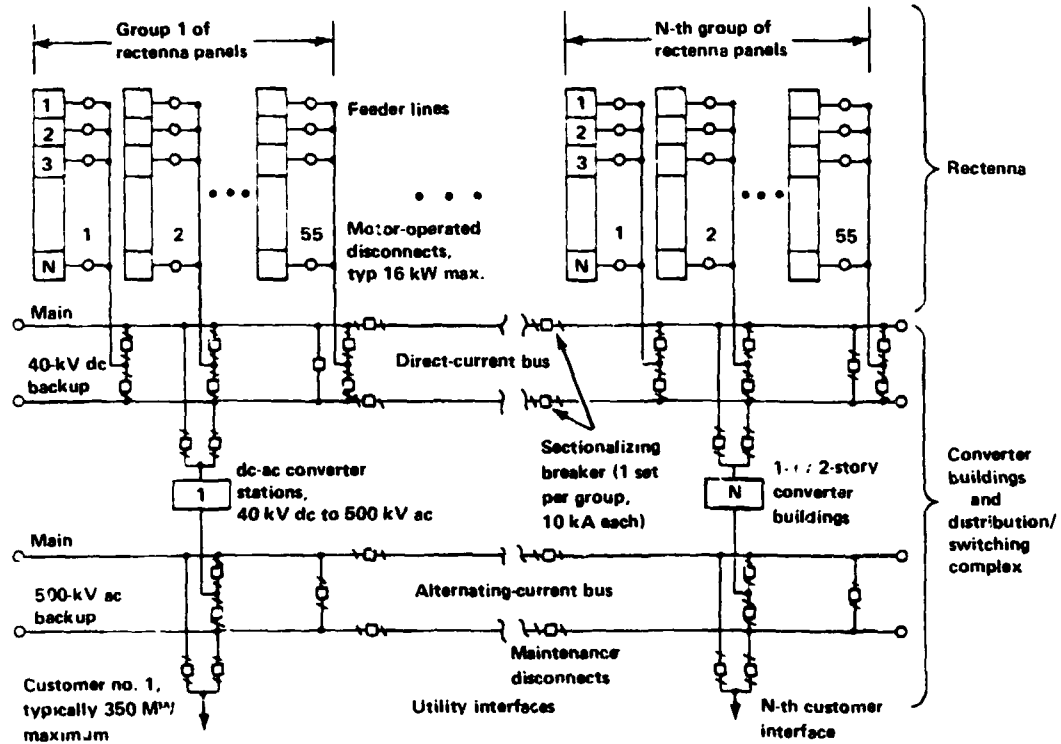
Figure V-6.- SPS maintenance time line.

Figure V-7.- Rectenna panels and power distribution interfaces to utility customers.
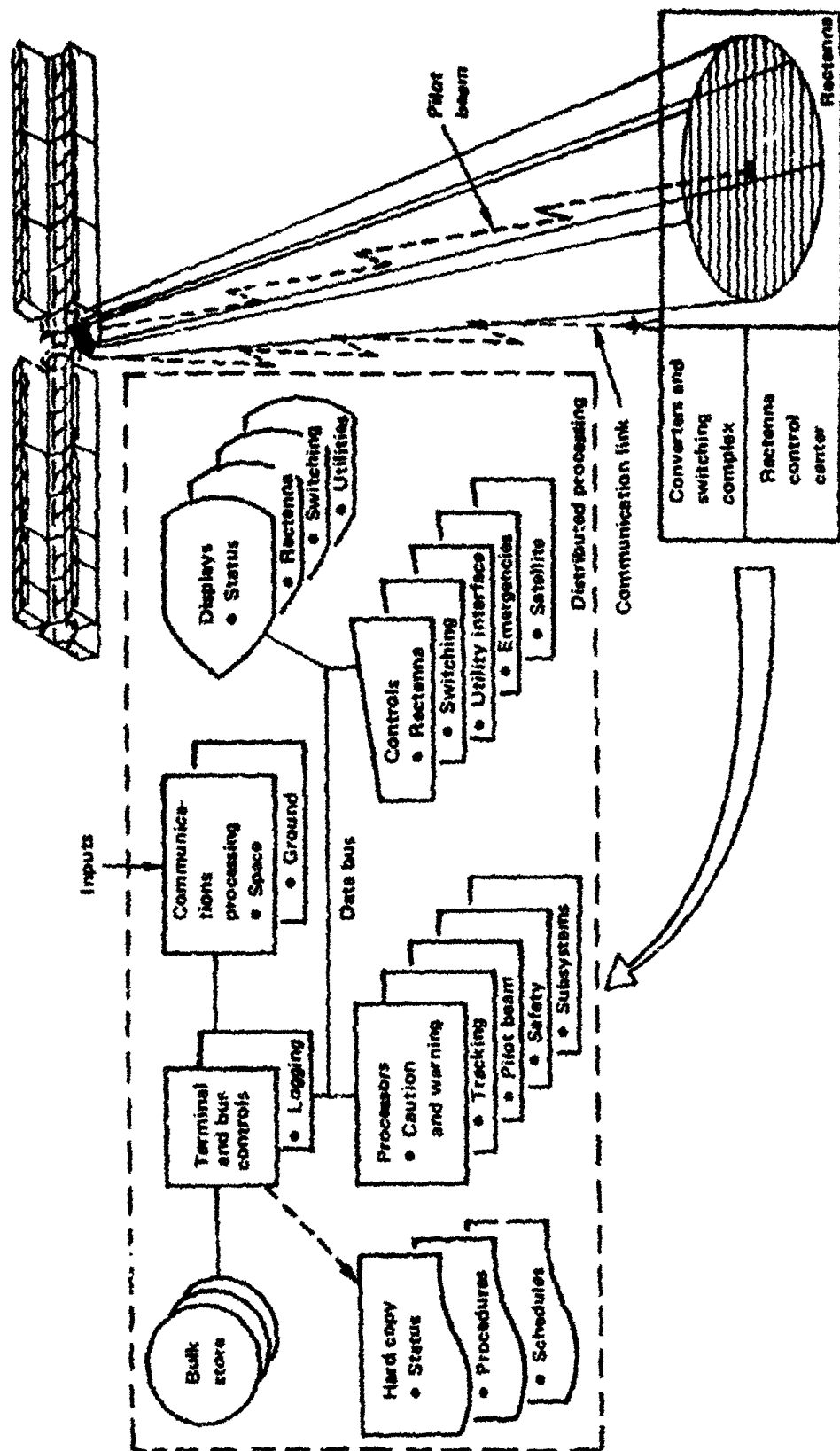
Figure V-8.- Ground receiving station rectenna control center concept.

179
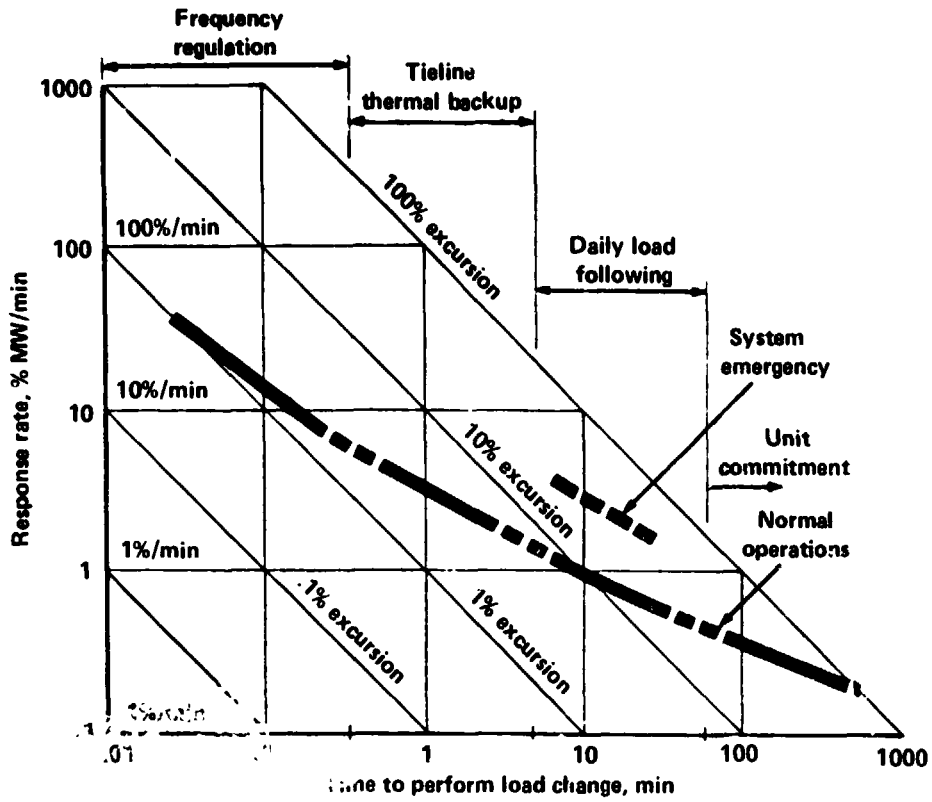
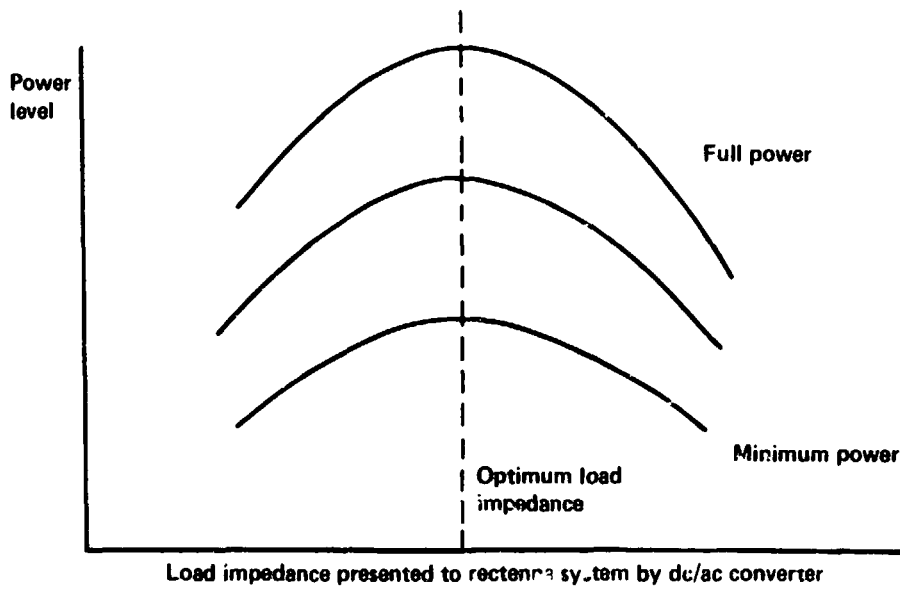Figure V-9.- Maneuvering requirements of generating units for utility system operation.

Figure V-10.- Assumed characteristic curves of rectenna system power output as a function of load impedance for several constant levels of radiation.
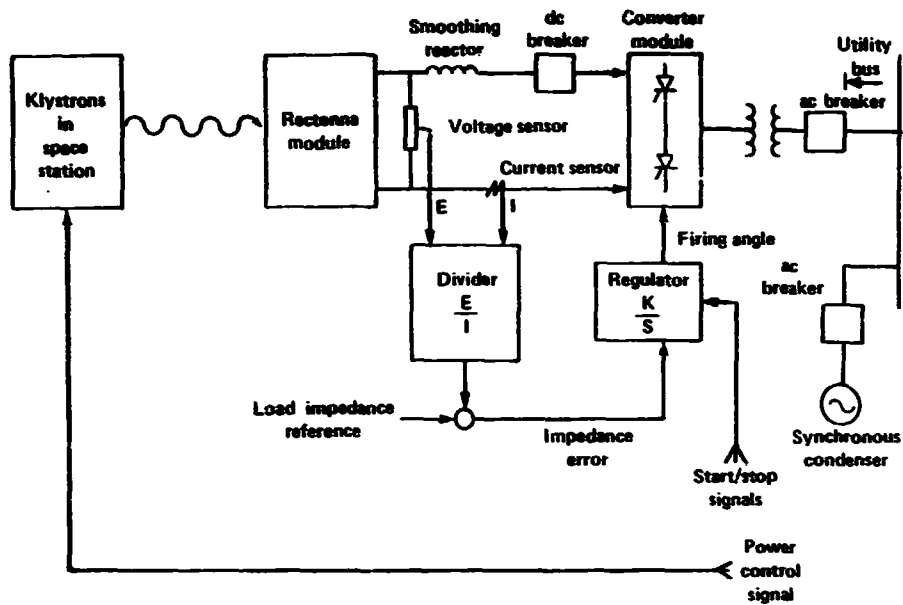
180

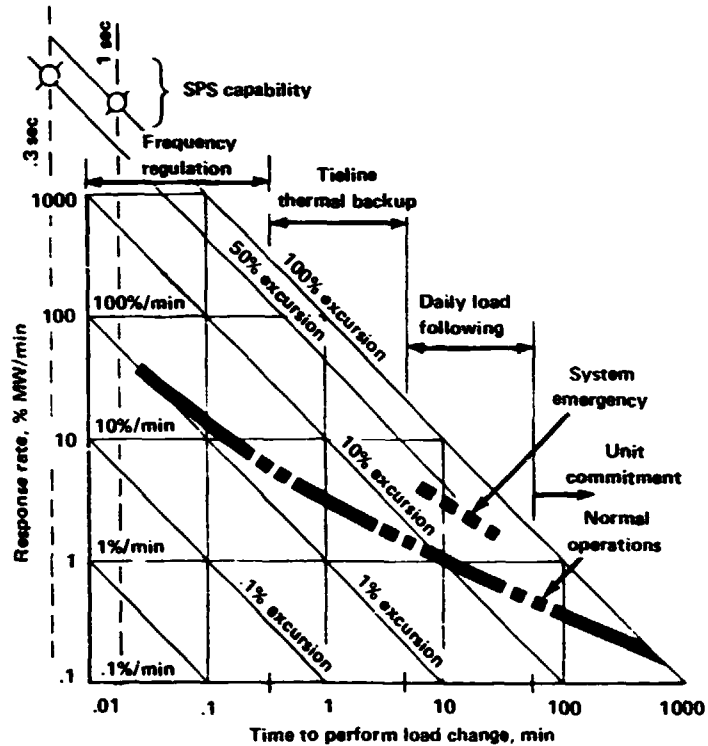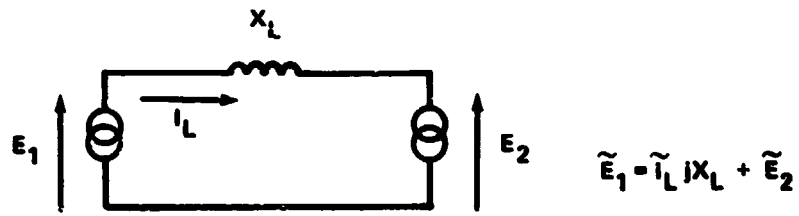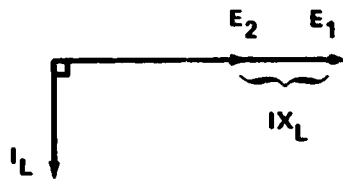Figure V-11.- Satellite/rectenna/utility control scheme.

Figure V-12.- SPS capability compared with maneuvering requirements of conventional generating units for utility system operation.
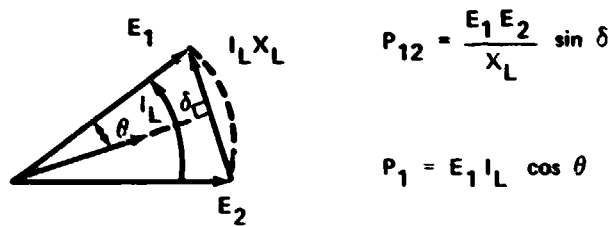
C - 3

$$\widetilde{E}_1 = \widetilde{I}_L \, jX_L + \widetilde{E}_2$$

(a) No current flow.

(b) Volt-ampere-reactive (var) flow.
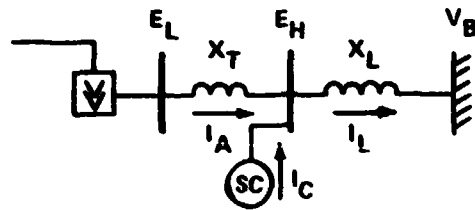

$$P_{12} = \frac{E_1 E_2}{X_L} \sin \delta$$

$$P_1 = E_1 I_L \cos \theta$$
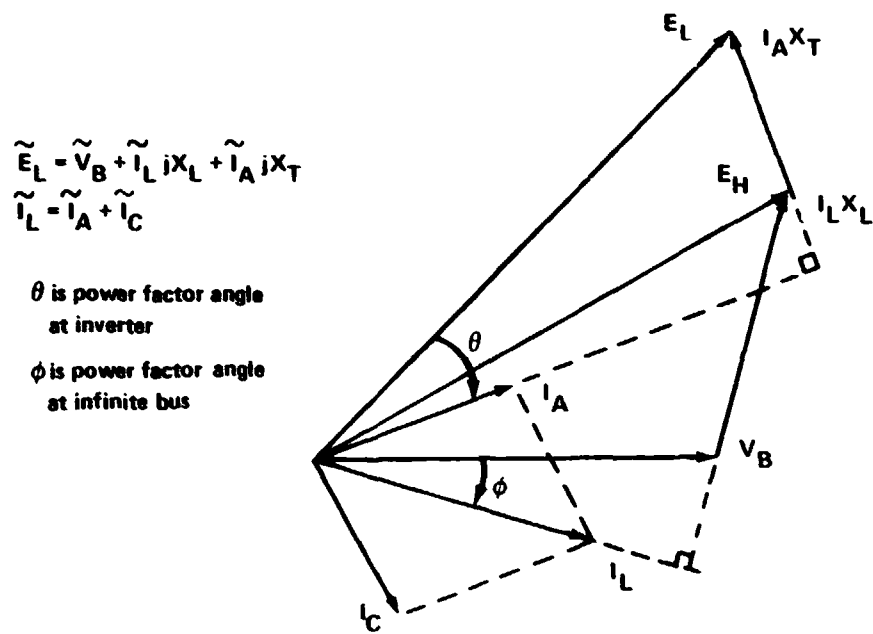
(c) Real power flow.

Figure V-13.- Graphical representation of alternating-current quantities.

(a) Var flow.

$$\widetilde{E}_L = \widetilde{V}_B + \widetilde{I}_L \, iX_L + \widetilde{I}_A \, iX_T$$

$$\widetilde{I}_L = \widetilde{I}_A + \widetilde{I}_C$$

θ is power factor angle at inverter

ϕ is power factor angle at infinite bus

(b) Real power flow.

Figure V-14.- SPS/utility system interface simplified analysis.
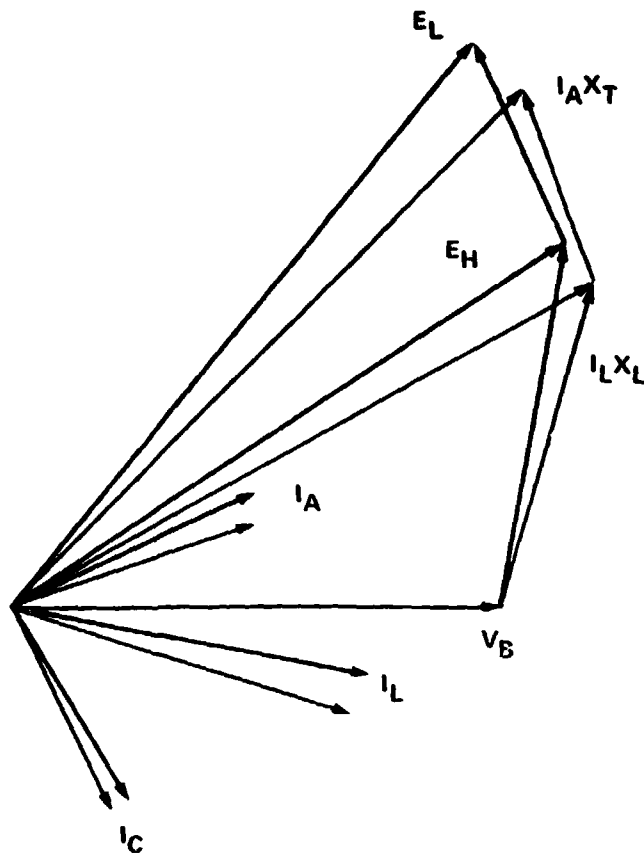
Figure V-15.- Effect of SPS power output variations.
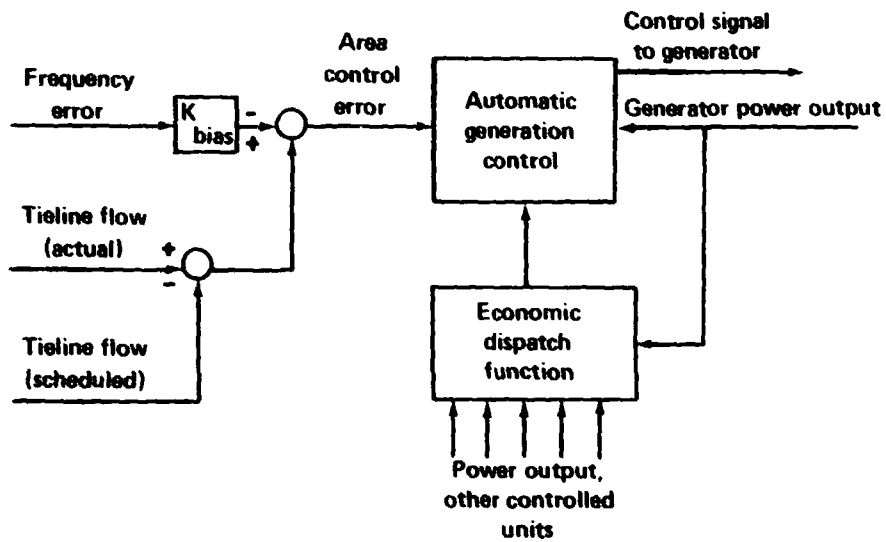
Figure V-16.- Automatic generation control block diagram.
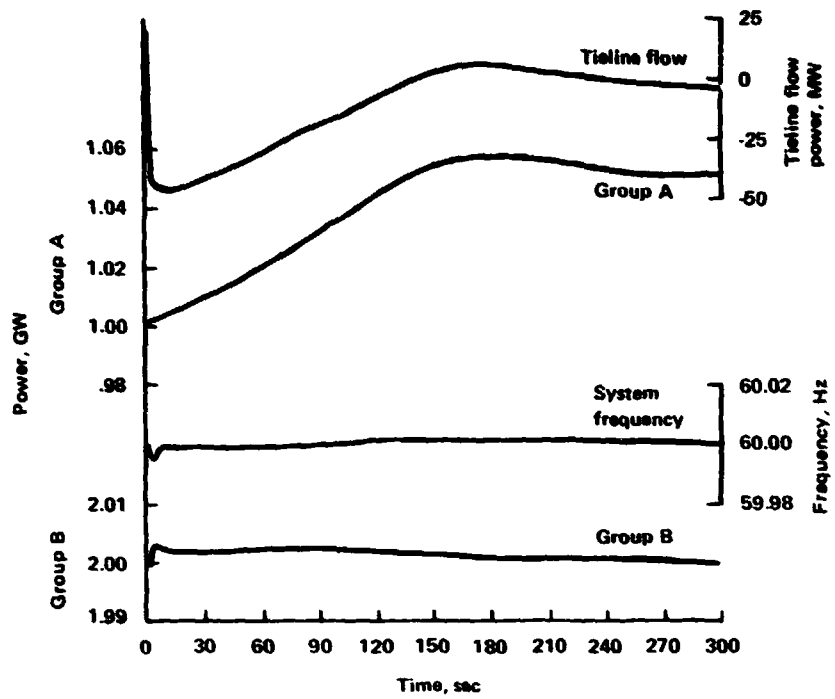
Figure V-17.- Illustration of AGC action.
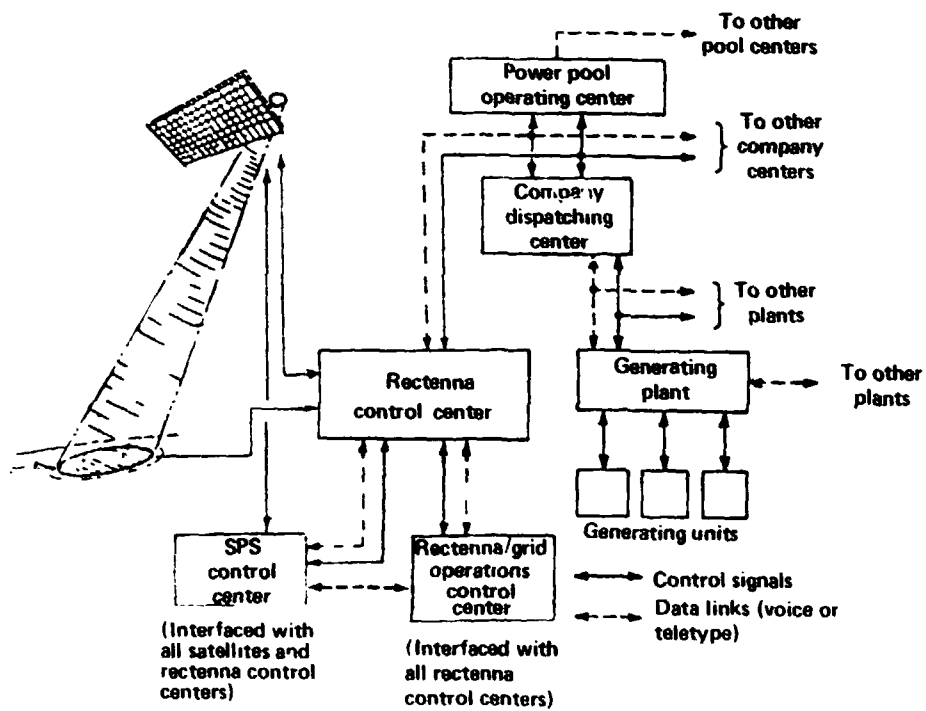
Figure V-18.- Utility system control structure.

185
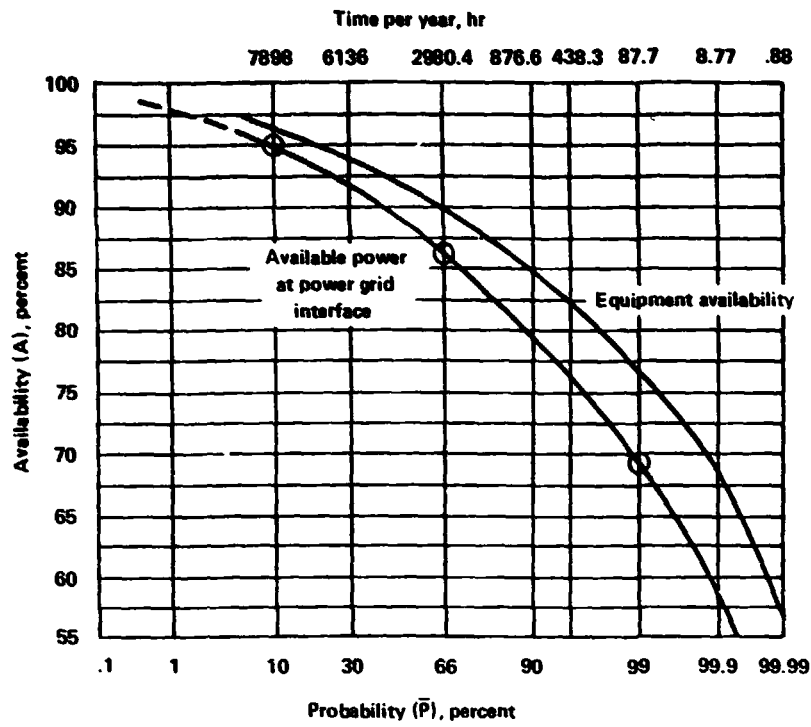
Figure V-19.- Utility system reliability: SPS reliability model.
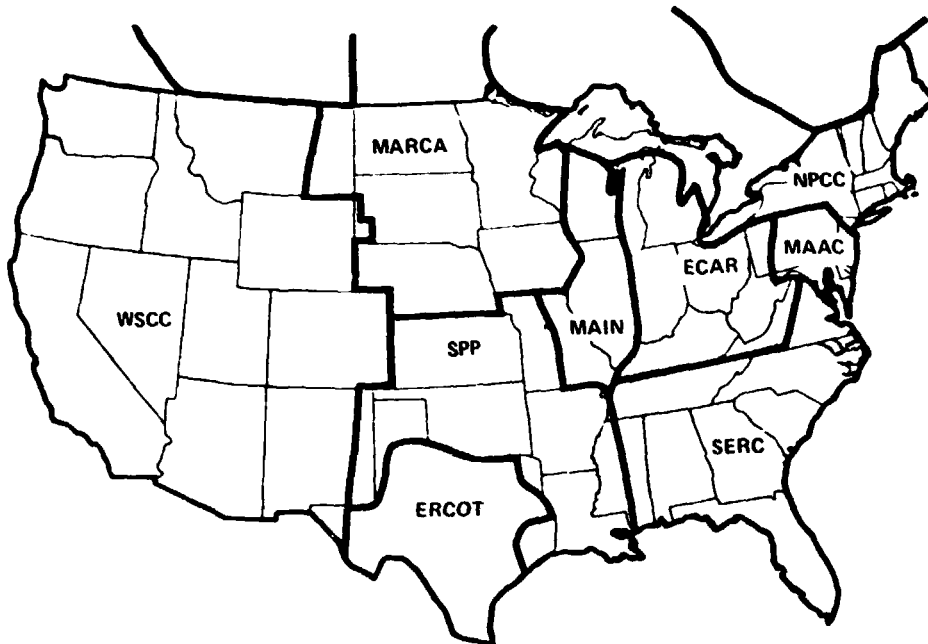
Figure V-20.- Regional reliability councils of the National Electric
Reliability Council.
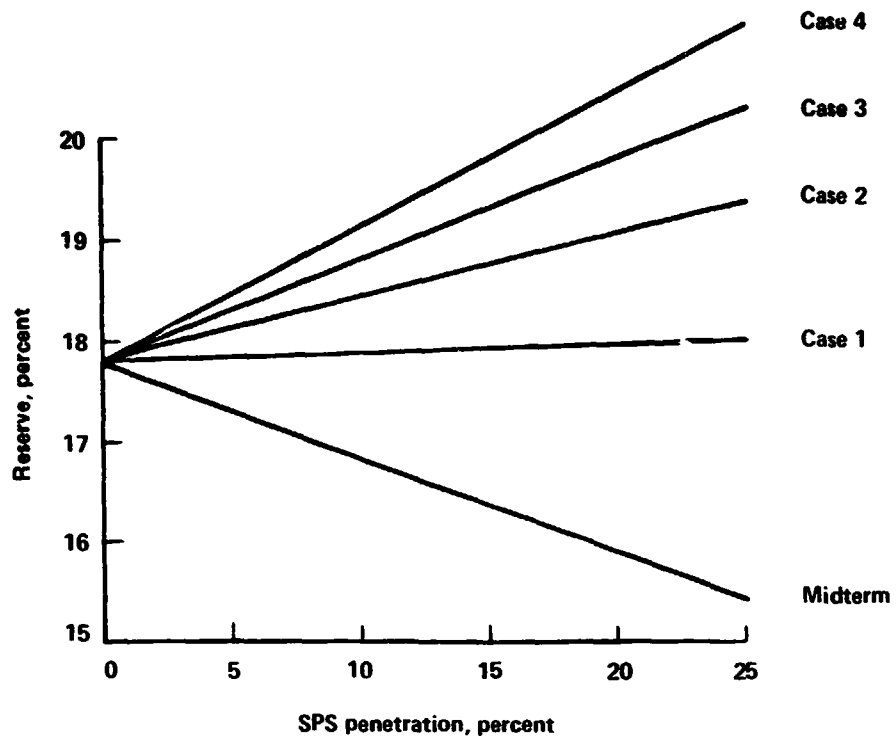
Figure V-21.- Utility system reserve levels compared to SPS penetration.
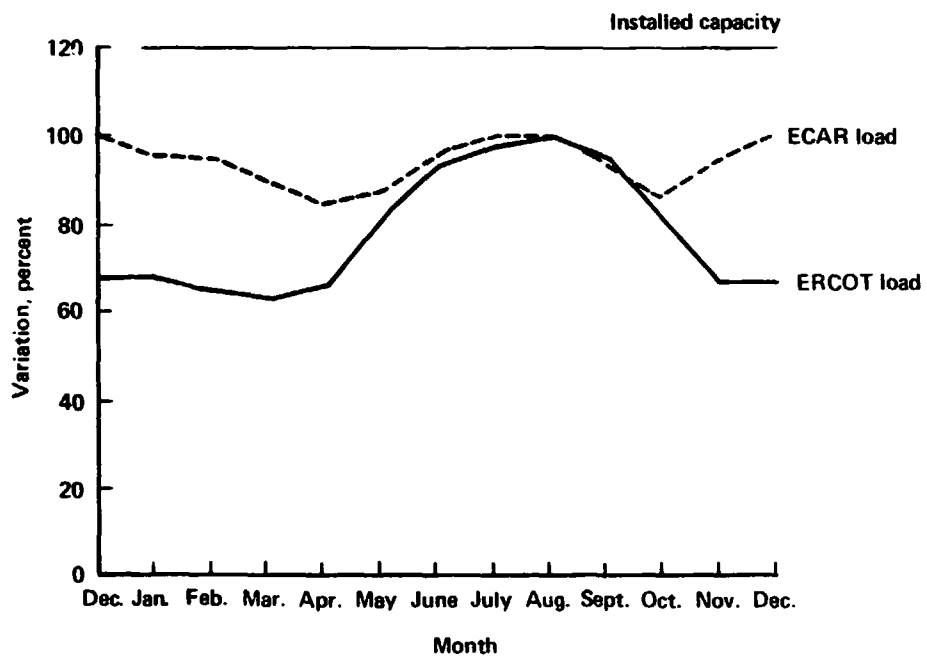
Figure V-22.- Monthly load variations in East Central Region (ECAR) and Energy Reliability Council of Texas (ERCOT).

VI. SPS CONSTRUCTION AND MATERIALS WORKSHOP

A workshop was held on January 24 and 25, 1980, to review the status of the SPS concept evaluation program with regard to construction and materials aspects. The Review Panel Final Report is included as an appendix. The Review Panel considered the assembly concepts credible and the Ground-Based Exploratory Development Program an excellent first attempt at near-term goals definition.

The Review Panel was made up of Professors Harm Buning, L. R. Cornwell, Marshal H. Kaplan, Robert G. Loewy, and Dr. M. F. Card. The Panel was chaired by Professor R. H. Miller.

VII. CONCLUSIONS AND REMAINING ISSUES

A key issue with a space system the size of SPS is the determination of practical means of constructing the system at a rate of production compatible with overall program economics. The construction facility provides a framework for the conduct of the many operations necessary for the completion of the satellite system. Since the primary structure of the SPS is not subjected to large-load conditions in geosynchronous orbit, the structure has very low mass and volumetric density. The material for the structural elements can be densely packaged for launch, then expanded by machines (beambuilder) to be assembled into a lightweight efficient structure. The SPS subsystems such as solar array blankets, reflectors, power conductors, and antenna subarrays will need a variety of special equipment and techniques for installation on the primary structure. Although these subsystems are fabricated on Earth, dense packaging will be necessary for launch into orbit, where final deployment and installation is accomplished. Delivery of the material encompasses a number of construction support functions involving transport, handling, positioning, alinement, and attachment of subsystems and modules. Equipment and operations to provide these support functions require a technology base which must be developed.

Another operational function which will be required is the capability to berth or dock very large elements or components. For example, controllable members might be extended to acquire the component, then retracted under controlled conditions to permit a firm attachment of the components without excessive loads or damage.

The operational SPS should be viewed as a long-range goal at the end of an extended evolutionary process. This evolution will include developing capability and experience for large-scale manned operations in space. Space evaluation of new technologies needed for very large satellites will require activities involving the space construction of scaled versions or whole modules of an SPS.

The type of work which could be conducted on Earth to support SPS construction technology can be grouped into three major areas.

A. Zero-g and space vacuum simulation

B. Analytical modeling

C. Automated construction equipment

Ground simulation development would include experiments conducted to develop space construction techniques including use of construction aids such as cranes and cherrypickers. These simulation facilities could be used as trainers when final equipment is developed. In addition to these simulations, joining experiments should be conducted including strength tests. Analytical modeling should include extensive loads analyses for SPS structural configurations to enable better understanding of loading conditions on an SPS. These analyses must include gravity-gradient, thermal-cycling, docking and berthing, and control loads. During construction, a wide range of control requirements will be

encountered. These wide variations and the flexible nature of the structure will entail a range of system dynamic parameters requiring extensive dynamic modeling and possible dynamic model tests in space.

Automated construction equipment includes items such as beambuilders, manipulators, and other programable equipment. This technology area is a high-leverage means of reducing manpower costs in space and on the ground. The rectenna system is extremely labor intensive, and automated fabrication, assembly, and field erection can be used to reduce costs.

These ground tests would provide a basis for refinement of the SPS analysis and the definition of flight tests or experiments needed for program decisions.

Rectenna construction presents a major challenge only in the size of the installation and the cost impact of the rectenna configuration. The size can be accommodated through application and automation of current construction techniques. These techniques must be integrated with low cost materials and fabrication methods to reduce the cost of the rectenna.

Space operation of the system becomes primarily an equipment maintenance activity since there are no expendable fuels for power generation, no waste products, and no corrosive elements in the environment. Most of the SPS components are highly reliable, redundant or relatively inert; howeve·, over 30 years, cumulative failures of active components such as microwave generators and dc-dc converters degrade the system performance. The provision of a maintenance capability to replace failed components results in improved system performance.

Integration of the SPS into the public utility system is feasible, although the operating characteristics of the SPS are different from conventional power systems. Ground operations are centered in a ground control facility which will control the SPS during startup, steady-state, and shutdown for maintenance or eclipse. It is probable that the SPS will operate near full output as a base-load plant with a satisfactory range of power control and time response.

Lyndon B. Johnson Space Center
    National Aeronautics and Space Administration
        Houston, Texas, March 18, 1981
            953-36-00-00-72

192

APPENDIX – REPORT OF THE SPS CONSTRUCTION
AND MATERIALS WORKSHOP, REVIEW PANEL FINAL REPORT

INTRODUCTION

The workshop met on January 24 and 25, 1980, to review the status of the solar power satellite (SPS) concept evaluation program and, in particular, to determine whether areas which could be considered critical to the construction and materials aspects of the program were adequately covered by the existing study data and the recommended follow-on work. Particular attention centered on the Ground-Based Exploratory Development (GBED) Program. The report which follows is addressed to these issues and covers an evaluation of GBED, together with comments pertaining to the structural and material elements of the program as a whole.

In general, the studies done to date are commendable in their efforts to truly visualize a complex assembly process. Although the range of assembly options has been necessarily limited, the assembly concepts investigated seem to be credible. The GBED appears to be an excellent first attempt at near-term goals definition. Work in the areas of construction techniques and development of actual machinery, such as beambuilders, seems well underway. Industrial presentations were impressive and clearly demonstrated the amount of thinking that has been done. Further work in this development area would be well supported if GBED plans are implemented.

Areas which could require greater emphasis are

1. Better definition of structural and, particularly, structural dynamic loads during construction and assembly

2. The interaction of these loads with the attitude stabilization control system, and those required for stationkeeping

3. A broader view of structural design and concepts beyond those envisaged for the immediate development program

4. More experimental verification of some of the assembly concepts, possibly including some early space-based experiments and a better definition of the advantages and disadvantages of automatic versus extravehicular-activity (EVA) assembly

5. A better definition of material requirements, in particular the use of polymer versus metallic structures

6. Further systems trade-off studies, in particular the optimization of the orbit-to-orbit transportation and the choice of geosynchronous orbit (GEO) or low Earth orbit (LEO) assembly

7. Members of the workshop felt that it was essential to keep in mind that the SPS Program at the present time is in a very evolutionary phase.

Recognizing the need for a baseline concept at the present time in order to plan the future program, it is nevertheless essential to keep advanced technology concepts going and to maintain a degree of flexibility in the program.

Each of these topics will be covered in greater detail in the comments which follow.

LOADS DURING CONSTRUCTION AND ASSEMBLY

Loads on the structure of the construction station in orbit and on the partially completed elements of the SPS under construction include those due to gravity gradients, thermal cycling, transport system docking, and control thruster (or momentum device) transients. The first two of these seem to be receiving reasonable attention, but the latter two do not. The GBED project 6.2.1, therefore, is well advised. It seems essential, however, that the "dynamic modeling" referred to in that project summary not be limited to rigid-body dynamics. The effect of flexible-body dynamics is likely to be too important to ignore even in a first attempt to establish docking loads.

The loads sustained by partially completed, but largely unsupported, structural elements of the SPS, still attached to the construction station, might be greatest when the construction station undergoes corrective thrust or control moment gyro (CMG) outputs for stationkeeping (in the former case) or attitude stabilization (in both former and latter cases). Such loads will be greatest when the element under construction protrudes the greatest distance or has the greatest nonstructural mass attached to it (solar arrays, bus bars, etc.) and when there is the greatest outward radial motion of the structural and nonstructural masses (coriolis forces). Such considerations could determine the greatest length of beam element that could be constructed, argue for delaying installation of nonstructural elements, and/or limit the control forces or moments used by the construction station, perhaps depending on the momentary state of SPS element construction. In the last of these alternatives, a simple "interrupter," which would allow no control force or moment application while the element under construction is being step-extended, could be desirable. None of these aspects may turn out to be limiting factors in construction but should be considered in the GBED Program. Analyses and perhaps dynamically scaled model tests in a vacuum should be performed to determine the seriousness of such transient dynamic stresses peculiar to the construction phase. Such might be included as an add-on to the proposed GBED 6.1.1 project; the maximum stresses encountered could well be ameliorated by the detailed treatment of the local area where beam caps emerge from the beambuilder.

It is stated that structural loads are very small compared to what they would be on Earth and that, since construction occurs in space, the structure does not have to withstand launch loads. Although this is certainly true, at least some consideration should be given to loads that occur on very large structures even in the absence of gravity-gradient moments. When structures become of appreciable size, certain "parts" are traveling along paths that are "unnatural" orbits and it requires steady-state structural loads to take

194

care of this situation. For instance, if a structure has its major dimension perpendicular to the orbital plane, the extremities travel along "minor circles" and this causes a compressive load on the structure. For a typical SPS, this may amount to several hundreds of pounds at the plane of symmetry in the orbital plane.

CONTROLS ASPECTS

Whatever the SPS construction satellite's control system turns out to be, its characteristics must be such as to be tolerant of a tremendously wide variation of natural modes and frequencies. The coupled behavior of the construction satellite with various lengths and masses of half-constructed SPS modules extended from it is, of course, one aspect. The tremendous range of mass and mass distribution as launch-dense construction material changes to orbital undense and, finally, released material is another. The change from largely "empty" construction satellite to just-reloaded condition is still a third. Such wide variations, considering the flexible nature of the structure being contemplated, may present a range of system dynamic parameters not yet encountered by controls designers.

STRUCTURAL DESIGN AND ASSEMBLY CONCEPTS

Under these subjects, comments from the panel fall in three categories: assembly concept development, structural concepts, and enabling technology.

In general, the studies done to date are commendable in their efforts to truly visualize a complex assembly process. Although the range of assembly options has necessarily been limited, the assembly concepts investigated seem to be credible. However, the assembly schemes are difficult to visualize in sufficient detail to engender complete confidence. The model of a construction station displayed by Grumman helps in this respect, but a great deal more work is needed. This area is probably one of the most difficult in the development of very large space structures in which to do meaningful research and development.

It is possible that the only way to acquire the assembly data needed to achieve a credible assembly concept is to approach construction as a scaled-down but still quite large-scale experiment; this seems essential in order to evaluate those details of an assembly process which establish or deny its feasibility. Significant progress could be made by large-scale ground activities. The answers to questions such as how to unfurl solar blankets, sequencing of construction operations, and manned support requirements could be answered by a series of ground experiments, perhaps with constraints on construction, to eliminate "one-g cheating." It is probable that many of the so-called construction aids (manned maneuvering units, cherrypickers, etc.) being developed for satellite servicing may require considerable modification before they would be suitable for on-orbit construction. Very little in the way of

advanced thinking is going into this area. The current remote manipulator system (RMS) is an example of a device that was never intended for large-scale construction. It is believed that by applying improved tool concepts, progress could be made much faster. For example, most construction processes find great utility in gigantic cranes. It is possible that a folded deployable structure could be used to provide the necessary stiffness for a space crane, rather than the RMS.

The beambuilder appears to be uniquely suited to the gigantic structures envisioned as part of SPS. The machine is an impressive technical development that may be ahead of its time. It is important for NASA to seek early applications and opportunities for demonstrations of this technology. It is possible that the speed of construction of beam machines (1 meter per minute) may need to be increased to be competitive with other types of construction.

As regards structural concepts, the solar collector is proposed as a large open truss with latticed column members. The structural weight, 145 kg/m^2, appears to be very light, even though a relatively "conventional" construction approach has been taken.

Two concepts appear to be proposed for the antenna structure: a tetrahedral truss with a stretched membrane (General Dynamics) and a hexagonal compression frame/mesh combination (Rockwell International). The truss configuration has received some attention in a recent study and appears to be quite suitable. The compression frame/mesh needs to have further study before it can be considered to be a good competitor. Preliminary studies at the NASA Langley Research Center indicate that considerable mass is required to stabilize the compression frame. A more effective configuration would be one in which a small tower with cables is used to stabilize the frame, as is done in "bicycle wheel" design concepts; e.g., Grumman's space-based radar.

In the development of structural concepts, it would be desirable to develop concepts that are not peculiar to the SPS system alone. These concepts might find earlier application than SPS and provide valuable experience in establishing concept credibility. The bicycle wheel concept seems to have a number of interesting applications ranging from solar reflectors to lens antennas and probably deserves study by SPS.

As one approach to gaining the technologies needed, the SPS team should be encouraged to entertain alternative types of construction (e.g., prefabricated structures) which may have fewer on-orbit construction problems. Of special concern is the precision with which straightness can be controlled, especially if demonstrations are to be performed in low orbit.

It seems especially important that a series of joining experiments should be conducted in GBED under conditions which duplicate LEO or GEO as closely as possible. Subsequent strength tests of these joints should then be performed under these same space-simulated conditions. For spotwelding of aluminum and ultrasonic welding of composites, this should include, as a minimum, both hard vacuum and the range of ambient temperatures expected in space construction.

MATERIALS

There appears to have been relatively little work done on the detailed choice of materials for SPS construction. There was a general feeling that composites would be desirable because of their low thermal expansion and yet it would appear that there are certain areas, particularly toward the center of the transmitting antenna, where temperatures will be higher than are tolerable with current polymer matrices. If polyimides are a solution, this should be dealt with explicitly, and a development program should be undertaken to provide high-temperature-capable composites. Alternatively, a construction utilizing composites at the outer reaches of the antenna, where temperatures are lower, and aluminum in the high-temperature areas may be a solution. There is also relatively little information available on the long-term exposure characteristics of composites when in a hard vacuum. Although applications on some existing satellites seem to have been successful, problems of embrittlement and outgassing may have to be solved before polymers can be accepted as suitable for loaded primary structures in space.

SYSTEMS TRADE-OFFS

There are a variety of trade-off analyses which should be considered in arriving at the final operational system. Fundamental to these are choice of orbital parameters for SPS operation. It is possible that a study of orbital parameters for their effect on what is demanded from ground and spacecraft system configuration and performance could yield some very interesting results. High-inclination GEO orbits above about 7° or 8°, for example, could essentially eliminate the thermal cycling associated with eclipses but at the expense of increasing attitude control requirements and ground antenna complexity. Another factor is the usage of orbital slots at geosynchronous altitude. The longitudinal positions which may be allowed for such satellites are very narrow. In addition, there may be several other applications for that same position in orbit. Thus, multiple usage of these orbital positions may be a necessity in the future.

Principal among system trade-offs is the decision as to how much construction is to take place in geosynchronous orbit and how much in LEO. This decision, or more properly series of decisions, should be made with great care considering radiation hazards, orbital dynamics, gravity and thermal effects, and transportation costs, as a minimum.

A particular subcase of great interest is the influence of acceleration during transportation from lower orbit to geosynchronous orbit. Regardless of how much or how little construction is done in LEO, when the effect of loss of revenue from the assembled SPS during transit time is introduced, it may be that higher accelerations than are currently envisioned may be desirable. This will clearly "trade off" with propulsion choices and, through the loading of the structure, with structural weight and complexity.

Continual review of assembly, structural, materials, and controls concepts, as discussed in earlier sections, will be necessary to ensure that the effects of systems trade-offs are properly reflected in construction station and SPS design optimization. Choices of orbital or other operational, overall system parameters are certain to influence both construction and structural choices, as well as allowable mass distributions, through changing criteria for attitude and stationkeeping accuracy, accelerations in orbital transfers, and the environment - thermal, radiation, gravitational, etc.

LONG-TERM CONSIDERATION

The concept of establishing, in geosynchronous orbit, a series of large solar power satellites should be viewed as a long-range goal at the end of an extended evolutionary process. This evolution must eventually involve acquiring expertise and experience in orbital operations, with multiple spacecraft and a reasonable size human population in low Earth orbit. The acquisition of this type of expertise stopped with the return of the last crew from Skylab. Operations of the Shuttle Orbiter will again start working in this direction, but achieving the capability to develop an SPS requires special manned-space-flight experience. We almost certainly have to develop some small orbital station in LEO devoted to space evaluation of the new technologies needed for the very large scale space stations and satellites.

Such activity should probably involve the construction of a smaller scale version or module of the SPS. It should include microwave transmission systems to transfer the power to Earth or to another spacecraft equipped with a receiver. The more critical environment in LEO with regard to gravity-gradient torques and pointing requirements (for beaming power to the ground) should make such experimentation particularly worthwhile for a LEO construction station and conservative, in some respects, for GEO satellite design. The cost of manned space operations will encourage performing as much preliminary research and development on Earth as is feasible within the limitations of the one-g environment.

The Ground-Based Exploratory Development Program appears to be an excellent start in this direction and will serve to define near-term goals for the SPS Program. Pertinent to construction materials are parts of the chapter entitled "Space Operations Issues." The two areas related to "Automated Construction" and "Hardware/Material Handling and Installation" (Sections 6.1 and 6.3) seem particularly suited for earthbound developmental work. Aspects of the GBED Program which emphasize the vast size of construction components, as discussed in Section 6.2, must be subjected to analytical and computer studies.

The scope of the GBED Program should be sufficient so that its results will support detailed recommendations for a demonstration spacecraft and for orbital experiments and other demonstrations to resolve issues not reasonably addressed in earthbound experiments. This is likely to include all new technologies related to the generation and transmission of power from space to

the ground, and hopefully will allow design of an operational power station of useful size.

Materials and structures options of low potential for SPS should also be identified in the GBED and a construction philosophy should evolve from it which will lead to designs suitable for operational stations.

From these comments, it is clear that a detailed planning cycle is essential: one that defines clearly the technical questions to be answered and outlines how the questions we don't yet know enough to ask will be unveiled. This will almost certainly entail a comprehensive systems engineering approach to guarantee that all such questions are answered and/or defined before the next phase ⌣. development commences.

REFERENCES

1. Satellite Power System: Concept Development and Evaluation Program, Reference System Report. Rep. DOE/ER-0023, Department of Energy, Oct. 1978. (Also available as NASA TM-79762, 1979.)

2. Solar Power Satellite System Definition Study - Phase I. Volume III - Reference System Description. Boeing Aerospace Co. (Contract NAS 9-15636). NASA CR-160372, 1979.

3. Satellite Power System (SPS) Concept Definition Study. Volume V - Transportation and Operations Analysis. Rep. SD 78-AP-0023-5, Rockwell International (Contract NAS 8-32475), Apr. 1978.