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Design Requirements for Orbit Maintenance of SPS Elements

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DOE/NASA
Satellite Power System
Concept Development
and
Evaluation Program

FOREWORD

The Design Requirements for Orbit Maintenance of SPS Elements study was initiated in February 1980 and was completed in May 1980. This study is a part of an overall SPS evaluation effort sponsored by the Department of Energy (DOE).

This study was managed by the Argonne National Laboratory (ANL). The ANL contracting officer was J. J. Wray, and the study technical manager was J. Lazar. This study was conducted by the Advanced Space Projects group of the Boeing Aerospace Company. The study manager was Harold B. Liemohn. The technical lead was Keith H. Miller.

Key team members and their contributions were the following:

- Keith H. Miller
    - SPS Element Configuration Definition
    - SPS Program Operations Definition
    - Orbit Maintenance Design and Operational Requirements Definition
- Daryl Bahls
    - Orbit Decay Analysis
- Richard L. Green/ Curt Betchley
    - Propellant Requirements Analysis

ABSTRACT

The objective of this study was to identify the design and operational requirements that will be imposed by the need to avoid unplanned reentry of SPS elements. The LEO Staging Base, Electric Orbit Transfer Vehicle, the LEO Construction Base, and SPS Self-Power Module were the SPS elements selected for this analysis.

The orbit decay rates and attitude control/orbit maintenance propellant requirements for nominal and worst case conditions were defined. The sequence of events that could cause unplanned reentry were defined. The design and operational requirements that will be used to prevent the various elements from deorbiting were defined.

KEY WORDS

Attitude Control/Orbit-Keeping
Electric Orbit Transfer Vehicle
GEO Construction Concept
LEO Construction Base
LEO Construction Concept
LEO Staging Base
Maneuver Control Operations
Orbit Decay
Orbit Maintenance
Propellant Requirements
Propulsion System Maintenance
Solar Power Satellite
Space Power Systems
SPS Self-Power Module

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ABBREVIATIONS AND ACRONYMS

C_D	Drag Coefficient
EOTV	Electric Orbit Transfer Vehicle
G, g	Gravitational Acceleration
GEO	Geosynchronous Earth Orbit
H	Hydrogen
HLLV	Heavy Lift Launch Vehicle
I_{SP}	Specific Impulse
KG, Kg	Kilogram
KM, km	Kilometers
LCB	LEO Construction Base
LEO	Low Earth Orbit
LH, LH2	Liquid Hydrogen
LOX, LO2	Liquid Oxygen
LSB	LEO Staging Base
M	Meters
MT	Metric Ton (1000 Kg)
M^2	Square Meters
O	Oxygen
PLV	Personnel Launch Vehicle
POTV	Personnel Orbit Transfer Vehicle
SPM	SPS Self-Power Module
SPS	Solar Power Satellite, Satellite Power System

1.0 INTRODUCTION

In both the Boeing and Rockwell solar power satellite system definition studies (ref. 1) there have been alternative construction location concepts developed where (1) portions of the satellite are constructed at low Earth orbit (the LEO construction concept), or (2) where the entire satellite is constructed at geosynchronous Earth orbit (the GEO construction concept). Regardless of the satellite configuration or the construction location finally selected for the SPS program, there will be two or more large system elements located permanently or temporarily in LEO.

Avoidance of unplanned reentry of these large elements will undoubtedly be a mandatory requirement. It will be an unacceptable risk for large fragments of these elements to reach the Earth. Also, the cost and schedule impact of the loss of one of these elements cannot be ignored.

The objective of this study was to identify, in quantitative terms, the design and operational requirements that will be imposed by the need to avoid unplanned reentry of SPS elements under any foreseeable circumstances.

In this study we have restricted our attention to the elements described in the Boeing SPS reference system (ref. 2 and 4) and the SPS operations document (ref. 3) from the 1979 contractual studies. We did not analyze the elements defined by Rockwell as (1) we had the latest detailed configuration and operations data available for the Boeing concepts and did not have comparable data for the Rockwell concepts, and (2) the design requirements defined for the Boeing-defined elements will be generally applicable to the Rockwell-defined elements.

The Earth-to-LEO boosters were declared to be outside the scope of this study. The unplanned reentry of these vehicles would be governed by range safety rules similar to those in current use.

We will first define the configurations of the SPS elements chosen for analysis (Section 2.0). This is followed by an analysis of the orbit decay characteristics (Section 3.0) for each of the elements. This analysis shows what will happen if no corrective orbit-keeping on attitude control is available. The maximum time available for troubleshooting and corrective action is specified. In the following section (Section 4.0), we have defined the sequences of events that may ultimately lead to unplanned reentry, if no countermeasures are taken. We then define the system design and operational countermeasure requirements. The mass penalty for the redundant systems and on-board spares is then estimated. The appendices provide supplemental data on propellant requirements (Appendix A), propulsion system maintenance concepts (Appendix B) and attitude control/station keeping maneuver operations concepts (Appendix C).

2.0 SPS ELEMENT CONFIGURATIONS

Over the past three years of contracted SPS system definition studies by Boeing (contracts NAS9-15636 and NAS9-15196), we have characterized two fundamentally different construction location concepts.

The current reference concept, called the GEO construction concept, is characterized by having the entire satellite constructed at a GEO construction base. This concept and the major system elements located in LEO are described in section 2.1.

An earlier reference concept, called the LEO construction concept, is characterized by having modules of the satellite constructed at a LEO construction base and then having these modules fly to GEO where they are connected together to form the complete satellite. This concept and the major system elements located in LEO are described in section 2.2.

2.1 SPS ELEMENTS LOCATED IN LEO FOR THE GEO CONSTRUCTION CONCEPT

The overall SPS program operations for the reference GEO construction concept are shown in figure 2-1 (ref. 2). In this concept, cargo is delivered to a LEO staging base by heavy lift launch vehicles (HLLV's). The cargo pallets are taken out of the HLLV and transferred to an electric orbital transfer vehicle (EOTV) that is flying in formation with the base. A cargo tug transports the cargo pallets between the base and the EOTV. The EOTV is loaded with 10 cargo pallets and is then flown to GEO where the pallets are transferred to the GEO construction base. This GEO base constructs the satellite.

We will restrict our attention to the major elements located in the low Earth orbit (LEO). These elements are (1) the LEO staging base, and (2) the electric orbital transfer vehicle.

2.1.1 LEO Staging Base

The LEO base is shown in figure 2-2 (see ref. 2 for complete details). It is used to construct EOTV's and it serves as a staging depot for cargo and crews destined for GEO.

The base gets its planform configuration (see figure 2-3) from the requirements imposed by the EOTV construction operations. The main deck size is approximately the size of one EOTV bay. The outriggers provide the capability for indexing the EOTV structure in one-bay increments in

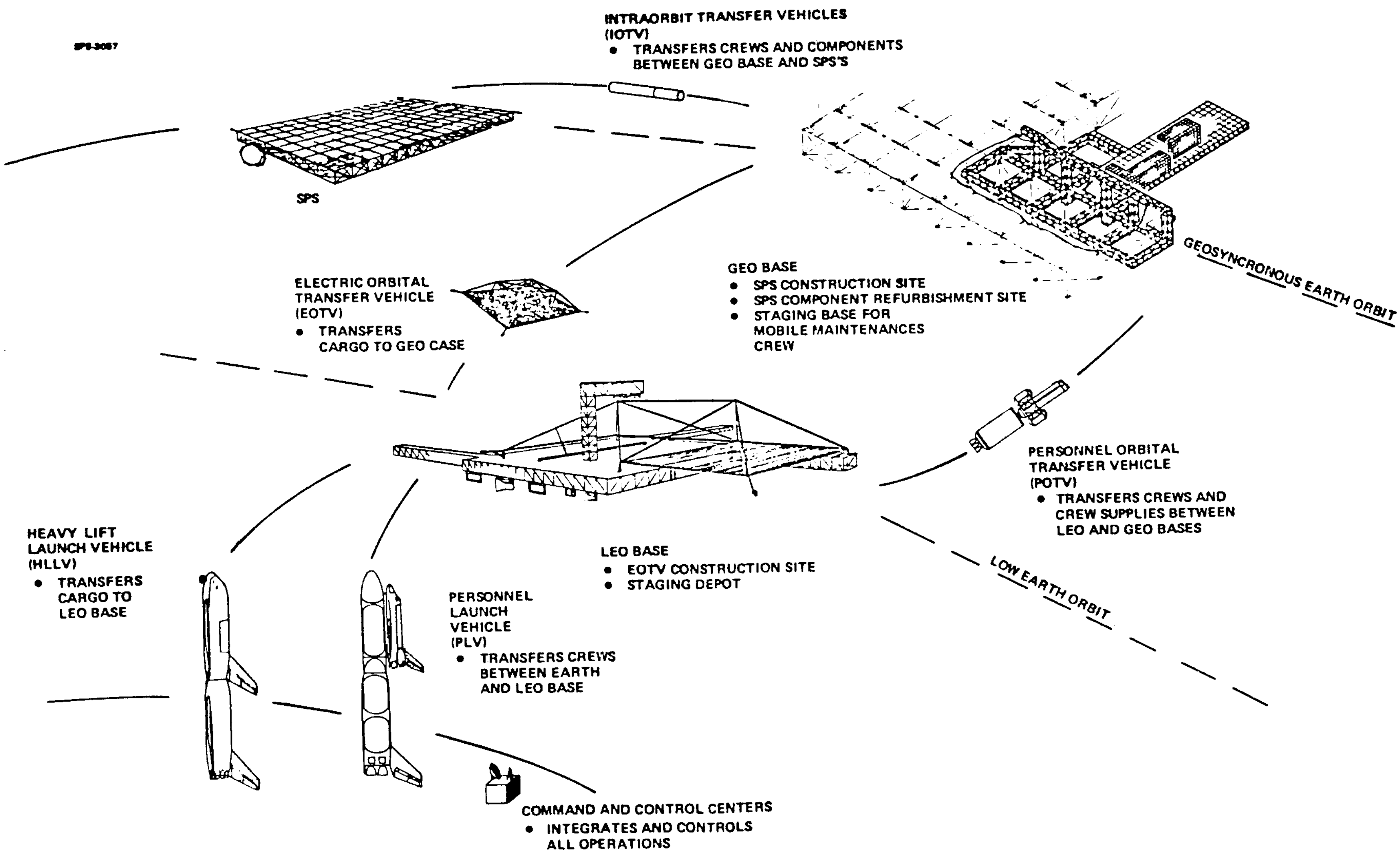

Figure 2-1. GEO Construction Concept

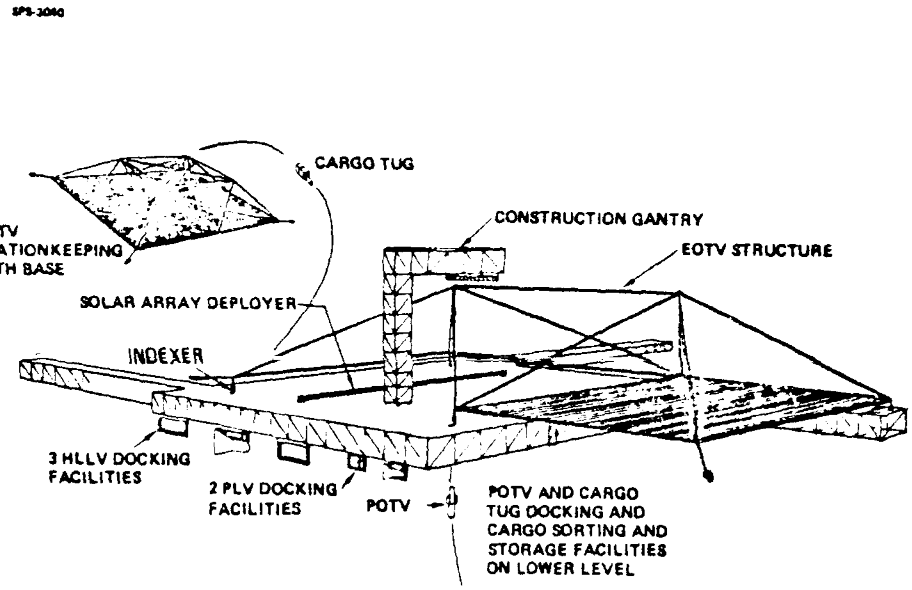

Figure 2-2. LEO Staging Base

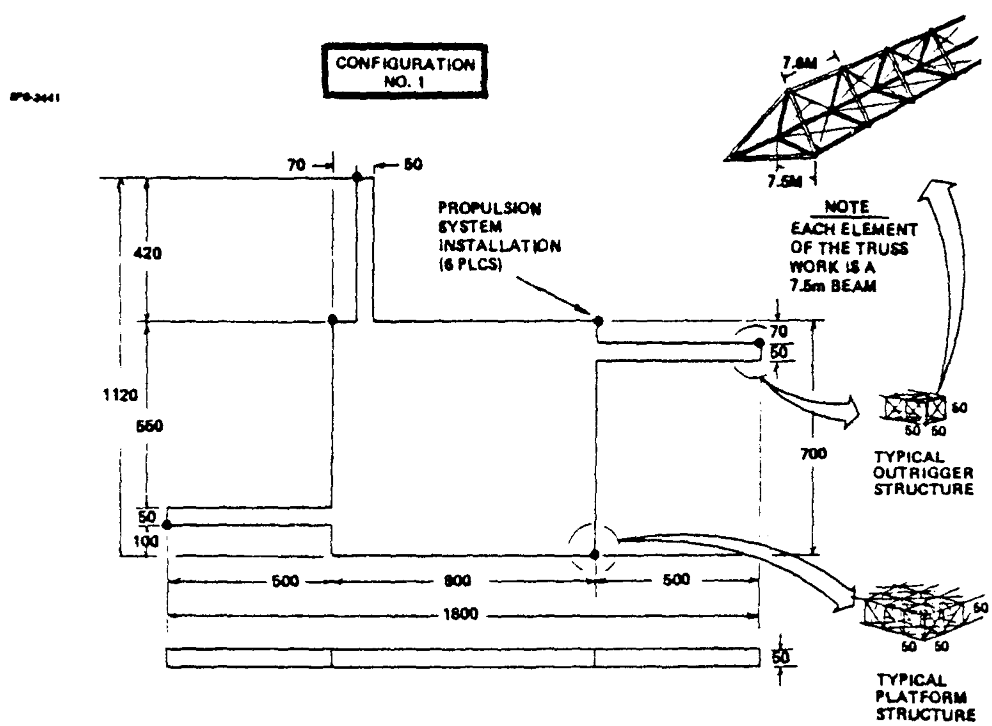

Figure 2-3. LEO Base Structural Envelope

three different directions during the construction process. The construction gantry and an assortment of construction equipment operate from the upper surface of the base.

The LEO base serves as a staging depot for cargo being transferred from HLLV's to EOTV's. The EOTV's will stationkeep with the LEO base during the cargo transfer operations conducted by cargo tugs. The LEO base also serves a staging depot for the crews on their way between Earth and the GEO base.

The mass of the LEO base is 1832 MT (metric ton = 1000 kg).

Figure 2-4 shows an arrangement of the base attitude control/stationkeeping propulsion system. There are 6 locations on the base where this chemical propulsion system arrangement is found. The chemical propulsion system is composed of redundant fixed thrusters, LOX and LH_2 storage and delivery systems (tanks, valves, controllers, etc.). There is a triple-redundant control system that is composed of computers, sensors, antennas, data transmission systems, etc.

Chemical thrusters were chosen over electric ion thrusters for this mission for several reasons. The ion thrusters require large amounts of electrical power. This in turn requires large solar cell arrays to be facing into the sun. These arrays will increase the drag making orbital maintenance that much harder. Furthermore, in LEO the SPS elements will be occulted during each revolution. With a 94 minute orbital period and a 15 minute start-up time for the ion engines, thrusting can occur only on about half of each orbit. Ion thrusters also have low thrust levels requiring longer durations of thrusting which can endanger personnel (entering the ion beam) and can interfere with work schedules.

A gaseous hydrogen, gaseous oxygen chemical thruster with specific impulse*, I_{sp}, of about 400 seconds was assumed for this study. The propellants are transported and stored in liquid form but are mixed as gasses. This is a very reliable type of thruster with quick response time in any emergency.

The LEO base configuration shown in figure 2-3 was used as one of the test cases (Configuration No. 1) in the orbital decay and propellant requirements analyses.

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* Isp = specific impulse = pounds of thrust $\div$ pounds of fuel consumed per second

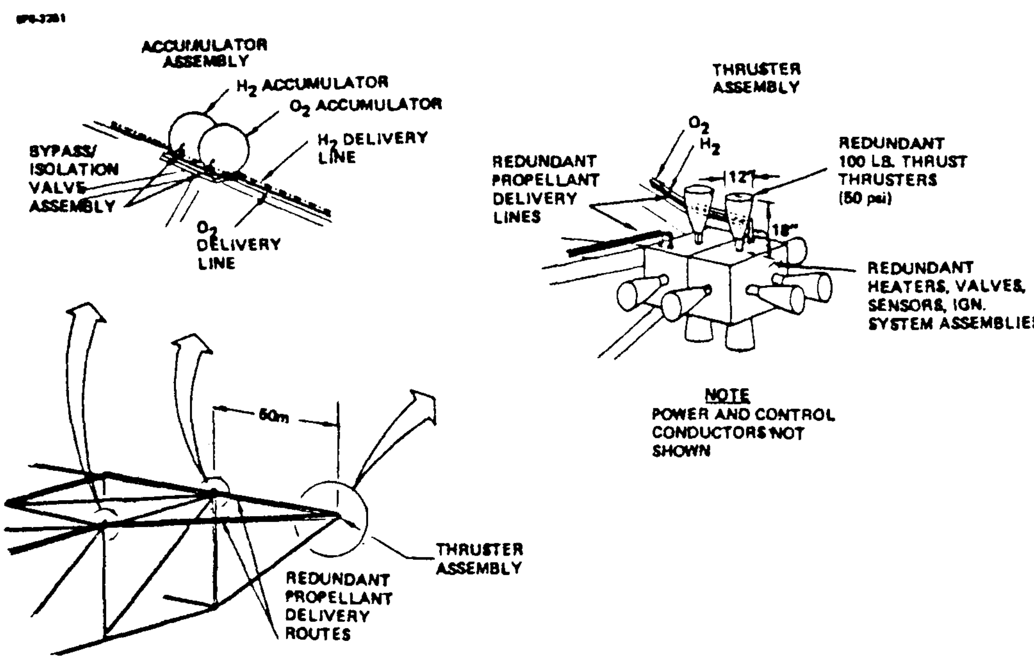

Figure 2-4. LEO Base Propulsion System Arrangement

A second configuration that was used as a test case (Configuration No. 2), was the LEO base with an attached, fully assembled EOTV, see figure 2-5. This configuration would occure just prior to flying a newly assembled EOTV away from the base on its maiden flight. The mass of Configuration No. 2 is 3810 MT.
Figure 2-6 shows a portion of the SPS commercialization schedule. It should be noted that Configuration No. 1, the LEO staging base without an attached EOTV, would be the normal configuration for 5-1/2 years (years 4-1/2 to 10). At year 10, the EOTV construction operations are then initiated and then conducted for a little over 3 years. This construction cycle is repeated every 5-1/2 years. Configuration No. 2 would occur only for a 5-day period on a 45-day repeating cycle during the 3-year EOTV construction schedule.

2.1.2 Electric Orbit Transfer Vehicle (EOTV)

The EOTV is shown in figures 2-7 and 2-8 (see Ref. 2 for complete details). The configuration shown in these figures is Configuration No. 3 that was used as a test case for orbital drag analysis.

Each of these vehicles flies in formation (stationkeeping) with the LEO staging base for a 6-day period during which cargo pallets and propellant pallets are transferred between it and the base. The EOTV's electric thrusters are changed out and miscellaneous maintenance is performed during the 6-day period.

This vehicle approaches and departs from the LEO staging base orbit under a very low thrust operating regime so it is in LEO over many days in addition to the 6-day stationkeeping time.

The total mass of Configuration No. 3 is the sum of the vehicle empty weight, the propellants, and the payload—a total of 5977 MT.

The EOTV's propulsion system is shown in more detail in figure 2-9. There is a combination of electrical and chemical propulsion systems. The electric propulsion system is used when the vehicle is in the sunlight and the chemical propulsion system is used when the vehicle is occulted and for the initial departure from LEO.

The electric propulsion system is composed of argon ion thrusters arranged on a gimballed panel, an electrical slipring assembly, power processor units (PPU's), a PPU thermal control system (pumps, valves, radiators, fluid lines, and coolant fluid), power buses, solar array, switch

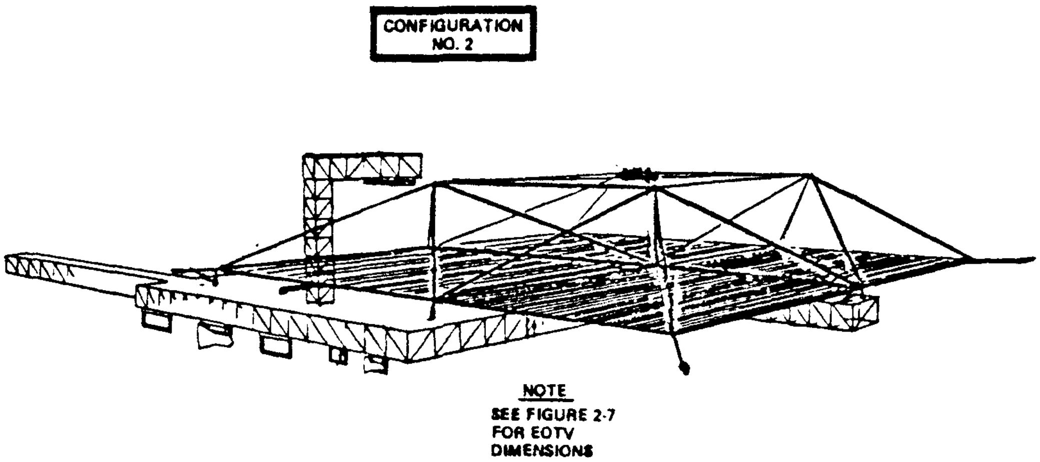

Figure 2-5. LEO Staging Base with Fully Assembled EOTV Attached

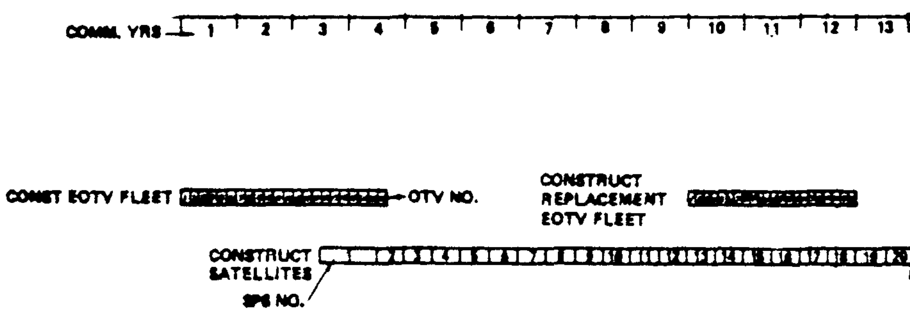

Figure 2-6. SPS Commercialization Schedule

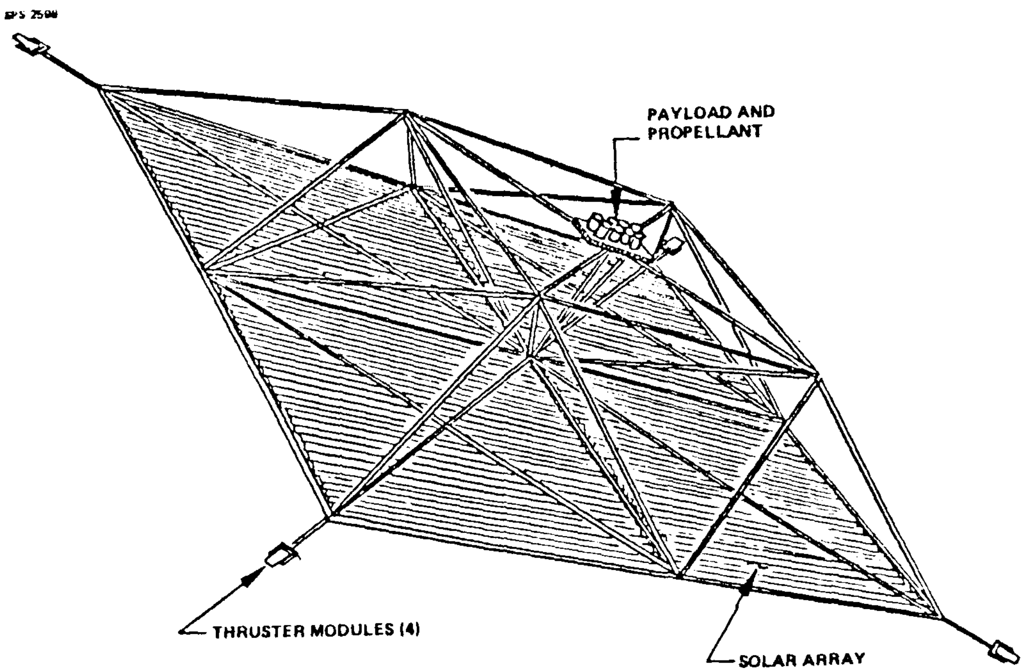

Figure 2-7. Electric Orbit Transfer Vehicle

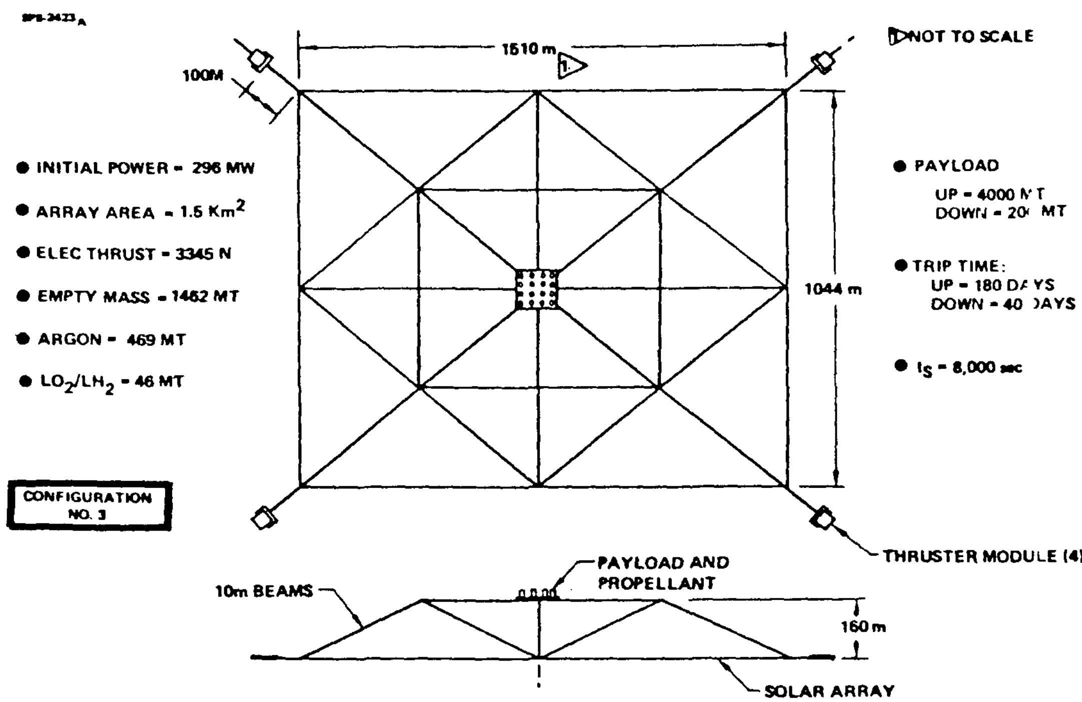

Figure 2-8 Electric Orbit Transfer Vehicle Details

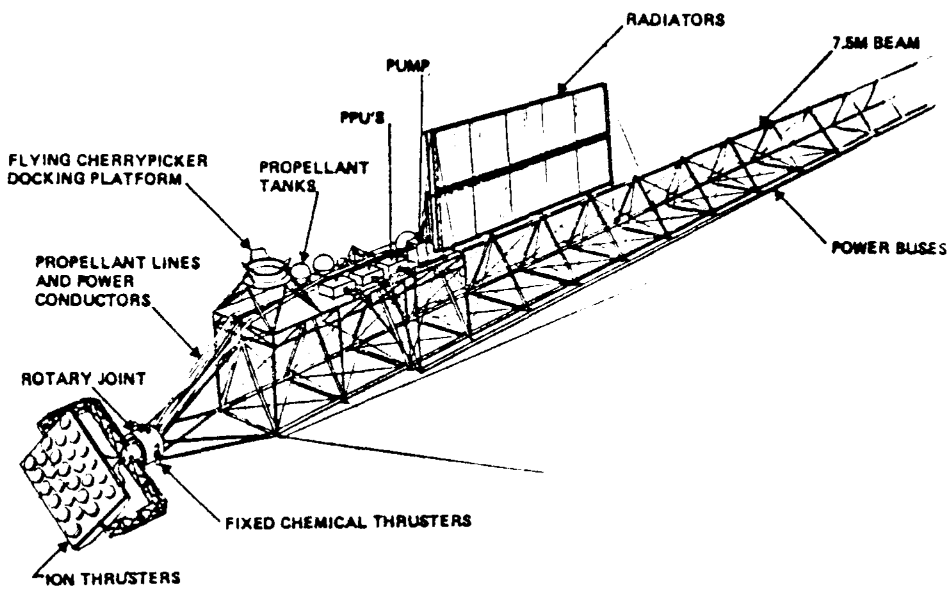

Figure 2-9. Propulsion System Arrangement

gear, argon storage tanks (located in removable pallets attached to the cargo platform), and an argon delivery system (delivery lines, valves, heaters, etc.).

The chemical oxygen-hydrogen propulsion system is composed of fixed thrusters, valves, sensors, ignition system, propellant delivery lines, and local propellant storage tanks.

There is also a triple-redundant control system composed of computers, sensors, antennas, data transmission systems, etc.

Maintenance access for the propulsion system is provided by a docking platform for a flying cherrypicker.

2.2 SPS ELEMENTS LOCATED IN LEO FOR THE LEO CONSTRUCTION CONCEPT

The LEO construction concept is depicted in figure 2-10 (adapted from Ref. 4). In this concept, cargo is delivered to a LEO construction base by heavy lift launch vehicles. This base constructs four satellite self-power modules and an antenna over a 6-month period. These modules fly to GEO using electric thrusters powered by a portion of the module's solar array that is deployed for this purpose. At GEO the modules are berthed together to form the total satellite. A GEO final assembly base is used for the berthing and final assembly, test, and checkout operations.

We will restrict our attention to the major elements located in LEO. Those elements are (1) the LEO construction base, and (2) the SPS self-powered modules.

2.2.1 LEO Construction Base

The LEO construction base is shown in figure 2-11 (adapted from ref. 3). It is used to construct satellite modules and antennas.

The 4-bay-wide by 8-bay-long satellite modules (to be described in section 2.2.2) are constructed in the facility area noted as "Solar Collector Assembly Facility" over a 45-day period. The antennas are constructed over a 180-day period in the antenna construction platform area behind the solar collector assembly facility. Toward the end of the 180-day period a yoke assembly is constructed adjacent to the antenna. The yoke and antenna are mated and then this combination is moved around to the side of the solar collector assembly

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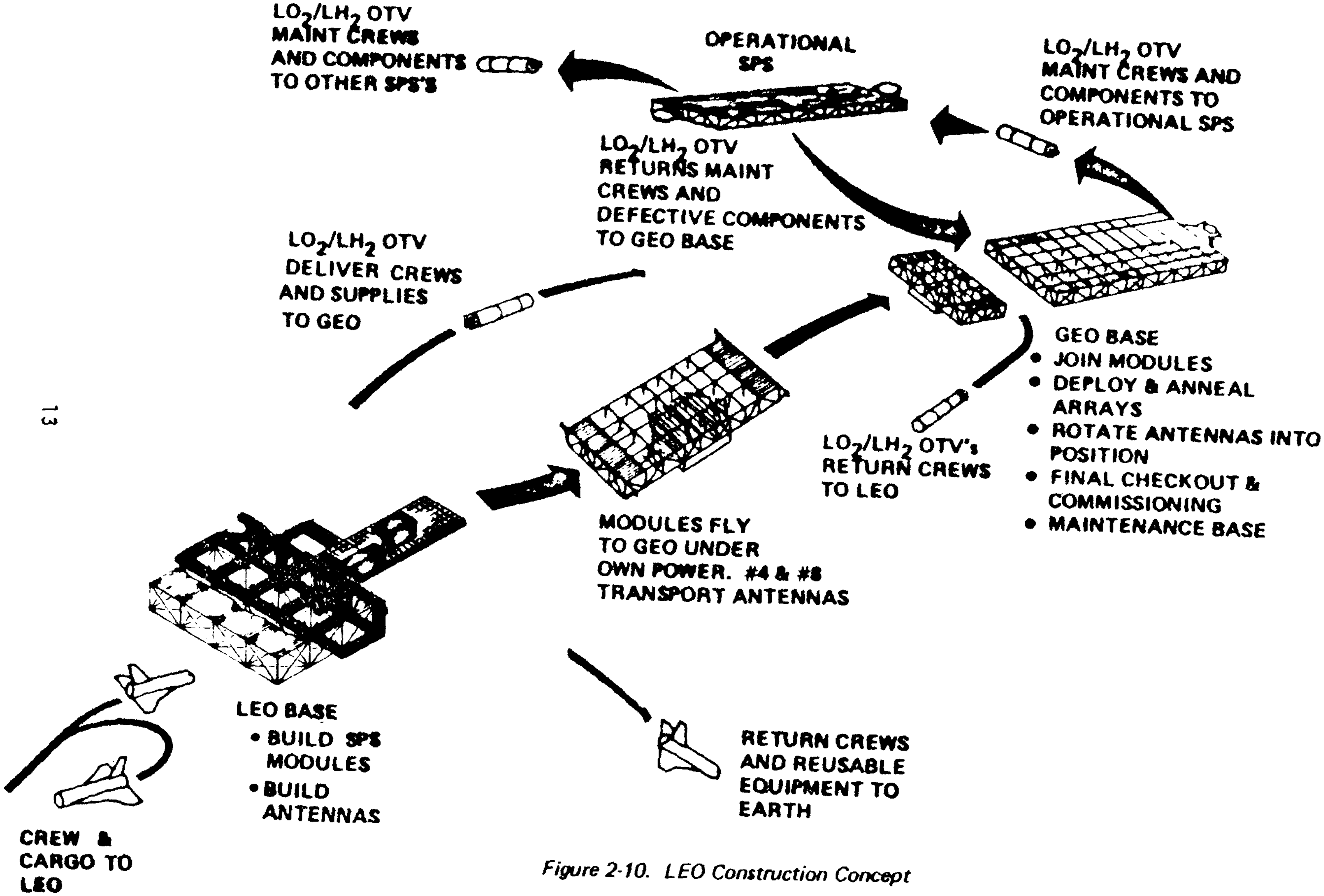


Figure 2-10. LEO Construction Concept

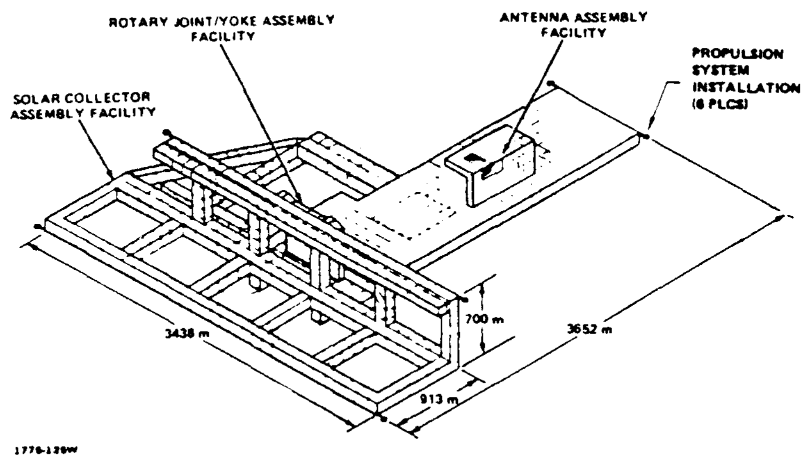


Figure 2-11. LEO Construction Base

facility. The yoke (with antenna attached) is mated to the side of one of the four satellite modules. After the antenna yoke is clear of the facility the antenna is folded under the module into its transport position.

One of the two worst case conditions for orbital decay will be the situations where a fully assembled SPS self-power module is still attached to the base, see figure 2-12. Configuration No. 4 is defined to be this situation.

The second worst case condition for orbital decay is the situation where the SPS module is still attached to the base and the antenna is rotated under the module. This is Configuration No. 5, see figure 2-12.

The total mass of these configurations is the sum of the masses of the base, the SPS self-power module, the antenna, and the propellants on the SPS module. This total mass is 40710 MT.

The propulsion system concept described in section 2.1.1 and shown in figure 2-4 is typical of the LEO construction base propulsion system.

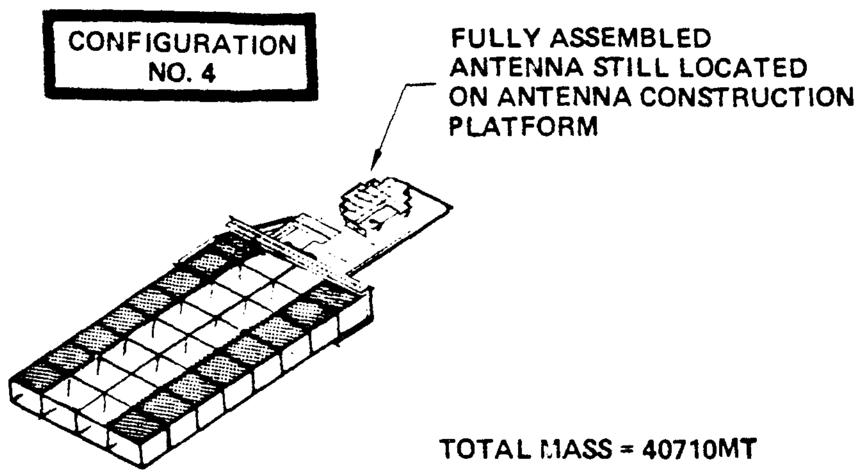
2.2.2 SPS Self-Power Module

The SPS self-power module (SPM) is shown in figure 2-13 (complete details are found in Ref. 4). This module is 1/4 of the final satellite. A portion of its solar array is deployed to provide power for the electric thrusters. The remainder of the array is stored in radiation-protecting cannisters on the structure.

There are two configurations of SPM's. Three of the four modules per satellite are considerably lighter than the other as they do not have an antenna attached to them. With propellants and systems for orbit transfer, these modules are 12353 MT whereas the one with the antenna is 34053 MT.

After the SPM is checked out, it is flown away from the LEO construction base and it starts its 180-day journey to GEO. As this is a very low-thrust journey, it is in LEO for a considerable number of days. The free-flying SPM with an antenna attached is Configuration No. 6.

The propulsion system concept for transport to GEO described in section 2.1.2 and shown in figure 2-9 is typical of the SPM's propulsion system.



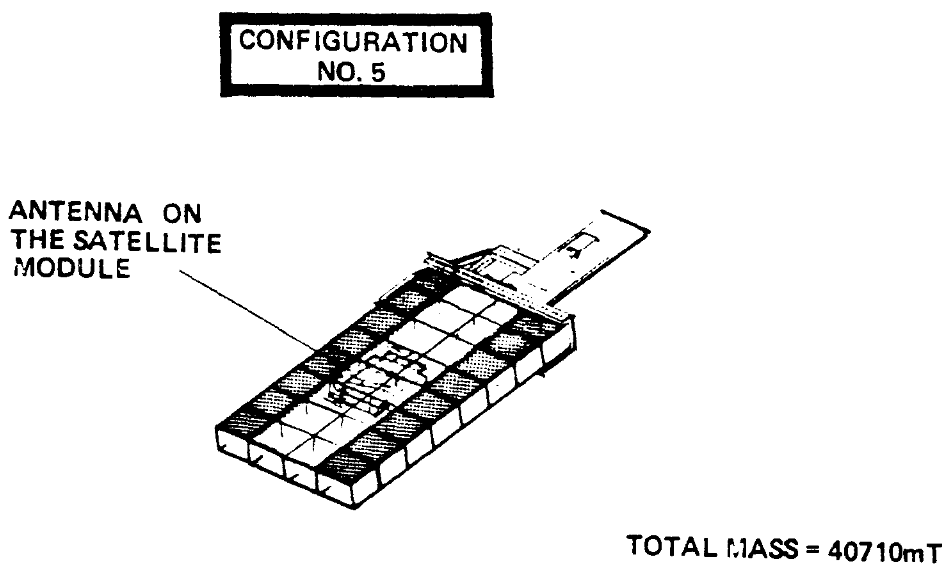


Figure 2-12. Configurations Used as Test Cases

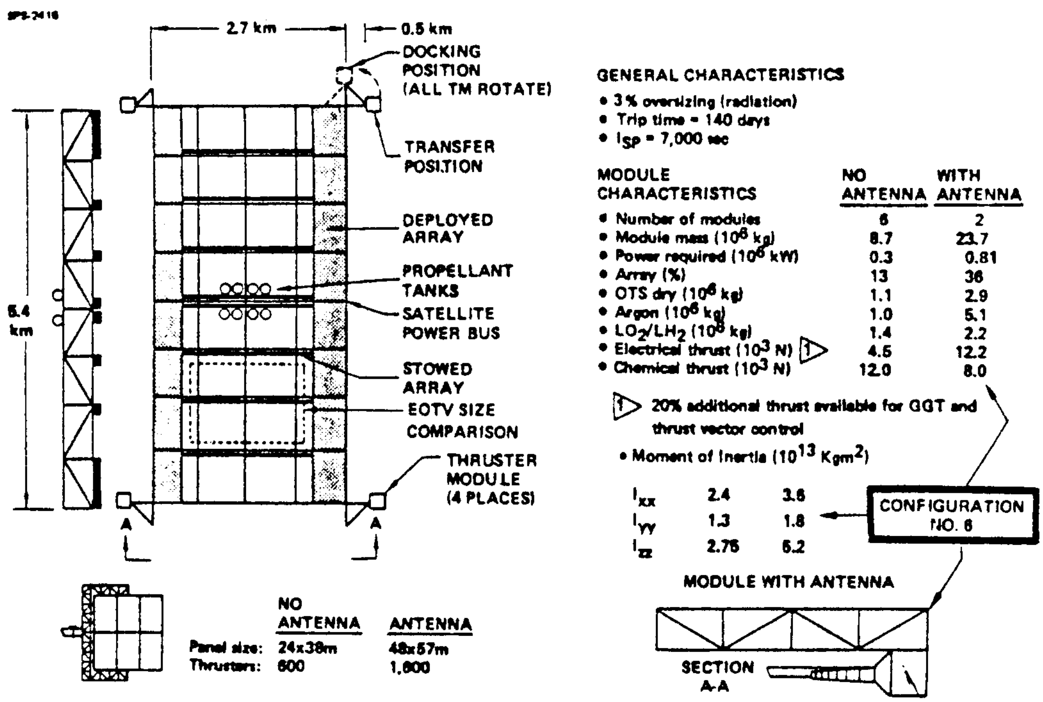


Figure 2-13. Self-Power Configuration Photovoltaic Satellite

3.0 ORBIT DECAY ANALYSIS

3.1 FORCES CAUSING ORBIT DECAY

The orbits and orbital attitudes of the LEO staging base and EOTV's are shown in figure 3-1. The orbits and attitudes of the LEO construction base and SPS self-power modules are shown in figure 3-2.

In order to avoid unplanned reentry of SPS elements, it is necessary to determine how the orbits of these various elements will change with time. Many forces contribute to changing the shape and orientation of a given orbit, the major ones being:

1. Earth's oblateness (nonsphericity)
2. Atmospheric drag of the satellite
3. Other gravitational effects (sun and moon)
4. Solar radiation pressure

3.1.1 Forces Deemed Insignificant

Although significant for some studies, most of these forces are not important for SPS orbit maintenance. Earth's oblateness, while it does affect the orientation of the orbit, does not contribute to orbit decay and unplanned reentry. Lunar and solar (luni-solar) gravitational perturbation effects are most pronounced on high altitude or highly elliptic orbits. Since the SPS elements are in low altitude circular orbits, these luni-solar effects are not significant. Solar radiation pressure can cause changes in the orbit eccentricity resulting in a lower perigee altitude and therefore faster decay rates due to increased drag during that part of the orbit. Studies were conducted using several different values for the coefficient of reflectivity (a measure of the effect of the solar radiation pressure on the vehicle) and the effect was found to be not significant.

3.1.2 Atmospheric Drag

The primary cause of orbit decay for SPS elements is atmospheric drag. The extent to which drag affects the orbit decay rate depends principally on three quantities; the frontal area of the vehicle, the atmospheric density, and the drag coefficient of the vehicle.

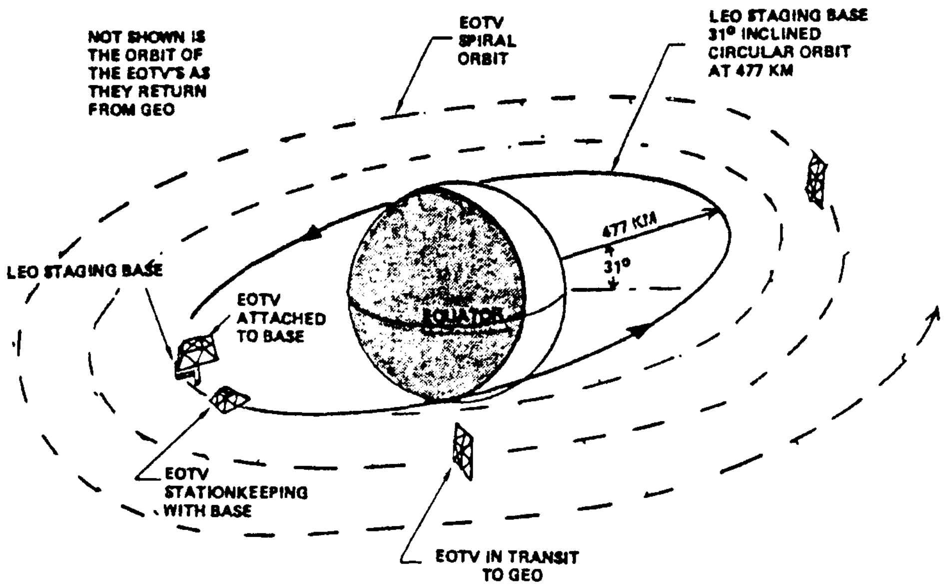


Figure 3-1. LEO Staging Base and EOTV Orbits and Orbital Atttude (GEO Construction Concept)

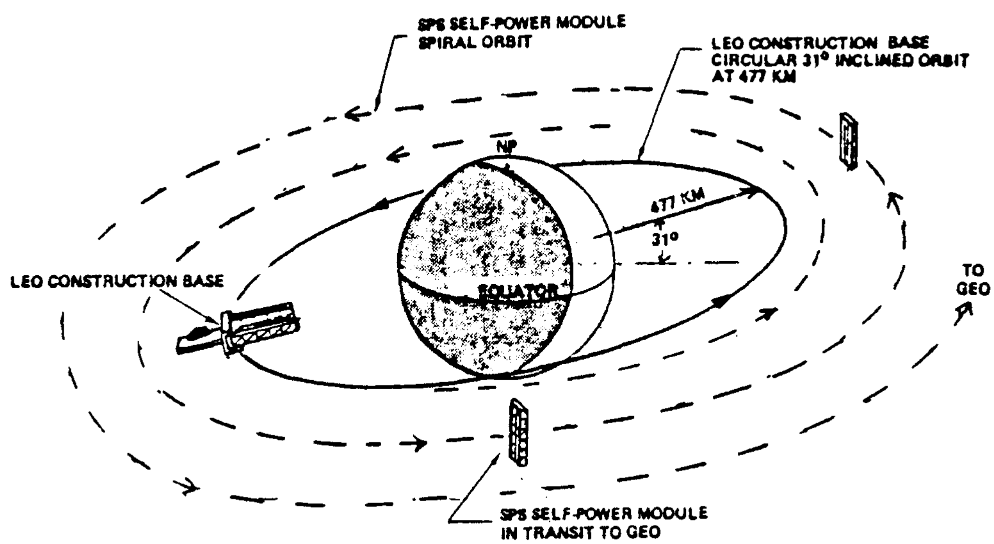


Figure 3-2. LEO Construction Base and SPS Self-Power Module Orbits and Orbital Attitudes (LEO Construction Concept)

Frontal area was computed by assuming that all beam structure consisted of 7.5 m triangular beams with 38 cm triangular components. Net flat plate areas were computed for three perpendicular sides of each vehicle. Two inertially fixed attitudes were examined and time average net flat plate areas for one revolution of the earth were obtained. The first attitude was the nominal attitude for elements (feathered into the "wind"). The second attitude examined was that which presented the largest time averaged net flat plate area. This "worst case" attitude could only occur if the element is tumbling as it progresses around its orbit. The average frontal area values and the masses used for the configurations examined are shown in table 3-1.

Atmospheric density at the SPS element altitude of 477 km depends on many factors. The primary effect is the solar radiation flux which varies with time. There are several cyclical variations to be considered when determining the value of the atmospheric density. These cycles are the eleven year solar cycle, the diurnal (day-night) cycle, the twenty-seven day cycle, and the semi-annual cycle. The atmospheric model used in determining orbit decay rates takes into account all of these effects. Orbit decay rates for two cases were determined. The first case was that of a normal solar radiation flux. The second case was for a +2 maximum solar radiation flux (corresponding to sun spot maximum) which greatly increases the upper atmosphere density. The latter case was taken to be the "worst case" in terms of atmospheric density (maximum solar activity).

Drag coefficients* of 2.2 and 3.0 were used to determine the upper and lower bound of the orbital decay rates. A drag coefficient of 2.2 is that of a sphere, representing a shape that has a constant net frontal area. This coefficient is typically applied to small satellites for their drag calculations. This would represent a lower bound of drag coefficients. A drag coefficient of 3.0 is that for a flat plate perpendicular to the velocity vector. This would represent the upper bound of drag coefficients. The exact drag coefficients for each of the SPS elements will have to be defined by a very detailed analysis at some future date. It is judged that the drag coefficients will fall somewhere between 2.2 and 3.0.

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* The drag coefficient is a measure of the retarding force (drag) experienced by an object as it moves through a resisting medium. It can be a function of many parameters including body shape and relative speed between the body and the medium it is moving through.

Table 3-1. SPS Element Characteristics

Config. No.	Configuration	Time Averaged Net Frontal Areas (M^2) Nominal Attitude	Worst Case Attitude	Mass (MT)
1	LEO Staging Base	13.51	39.89	1832
2	LEO Staging Base with fully assembled EOTV attached	19.46	1022.20	3809
3	Electric Orbit Transfer Vehicle (EOTV) (with payload)	5.95	1008.49	5977
4	LEO Construction Base with fully assembled SPS Self-Powered Module attached (antenna still on construction platform)	85.37	4033.10	40710
5	LEO Construction Base with fully assembled SPM with antenna folded under SPS Self-Powered Module	85.37	4037.70	40710
6	SPS Self-Powered Module	27.77	3892.35	34053

3.2 ORBIT DECAY RATES

Table 3-2 contains the orbit decay rates, based on the above criteria, and the daily velocity increment (delta-V) required to keep the vehicle in the required orbit. The decay rates shown are the initial rates (Ref. 5). The delta-v's were obtained by assuming a constant tangential low-thrust propulsion system was to be used (Ref. 6).
Limiting orbit decay vs. time plots for each configuration in the nominal attitude were made, see figures 3-3 thru 3-7. One limit is the nominal solar activity, $C_D = 2.2$ curve. The other limit is the worst solar activity, $C_D = 3.0$ curve. For all configurations, both these limiting curves are very flat. Configurations 4 and 5 have the same curves.

Also plotted is the curve for worst attitude, worst solar activity, and $C_D = 3.0$. For this to occur, attitude control of the SPS element must be lost, and this must result in tumbling in orbit. The tumbling must be about the axis which produces the maximum time averaged frontal area to the oncoming atmosphere. This event must occur right at the sun spot maximum, and our worst estimate of the coefficient of drag must turn out to be true.

3.3 TIME AVAILABLE FOR TROUBLESHOOTING AND CORRECTIVE ACTION

In figures 3-3 thru 3-7, it was seen that the decay rates increases rapidly below an altitude of 400 km. An altitude of 400 km was therefore taken as the limit below which successful recovery is doubtful. For all of the SPS elements, it is possible to stop the orbital decay at 400 km without exceeding the 10^{-4} g's structural design loads. The major aspect of recovery consists simply of regaining attitude control.

Using 400 km as a "point of no return", it is possible to estimate the time available for troubleshooting and corrective action. Table 3-3 shows the minimum and maximum time required for the SPS elements to decay from 477 km to 400 km assuming nothing is done to prevent the decay. It is seen that for the nominal attitudes/nominal solar activity cases that it would require hundreds of days for the various elements to reach the "point of no return" if no orbit keeping capabilities were available. For the worst case attitude (tumbling)/worst case solar activity cases, the orbits could decay to 400 km within a few days. This decay would be arrested as soon as attitude control were regained. The maximum time available for troubleshooting and corrective action is set by this criteria.

Table 3-2. SPS Elements Orbital Maintenance Parameters

Config. No.	Configuration	Nominal Attitude (Initial Decay Rate (m/day)/ Correction ΔV (m/sec/day))				Worst Case Attitude [1] (Initial Decay Rate (m/day)/ Correction ΔV (m/sec/day))			
		Nominal Solar Activity		Worst Case Solar Activity		Nominal Solar Activity		Worst Case Solar Activity	
		C_D=2.2	C_D=3.0	C_D=2.2	C_D=3.0	C_D=2.2	C_D=3.0	C_D=2.2	C_D=3.0
1	LEO Staging Base	-45/ 0.025	-62/ 0.0345	-195/ 0.109	-269/ 0.150	-135/ 0.075	-186/ 0.104	-565/ 0.315	-779/ 0.435
2	LEO Staging Base with fully assembled EOTV attached	-35/ 0.019	-48/ 0.0262	-135/ 0.075	-186/ 0.103	-1655/ 0.921	-2284/ 1.27	-7185/ 4.003	-9915/ 5.524
3	EOTV (loaded)	-5/ 0.003	-7/ 0.004	-25/ 0.014	-34/ 0.019	-1035/ 0.576	-1428/ 0.795	-4445/ 2.476	-6134/ 3.417
4	LEO Construction Base with fully assembled SPM attached (antenna still on construction platform)	-15/ 0.008	-21/ 0.011	-55/ 0.03	-76/ 0.043	-605/ 0.337	-835/ 0.465	-2575/ 1.434	-3553/ 1.979
5	LEO Construction Base with fully assembled SPM with antenna folded under SPS Self-Power module	-15/ 0.008	-21/ 0.011	-55/ 0.031	-76/ 0.043	-605/ 0.337	-835/ 0.465	-2585/ 1.439	-3567/ 1.986
6	SPS Self-Power Module	-5/ 0.003	-7/ 0.004	-25/ 0.014	-34/ 0.019	-705/ 0.392	-973/ 0.541	-2985/ 1.662	-4119/ 2.294

[1] This "worst case" attitude could only happen if the element were tumbling as in progresses around its orbit. This condition will be prevented from happening by system design.

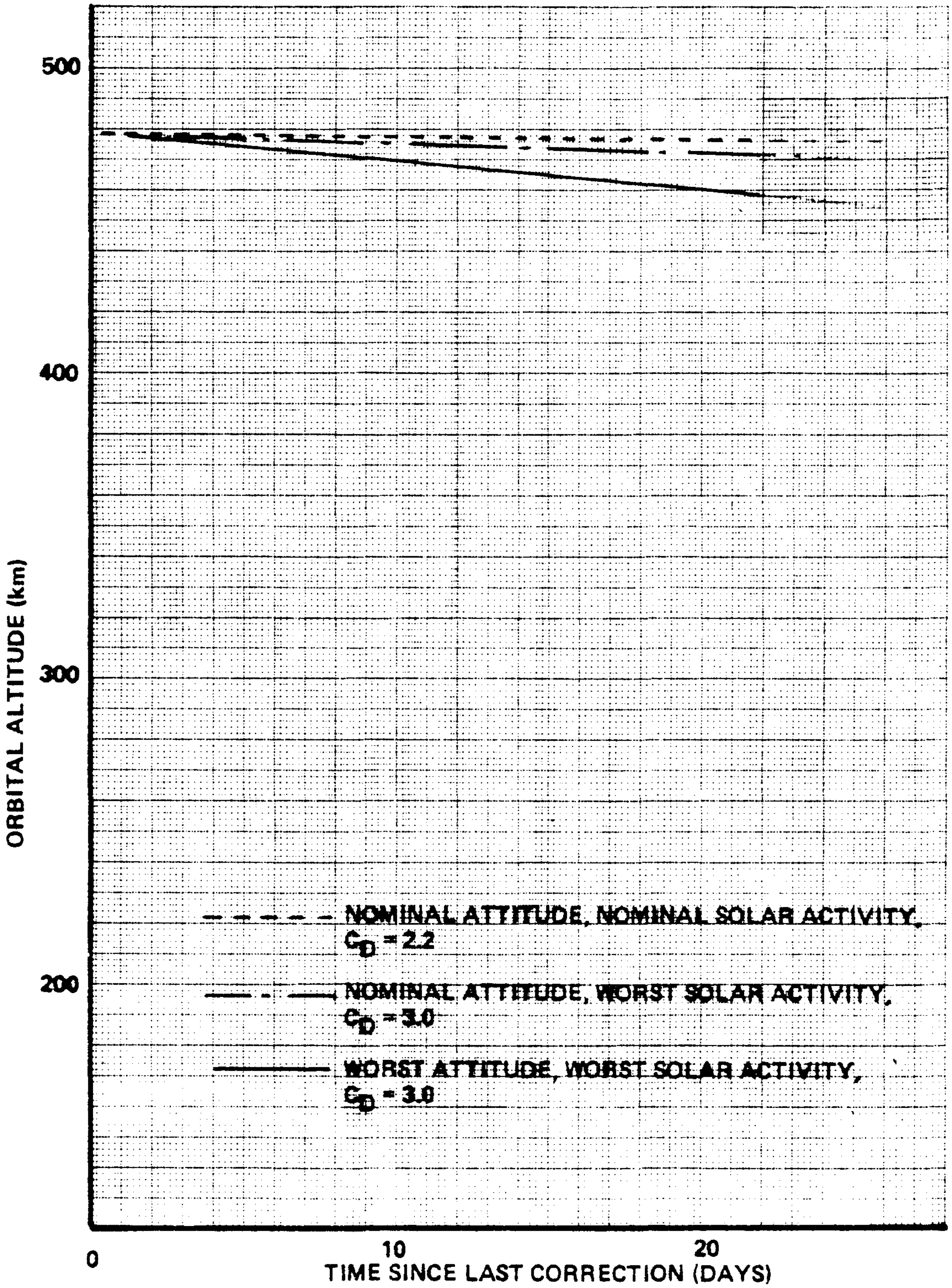


Figure 3.3. Orbital Decay vs. Time for Configuration 1 – LEO Staging Base

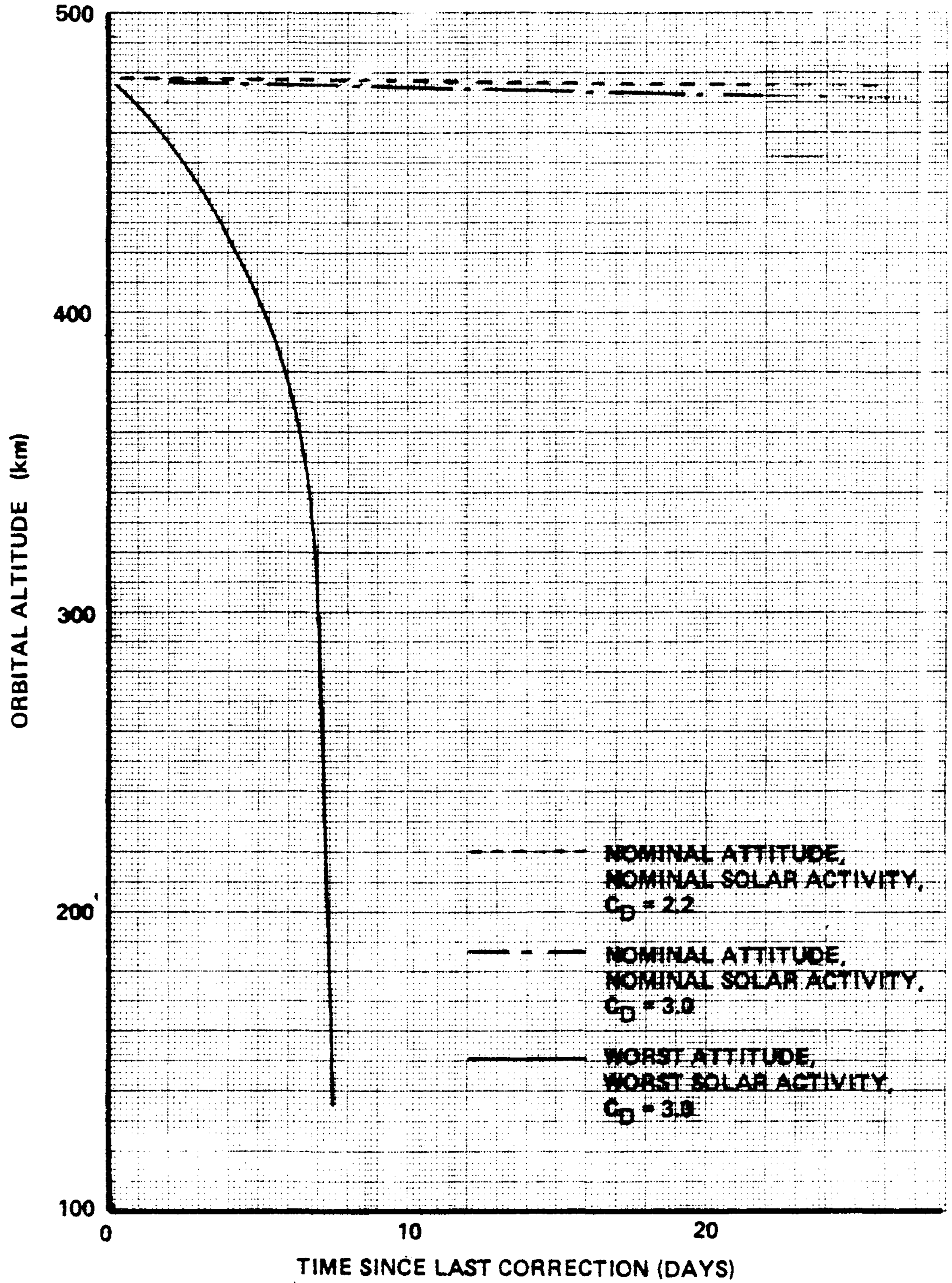


Figure 3-4. Orbital Decay vs. Time
Configuration 2 – LEO Staging Base Plus EOTV

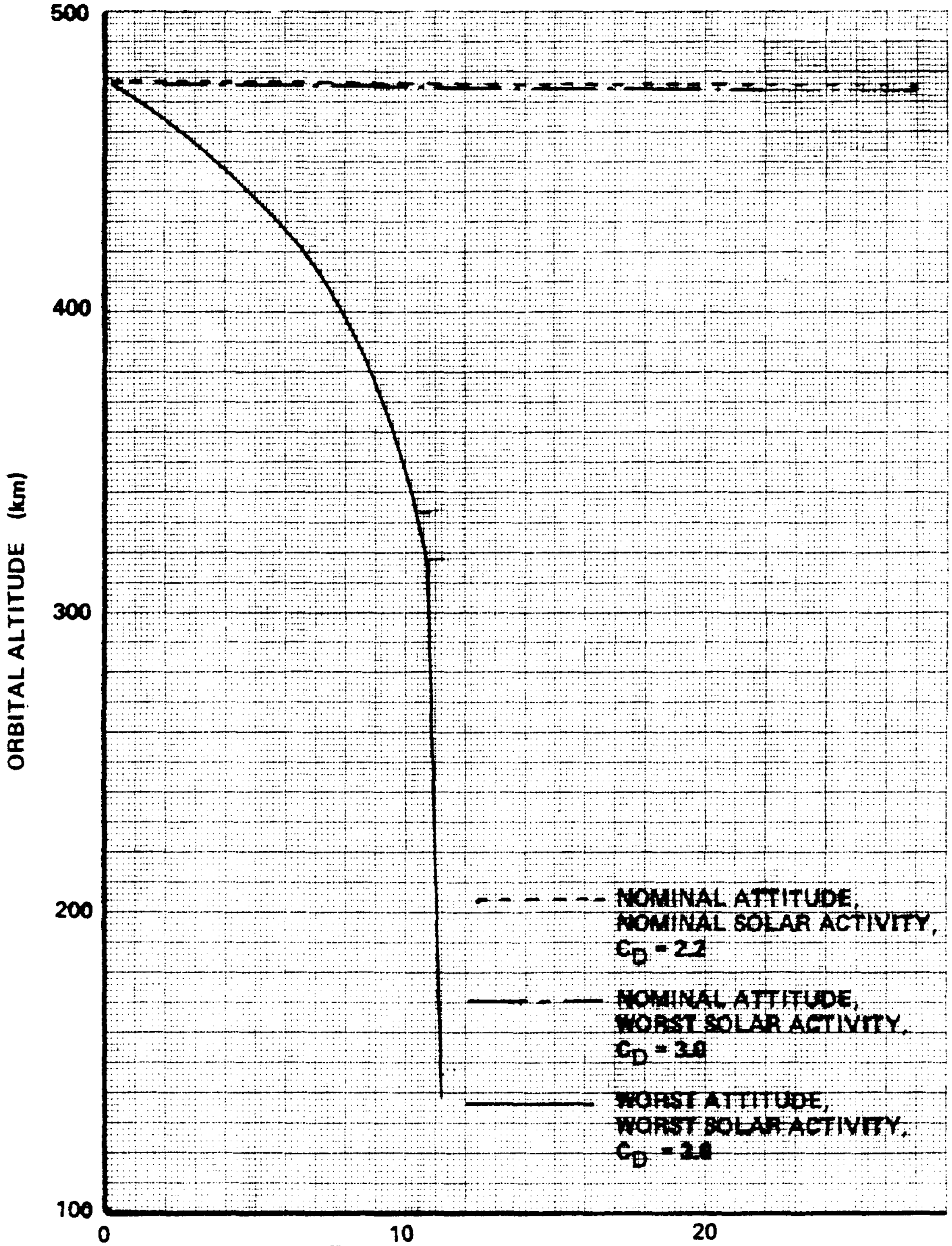


Figure 3-5 Orbital Decay vs. Time for Configuration 3 - EOTV

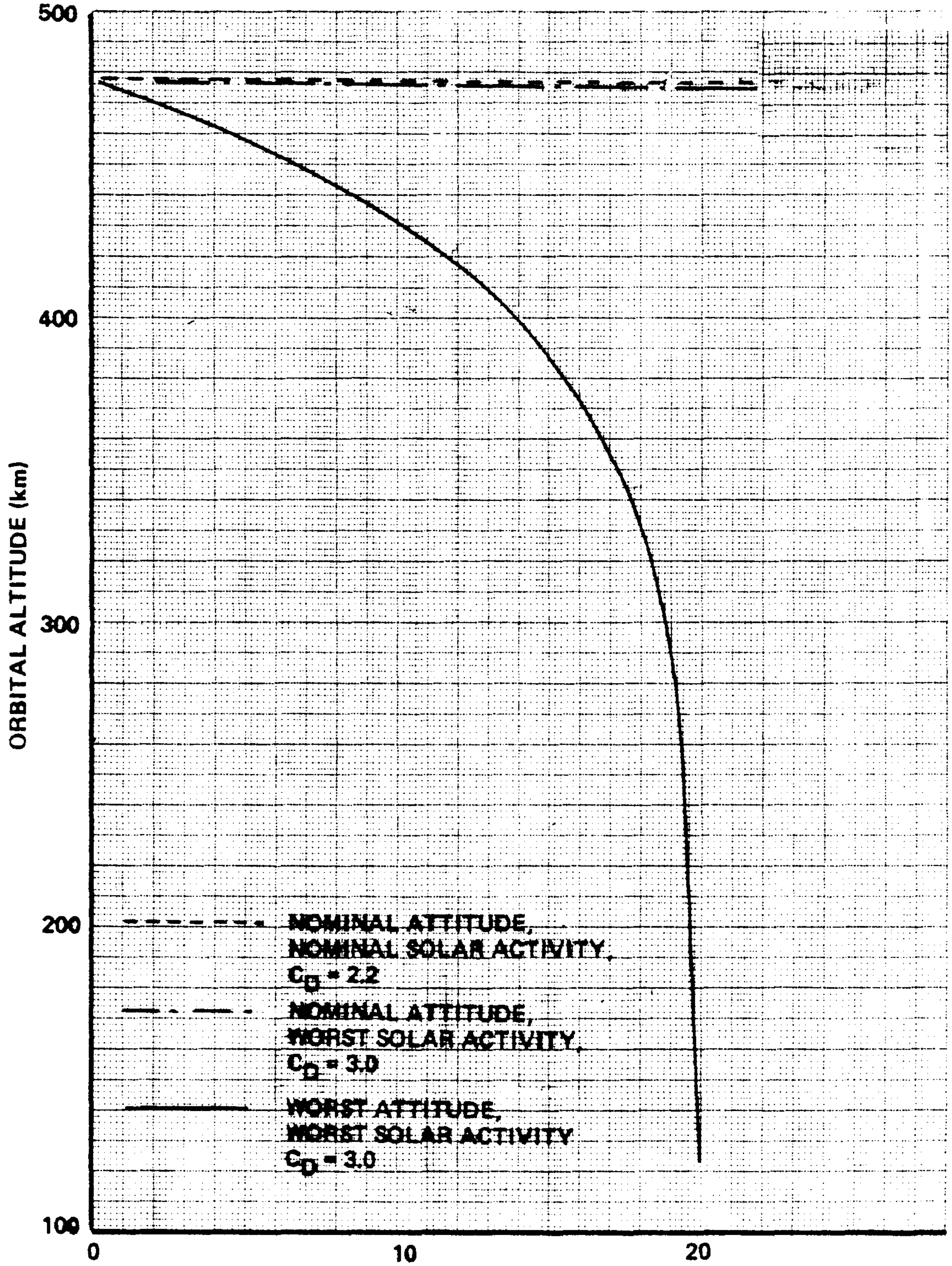


Figure 3-6. Orbital Decay vs. Time for Configurations 4 and 5 – LEO Construction Base Plus SPS Self-Powered Module

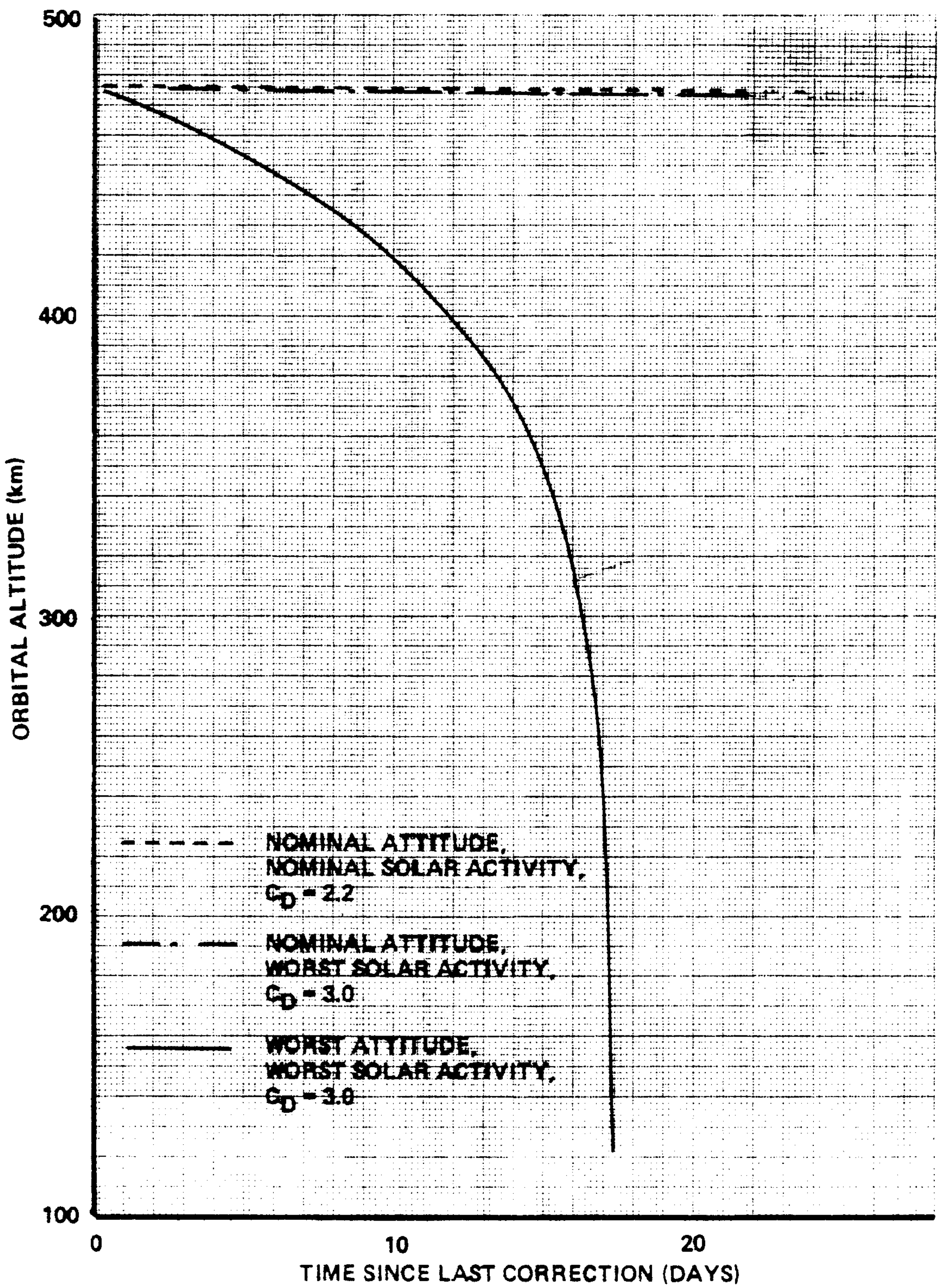


Figure 3-7. Orbital Decay vs. Time for Configuration 6 – SPS Self-Powered Module

TABLE 3-3 Time Required For Orbits To Decay To 400 km

Config. No.	Configuration	Worst Attitude, Worst Solar Activity $C_D = 3.0$	Nominal Attitude, Nominal Solar Activity, $C_D = 2.2$
1	LEO Staging Base	40 days	700 days
2	LEO Staging Base with fully assembled EOTV attached	5 days	960 days
3	EOTV (loaded)	8 days	5130 days
4	LEO Construction Base with fully assembled SPM attached (antenna still on construction platform)	13 days	2200 days
5	LEO Construction Base with fully assembled SPM with antenna folded under SPS Self-Power module	13 days	2200 days
6	SPS Self-Power Module	11 days	5130 days

MAXIMUM TIME
AVAILABLE FOR
TROUBLESHOOTING AND
CORRECTIVE ACTION

4.0 ORBIT MAINTENANCE DESIGN AND OPERATIONAL REQUIREMENTS

4.1 CAUSES OF UNPLANNED REENTRY

The "no unplanned reentry groundrule" is that the SPS elements located in low Earth orbit (launch vehicles are not included) shall be designed and operated in such a way that there will be no possibility for the element to deorbit and fall to Earth under any foreseeable circumstances. Figure 4-1 shows the "foreseeable circumstances" that could cause an SPS element to deorbit as best as we can define these circumstances at this time. As the SPS program progresses through the design process, this listing of unplanned reentry causing events will be elaborated upon in great detail. Probabilities of occurrence will be assigned to each of the possible events.

4.2 GENERAL APPROACHES TO PREVENTING UNPLANNED REENTRY

The general approaches to preventing unplanned reentry of SPS elements are (1) to eliminate causing events, (2) to minimize the chances of occurrence of the causing events, and (3) to minimize the impact of the causing events which cannot be eliminated.

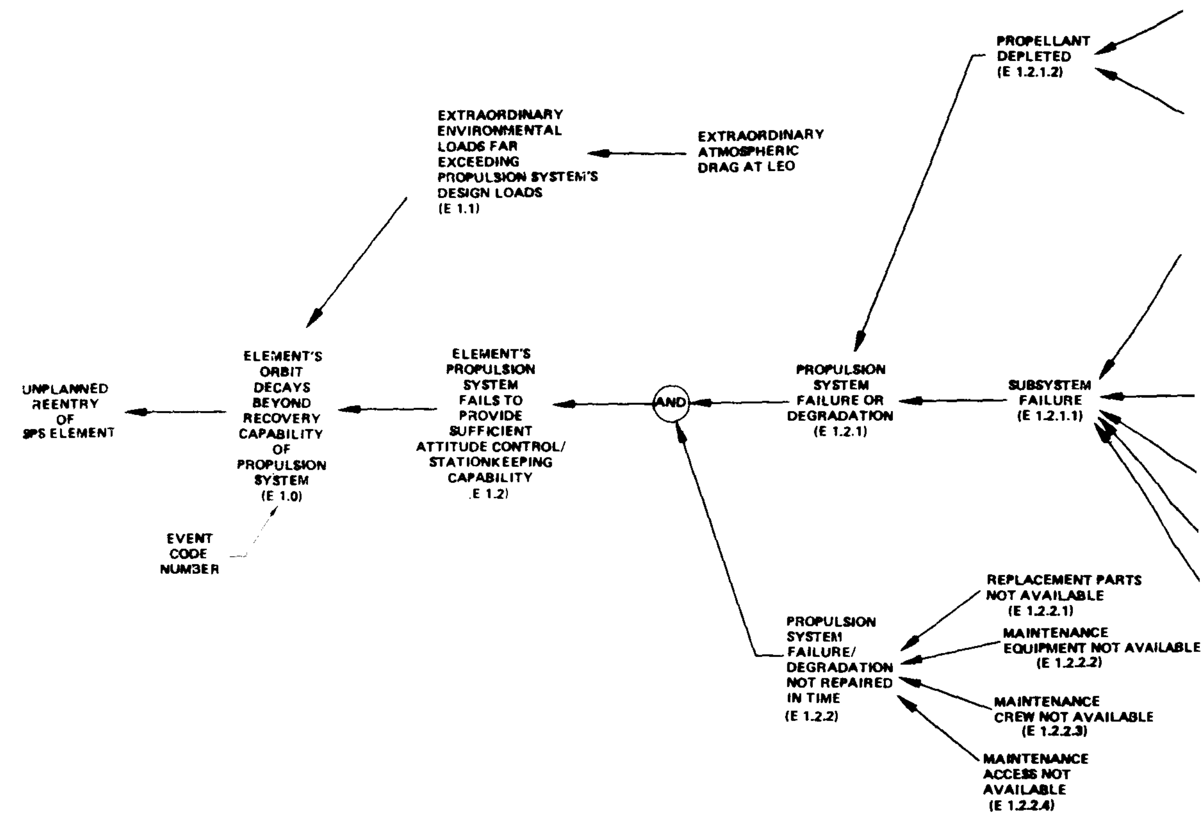
An example of eliminating causing events would be to remove all orbital debris that may intersect the orbital paths of the various elements so that there is no chance of collision from this class of objects.

An example of minimizing the chances of occurrence of a causing event would be to have the EOTV's stationkeep with the LEO staging base at a standoff distance of tens of kilometers to minimize the chance of collision.

An example of minimizing the impact of a causing event would be to require that the EOTV have redundant propulsion systems so that it remains completely controllable in the event that the entire propulsion system on one corner of the vehicle is totally disabled.

4.3 SYSTEM DESIGN AND OPERATIONAL REQUIREMENTS

Table 4-1 lists the specific design and operational requirements imposed by the "no unplanned reentry groundrule." The SPS elements to which each requirement will apply is designated. The



UNPLANNED REENTRY OF SPS ELEMENT
ELEMENT'S ORBIT DECAYS BEYOND RECOVERY CAPABILITY OF PROPULSION SYSTEM (E 1.0)
EVENT CODE NUMBER
EXTRAORDINARY ENVIRONMENTAL LOADS FAR EXCEEDING PROPULSION SYSTEM'S DESIGN LOADS (E 1.1)
EXTRAORDINARY ATMOSPHERIC DRAG AT LEO
ELEMENT'S PROPULSION SYSTEM FAILS TO PROVIDE SUFFICIENT ATTITUDE CONTROL/ STATIONKEEPING CAPABILITY (E 1.2)
AND
PROPULSION SYSTEM FAILURE OR DEGRADATION (E 1.2.1)
PROPELLANT DEPLETED (E 1.2.1.2)
SUBSYSTEM FAILURE (E 1.2.1.1)
PROPULSION SYSTEM FAILURE/ DEGRADATION NOT REPAIRED IN TIME (E 1.2.2)
REPLACEMENT PARTS NOT AVAILABLE (E 1.2.2.1)
MAINTENANCE EQUIPMENT NOT AVAILABLE (E 1.2.2.2)
MAINTENANCE CREW NOT AVAILABLE (E 1.2.2.3)
MAINTENANCE ACCESS NOT AVAILABLE (E 1.2.2.4)

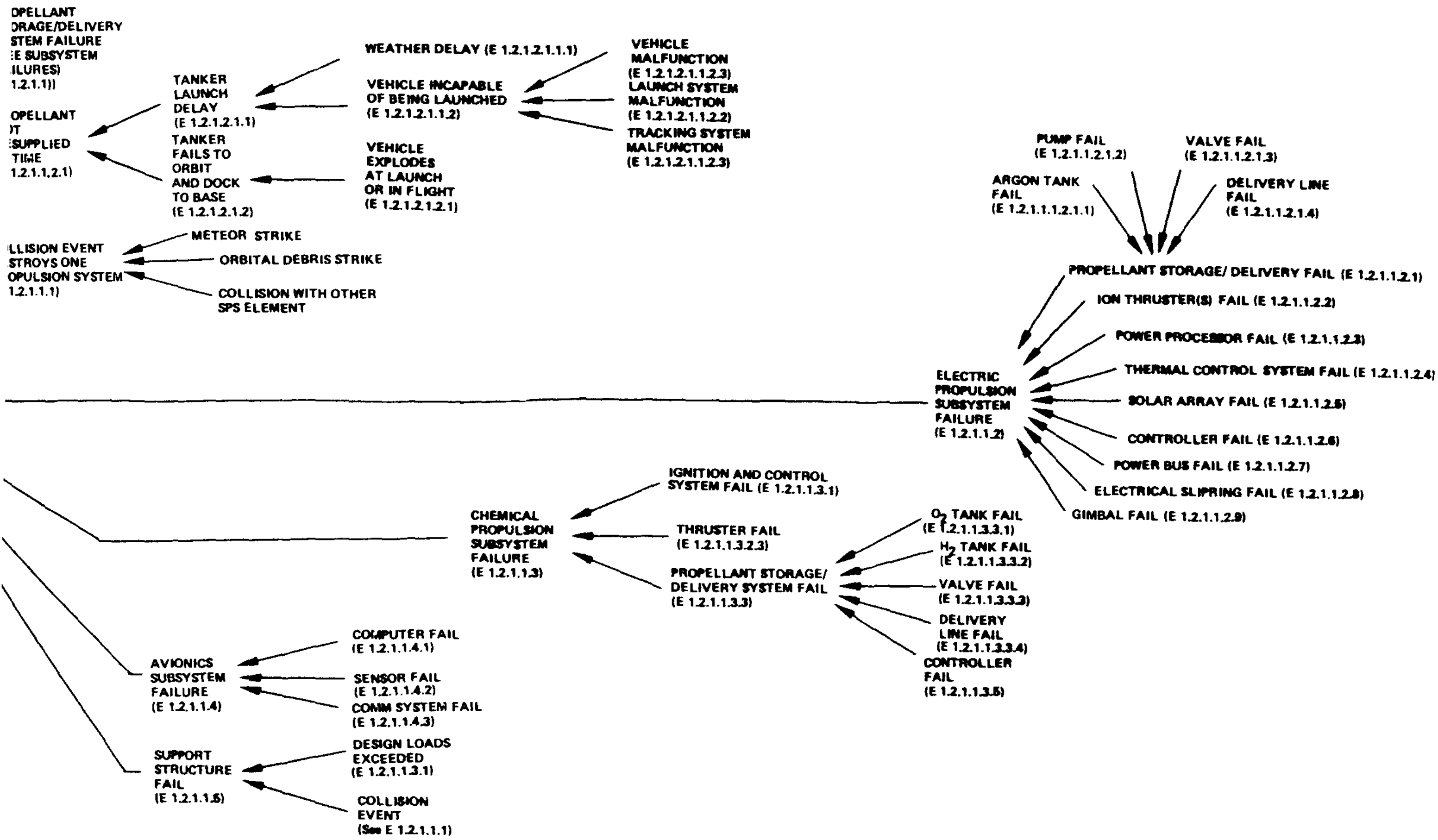


Figure 4-1. Events That Could Cause Unplanned Reentry of SPS Elements

Table 4-1. Design and Operational Requirements Imposed by No Unplanned Reentry Groundrule

Reqmt No.	Requirement Description	Applies To [1] LSB	EOTV	LCB	SPM	Requirement Source [2]	Comments
1.0	SPS elements located in low Earth orbit shall be designed and operated in such a way that there will be no possibility for the element to deorbit and fall to Earth under any foreseeable circumstances	*	*	*	*	E1.0	This is the "no unplanned reentry groundrule"
1.1	Environmental Design Loads—						
1.1.1	o The atmospheric drag for LEO shall be modeled from the 2σ maximum solar radiation flux	*	*	*	*	E1.1	
1.1.2	o The coefficient of drag shall be calculated for all known environmental situations and all orientations of all configurations of the element	*	*	*	*	E1.2	
1.2	Propulsion System Design and Operational Requirements						
1.2.1	The propulsion system must be sized to provide attitude control/stationkeeping capability for all element configurations under the worst case environmental conditions	*	*	*	*	E1.0 E1.1 E1.2	
1.2.2	There shall be redundant propulsion system installations	*	*	*	*	E1.2.1	
1.2.2.1	o The element must be controllable in the event that any propulsion system installation is totally disabled	*	*	*	*	E1.2	
1.2.2.2	o The element must be controllable in the event that any single thruster cannot be shut off	*	*	*	*	E1.2.1.1.2 E1.2.1.1.3	

[1] LSB = LEO staging base; EOTV = electric orbit transfer vehicle; LCB = LEO construction base; SPM = SPS self-power module

[2] Refer to event codes in Figure 4-1.

Table 4-1. Design and Operational Requirements Imposed by No Unplanned Reentry Groundrule

Reqmt No.	Requirement Description	Applies To [1] LSB	EOTV	LCB	SPM	Requirement Source [2]	Comments
1.2.3	<u>Propellant Storage</u>						See Appendix 1
1.2.3.1	The propellant storage capacity must be sized to take into account the following factors:						
	o Quantity required for normal operations						
	o 3 months orbit keeping/attitude control	*		*			
	o 180-day LEO-to-GEO trip		*		*		
	o 39-day GEO-to-LEO trip		*				
	o 6-day loiter at LEO		*				
	o 6-day loiter at GEO		*				
	o Reserve quantity for contingencies					E1.2.1.2	
	o 2-week propellant resupply delay due to weather	*		*		E1.2.1.2.1.1	
	o 1-week propellant resupply delay due to maintenance	*	*	*	*	E1.2.1.2.1.2	
	o 2 weeks of solar maximum flux	*	*	*	*	E1.1	
1.2.3.2	Provide redundant propellant storage tanks	*	*	*	*	E1.2.1.1.2.1.1 E1.2.1.1.3.1.3.1 E1.2.1.1.3.1.3.2	
1.2.4	<u>Propellant Delivery Systems</u>					E1.2.1.1.2.1.4 E1.2.1.1.3.3.4	
1.2.4.1	Provide redundant propellant delivery lines along independent paths between propellant storage tanks and each propulsion system installation	*	*	*	*		

[1] LSB = LEO staging base; EOTV = electric orbit transfer vehicle; LCB = LEO construction base; SPM = SPS self-power module

[2] Refer to event codes in Figure 4-1.

Table 4-1. Design and Operational Requirements Imposed by No Unplanned Reentry Groundrule

Reqmt No.	Requirement Description	Applies To [1] LSB	EOTV	LCB	SPM	Requirement Source [2]	Comments
1.2.4.2.1	Accumulators sized to provide TBD hours of propulsion system operation in case propellant delivery from storage tanks is cut off	*	*	*	*		
1.2.4.2.2	Provide capability to bypass accumulators	*	*	*	*		
1.2.4.2.3	Provide capability to isolate accumulators on propellant input side	*	*	*	*		
1.2.5	Chemical Propulsion System						
1.2.5.1	Provide redundant, fixed thrusters at each propulsion system installation	*	*	*	*	E1.2.1.1.3.2	
1.2.5.2	Provide redundant heaters/valves/sensors/ignition system assemblies at each propulsion system installation	*	*	*	*	E1.2.1.1.3.1	
1.2.5.3	Provide redundant electrical power conductors to each propulsion system installation	*	*	*	*		
1.2.5.4	Provide redundant control signal conductors to each propulsion system installation	*	*	*	*	E1.2.1.1.4.3	
1.2.6	Electric Propulsion System						
1.2.6.1	Provide redundant electric thrusters (20% more than required for normal operations)		*		*	E1.2.1.1.2.2	
1.2.6.2	Provide redundant power processors (PPU's) (enough to accept 20% more thrusters)		*		*	E1.2.1.1.2.3	
1.2.6.3	Provide redundant PPU thermal control system components		*		*	E1.2.1.1.2.4	
1.2.6.4	Oversize the solar array area by TBD% over the nominal requirements		*		*	E1.2.1.1.2.5	

[1] LSB = LEO staging base; EOTV = electric orbit transfer vehicle; LCB = LEO construction base; SPM = SPS self-power module

[2] Refer to event codes in Figure 4-1.

Table 4-1. Design and Operational Requirements Imposed by No Unplanned Reentry Groundrule

Reqmt No.	Requirement Description	Applies To [1] LSB	EOTV	LCB	SPM	Requirement Source [2]	Comments
1.2.6.5	Provide redundant electrical power bases		*		*	E1.2.1.1.2.7	
1.2.6.7	Provide oversized electrical slipring assembly					E1.2.1.1.2.8	These are the only components that cannot be redundant. Overdesign several hundred percent.
1.2.6.8	Provide oversized mechanical rotary joint					E1.2.1.1.2.8	
1.2.6.9	Provide redundant gimbal motors					E1.2.1.1.2.9	
1.2.7	<u>Avionics Subsystem</u>						
1.2.7.1	Provide triple-redundant avionic system	*	*	*	*	E1.2.1.1.4	
1.2.7.2	Provide separate paths for each signal conductor	*	*	*	*	E1.2.1.1.4.3	
1.2.8	<u>Structure</u>						
1.2.8.1	Provide redundant load paths	*	*	*	*	E1.2.1.1.5.1	
1.2.9	<u>Cargo Tug Docking</u>						
	Provide docking systems for two cargo tugs		*			See para. 3.2.3 in Appendix A	

[1] LSB = LEO staging base; EOTV = electric orbit transfer vehicle; LCB = LEO construction base; SPM = SPS self-power module

[2] Refer to event codes in Figure 4-1.

Table 4-1. Design and Operational Requirements Imposed by No Unplanned Reentry Groundrule

Reqmt No.	Requirement Description	Applies To [1] LSB	EOTV	LCB	SPM	Requirement Source [2]	Comments
1.3	<u>Propulsion System Maintenance Requirements</u>						See Appendix 2
1.3.1	All propulsion system components must be capable of being accessed by maintenance equipment and crew	*	*	*	*	E1.2.2.4	
1.3.2	All propulsion system LRU's must be capable of being removed/replaced by remote-controlled manipulators	*	*	*	*	E1.2.2	
1.3.3	There shall be at least one full set of propulsion system LRU's in storage at the LEO base at all times. This includes the LRU's for the bases' propulsion system as well as for the LEO-to-GEO element.	*		*		E1.2.2.1	
1.3.4	Propulsion system maintenance specialists shall be assigned to the LEO base at all times	*		*		E1.2.2.3	
1.3.5	Propulsion system maintenance equipment shall be available at the LEO base at all times	*		*		E1.2.2.2	

[1] LSB = LEO staging base; EOTV = electric orbit transfer vehicle; LCB = LEO construction base; SPM = SPS self-power module

[2] Refer to event codes in Figure 4-1.

source of the requirements are defined by designating the anomaly event codes (from fig. 4-1) that are applicable.

It must be emphasized that this list of requirements should be considered to be preliminary. Very detailed and extensive systems requirements analyses will be conducted as the SPS program goes through its evolutionary design and development.

4.4 MASS PENALTY FOR REDUNDANT SUBSYSTEMS AND SPARES

One of the requirements of this study was to identify the mass "penalty" caused by the redundant subsystems and the additional spares required to meet the "no unplanned reentry" groundrule. There really is not a "penalty" in that normal aerospace design practice leads to the inclusion of redundant systems and stocking of spare parts. Even if there were no "unplanned reentry" ground rule, redundant systems would be required so that the various elements could meet mission performance reliability goals and spare parts would be stocked as part of the overall maintenance plan.

Table 4-2 lists the mass estimates of the chemical propulsion systems on each of the SPS elements, the mass of the redundant components, and the mass of the on-board spares. These are very generous mass estimates. If we assume 100% redundancy (a very conservative assumption) then we can assume that one-half of the chemical propulsion system mass is the "penalty." The mass of the on-board spares was estimated by assuming that 10% of all of the chemical propulsion system except for the storage tanks will be stocked as spare parts.

It must be emphasized that the additional mass encurred by installing redundant components/subsystems and stocking space parts is of little consequence. These contribute less than 1% to the total mass of the SPS element.

Table 4-2 Mass of Redundant Propulsion System Components and Spare Parts

		Mass Estimate, MT			
I.	CHEMICAL PROPULSION SYSTEM MASS	LSB	ETOV	LCB	SPM
	o Propellant Storage System	27	3.7	228	160
	o Propellant Delivery	2	1	4	2
	o Ignition and Control System	3	2	3	2
	o Thrusters	3	2	3	2
	o Avionics	0.5	0.5	0.5	0.5
	Total Mass	35.5	9.2	238.5	166.5
II.	REDUNDANT PARTS				
	o 50% of Total Mass	18	5	119	83
III.	ON-BOARD SPARES				
	o 10% of Total Mass less Propellant Storage System	.85	0.55	1	0.65
	Total Mass of Chem. Prop. System Spares Carried at LEO Base	1.4		1.65	

5.0 SUMMARY

The objective of this study was to identify the design and operational requirements that will be imposed by the need to avoid unplannned reentry of SPS elements. In this study, we restricted our attention to elements described in the Boeing SPS system definition studies. The results of the study, however, are generally applicable to the elements defined by the Rockwell system definition studies.

The SPS elements that were selected for analysis come from two fundamentally different construction location concepts. For the GEO construction concept, the elements located in low Earth orbit that were selected for study were the LEO staging base and the EOTV. For the LEO construction concept, the elements located in low Earth orbit that were selected for study were the LEO construction base and the SPS self-powered module.

We selected the worst-case configurations for each of these elements for orbital decay and propellant consumption analyses. The normal LEO orbit for the SPS elements is a 477 km circular orbit at 31° inclination. Atmospheric drag is the only environmental force that will cause orbit decay. We used two values of drag coefficients: $C_D = 2.2$, which corresponds to a sphere, and $C_D = 3.0$, which corresponds to a flat plate. The drag coefficients for the various elements will fall somewhere between these extremes. We also used two atmospheric density models: a normal solar radiation flux and a $+2\sigma$ maximum solar radiation flux corresponding to sun spot maximum.

Table 5-1 shows the results of the orbital decay analysis. It is seen that for the nominal conditions that the elements would require years for the orbit to decay to the "point of no return" (estimated to be at 400 km) if no attitude control or orbit-keeping maneuvers were possible. If control of the element was totally lost and the vehicle started tumbling during the worst solar flare, the data shows that the elements could decay to 400 km within a few days. However, it must be emphasized that once altitude control is reestablished (the tumbling is stopped) that the element would then require hundreds to thousands of days for it to decay to the 400 km altitude.

We defined the sequences of events that could lead to unplanned reentry of SPS elements. All of these events can and will be countered by applying design and operational requirements. We have identified which of these requirements apply to each of the elements. In general, we will use very conservative design criteria and will require redundant fail-safe propulsion systems to

TABLE 5-1 Time Required For Orbits To Decay To 400 km

Config. No.	Configuration	Worst Attitude, Worst Solar Activity $C_D = 3.0$	Nominal Attitude, Nominal Solar Activity, $C_D = 2.2$
1	LEO Staging Base	40 days	700 days
2	LEO Staging Base with fully assembled EOTV attached	5 days	960 days
3	EOTV (loaded)	8 days	5130 days
4	LEO Construction Base with fully assembled SPM attached (antenna still on construction platform)	13 days	2200 days
5	LEO Construction Base with fully assembled SPM with antenna folded under SPS Self-Power module	13 days	2200 days
6	SPS Self-Power Module	11 days	5130 days

MAXIMUM TIME AVAILABLE FOR TROUBLESHOOTING AND CORRECTIVE ACTION ensure that the systems cannot degrade to a point where attitude control/orbit-keeping control is jeopardized.

The additional mass and cost of these redundant systems is of little consequence as they contribute less than 1% to the total mass and cost of the elements.

We also looked at the onboard propellant storage requirements to see if there was sufficient quantities of propellants available to cover contingency conditions. It turns out that for all but one of the combinations of SPS elements/contingency conditions that there will always be orders of magnitude more propellant stored onboard than would be required to handle the contingency conditions. The only exception was for the case where an EOTV started tumbling during a solar flare. We have specified the design and operational requirements that must be satisfied to prevent this event from ever happening and to rectify the situation if it were to occur.

We have also identified the propulsion system maintenance support equipment, crew, and operations for each of the elements. The propulsion system control operations were also defined.

In conclusion, it is evident that there are design and operational approaches available that will be applied to the design of the various SPS elements that will negate the possibility of these elements reentering the atmosphere and falling back to Earth.

6.0 REFERENCES

1) Satellite Power System Concept Development and Evaluation Program, Reference System Report, US Dept. of Energy and NASA, DOE/ER-0023, October 1978.

2) Vol. II, Phase II Final Report, Reference System Description, Solar Power Satellite System Definition Study (Contract NAS9-15636), Boeing Aerospace Company, D180-25461-2 November, 1979.

3) Vol III, Phase II Final Report, Operation and Systems Synthesis, Solar Power Satellite System Definition Study (Contract NAS9-15636), Boeing Aerospace Company, D180-25461-3, November, 1979.

4) Preferred Concept Description, Solar Power Satellite System Definition Study, Part III (Contract NAS9-15196), Boeing Aerospace Company, D180-24071-1, March 1978.

5) Hargraves, C. R., and Itzen, B.V., Long Term Earth Satellite Orbit Prediction (LTESOP), Boeing Company, D2-114257-1, 1968.

6) Zee, Chong-Hung, Low Constant Tangential Thrust Spiral Trajectories, AIAA Journal, Vol. 1, No. 7, Pages 1581-83, July 1963.

APPENDIX I

PROPELLANT REQUIREMENTS ANALYSIS

1.0 INTRODUCTION

In table 4-1, the system requirements for propellant storage were identified. Each of the SPS elements will have to carry enough on-board propellants to provide for both normal and contingency propulsion system operations. In this appendix, we will define the propellant storage required for normal operations. Next, we will discuss the contingencies and assess the additional reserve propellant storage capacity that will be required at the various elements to accommodate these contingencies.

2.0 PROPELLANT STORAGE REQUIRED FOR NORMAL OPERATIONS

2.1 Daily Propellant Requirements

Table A1-1 presents the daily propellant requirements values for I_{sp} = 400 seconds. From the table it is seen that the yearly propellant mass requirements even during solar maximum, which does not last an entire year, are less than 1% of the mass of the configuration with the exception of Configuration 1, the LEO staging base. For nominal and minimum (not shown) solar activity, the mass of propellants required is much less.

The SPS elements are considered strong enough to withstand an acceleration of 10^{-4} g's. Table A1-2 shows the allowable thrust levels and the amount of time spent each day maintaining the orbit. These thrust levels can be reduced and the duration of thrusting correspondingly increased. Even so the decay rates in nominal attitude are so small and the needed thrusting time so small that orbit maintenance can be performed once every few weeks. The orbit keeping/attitude control operational concepts for each of the SPS elements are discussed in Appendix 3.

2.2 LEO Bases Propellant Storage Requirements

The attitude control/stationkeeping propellants for the LEO Staging Base or the LEO Construction Base represent only a small fraction of the total propellants that must be stored at the base. There must be propellants available for all space-based vehicles operating from the

Table A1-1 - SPS Element Propellant Requirements

Nominal Attitude I_{sp} = 400 Seconds Units (kg/day) (Mt/year)

	Configuration	Nominal Solar Activity		Worst Case Solar Activity	
		$C_D = 2.2$	$C_D = 3.0$	$C_D = 2.2$	$C_D = 3.0$
1.	LEO Staging Base	11.68 / 4.266	16.12 / 5.888	50.92 / 18.60	70.27 / 25.67
2.	LEO Staging Base + EOTV (No Payload)	18.45 / 6.739	25.46 / 9.299	72.83 / 26.60	100.5 / 36.71
3.	EOTV (With Payload)	4.571 / 1.670	6.038 / 2.304	21.33 / 7.791	29.44 / 10.75
4.	LEO Construction Base + SPS Self-Powered Module (Antenna On Base)	83.03 / 30.33	114.6 / 41.86	321.7 / 117.5	444.0 / 162.2
5.	LEO Construction Base + SPS Self-Powered Module (Antenna On Module)	83.03 / 30.33	114.6 / 41.86	321.7 / 117.5	444.0 / 162.2
6.	SPS Self-Powered Module	26.04 / 9.511	35.94 / 13.13	121.5 / 44.38	167.7 / 61.25

Table A1-2 - SPS Element Thrust Requirements

Nominal Attitude I_{sp} = 400 Seconds Units (kg/day) (Mt/year)

	Configuration	Mass In (Mt)	Thrust to Produce 10^{-4} g's (nts) / (lbs.)	Duration Of Thrusting To Maintain Orbit (Sec/Day			
				Nominal Solar Activity		Worst Case Solar Acti	
				C_D = 2.2	C_D = 3.0	C_D = 2.2	C_D =
1.	LEO Staging Base	1832.4	1797 / 404	25.5	35.2	111.1	153.
2.	LEO Staging Base + EOTV (No Payload)	3809.4	3736 / 840	19.4	26.7	76.5	105.
3.	EOTV (With Payload)	5977.0	5861 / 1318	3.06	4.22	14.3	19.7
4.	LEO Construction Base + SPS Self-Powered Module (Antenna On Base)	40710.0	39923 / 8975	8.16	11.3	31.6	43.6
5.	LEO Construction Base + SPS Self-Powered Module (Antenna On Module)	40710.0	39923 / 8975	8.16	11.3	31.6	43.6
6.	SPS Self-Powered Module	34053.0	33395 / 7507	3.06	4.22	14.3	19.7

LEO bases. The total propellant storage required to support the normal operations at these bases are summarized in tables A1-3 and A1-4. The LOX/LH2 propellants stored at the bases are available for use by any of the system elements.

3.0 PROPELLANT STORAGE RESERVES REQUIRED FOR CONTINGENCIES

Now that we have seen how much propellant will be available at the LEO bases, it is necessary to examine a few anomaly situations to see if this stored propellant is sufficient to cover anomalous events.

3.1 PROPELLANT RESUPPLY SCENARIO

Before analyzing the anomalies, it is necessary to establish the propellant resupply scenario. At this time, in the SPS System Definition studies, the propellant resupply operations have not been specifically defined. There are two general approaches being considered:

1) **Propellant delivered in HLLV Cargo Pallets**

Propellant makes excellent ballast for bringing low-density payloads up to the full mass limit of the HLLV. The amount of propellant delivered per flight may vary from 100 to 250 MT out of the total 400 MT payload. The propellant would have to be contained in pallets that would be incorporated into the large HLLV cargo pallet along with hardware racks. It would not be feasible to have the propellant pallets exterior to the cargo pallet. These propellant pallets would be moved about like any other cargo rack. These propellant pallets serve as portable storage tanks. Propellants would be pumped out of these pallets directly into the user vehicle—there would be no dedicated storage tanks.

2) **Propellant delivered by HLLV Tankers**

It is feasible that some of the HLLV's would be configured as tanker vehicles. This would provide the capability of delivering approximately 400 MT of propellant per flight. The tankers would deliver LOX, LO2, and Liquid Argon in internal tanks. The propellants would be pumped out of the HLLV and into storage tanks at the LEO base. The propellants would then be delivered to the users by pipeline.

Table A1-3 Propellant Storage Required at the Leo Staging Base for Normal Operations

For Chemical Propulsion Systems (LOX+LH2)

o 3 month's atitude control/stationkeeping based on LSB with fully assembled EOTV attached, worst case solar activity, $C_D = 3.0$	
(100.5 KG/DAY) x (90 days)	9,045 KG
o Propellant for 2 EOTV's (for the EOTV under construction plus enough for incoming EOTV)	
(46000 KG/EOTV) x (2 EOTV's)	92,000 KG
o Propellants for 2 cargo tugs servicing 1 EOTV	
(10000 KG/cargo tug) x (2 cargo tugs)	32,400 KG
o Propellants for 1 POTV	200,000 KG
Total LOX/LH2 Storage =	333,445 KG

For Electric Propulsion System (Liquid Argon)

o Propellant for 2 EOTV's	938,000 KG
469,000KG x 2	

(Note: Estimated that propellants can be resupplied at the rate of 800 MTper week - see Section 3.1)

Table A1-4 Propellant Storage Requred at the Leo Construction Base for Normal Operations

For Chemical Propulsion Systems (LOX +LH2)

o	3 month's attitude control/stationkeeping based on LSB with fully-assembled SPM attached, worst case solar activity, C_D = 3.0 (444 KG/DAY) x (90 days)	39,960 KG
o	Propellant for SPM with antenna	2,000,000 KG
o	Propellant for 1 POTV	200,000 KG
o	Propellant for 1 Cargo OTV	415,000 KG
	Total LOX/LH2 Storage =	2,854,960 KG

For Electric Propulsion System (Liquid Argon)

o	Propellant for 1 SPM with antenna	5,100,000 KG

(Note: Estimated that propellants can be resupplied at the rate of 800 MT per week - see Section 3.1)

During a typically busy year in the SPS production program (say the 12th year), there would be about 8 HLLV flights per week. If the propellant is delivered in HLLV cargo pallets, it is estimated that at least 4 of the flights each week would have propellant pallets. If we assume that an average of 200 MT of propellant is delivered in these pallets, then there will be approximately 800 MT delivered each week. If the propellant were delivered by tankers it is estimated that 2 flights each week would be required (800 MT of propellant per week).

3.2 ANALYSIS OF CONTINGENCIES

In this section, we will examine 3 contingency situations that may lead to requirements for propellant storage reserves in addition to those specified in tables A1-3 and A1-4.

3.2.1 Loss of a Scheduled Propellant Delivery Flight

A scheduled propellant delivery could be missed if an HLLV were destroyed. Depending upon the propellant resupply scenario, this lost flight would represent a loss of 200 to 400 MT of propellant. The next regularly scheduled HLLV would be 2-3.5 days later. Will additional propellant storage have to be provided at the LEO Bases to accommodate this anomaly?

For the LEO Construction Base—No additional propellant reserves are required to cover this contingency. At the rate of 100.5 kg/day x 3.5 days (max), the 352 kg of propellant required for attitude control/stationkeeping is available from the on-board stores.

For the EOTV—No additional propellant reserves are required to cover this contingency. At the rate of 29.44 kg/day x 3.5 days, the 103 kg of propellant required for attitude control/stationkeeping is available from either on-board propellant stores or is available within hours by delivery from the LSB propellant storage.

For the LEO Construction Base—No additional propellant reserves are required to cover this contingency. At the rate of 444 kg/day x 3.5 days, the 1554 kg of propellant required for attitude control/stationkeeping is available from the on-board stores.

For the SPS Self-Power Module—No additional propellant reserves are required to cover this contingency. After the SPM is separated from the base, it is committed to its trip to GEO and is, therefore, not dependent upon Earth-to-LEO propellant delivery interruptions.

3.2.2 Launch Delay

Scheduled propellant deliveries could be delayed by severe weather conditions at the launch site, vehicle maintenance delays, launch pad system delays, etc. The worst of these situations would be a hurricane that may disrupt HLLV launches for several weeks. It is conceivable that there could be as much as 30 days of interruption if all launch pads suffered substantial damage. It would be likely that an all-out attempt would be made to get at least one of the pads operational so that propellant deliveries and crew transportation flights could be resumed on an emergency basis. Given this scenario, as much as 800 MT/week x 4 weeks = 3200 MT of propellant deliveries could be delayed. We will estimate that upon resumption of emergency flight operations that 5 HLLV flights per week could be available (7 days/week x 24 hrs/day ÷ 34 hr pad time ≈ 5 flights per week from one launch pad). This emergency delivery rate could deliver up to 2000 MT per week of propellants (if we assume that only propellants are delivered—no hardware). Will additional propellant storage have to be provided at the LEO bases to accommodate this anomaly?

For the LEO Staging Base—No additional propellant reserves are required to cover this contingency. At the rate of 100.5 kg/day x 30 days, the 3015 kg of propellant required for attitude control/stationkeeping is available from on-board stores.

For the EOTV—No additional propellant reserves are required to cover this contingency. At the rate of 29.44 kg/day x 30 days, the 883 kg of propellant required for attitude control/stationkeeping is available from either on-board stores or is available within hours by delivery from the LSB propellant stores.

For the LEO Construction Base—No additional propellant reserves are required to cover this contingency. At the rate of 444 kg/day x 30 days, the 13,320 kg of propellant required for attitude control/stationkeeping is available from the on-board stores.

For the SPS Self-Power Module—No additional propellant reserves are required to cover this contingency. After the SPM is separated from the base, it is committed to its trip to GEO and is, therefore, not dependent upon propellant delivery interruptions.

3.2.3 Worst Case Orbital Decay

In the orbital decay analysis (section 3.0), the worst case situation was defined as one where the element started tumbling during the sun spot maximum condition and the worst estimate of coefficient of drag were to turn out to be true. It was estimated that 400 km is the "point of no return."

Table A1-5 shows the time required for the various elements to decay from 477 km to 400 km given the combination of worst conditions stated above.

This table also gives the propellant and thrust durations required to maintain the orbit at 400 km after attitude control is achieved. Finally, the table gives the amount of propellant that would be required to regain the design altitude of 477 km.

If we compare the daily propellant consumption at 400 km to that required at 477 km (see table A1-1), we see that it will take about 3 times as much propellant to maintain the lower altitude orbit. The propellant required to regain the lost altitude is generally several times the yearly demand for maintenance at 477 km (again see table A1-1). Will additional on-board propellant storage reserves have to be provided to cover this contingency?

For the LEO Staging Base—No additional propellant storage will have to be provided to cover this contingency. The 42 MT of propellant required to regain the 477 km orbit would be available from on-board propellant stores. In this emergency situation, there would be no other demand on these stores as normal operations would cease while the problem is solved.

For the EOTV—If an EOTV got into this predicament, there would not be enough propellant on-board even if it were fully fueled (normal capacity is 46 MT vs. the 66 MT required to regain the lost altitude). However, once attitude control is reestablished, orbital maintenance is easily handled by on-board propellant. There would be plenty of time for propellant resupply and for regaining the lost altitude once attitude control is established. Requirement 1.2.9 in table 4-1 was added to provide docking locations for the cargo tugs that would be sent to the EOTV from the LEO base to rescue the EOTV.

For the LEO Construction Base—No additional propellant storage reserves will be required to cover this contingency. The 448 MT of propellant required to regain the 477 km orbit would be available from on-board propellant stores. In this emergency situation, normal operations

Table A1-5 - SPS Element Recovery Propellant Requirements

Nominal Attitude, I_{SP} = 400 Seconds

Configuration	Days to Decay to 400 km in Worst Situation	Correction ΔV at 400 km (m/sec/day)		Propellant to Maintain 400 km Orbit (kg/day)		Duration of Thrusting at 10^{-4} g's to Maintain Orbit (sec/day)		Propellant Reqd. to Regain 477 km Altitude (MT)
		Nom. Solar $C_D = 2.2$	Worst Solar $C_D = 3.0$	Nom. Solar $C_D = 2.2$	Worst Solar $C_D = 3.0$	Nom. Solar $C_D = 2.2$	Worst Solar $C_D = 3.0$	
1. LEO Staging Base	>40	.099	.427	46.25	199.5	101.0	435.4	20.17
2. LEO Staging Base EOTV (no payload)	5	.071	.297	68.94	288.4	72.4	302.9	41.94
3. EOTV (with payload)	8	.014	.059	21.33	90.00	14.3	60.2	65.80
4. LEO Construction Base + SPS (self-powered module) (antenna on base)	13	.031	.122	321.7	1266	31.6	124.4	448.16
5. LEO Construction Base + SPS Self-Powered Module (antenna on module)	13	.031	.122	321.7	1266	31.6	124.4	448.16
6. SPS Self-Powered Module	11	.014	.048	121.5	417.1	14.3	48.9	374.88

would be suspended, and then the total propellant storage capacity would be available to solve the problem.

For the SPS Self-Power Module—No additional on-board propellant storage reserves are required to cover this contingency. The 375 MT of propellant required to regain the 477 km orbit would be available from the 2200 MT of propellant carried on-board.

APPENDIX 2

MAINTENANCE OPERATIONS

1.0 INTRODUCTION

In Section 4.0, it was shown where maintenance operations will have to be directed at correcting propulsion system degradations/failures in a timely manner so that the SPS elements can maintain their required attitude control/orbit keeping. In this appendix, we will summarize the maintenance concepts that are pertinent to the propulsion systems of the various elements. These concepts were developed and documented in the Boeing SPS Concept Definition Studies (see References 2 and 3).

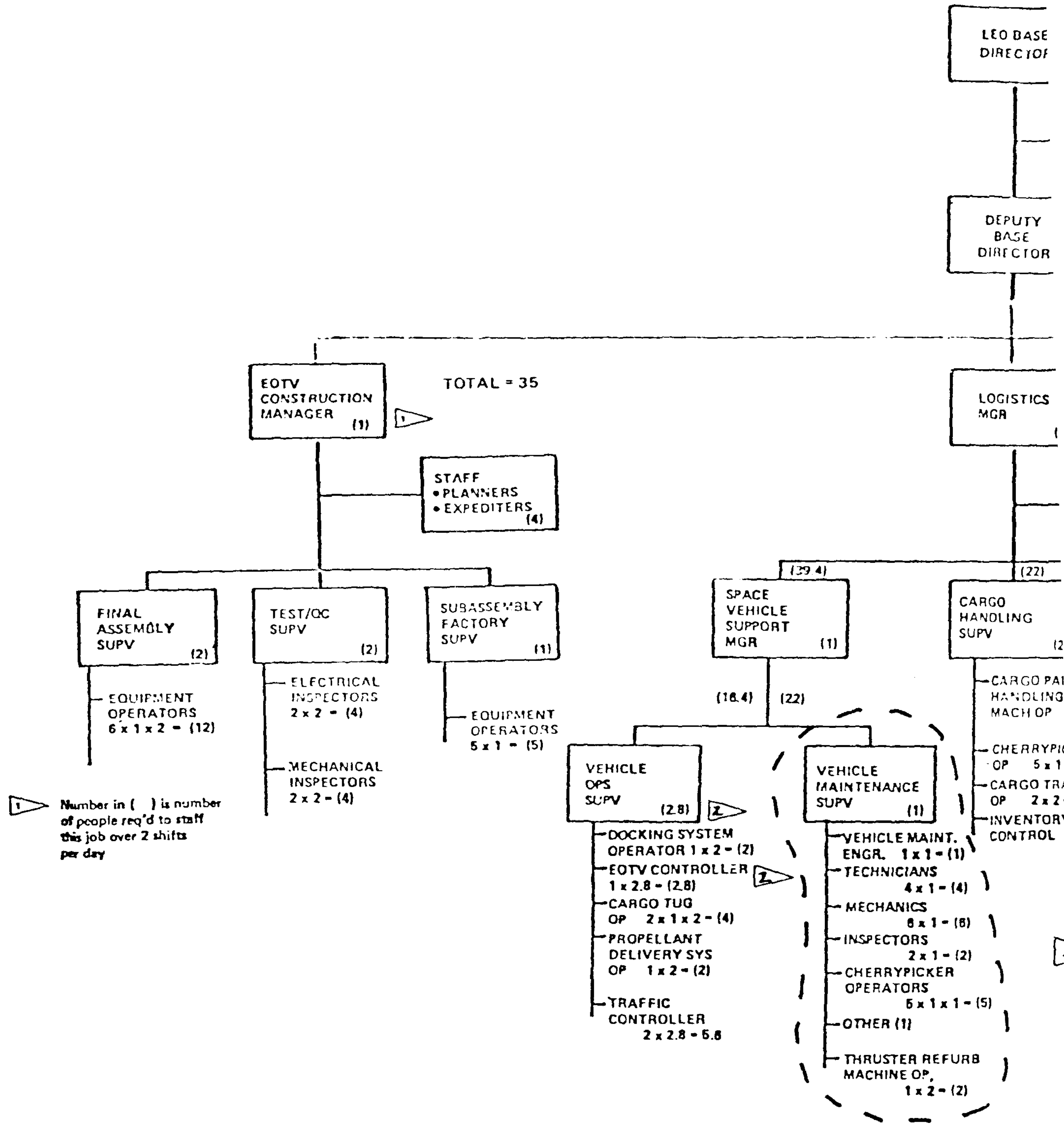
2.0 MAINTENANCE CONCEPTS FOR THE LEO STAGING BASE AND EOTV

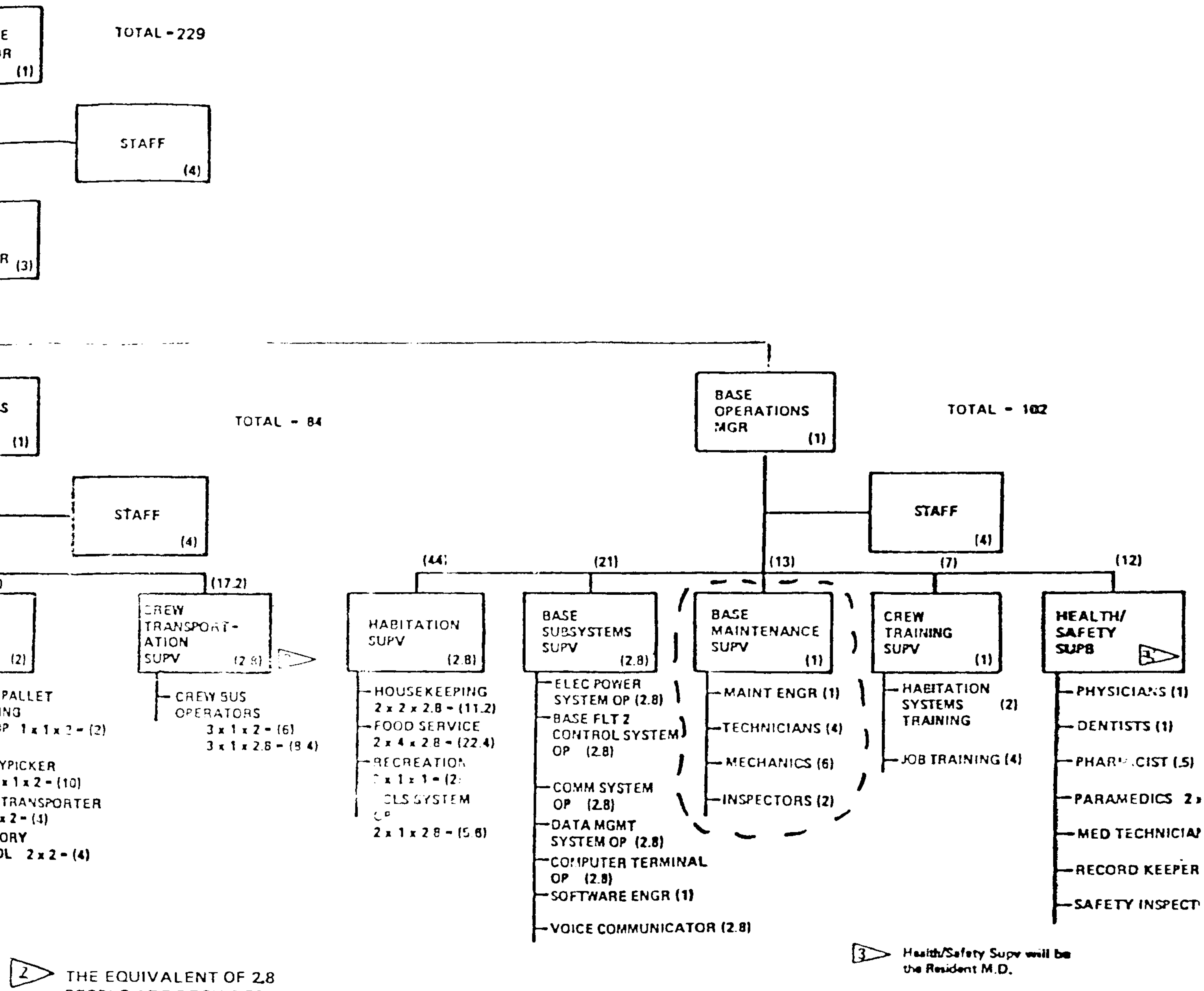
The maintenance crews located at the LEO Staging Base are highlighted in Figure A2-1. Table A2-1 elaborates on the descriptions of the vehicle maintenance crew.

The Base Maintenance crew will take care of the base's propulsion system maintenance problems as well as servicing other base equipment and subsystems. Propulsion system maintenance specialists and maintenance equipment will be borrowed from the Vehicle Maintenance crew as required.

The maintenance equipment that will be permanently located at the LEO Staging Base are listed in Table A2-2.

The thruster refurbishment machine is shown in Figure A2-2. Four of these machines are required. This machine incorporates a magazine where replacement accelerator grids are stored and dispensed and where defective grids are stored after removal. The magazine is loaded at the LEO Base Maintenance Module and then is mounted into the refurb machine. The flying cherrypicker transports the machines over to the EOTV and mounts them onto the ACS yokes, see figure A2-3. An operator in the LEO Base command center would then remotely activate the machines. These thruster refur- bishment machines will changeout accelerator grids at the rate of one grid every 10 minutes. All grids are replaced after every EOTV round


LEO BASE DIRECTOR
DEPUTY BASE DIRECTOR
EOTV CONSTRUCTION MANAGER (1)
TOTAL = 35
STAFF
• PLANNERS
• EXPEDITERS (4)
FINAL ASSEMBLY SUPV (2)
EQUIPMENT OPERATORS 6 x 1 x 2 = (12)
TEST/QC SUPV (2)
ELECTRICAL INSPECTORS 2 x 2 = (4)
MECHANICAL INSPECTORS 2 x 2 = (4)
SUBASSEMBLY FACTORY SUPV (1)
EQUIPMENT OPERATORS 5 x 1 = (5)
Number in ( ) is number of people req'd to staff this job over 2 shifts per day
LOGISTICS MGR
(39.4)
(22)
SPACE VEHICLE SUPPORT MGR (1)
(16.4)
(22)
VEHICLE OPS SUPV (2.8)
DOCKING SYSTEM OPERATOR 1 x 2 = (2)
EOTV CONTROLLER 1 x 2.8 = (2.8)
CARGO TUG OP 2 x 1 x 2 = (4)
PROPELLANT DELIVERY SYS OP 1 x 2 = (2)
TRAFFIC CONTROLLER 2 x 2.8 = 5.6
VEHICLE MAINTENANCE SUPV (1)
VEHICLE MAINT. ENGR. 1 x 1 = (1)
TECHNICIANS 4 x 1 = (4)
MECHANICS 6 x 1 = (6)
INSPECTORS 2 x 1 = (2)
CHERRYPICKER OPERATORS 5 x 1 x 1 = (5)
OTHER (1)
THRUSTER REFURB MACHINE OP. 1 x 2 = (2)
CARGO HANDLING SUPV
CONTROL



THE EQUIVALENT OF 2.8 PEOPLE ARE REQUIRED TO STAFF THIS JOB OVER 24 HOURS/DAY, 7 DAYS/ WEEK

- ALL CREWMEMBERS WORK 10 HOUR SHIFTS, 6 DAYS ON/1 DAY OFF, 90 DAY STAYTIME
- AN EQUIVALENT CREW SIZE IS ON EARTH RECEIVING TRAINING, ON LEAVE, ETC.

Figure A2-1 LEO Base Crew Size and Organiza

TABLE A2-1

SPACE VEHICLE IN-SPACE MAINTENANCE CREW

JOB TITLE	NO. REQ'D AT LEO BASE [1]
Vehicle Maintenance Supervisor [4]	1
Vehicle Maintenance Engineer [4]	1
Vehicle Maintenance Technicians [4]	
o Propulsion and Cryogenics	1
o Electrical/Electronic Systems	1
o Mechanical/Structural Systems	1
o Environmental Control Life Support Systems	1
Vehicle Maintenance Mechanics [4]	
o Electrical Systems	2
o Mechanical/Structural Systems	2
o Vacuum/Gas/Fluid/Cryo System	2
Inspectors [4]	
o Safety	1
o Quality Control	1
Cherrypicker Operator	5 [2]
Thruster Refurbishment Machine Operator	2
Component Refurbishment Mechanics and Technicians	[3] -
Other	1
TOTAL	22

[1] Number listed is the number of people required to staff the position over 2 shifts
[2] Includes flying cherrypicker operators
[3] Technicians and mechanics perform the refurbishment tasks between the times when they work at the vehicles
[4] These crew members will be EVA qualified.

Table A2-2—Space Vehicle Maintenance Support Equipment
(From WBS 1.2.2.1.6 in Ref.2)

NAME
90M Cherrypicker
Electrical Power Test Set
Electrical Load Banks
Communications Test & Checkout Equipment
Guidance & Navigation Test & Checkout Equipment
Control & Data Acquisition Console
EMI Test Equipment
Memory Load & Verify Unit
Electronics Calibration Equipment
Engine Handling Kit
Engine Alignment Fixture
Engine Actuator Support Fixture
Engine Actuator Adjustment Kit
Insulation Handling Kit
APS Pressure Instrumentation Kit
Main Propulsion System Checkout Accessories Kit
APS Checkout Accessories Kit
Inspection Equipment
Ultrasonic Scan Unit
Radiography Unit
Mass Spectrometer Leak Detection Unit
Acoustic Leak Detection Unit
Borescope and Fibre Optics
Theodolite
Ground Servicing Umbilical Set
Flying Cherrypicker (2)
Thruster Refurbishment Machines (4)

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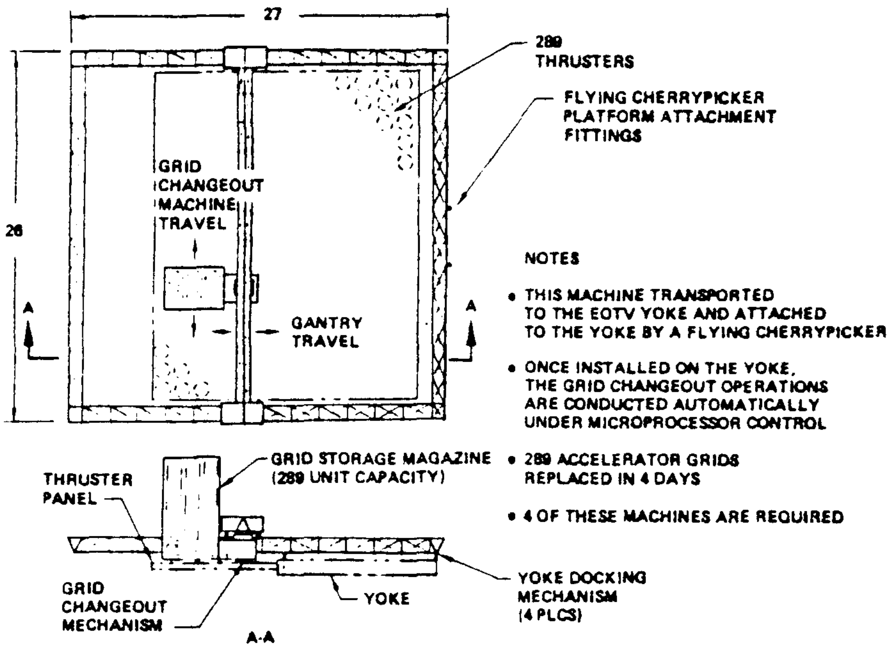

Figure A2-2. EOTV Electric Thruster Refurbishment Machine

SPS-2775

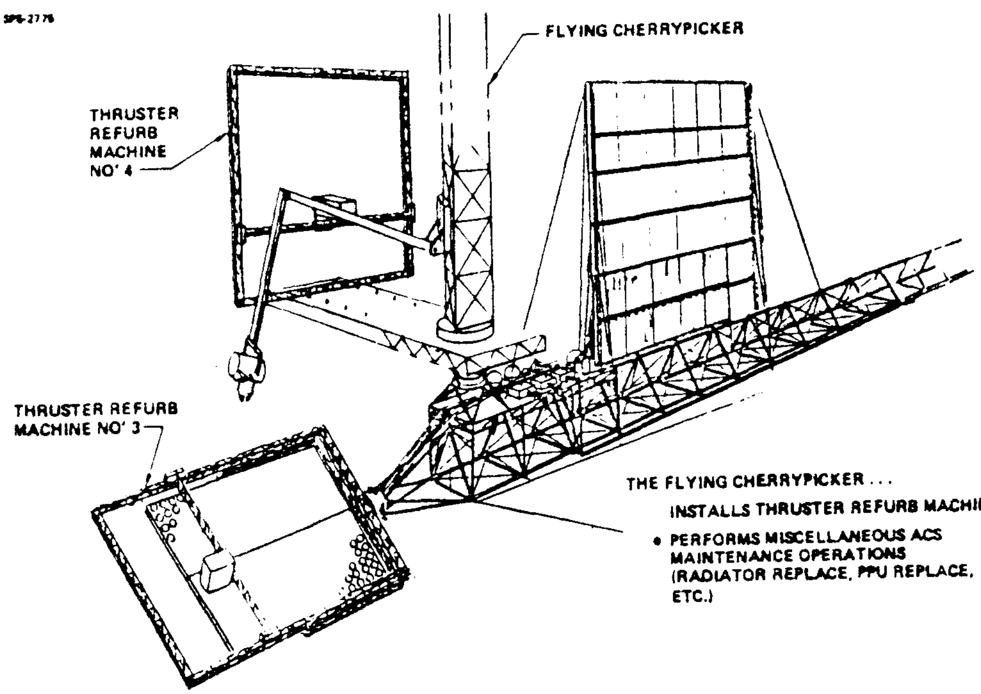

Figure A2-3. EOTV Attitude Control System Mantenance Equipment trip. After approximately 4 days, the flying cherrypicker will retrieve the machines and return them to the LEO Base. The flying cherrypicker attends to other propulsion system maintenance tasks while the thruster refurbishment operations are being conducted.

Figure A2-4 shows the EOTV maintenance timeline at the LEO Base.

Once the EOTV has departed for GEO, it is committed to complete the 180 day trip before any other maintenance is performed. As was described in Section 4.0, there will be enough redundancy in the propulsion system to allow this journey to be completed despite component/ subsystem failures incurred in-transit.

3.0 MAINTENANCE CONCEPTS FOR THE LEO CONSTRUCTION BASE AND THE SPS SELF-POWER MODULES

The maintenance concept for these elements are similar to that described in the previous section. The major difference is that the EOTV maintenance crews, equipment, and operations are deleted. The vehicle maintenance crew is listed in Table A2-3. The maintenance equipment list shown in Table A2-2 becomes applicable to the LEO Construction Base by deleting the flying cherrypickers and thruster refurbishment machines.

Once the Self-Power Module is separated from the base, it is committed to its 180 day journey to GEO. Enough redundancy is designed in to allow it to complete the trip despite some propulsion system failures.

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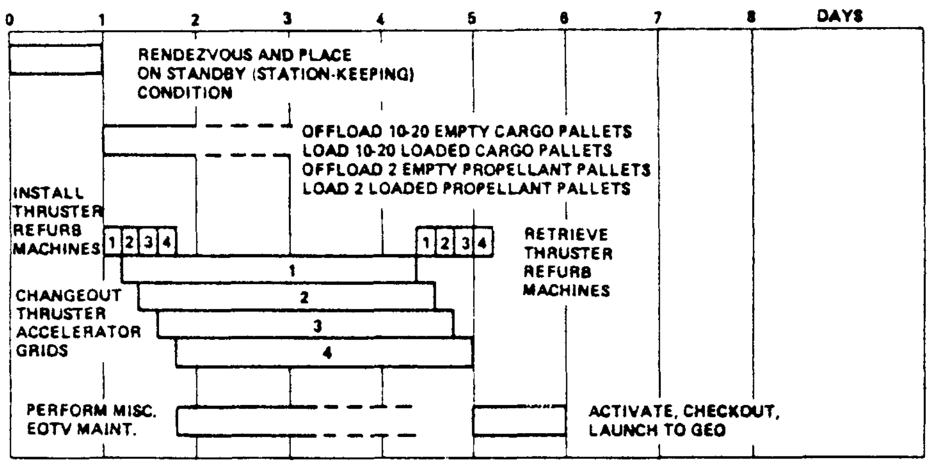

Figure A2-4. EOTV Operation at LEO

TABLE A2-3

SPACE VEHICLE IN-SPACE MAINTENANCE CREW

JOB TITLE	NO. REQ'D AT LEO BASE [1]
Vehicle Maintenance Supervisor [4]	1
Vehicle Maintenance Engineer [4]	1
Vehicle Maintenance Technicians [4]	
o Propulsion and Cryogenics	1
o Electrical/Electronic Systems	1
o Mechanical/Structural Systems	1
o Environmental Control Life Support Systems	1
Vehicle Maintenance Mechanics [4]	
o Electrical Systems	2
o Mechanical/Structural Systems	2
o Vacuum/Gas/Fluid/Cryo System	2
Inspectors [4]	
o Safety	1
o Quality Control	1
Cherrypicker Operator	
Component Refurbishment Mechanics and Technicians	[3]
Other	1
TOTAL	15

[1] Number listed is the number of people required to staff the position over 2 shifts

[3] Technicians and mechanics perform the refurbishment tasks between the times when they work at the vehicles

[4] These crew members will be EVA qualified.

APPENDIX 3

ATTITUDE CONTROL/ORBIT KEEPING MANEUVER OPERATIONS

1.0 INTRODUCTION

In Appendix 1, the attitude control/orbit-keeping maneuvers for the various SPS elements were described. In this appendix, we will briefly describe who will control these maneuvers and how this control operation will be conducted.

2.0 LEO STAGING BASE MANEUVER CONTROL OPERATIONS

The LEO Staging Base maneuvers will be controlled by Base Flight Control System Operators. There will be one of these operators on duty at all times. He is stationed in the Base Operations Module control center.

The base's orbital trim maneuvers will be scheduled to be performed once a day. It will probably be scheduled to be done during the 4-hour base operations shutdown period that occurs between the end of the second shift and the beginning of the first shift. This is necessary to eliminate orbit keeping acceleration forces during EOTV construction operations.

The LEO Base will be tracked by radars on the Earth, as will all SPS elements. This ground tracking system's controllers will keep the LEO Base's flight control operators advised of any out-of-tolerance orbital pertebations by the base. The base's orbital time maneuvers will be very predictable and routine so there will be very few surprises.

The operator will key in the desired orbital time maneuver parameters. The actual operation of the base's propulsion system will then be controlled and monitored by computer.

3.0 EOTV MANEUVER CONTROL OPERATIONS

The EOTV's approach and departure to/from LEO will be monitored and controlled from Earth. Ground-based operators will monitor the orbital position and attitudes of all EOTV's In-transit between LEO and GEO. The maneuvering operations will be controlled via computer commands uplinked to the vehicles. There will be on-board computers that will monitor/control the EOTV's propulsion system operations using the uplink commands to initiate the operations.

In the immediate vicinity of the LEO Staging Base (say, within 25 km), the EOTV control task will be turned over to EOTV Control Operator's stationed at the base. There will be at least one of these operators on duty at all times. They are stationed in the control center in the Base Operations Module.

The EOTV maneuvers will be syncronized with base orbit-keeping maneuvers so that the EOTV's can maintain a station keeping position relative to the base. There will be tracking radars located on the LEO Base to provide precise tracking of the EOTV's.

The EOTV's maneuvers are controlled by remote data commands from the base. The EOTV's computers will control/monitor the operation of the propulsion system and down-link status to the base.

4.0 LEO CONSTRUCION BASE MANEUVER CONTROL OPERATIONS

These operations are identical to those described for the LEO Staging Base.

5.0 SPS SELF-POWER MODULE MANEUVER CONTROL OPERATIONS

The SPM's departure from the LEO Construction Base will be controlled by the operators located in the control center. After the SPM has reached a safe separation distance (say 10 km), control of the vehicle will be turned over to a ground-based control as was described in Section 3.0 above.

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