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Satellite Power System Salvage and Disposal Alternatives

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1. INTRODUCTION

SPS system cost and trade studies conducted to date have, by and large, assumed a 30-year satellite life with zero net salvage value at the end of that time. Many factors make this assumption inappropriate:

1. The SPS satellite represents a very large source of power in geosynchronous orbit that might be put to many uses, such as:

   - Power for other space-based platforms, satellites, habitats, manufacturing facilities, bases, etc.
   - Power for laser transportation systems including geocentric space, earth escape and laser-powered aircraft
   - Power for a large, low-thrust space transportation system for missions such as asteriod recovery
   - Power for space-based science such as particle physics.

2. The SPS satellite represents a large supply of subsystems and components for use in other space activities such as:

   - Spares and materials for other SPS satellites
   - Solar arrays and other components for non-SPS satellites.

3. The SPS satellite represents a fairly large source of raw materials located in geosynchronous orbit that might be recovered and put to use either in space or returned to earth for reuse.

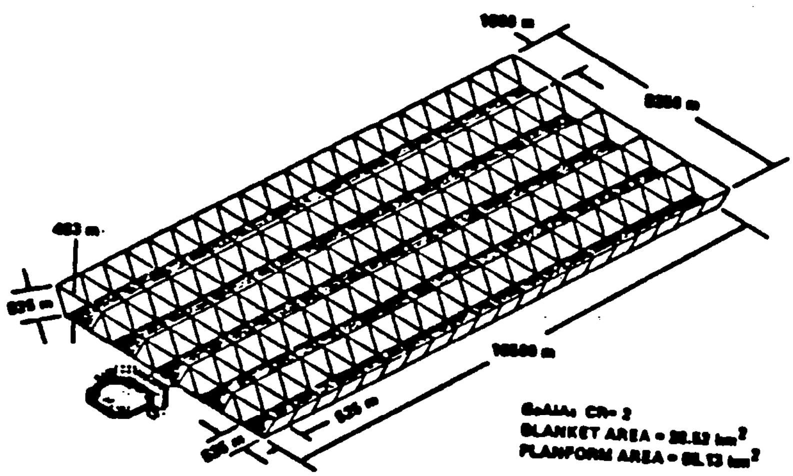
The first SPS satellite will approach the end of its useful life around the year 2030; some 30 years sooner, the SPS demonstration satellite will have served its initial purpose. The demonstration satellite represents a somewhat similar, albeit considerably smaller, resource.

To the extent to which there develops a demand for energy, SPS-like subsystems and raw materials in space, one can expect that SPS will derive some salvage value. If, on the other hand, no such demand develops, the SPS satellite will have to be removed from geosynchronous orbit (GEO), either for storage and possible later salvage use or for permanent disposal. In this case it is important to have estimates of the cost of SPS satellite disposal.

The objectives of this study are to find potential salvage uses for both the SPS demonstration and full-scale satellites, to determine the satellite salvage values for each potential use, to prioritize these uses in order to determine likely salvage value per satellite as a fraction of satellite capital cost and to determine the cost of disposal for unsalvaged satellites or portions thereof.

1.1 Background

The salvage uses and values and disposal costs estimated in this study are based on the Rockwell International SPS satellite configuration and development program. The basic satellite configuration is shown in Figure 1.1 and its major physical characteristics are provided in Table 1.1. The satellite uses gallium aluminum arsenide solar cells with a concentration ratio of 2 and a graphite composite structure.



SOURCE: SATELLITE POWER SYSTEMS (SPS) CONCEPT DEFINITION STUDY, EXECUTIVE SUMMARY, SSD 79-0010-1, ROCKWELL INTERNATIONAL, DOWNEY, CA, MARCH 1979.

FIGURE 1.1 REFERENCE SATELLITE CONFIGURATION

TABLE 1.1 REFERENCE SATELLITE CHARACTERISTICS*

SPS GENERATION CAPABILITY (UTILITY INTERFACE)	5 GW
OVERALL DIMENSIONS (KM)	5.3 X 10.4
SATELLITE MASS (KG)	34×10^6
POWER CONVERSION-PHOTOVOLTAIC	GaAlAs (CR = 2)
STRUCTURE MATERIAL	GRAPHITE COMPOSITE (GFRTP)
CONSTRUCTION LOCATION	GEO
TRANSPORTATION	
• EARTH-TO-LEO -CARGO (PAYLOAD)	VERTICAL TAKEOFF, WINGED 2-STAGE (424,000 KG)
-PERSONNEL (NUMBER)	MODIFIED SHUTTLE (75)
• LEO-TO-GEO -CARGO	DEDICATED ELECT. OTV
-PERSONNEL (NUMBER)	2-STAGE LOX/LH_2 (75)
MICROWAVE POWER TRANSMISSION	
• NO. OF ANTENNAS	1
• ANTENNA POINTING/CONTROL	CONTROL MOMENT GYROS (CMGs)
• DC-RF CONVERTER	KLYSTRON
• FREQUENCY (GH)	2.45
• RECTENNA DIMENSIONS (KM)	10 X 13
• RECTENNA POWER DENSITY (mW/CM^2)	
-CENTER	23
-EDGE	1

*SOURCE: SATELLITE POWER SYSTEMS (SPS) CONCEPT DEFINITION STUDY, EXECUTIVE SUMMARY, SSD 79-0010-1, ROCKWELL INTERNATIONAL, DOWNEY, CA, MARCH 1979.

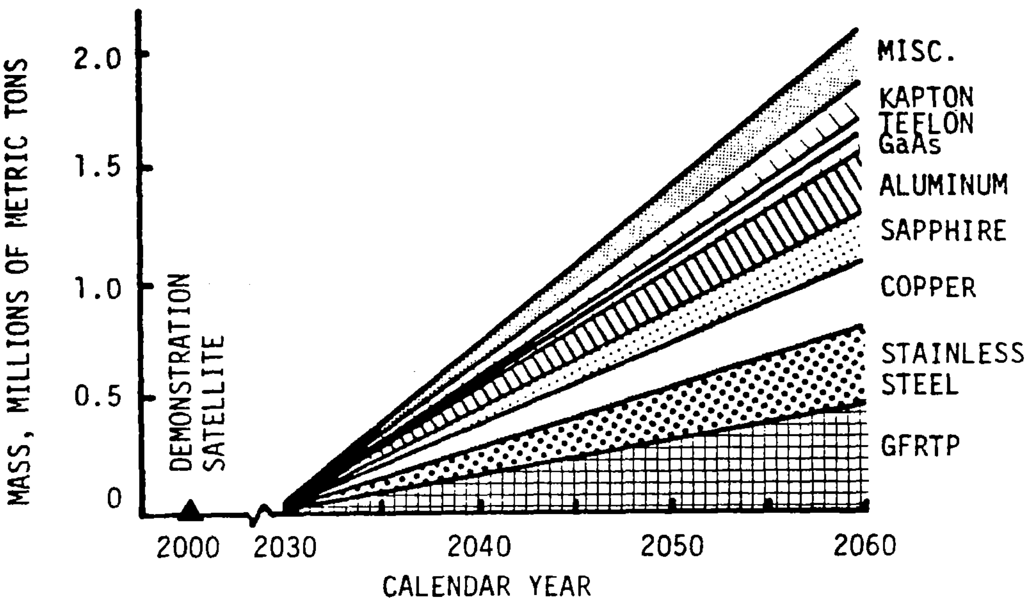
The development and implementation program for this satellite calls for deployment of a geosynchronous demonstration satellite, with a power generation capability of 335 MW at beginning of life, early in the year 1999. Shortly thereafter, the demonstration satellite is grown into a full-scale satellite with a generation capability (in space) of 9.53 GW (8.92 GW power into the microwave antenna). The first full-scale SPS satellite becomes operational late in the year 2000. Following the first full-scale SPS, the reference program calls for bringing two 5 GW systems on line each year, beginning in the year 2001, until a total of 60 systems, 300 GW capacity, are installed.

Using the above program plan, the demonstration satellite becomes available for salvage early in the year 2000 and full-scale SPS satellites become available for salvage at the rate of two per year beginning late in the year 2030. Concurrent with the full-scale satellites, the rectenna also becomes available for salvage. It is possible that the rectenna will be used for a subsequent SPS if the program continues. If this is the case, some amount of refurbishment may be necessary and/or desirable, thus allowing evolutionary changes in the satellite portion of the system, such as beam power density, beam shape and size, frequency and polarization. In any event, rectenna reuse may be considered to be a salvage use. Figure 1.2 shows the amount of SPS materials which will have become available for salvage as a function of time.

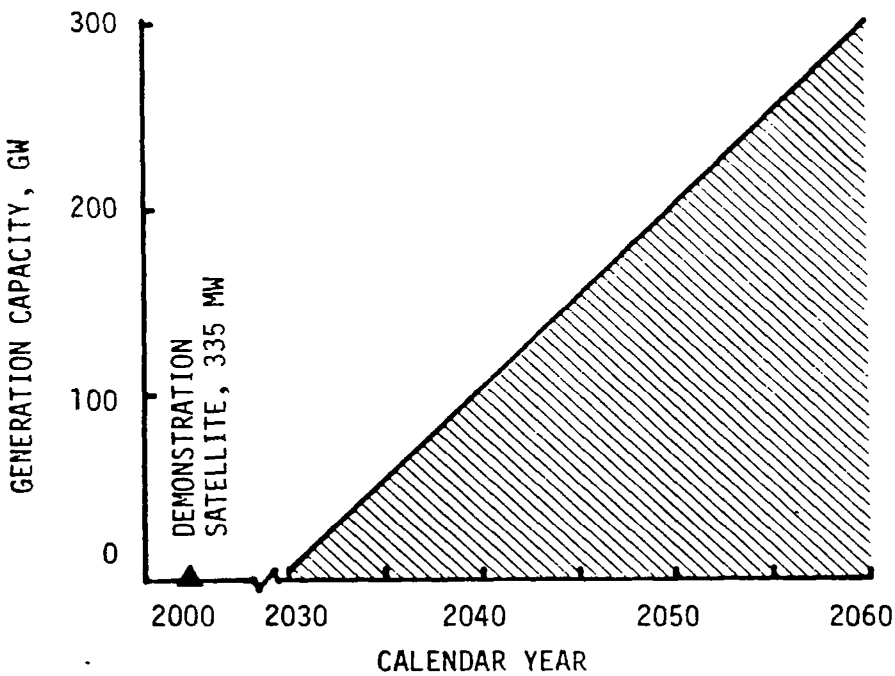
The utilization of geosynchronous orbit in the post-2000 time period is likely to be quite intense. Thus it is likely that any structures or satellites that are placed in this orbit will have to be removed upon completion of their useful life. Accordingly, any unsalvaged SPS-related structures, facilities or satellites will have to be disposed of at the end of their useful life.

1.2 Approach

It is clear from Figure 1.2 that all salvage and disposal activities will occur in the post-2000 time period. Salvage or disposal of the demonstration satellite will occur somewhere in the 2000 to 2010 time period; salvage or disposal of full-scale satellites will begin sometime after 2030 and continue at least through 2060. In order to make any estimates of salvage uses and salvage values, it is necessary to place the potential salvage activities into the context of a space program. Thus it is necessary first to establish a mission model for the period 2000 to 2060 as a basis for analysis. Obviously any such mission model will suffer from major uncertainties and, in the end, one can identify only certain long-term trends without becoming specific about particular missions.



(a) CUMULATIVE SALVAGEABLE MASS



(b) CUMULATIVE SALVAGEABLE GENERATION CAPACITY

FIGURE 1.2 SALVAGEABLE SPS MASS AND GENERATION CAPACITY

The generic trends which one can identify today that are likely to carry over into the 21st century include mainly an "industrialization" of space; that is, a gradual transition from government-funded activities primarily of a research nature to activities promoted and conducted in the private sector because they are profitable. It is likely that these activities will be encouraged by significant reductions in the cost of space-based activities resulting from a transition to the Space Shuttle and more advanced space transportation systems, and by the introduction and proliferation of multipurpose platforms.

Much of the activity in space in the post-2000 time period will take place in geosynchronous orbit. This activity is likely to generate a considerable amount of low earth orbit (LEO) to GEO traffic, independent of SPS. There is also likely to be considerable other geocentric traffic, however, including LEO to GEO, GEO to GEO and lunar traffic, as well as earth escape traffic. Within the context of these space activities, potential salvage uses for both the SPS demonstration satellite and full-scale SPS satellites were identified and evaluated.

It is not clear today that the SPS demonstration will be a success; that is, that upon completion of the demonstration satellite project, it will be found desirable to proceed with construction of full-scale SPS satellites as planned. (If it were known today that the demonstration would be successful, it would be unnecessary.) Thus salvage uses of the demonstration satellite need to recognize that there may or may not be a continuing SPS program.

On the other hand, salvage of full-scale SPS satellites will occur only if there is an SPS program and, consequently, the salvage uses for full-scale SPS satellites are appropriately identified in the context of a space program which includes SPS. Such a program clearly requires a space transportation system that can inexpensively transport large amounts of materials to geocentric space, and it includes capabilities in large space structures, space-based construction, manned LEO and GEO facilities, and so on. These capabilities infer such space-based activities as space manufacturing, the utilization of large applications platforms, lunar exploration and exploitation, and physics and astronomy.

The above space-based activities lead to identification of the following potential salvage uses:

Demonstration Satellite

- Growth into full-scale SPS satellite (Rockwell International reference program plan, applicable only if the demonstration is successful)
- Use as a source of power for other space activities such as GEO platforms, a manufacturing base or an electric orbit transfer vehicle
- Use as a power supply for a laser space transportation system
- Use as a source of raw material.

Full-Scale SPS Satellites

- Use as spares and materials for other SPS satellites
- Use as a power supply and platform for other space activities such as platforms, a manufacturing base, a lunar base or space habitats
- Use as a power supply for laser transportation systems including geocentric space, especially LEO to GEO, earth escape and aircraft on oceanic routes
- Use as a power supply to recover Amor and Apollo asteriods
- Use as a power supply for a high-energy, high-vacuum physics laboratory in space.

Next, the salvage value of the SPS satellites was estimated for most of the above potential uses. In all cases the salvage value is taken to be the present value of the cost savings afforded by the salvage use referenced to the initial operation date of the salvaged article. The discount rate used throughout this study is a real (i.e., inflationary effects removed) rate of 4 percent. Thus, the salvage values presented represent the effective amount by which the capital cost of the satellite is reduced because it will provide a positive net salvage value. The present value of SPS revenue requirements, reflected in the SPS charge rates, may accordingly be reduced by this amount. For example, if it is found that the salvage value of an SPS satellite is equal to ten percent of the capital cost of the satellite, then the annual capital carrying charge for the satellite, for purposes of comparison to alternative systems, may be reduced by ten percent.

Any SPS satellites or portions thereof which are not salvaged will, in all likelihood, have to be removed from geosynchronous orbit. An objective of this study is to estimate SPS satellite disposal costs. To do this a number of disposal alternatives were identified, the velocity requirements for each were estimated and then the costs of each were determined. SPS disposal costs include four major cost categories: cost of propellant, cost of transporting the propellant to GEO, cost of modifying the SPS satellite as necessary (mainly installation of thrusters, tankage and controls) and the cost of mission operations. Cost estimates provided are based on the assumption that the satellite is disposed of intact.

Wherever possible cost estimates used in this study were derived from the SPS Concept Definition Study performed by Rockwell International,* and are in 1977 dollars, consistent with this report. Thus while these cost estimates contain considerable uncertainty, the variation in estimates of salvage value and disposal costs are likely to approximate the variations in satellite captial costs. Hence the estimates provided can be taken to be relatively firm when viewed in comparison to the capital cost estimates.

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*Satellite Power Systems (SPS) Concept Definition Study, System Engineering, Part 2 (Cost and Programmatics, Rockwell International Report No. SSD 79-0010-2-2, March 1979.

1.3 Results

Discussion of the results is appropriately divided into four parts: salvage value for potential salvage uses of the demonstration satellite, salvage value for potential salvage uses of full-scale SPS satellites, salvage value of rectennae and disposal costs for the demonstration and full-scale satellites. The major study results are summarized in Table 1.2.

Two principal salvage uses for the demonstration satellite are apparent: growth to a full-scale satellite and use as a power supply for a laser space transportation system. Obviously, the former use applies only if the demonstration program is a success; that is, if it is found desirable to continue the SPS program beyond the demonstration phase. If this salvage use is implemented, the salvage value of the demonstration satellite is about 80 percent of the on-orbit cost of the salvageable hardware. Since almost all of the demonstration satellite is salvageable (except perhaps the ion thrusters and associated systems used to transport it from LEO to GEO), one can take the salvage value to be essentially 80 percent of the on-orbit cost of the demonstration satellite. The reason that the salvage value of the demonstration satellite is not 100 percent of its cost is because of the time value of money (discounting) and the time delay between investment in the demonstration satellite and start of construction of the full-scale satellite.

The second principal salvage use of the demonstration satellite, use as a power source for a laser space transportation system, is a viable salvage use whether the demonstration program is a success or not. The salvage value for this use derives mainly from cost savings in the cost of transporting chemical propellants from earth to LEO for use in LEO to GEO transportation of personnel and logistics. The considerably higher specific impulse of a laser rocket permits about a 70 percent reduction in the mass of propellant that must be transported to

TABLE 1.2 SPS SATELLITE AND RECTENNA SALVAGE VALUE

POTENTIAL SALVAGE USE	SALVAGE VALUE	POTENTIAL DEMAND FOR SALVAGE USE	REMARKS
DEMONSTRATION SATELLITE			
• GROWTH TO FULL-SCALE	80% OF ON-ORBIT COST OF SALVAGEABLE HARDWARE	ENTIRE DEMONSTRATION SATELLITE	VALID USE ONLY IF DEMONSTRATION IS SUCCESSFUL
• POWER SUPPLY FOR OTHER SPACE ACTIVITIES	SMALL	LIMITED TO SMALL FRACTION OF AVAILABLE POWER	SALVAGE SPREAD OVER SEVERAL YEARS
• POWER SUPPLY FOR LASER SPACE TRANSPORTATION SYSTEM	\$1.7 BILLION +	DOES NOT MAKE USE OF TRANSMITTING ANTENNA	BENEFIT OF SALVAGE USE LIKELY TO BE CONSIDERABLY HIGHER IF DEMONSTRATION IS SUCCESSFUL
• SOURCE OF RAW MATERIAL	VERY SMALL	VERY LIMITED	NOT A LIKELY SALVAGE USE
FULL-SCALE SPS SATELLITES			
• SPARES AND MATERIALS FOR OTHER SPS SATELLITES	VERY SMALL	SUBSTANTIAL DEMAND FOR KLYSTRONS--LIMITED DEMAND FOR OTHER COMPONENTS	NOT CLEAR THAT ANY SPS COMPONENTS WILL BE REUSABLE AFTER SERVICE
• POWER SUPPLY FOR OTHER SPACE ACTIVITIES	VERY SMALL	DEMAND FOR POWER IN SPACE LIKELY TO BE ONLY A VERY SMALL FRACTION OF AVAILABLE POWER	LIKELY THAT SOME REUSE OF SPS SOLAR ARRAYS WOULD OCCUR
• POWER SUPPLY FOR LASER TRANSPORTATION SYSTEMS	\$1-3 BILLION	TOTAL DEMAND COULD REACH OVER 20 SATELLITES	VERY PROMISING SALVAGE USE
• POWER SUPPLY TO RECOVER AMOR AND APOLLO ASTEROIDS	\$.5-3 BILLION	DEPENDS ON LEVEL OF SPACE ACTIVITY	NOT SUFFICIENT KNOWLEDGE TO DETERMINE VALUE ACCURATELY--COULD USE MANY SATELLITES
• POWER SUPPLY FOR HIGH-ENERGY, HIGH-VACUUM PHYSICS LAB	NOT DETERMINED	POSSIBLY MORE THAN ONE SATELLITE	
RECTENNAE			
• SALVAGE AND RESALE OF LAND	\$30 MILLION	ALL RECTENNA SITES	SALVAGE VALUE OF STEEL AND ALUMINUM OFFSET BY REMOVAL COST FOR CONCRETE
• REUSE WITH NEW SATELLITE	UP TO 30% OF RECTENNA COST	ALL RECTENNA SITES	SALVAGE VALUE DEPENDS ON REFURBISHMENT COST

LEO compared to chemical rockets. The availability of a multi-100 MW power supply enables laser rocket transfer times from LEO to GEO to be quite comparable to chemical rocket transfer times.

The value of a laser space transportation system is clearly dependent upon the amount of LEO to GEO and other geocentric space traffic. If the SPS program does not proceed beyond the demonstration phase, the bulk of the geocentric traffic will be in support of geosynchronous platforms, providing the salvage value shown in Table 1.2. If the SPS program continues into an operational phase, however, the value of a laser space transportation system is substantially greater. Particularly with a continuing SPS program, the laser space transportation system appears so attractive that it is likely that it will be developed and used independent of what is done with the demonstration satellite.

Many potential salvage uses of substantial value exist for full-scale SPS satellites. Their value, however, is very uncertain due to the fact that these uses occur 50 to 80 years in the future. The uses which appear to be most attractive include laser transportation systems, both space-to-space and for aircraft on oceanic routes, as a power supply to recover Amor and Apollo asteroids and, although not quantitatively evaluated, as a power supply for a high-energy, high-vacuum physics laboratory in space. It is conceivable that these uses, plus other less exciting salvage uses such as power for a space manufacturing base or space habitat, could provide sufficient demand for salvage use of an entire fleet of 60 5GW SPS satellites.

The SPS rectennae will most likely all be salvaged. The salvage will include recovery of steel and aluminum which have a combined value of about $290 million (at current prices) less removal cost plus recovery of the land. Taking the removal cost to be 25 percent of value (and adding discounting) the net salvage value of these materials would be about \$67 million. It is likely, however, that the cost of removing the concrete for recovery of the land would be approximately equal to the net value of the steel and aluminum. Thus the principal salvage value of the rectennae is likely to be the present value of the land referenced to the initial operation date of the system. This is approximately \$33 million* at a land value of about \$1,000 per acre.

A more valuable salvage use of the rectennae would be their reuse with new SPS satellites. In this case, especially if existing concrete footings and other components are reusable, the salvage value of the rectennae could approach 30 percent of their new cost. Since the rectennae cost represents about 26 percent of the total SPS cost of about \$13.9 billion, this value could approach \$1.1 billion. If only land and the rectenna support structures are salvageable, the salvage value is about \$620 million. This lower number allows substantial evolution to occur in the rectenna technology.

Finally, those items which are not salvaged must be disposed of. The disposal options considered and their respective costs are given in Table 1.3. Five disposal options are considered. Disposal to L_4 or L_5, the stable (equilateral) libration points in the earth-moon system would provide a location where the satellites might be recovered at some point in the distant future and salvaged for some, presently unknown, use. No stationkeeping or control of the satellites would be necessary once they are in this orbit. The second disposal option presented is to boost the satellite to an orbit above GEO. Twice GEO is presented arbitrarily. The ΔV required is obviously a function of how high the satellite is boosted and the value provided is nominal. This orbit could utlimately require some stationkeeping

*Corresponds to WBS item 1.4.1.1.1 in the Rockwell International cost estimate.

TABLE 1.3 DISPOSAL OPTIONS AND COSTS

OPTION	APPROXIMATE ΔV* KM/S	DISPOSAL COST $ MILLION	REMARKS
L_4 OR L_5	3.23	93	STABLE LOCATIONS, SATELLITES COULD BE AVAILABLE FOR SALVAGE AT SOME FUTURE DATE, NO STATIONKEEPING NECESSARY
SUPRA-GEO (2X)	1.75	66	LOW ΔV REQUIREMENTS BUT MANY REQUIRE SOME FORM OF ACTIVE CONTROL OR REMOVAL AT A DISTANT TIME IN THE FUTURE
MOON	3.23	93	SATELLITE IS REMOVED FOREVER BY IMPACT ON LUNAR SURFACE
HELIOCENTRIC ORBIT	~5.00	125	SOMEWHAT MORE EXPENSIVE BUT REMOVAL IS PERMANENT
EARTH REENTRY	8.03	179	MOST EXPENSIVE OPTION AND PROBABLY NOT ACCEPTABLE DUE TO ENVIRONMENTAL AND RISK CONSIDERATIONS

*ΔV (VELOCITY INCREMENT) DEPENDS ON MISSION MODE. NUMBERS PRESENTED ARE BASED ON TWICE IMPLUSIVE ΔV REQUIREMENTS WHICH APPROXIMATE CONTINUOUS LOW THRUST ΔV. LOWER IMPULSE REQUIREMENTS COULD BE ACHIEVED BY LENGTHENING TRIP TIME. THIS WOULD REDUCE PROPELLANT-ASSOCIATED COSTS AND INCREASE MISSION ASSOCIATED COSTS. THE NET EFFECT WOULD BE SOME REDUCTION IN TOTAL DISPOSAL COST. HENCE, COSTS PRESENTED ARE PROBABLY SOMEWHAT CONSERVATIVE.

activity; however, this activity might be very minimal (once every 1000 years, for example, depending on requirements).

The third and fourth options dispose of the satellite forever by removing it from geocentric space. These could be desirable options if it becomes important to assure that no future concern need be given to the satellite.

The final disposal option, earth reentry, is probably the least desirable from not only the aspect of cost--it requires the highest velocity increment--but from environmental and risk concerns as well. This disposal mode is unlikely to be implemented.

1.4 Conclusions and Recommendations

The conclusions and recommendations with respect to the demonstration satellite are as follows. The preferred salvage use is to use the demonstration satellite as a power source for a laser space transportation system. This will require installation of a laser power transmitter on the satellite. Accordingly it is recommended that the demonstration satellite be equipped with both a microwave power transmitter and a laser power transmitter and be used to demonstrate both SPS configurations. Upon completion of the demonstration, the microwave power transmission system could be salvaged for use on a full-scale SPS satellite if the microwave SPS option is found desirable. The demonstration vehicle, however, would remain in GEO and, using the laser power transmission system, power laser rockets for LEO to GEO transportation.

The value of the recommended salvage use is strongly dependent on the continuation of the SPS program, but even in the absence of a continuing SPS program, it appears sufficient to justify the development of a laser space transportation system exclusive of the SPS demonstration project. For planning purposes it is reasonable to assume that this salvage use will offset about 80 percent of the on-orbit cost of the demonstration satellite hardware.

The conclusions and recommendations with respect to the full-scale satellites are as follows. Several potential salvage uses exist for full-scale SPS satellites, each with a salvage value ranging up to about $3 billion. Preferred salvage uses appear to be use as a power supply for a laser space transportation system, use as a power supply for powering aircraft on oceanic routes, use as a power supply to recover Amor and Apollo asteroids and use as a power supply for a high-energy, high-vacuum physics laboratory in space.

The average salvage value of an SPS satellite appears to be in the range of 5 to 10 percent of the satellite capital cost or about $500 million to $1 billion. Some specific uses, however, may provide significantly higher salvage values, but they are likely to be limited to only a few satellites.

A basic theme which seems to dominate the salvage value results is that the uses which utilize the entire satellite intact have a higher value than those which require segmenting the satellite. The more the satellite is cut up, the less it appears to be worth as salvage.

In any event, if it becomes necessary to dispose of SPS satellites, a number of disposal options appear feasible. The cost of disposal is on the order of \$100 million. This amount has a present value referenced to the initial operation date of the satellite of about \$30 million or only about 0.3 percent of the capital investment cost of the satellite.

It is clear from the above analysis that an assumption of zero net salvage and disposal cost for the SPS satellites is conservative. A less conservative assumption, for purposes of comparing SPS to alternative systems, would be to take a net salvage value between 5 and 10 percent of satellite capital investment cost.

1.5 Backup Documentation

The remaining sections of this report provide backup documentation to the results shown above. Both in review of the backup documentation and interpretation of the above results, the reader should keep in mind that the analyses and results presented here are based upon long-range projections of space and other activities and thus contain considerable uncertainty.

2. A POST-2000 MISSION MODEL

Oscar Morgenstern once said, "Predicting things is very difficult, especially the future." Yet, if one is to establish the salvage value of SPS demonstration and full-scale satellites, one must describe the environment within which these satellites are salvaged. At the very least, this means identifying a space mission model for the time period during which the salvage operation will take place. Basically this time period may be divided into two parts: the years 2000 to 2030 during which time the principal object of salvage is the SPS demonstration satellite; and the period 2030 to 2060, and possibly beyond, when full-scale SPS satellites would become available for salvage.

To begin with, one should recognize that these time frames, at least in terms of specific economic projections, are quite far in the future. The earlier time frame begins 20 years from now and spans a period of 30 years, ending half a century from today. The second period, beginning in the year 2030, is a period of projection that is one-half a century and more in the future. On the scale of life of five-year and ten-year plans, and of long-range planning that does not go beyond the end of the 20th century, it is, for all practical purposes, impossible to develop a mission model containing specific space missions. Rather, over the period 2000 to 2030, projections of space activities are highly uncertain, although there is some hope to identify and establish general trends. These trends can be identified on the basis of existing technologies and technology projections for the relatively near term. For example, an operational space transportation system based on the Space Shuttle and advanced Shuttle derivatives is likely to lead to reduced costs for space activities and, subsequently, to an increasing level of commercial business in space.

Furthermore, there is some hope for identifying the major directions which this "industrialization of space" will take.

Beyond the year 2030, however, one's ability to project even general trends diminishes greatly. A fifty-year period is sufficient for major new and totally unforeseen technologies to develop and become commercialized. Without specific knowledge of these technologies (and that knowledge cannot be had today), projections of post-2030 space activities are entirely speculative. It is with the above qualifications that the following projections of future space activities are made. The first steps in making a long-range projection of space activities is to determine where the impetus for such activities will arise. At the present time funding for space activities derives almost entirely from national governments; principally the U.S. and U.S.S.R. U.S. Federal Government expenditures on space, spanning both DOD and NASA, encompass about $6 billion for FY 1980.* Looking at free world activities and taking this $6 billion to be a measure of free world government sponsorship of space activities and assuming, furthermore, that at the very most this government sponsorship is unlikely to accelerate at a real rate of growth greater than 3 percent per year, one sees a potential level of government-sponsored activitiy in space by the year 2060 of only some ten times larger, or $60 billion per year (1980 $), than the present amount. A space program sponsored only by NASA and DOD (assuming that they exist in the year 2060) at the level of $60 billion per year could possibly support some salvage activities on SPS satellites, but they would be severely limited.

It is highly unlikely, however, that one would be faced with the problem of salvaging SPS satellites in a space program that is principally funded by NASA and DOD, and to a lesser extent by other governments. The simple fact is that one

*The Budget of the United States Government, Fiscal Year 1980.

would not be concerned about salvage of SPS satellites unless an SPS program is indeed implemented. Furthermore the presence of an SPS program infers, in itself, the successful development of a number of space-based technologies that should lead to widely expanding use of space by the private sector. The transition from federal funding to private sector funding for space activities is already evident with communications and information satellite programs, and the acceleration of these trends due to improved space transportation technologies is clearly forthcoming. The successful implementation of an SPS program assures that highly advanced technologies in low cost space transportation including both earth to LEO and LEO to GEO will have been successfully developed. In addition, technologies for the construction and deployment of large-scale space structures, long duration manned facilities and low cost solar cells are assured. These technologies will be available by about the year 2000, or at the time of implementation of the SPS system, and will thus contribute to the economic development of space in the intervening period (2000 to 2030).

At the present time the private sector is making significant strides forward in space-based activities with a focus on communications and data gathering. Present communications activities in the private sector include not only COMSAT (a quasi-private sector organization) but a number of U.S. corporations such as Western Electric, RCA, IBM and so on. These activities should begin to mature around the year 2000 with the implementation of large communications platforms in geosynchronous orbit. Both these and lower altitude platforms will also probably be implemented by the private sector for data collection. The data collection systems will include both natural resources and environment monitoring such as the LANDSAT and SEASAT satellites have done to date. It is conceivable that the communications industry alone could grow to a level of expenditure of between

\$15 billion and \$100 billion per year by the year 2060, and that data collection activities would be on the order of \$10 billion to \$100 billion per year by that time.

Space-based communications expenditures are likely to grow in order to handle personal communications, business data transfer and video communications including teleconferencing. The advantages of teleconferencing in business applications are fast becoming apparent and this mode of communication is likely to supplant a significant fraction of business travel. It is an interesting aside to note that advanced communications activities such as this are highly energy conservative. By the year 2060 it is conceivable that between 30 and 60 large communications platforms will be in place, many in geosynchronous equatorial orbit, but some in other orbits to serve more extreme latitudes. The present desire for geostationary satellites is clearly shown in Figure 2.1. By the year 1990 some 150 satellites will have served various functions, mostly communications, in that orbit.

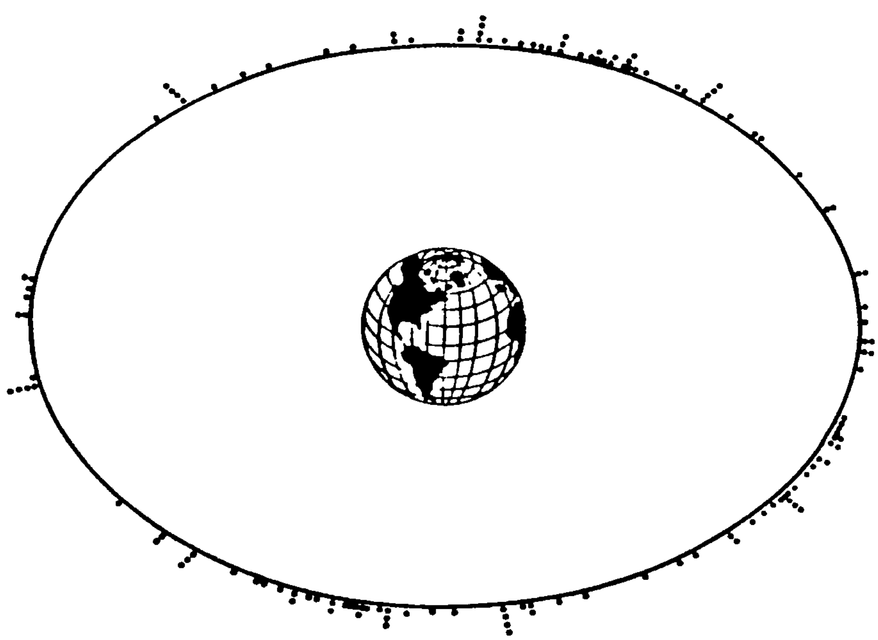


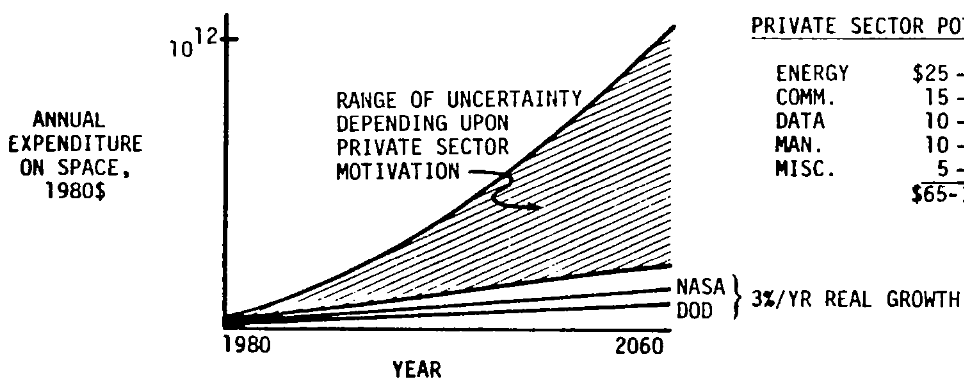
FIGURE 2.1 GEOSTATIONARY SATELLITES--TO DATE AND PLANNED

As data collection in space becomes an economic reality, it is rapidly found that satellites can produce prodigious quantities of data. A single advanced earth resources satellite, for example, might produce as much as 10^9 bits of data per second. Clearly, no human will ever examine all of the available data. Thus it is reasonable to expect a substantial amount of space-based data processing in order to reduce these data to an informational level upon which decisions can be based. Space-based data processing in large (by current standards) computers, co-located with the data collection sensors in space, thus enabling the communications link with earth to carry minimal amounts of processed data, is likely.

An intriguing and totally unpredictable area of space activity is space-based manufacturing. Space, of course, offers a unique environment including high vacuum and zero gravity which should be of considerable benefit to particular manufacturing processes. The unfortunate fact at this time is that since this environment has heretofore not been available to the private sector, the technology for using it has not been developed. As a result, to date, NASA and others have studied a variety of products that might potentially be manufactured in space and found that indeed there may be benefits in doing so. Unfortunately there is a considerable time lag between today and the date at which commercial space-based manufacturing facilities will be available to the private sector. Thus the principal conclusion to which one might arrive is that there are many potential products that could be beneficially manufacturered in space, but none of them are the products that have been examined to date, nor are they products that one would choose to manufacture in space based upon what is known today. Accordingly the annual expenditures on space-based manufacturing is highly uncertain at this time. Conceivably they could be as low as a fraction of a percent or as high as possibly 10 percent of the gross national product, say a range of $10 billion to $500 billion per year.

The third major category of private sector activity in space is energy. If SPS is implemented, these expenditures will be quite high. For example, the operation and maintenance expense on a fleet of 60 SPS satellites will be on the order of $30 billion per year. Capital construction of new SPS satellites could add another $20 billion to $50 billion or more to this amount. Worldwide implementation of SPS on a large scale plus construction of space-based energy systems for lunar exploration, asteriod retrieval and space habitation could increase this amount to as much as $250 billion per year.

In addition to the above four categories of space-based activities, there are a number of other activities that are likely to occur in space. These include physics and astronomy, solar system exploration, basic and applied research, space tourism, space-based navigation systems and so on. These miscellaneous activities are likely to involve expenditures in the range of $5 billion to $50 billion per year by the year 2060. Summing these figures as shown in Figure 2.2, the private sector potential activities in space range from a low of about $65 billion per year in the year 2060 to a high of about $1 trillion per year.



PRIVATE SECTOR POTENTIAL

ENERGY	$25 - 250B
COMM.	15 - 100
DATA	10 - 100
MAN.	10 - 500
MISC.	5 - 50
	$65-1000

FIGURE 2.2 POTENTIAL SPACE ACTIVITY LEVELS, 1980-2060

The major observation which one draws from Figure 2.2 is that dramatic growth in space-based activities, if such growth indeed occurs between now and the year 2060, will derive mainly from private sector ventures undertaken because they are economic. The challenge to NASA is to focus space programs between now and the year 2000 in such a way as to promote the economic utilization of space. Given the proper opportunities, it is conceivable that as much as 20 percent of the gross national product in the year 2060, or say $1 trillion per year, will be derived from space-based activities. On the other hand, without proper encouragement and technology development from NASA and other government agencies, this amount could be very much smaller and the government could still dominate annual expenditures on space activities as late as the year 2060.

2.1 The Period 2000 to 2030

In the context of the above discussion, it is possible to make useful observations on space-based activities during the period 2000 to 2030. A principal activity in space during this period will quite clearly be space-based communications, data collection and data processing. It is also evident that the current trend of placing an ever increasing number of relatively small satellites in geosynchronous orbit cannot continue. Communications and data needs will be satisfied in the future by the use of large geosynchronous platforms rather than by a number of smaller satellites. Accordingly the following general trends are identified for the post-2000 time period:

1. Space will be populated with fewer larger spacecraft. This will be accomplished by transition to large mutli-purpose platforms.

2. Bandwidth limitations will be overcome by using higher power levels and spot beams.

3. Multi-purpose platforms will not be co-located with SPS due to conflicting requirements such as the potential need for turning SPS satellites out of the sun during maintenance periods.

4. Mutli-purpose platforms will occupy many important orbits, not only GEO.

5. On-orbit servicing capability will be maintained for all multi-purpose platforms. Because of their high value, downtime on these platforms will be extremely expensive. The balance between man and robotics for providing on-orbit servicing capability is very uncertain at this time.

6. Many activities in space will be internationally sponsored, and it is likely that large geosynchronous platforms will be considered multinational territory.

7. Many of the activities performed in space in the post-2000 period will be performed there because it is economic to do so independent of government funding. These activities will thus represent a significant transformation of space-based activities from the government to the private sector.

8. A fully reusable space transportation system and multi-purpose platforms will dramatically lower the cost of the space activities and thus promote increasing private sector investments in space.

9. System complexity will shift from the ground segment where it is presently to the space segment, enabling ground-based users to participate in the use of space-based communications and data collection with relatively low investment. However this does not infer that the majority of expenditures on a particular system will be on the space segment. To the contrary, the lowering of costs for ground-based users is likely to increase the number of ground-based users dramatically, thus maintaining the preponderance of expenditures on the ground segment. For example, if the worldwide market for personal communicators at $100 per communicator is 100 million units, a total expenditure on the ground segment of some $10 billion will ensue. This might be compared to an expenditure on the space segment in support of these communicators of, say, $5 billion.

Of particular interest in the post-2000 time period are geosynchronous platforms. It has already been observed that geosynchronous orbit will be dominated by large platforms during this period. The seeds of this transformation have already been sown, and it is expected that during the late 80s and early 90s a number of U.S. domestic and Intelsat platforms in the 25 kilowatt class will be placed in geosynchronous orbit. During the period of the mid-90s to about the year 2010, the placement of some five to ten larger platforms in the 100 to 500 kW class is likely. Beyond the year 2010 one can look for the replacement of the earlier platforms by a new class of platforms in the 1 to 5 MW class, growing to a total of some 15 to 30 platforms by the year 2030. The larger platforms are likely to be manned either by robots or by two-man crews rotated periodically. The purpose of man will be to effect immediate service, repair and maintenance as necessary to keep the platform properly functioning. The cost of the advanced platforms will be in the range of $2 billion to $10 billion each, and they will have a structure and power supply life approaching 50 years with other systems being updated on about a ten-year cycle.

The advanced geosynchronous platforms will be supported by a manned geosynchronous facility which is also likely to be a space-based manufacturing facility to manufacture and rebuild components and subsystems for the geosynchronous and other space platforms. As a result it is likely that 50 to 500 persons will be stationed in geosynchronous orbit in support of the geosynchronous platforms.

Spacecraft power and lifetime trends to date, as shown in Figure 2.3, clearly reflect these trends. Twenty-five kW platforms are presently in the planning stage* and studies on 100 to 500 kW platforms for the late 1990s time period have already been performed.** The continuing improvements in lifetime and growth in power levels shown in Figure 2.3 are fully compatible with SPS-based technologies.

It is interesting to consider the traffic necessary to support the geosynchronous platforms that are likely to be put in place in the 2000 to 2030 period.

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*Payloads Requirements/Accommodations Assessment Study for Science and Applications Space Platforms, Second Quarterly Review, TRW, June 10, 1980.

Third Quarter Briefing: Conceptual Design Study--Science and Applications Space Platform (SASP), McDonnell Douglas Astronautics Company, June 11, 1980.

**Space Industrialization--Background, Needs and Opportunities, Rockwell International, Report No. SD-78-AP-0055, April 14, 1978.

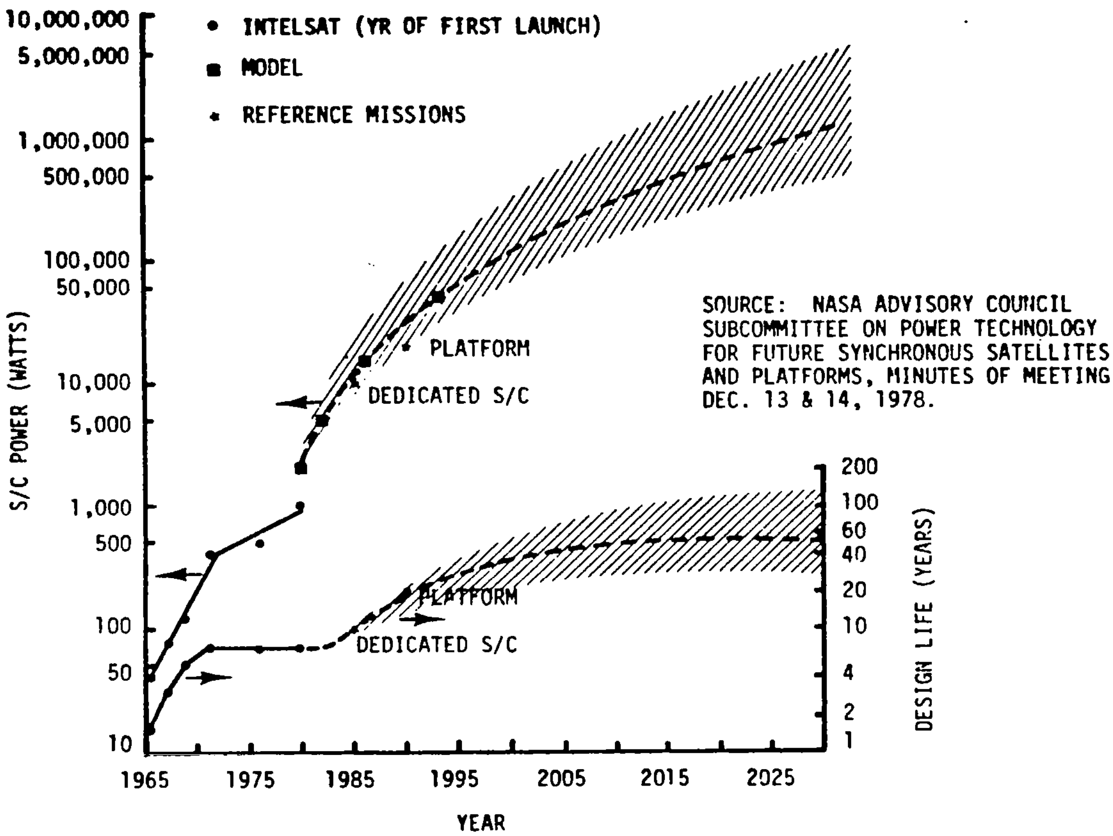

FIGURE 2.3 HISTORICAL AND PROJECTED GROWTH OF SPACECRAFT POWER AND LIFETIME

These traffic requirements are shown in Table 2.1. This table reflects the fact that there are two fundamentally different classes of payloads which need to be transported to geosynchronous orbit. The first class involves durable goods such as the materials for construction of new platforms. It is probably economic to transport these materials between LEO and GEO using a low-thrust electric cargo orbit transfer vehicle (COTV). The implications in this decision indicate that the cost of capital for the durable goods during the period of transportation is more than offset by the cost savings afforded by the electric COTV. Nondurable goods, however, such as man and his logistics, require more rapid forms of transportation. The present option for the personnel orbit transfer vehicle (POTV) involves the use

TABLE 2.1 TRAFFIC TO SUPPORT GEO PLATFORMS (KG/YR)

ELEMENT	LEO-GEO	GEO-GEO
• MATERIAL FOR CONSTRUCTION OF NEW PLATFORMS (50,000-200,000 KG EACH)	25,000 - 300,000	25,000 - 300,000
• REPLACEMENTS, CHANGEOUTS AND SPARES (5% CHANGEOUT/YR, HALF BROUGHT UP FROM EARTH, HALF REMANUFACTURED IN ORBIT)	20,000 - 150,000	40,000 - 300,000
• MAN (100-1000 PERSON-TRIPS LEO-GEO--6 MO. WORK CYCLE, 50-500 GEO-GEO PERSON-TRIPS)	8,000 - 80,000	4,000 - 40,000
• LOGISTICS (1800 KG/PERSON-YR)	90,000 - 900,000	30,000 - 300,000
• COTV AND POTV PAYLOAD MODULES		
- COTV (5% OF PAYLOAD)	2,000 - 23,000	3,000 - 25,000
- POTV (200 KG/PERSON, PLUS 13.5% OF LOGISTICS)	32,000 - 322,000	14,000 - 141,000
• SUBTOTALS	177,000 - 1,775,000	116,000 - 1,106,000
- COTV TRAFFIC	(47,000 - 473,000)	(68,000 - 625,000)
- POTV TRAFFIC	(130,000 - 1,302,000)	(48,000 - 481,000)
• PROPELLANTS		
- COTV (ELECTRIC, 10,000 SEC)	6,000 - 60,000	NIL
- POTV (CHEMICAL, 460 SEC)	400,000 - 4,000,000	1,000 - 10,000

of chemical propellants (oxygen and hydrogen) to enable LEO to GEO trips to be made on the order of one-half day. It is evident from Table 2.1 that rather large quantities of chemical propellants are necessary to support a POTV system. It is thus apparent that alternatives to the use of a chemical POTV could be quite advantageous.

2.2 The Post-2030 Time Period

Very little more can be said about space activities in the post-2030 time period than has been noted already above. It is likely that this period will see the widespread use of space by man including space habitation and utilization of extraterrestrial resources. It is also likely that many scientific endeavors will move into space: astrophysics, astronomy, high-energy physics and biological research are examples. It is this context in which salvage value of SPS satellites was considered.

3. SPS DEMONSTRATION SATELLITE SALVAGE ALTERNATIVES

According to the Rockwell International SPS development program plan,* the completion of the SPS Technology Advancement phase by 1990 will provide the technical confidence to proceed with a pilot plant demonstration phase. The primary objective of this development phase would be the demonstration of all SPS technologies to those utility firms and consortiums that would ultimately capitalize and operate the production or full scale operational system.

The pilot-plant or demonstration satellite will be constructed in low earth orbit using a heavy lift launch vehicle (HLLV) for mass transportation and construction support systems. The demonstration satellite will be transferred to geosynchronous orbit by an on-board electric propulsion system. The demonstration satellite will operate in the same mode as the full-scale SPS satellite by directing a microwave power beam at a total power level of a few hundred MW to a standard modular segment of the proposed operational ground rectenna. The demonstration/operational period may range from six months to a few years, during which time the SPS elements of the full-scale solar power satellite will be operated in the operational environment. Operational data will provide the quantitative basis for analyses which will support full SPS commercial capability.

The initial step will be to establish a base in low-earth orbit that is capable of constructing the demonstration satellite. The demonstrator satellite, shown near completion in Figure 3.1, is sized to the projected electric orbit transfer vehicle (EOTV) power level of 335 MW at the array. Allowing for radiation degradation

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*Satellite Power Systems (SPS) Concept Definition Study, Final Report, Vol. 1, Rockwell International, Contract NAS8-32475, March 1979.

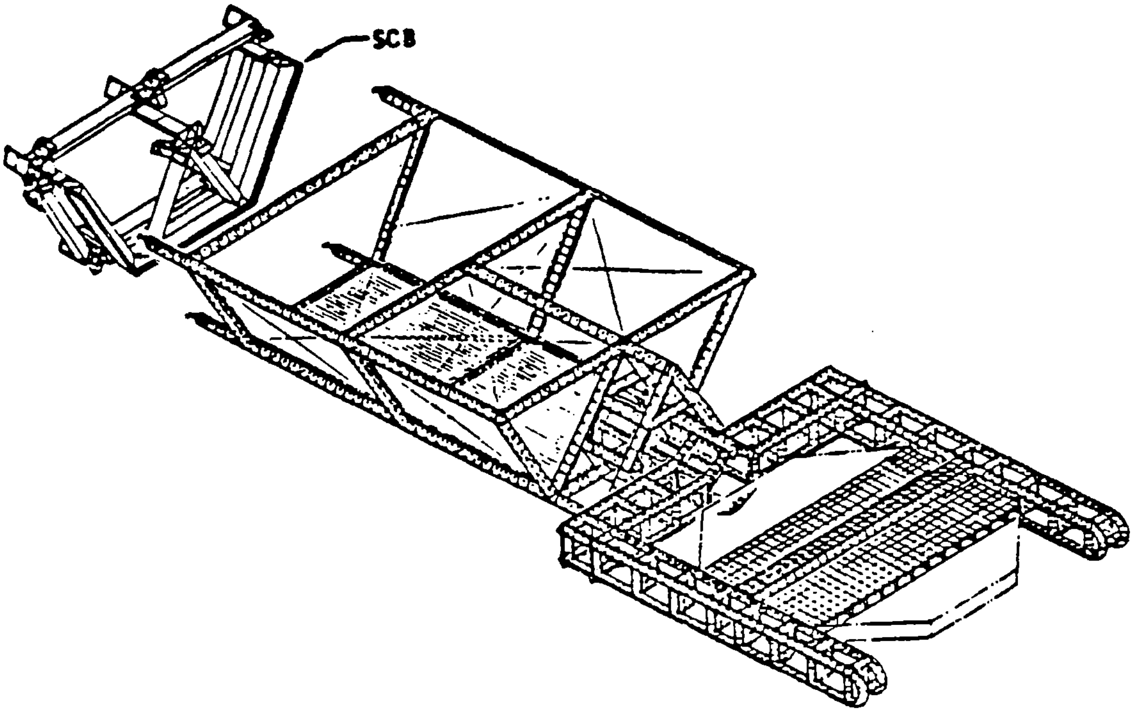


FIGURE 3.1 SPS DEMONSTRATION SATELLITE IN FINAL PHASES OF CONSTRUCTION (SOURCE: ROCKWELL INTERNATIONAL)

and power distribution losses, power to the microwave antenna will be approximately 285 MW. Microwave transmission losses further reduce this value to about 230 MW at the rectenna, resulting in recovery of 8 MW of power for a sparsely populated 7-km-diameter demonstration rectenna or 2 MW of power for a 1.75-km demonstration rectenna.

The demonstration satellite is a single unit or bay of the operational SPS which consists of 30 such bays as shown in Figure 3.2. A list of the basic items which comprise the demonstration satellite and their related DDT&E and first unit costs are summarized in Table 3.1. The mass properties of the full-scale and demonstration satellites are summarized in Table 3.2.

Because of the large investment in the demonstration satellite and the associated transportation costs and the on-orbit capability that will exist, there is

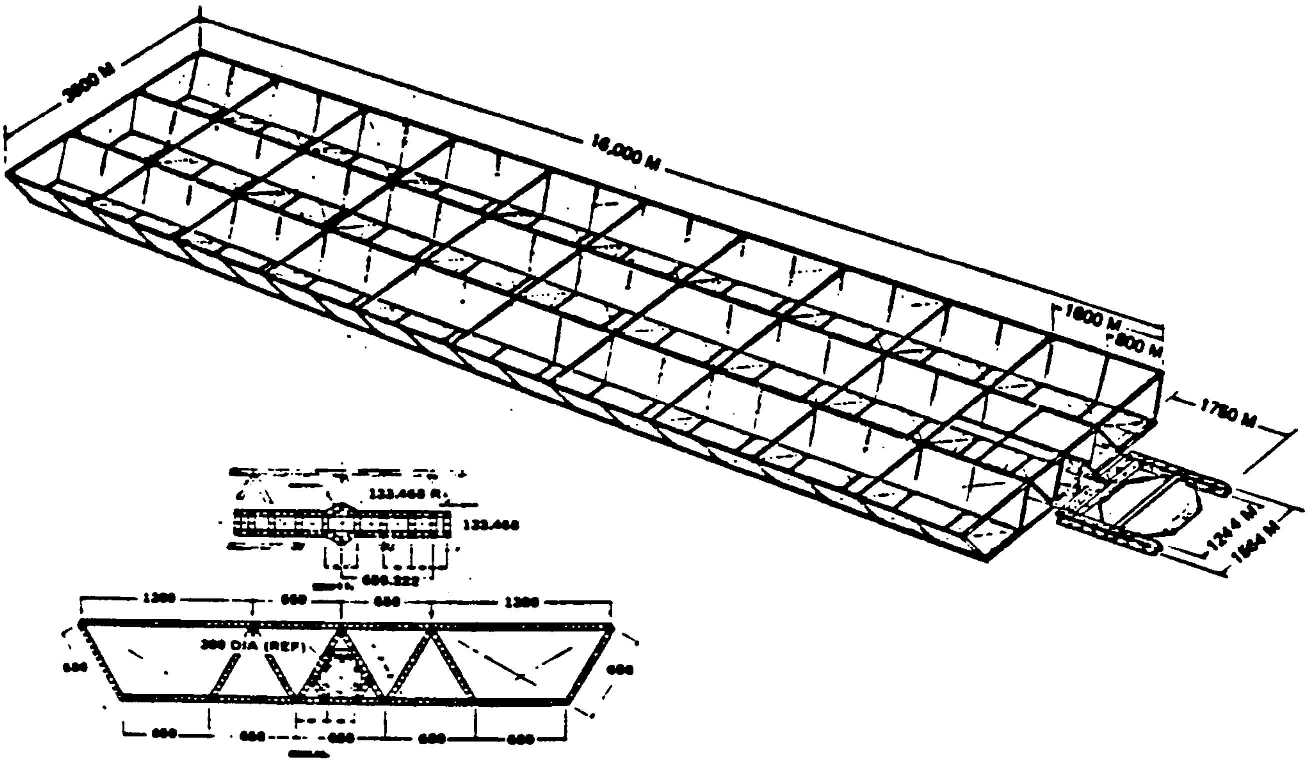


FIGURE 3.2 FULL-SCALE OPERATIONAL SPS SATELLITE CONFIGURATION (SOURCE: ROCKWELL INTERNATIONAL)

a natural concern as to the alternative uses of the demonstration satellite upon completion of the demonstration program, and the economic value associated with these uses. The following sections discuss alternative uses, and the value derived therefrom, to which the demonstration satellite may be put upon completion of the demonstration program. Four alternative uses have been considered, namely:

1. Use of the demonstration satellite as the first building-block of the first full-scale SPS satellite. The economic value, or salvage value, of the demonstration satellite derives primarily from the costs which would be foregone in the construction of the full-scale satellite through the incorporation of the demonstration satellite into the full-scale satellite.

2. Use of the demonstration satellite as a source of power for non-SPS space activities. This use requires the systematic disassembly of the demonstration satellite and transferral and use of the disassembled power subsystems as power supplies in other space missions. Here the salvage value of the demonstration satellite derives primarily from the costs (both hardware and associated transportation) foregone by the other space missions through their use of the demonstration satellite power subsystems.

WORK BREAKDOWN STRUCTURE NUMBER	DESCRIPTION	DDT&E ($10^6$$)+	FIRST UNIT ($10^6$$)+	TOTAL ($10^6$$)+
TABLE 3.1 DEMONSTRATION SATELLITE COST STRUCTURE*				
1.1.9	DEMONSTRATION SATELLITE	748.7	1,738.5	2,487.1
1.1.9.1	DEMONSTRATION SATELLITE VEHICLE	748.7	1,737.8	2,486.5
1.1.9.1.1	PRIMARY STRUCTURE--E.C.	89.9	1.5	91.4
1.1.9.1.2	SECONDARY STRUCTURE--E.C.	21.2	533.6	554.8
1.1.9.1.3	CONCENTRATOR--E.C.	7.9	2.8	10.7
1.1.9.1.4	SOLAR BLANKET--E.C.	47.0	60.3	107.3
1.1.9.1.5	SWITCHGEAR & CONVERTERS--E.C.	3.5	1.7	5.2
1.1.9.1.6	CONDUCTORS & INSULATION--E.C.	7.0	1.4	8.5
1.1.9.1.7	ACS HARDWARE--E.C.	12.2	620.6	632.8
1.1.9.1.8	SLIPRINGS--PRECURSOR	54.6	31.0	85.5
1.1.9.1.9	PRIMARY STRUCTURE--INTERFACE	152.8	6.0	158.8
1.1.9.1.10	SECONDARY STRUCTURE--INTERFACE	15.2	4.0	19.2
1.1.9.1.11	MECHANISMS--INTERFACE	78.9	221.6	300.5
1.1.9.1.12	CONDUCTORS & INSULATION	4.0	.2	4.2
1.1.9.1.13	SLIPRINGS BRUSHES--PRECURSOR	2.5	2.3	4.8
1.1.9.1.14	PRIMARY STRUCTURE--POWER TRANS.	20.9	.3	21.2
1.1.9.1.15	SECONDARY STRUCTURE--POWER TRANS.	17.0	2.5	19.6
1.1.9.1.16	TRANSMITTER SUBARRAYS--KLYSTRONS	.0	141.5	141.5
1.1.9.1.17	SWITCHGEAR & CONVERTERS--P.T. PRECURSOR	6.8	47.5	54.3
1.1.9.1.18	CONDUCTORS & INSULATION--P.T. PRECURSOR	4.1	.2	4.4
1.1.9.1.19	BATTERIES--P.T. PRECURSOR	27.1	11.5	38.6
1.1.9.1.20	THERMAL CONTROL--INSULATION--PRECURSOR	26.5	46.0	72.5
1.1.9.1.21	REFERENCE FREQUENCY GENERATOR--PRECURSOR	.5	.1	.6
1.1.9.1.22	DIST. SYSTEM, COAXIAL CABLE	.3	.5	.8
1.1.9.1.23	DIST. SYSTEM DEVICES	.0	.5	.5
1.1.9.1.24	TRANSMITTER SUBARRAYS--KLYSTRONS DDT&E	148.7	.0	148.7
1.1.9.2	DEMONSTRATION SATELLITE OPERATIONS	.0	.6	.6

*SOURCE: SATELLITE POWER SYSTEMS (SPS) CONCEPT DEFINITION STUDY, VOL. II, ROCKWELL INTERNATIONAL, MARCH 1979.

+1977 DOLLARS.

TABLE 3.2 MASS PROPERTIES OF FULL-SCALE AND DEMONSTRATION SPS SATELLITES (10^6 KG)

SUBSYSTEM	FULL-SCALE* SATELLITE	DEMONSTRATION+ SATELLITE
SOLAR ARRAY	(13.926)	(0.464)
PRIMARY STRUCTURE	4.172	0.139
SECONDARY STRUCTURE	0.581	0.019
SOLAR BLANKETS	6.696	0.223
CONCENTRATORS	0.955	0.032
POWER DISTRIBUTION & CONDITIONING	1.144	0.038
INFORMATION MANAGEMENT & CONTROL	0.050	0.002
ATTITUDE CONTROL	0.128	0.004
ANTENNA	(13.254)	(0.683)
PRIMARY STRUCTURE	0.250	0.250
SECONDARY STRUCTURE	0.786	0.026
TRANSMITTER SUBARRAYS	7.178	0.239
POWER DISTRIBUTION & CONDITIONING	2.189	0.073
THERMAL CONTROL	2.222	0.074
INFORMATION MANAGEMENT & CONTROL	0.630	0.021
ARRAY/ANTENNA INTERFACES	0.147	0.147
SUBTOTAL	27.327	1.294
CONTINGENCY (25%)	6.832	0.324
TOTAL	34.159	1.618

*SOURCE: SATELLITE POWER SYSTEMS (SPS) CONCEPT DEFINITION STUDY, FINAL REPORT, VOL. II, ROCKWELL INTERNATIONAL, CONTRACT NAS8-32475, MARCH 1979.

+DEMONSTRATION SATELLITE SCALED FROM FULL-SCALE SATELITE ACCORDING TO THE RATIO OF POWER GENERATED.

3. Use of the demonstration satellite as a power supply for a laser orbit-to-orbit transportation system. A laser orbit-to-orbit transportation system would derive value through transportation cost savings primarily on the cost of transporting otherwise-needed propellants to LEO.

4. Use of the demonstration satellite as a source of space-based materials. The salvage value of this use derives from transportation costs and material costs which may be foregone by using the basic materials existing in the demonstration satellite.

3.1 Growth to Full-Scale Satellite

It is currently envisioned that the demonstration satellite will consist of an energy conversion segment, an interface segment and a power transmission segment. The energy conversion segment will consist of primary and secondary structure, concentrators, solar blankets, switchgear and converters, conductors and insulation, attitude control and information management subystems. The interface segment includes the primary and secondary structure, mechanisms, conductors/insulation and slipring brushes. The power transmission segment will be representative of the full-scale satellite antenna to the extent of using identical components. It will include structures, transmitter subarrays, power distribution and conditioning, batteries, insulation and phase control elements.

Current plans call for growth of the demonstration satellite into the first full-scale SPS satellite. By growing the demonstration satellite into the first full-scale satellite, certain costs may be foregone (that is, a cost item that would have to be incurred if the demonstration satellite were not available for use, would not be incurred since the demonstration satellite is available for use) whereas others may be incurred. The present value of the net of these costs referenced to the initial operation date of the demonstration satellite, is the salvage value that may be derived from this use of the demonstration satellite. It is assumed throughout the following that the demonstration satellite is in orbit and all associated DDT&E and first unit costs are sunk.

The salvage value of the demonstration satellite when used as an initial element in a full-scale satellite is summarized in Figure 3.3 and discussed below. The salvage value, SV, is

$$SV = PV1 + PV2 - PV3 - PV4$$

where PV1 is the present value of the full-scale satellite costs that may be foregone. PV1 accounts for the hardware costs for providing a capability equivalent to the demonstration satellite capability and the transportation costs associated with transporting this equivalent capability. The demonstration satellite capability must be adjusted for degradation effects which are a function of time (the time interval to the deployment of the first full-scale satellite) and both hardware and transportation costs must be adjusted for learning effects (assumed to be a function of time) that may also take place during this interim period. PV2 is the present value of consumer surplus benefits that will result if the marginal

SV → {VALUE OF SPS DEMO SATELLITE} =

{PRESENT VALUE OF INITIAL INVESTMENT FOREGONE
- SPACE HARDWARE COSTS FOR PROVIDING CAPABILITY EQUIVALENT TO DEMO - SPS (ADJUSTED FOR LEARNING & TIMING)
- COSTS FOR TRANSPORTING EQUIVALENT OF DEMO-SPS} ← PV1

\+ {PRESENT VALUE OF CONSUMER SURPLUS BENEFITS
- REDUCED PRICE OF ELECTRICITY FROM USE OF DEMO-SPS IN THE TIME INTERVAL TO ON-ORBIT CONSTRUCTION OF OPERATIONAL SPS} ← PV2

\- {PRESENT VALUE OF INCREASE IN CONSTRUCTION (INTERFACE) COSTS
- CANNOT TAKE ADVANTAGE (AT LEAST FOR INTERFACING WITH DEMO-SPS) OF KNOWLEDGE GAINED FROM DEMO PROGRAM} ← PV3

\- {PRESENT VALUE OF INCREASE IN DEMO-SPS INVESTMENT COST TO ACHIEVE RELIABILITY CHARACTERISTICS OF OPERATIONAL SPS} ← PV4

FIGURE 3.3 SALVAGE VALUE--GROWTH TO FULL-SCALE SATELLITE cost of energy from the SPS system is below that resulting from other energy sources. The consumer surplus benefits are directly proportional to the price differential, the energy produced and the time interval from demonstration completion to on-orbit construction of the operational satellite. PV3 is the present value of possible increases in construction (interface) costs that result from not being able to take advantage of knowledge gained from the demonstration program. PV4 is the present value of the increase in demonstration satellite investment cost to achieve the same reliability characteristics that would be achieved by the first full-scale operational satellite. Since no information is available on demonstration satellite cost in terms of reliability characteristics, PV4 has been assumed to be zero. The detailed value model is indicated below together with definitions of the variables and the nominal values utilized in the analysis. It should be noted that the annual transportation investment cost is treated parametrically and is obtained by spreading the cost to deliver 1.618×10^6 kg to geosynchronous orbit over a three year period (30%, 40% and 30% respectively). The basic range of transportation cost has been considered from 0 to 100 \$/kg predicated upon the assumption that low transportation costs will have to be achieved in order to proceed with an economically viable full-scale operational SPS system.

$$PV1 = (IOD-IOC)^{L1} * (1-\frac{D}{100})^{IOD-IOC} * \sum_{i=1}^{I} DCSTIH_i * (1+\frac{DR}{100})^{I-i}$$

$$+ (IOD-IOC)^{L2} * \sum_{i=1}^{I} DCSTIT_i * (1+\frac{DR}{100})^{I-i}$$

where $L1 = (\log_{10} LINVH - 2.0)/\log_{10} 2.$

$L2 = (\log_{10} LINVT - 2.0)/\log_{10} 2.$

$$PV2 = 876 * DSPSP * \sum_{i=1}^{IOD-IOC} (PCONE_i - PSPSE_i) * (1 - \frac{D}{100})^i * (1 + \frac{DR}{100})^{2000-IOC-i}$$

$$PV3 = CINTF * \frac{PCINTF}{100} * DSPSP * (1 + \frac{DR}{100})^{2000-IOD}$$

$$PV4 = 0$$

Variable	Definition	Nominal Value
i	Time subscript (years)	
I	Number of years from time of first unit cost expenditure to 2000	3
DR	Discount rate (%)	4
IOC	Date of initial operating capability for supplying electric energy to the grid from the demonstration satellite (year)	1998
IOD	Date of initial operating capability for supplying electric energy to the grid from the SPS operational satellite (year)	2000
$DCSTIH_i$	Annual nontransportation investment cost of demonstration satellite ($/year)	521×10^6 (1996) 695×10^6 (1997) 521×10^6 (1998)
$DCSTIT_i$	Annual transportation investment of demonstration satellite ($/year)	See Text
LINVH	Cumulative average learning rate for SPS nontransportation costs (%)	90
LINVT	Cumulative average learning rate for SPS transportation costs (%)	90
$PCONE_i$	Average cost of energy from non-SPS sources displaced by SPS in year i (mills/kWh)	Differences Assumed Small
$PSPSE_i$	Cost of energy from SPS in year i (mills/kWh)	
DSPSP	Demonstration satellite power available to grid (kW)	162×10^3 kW

Variable	Definition	Nominal Value
D	Percent power degradation (due to both random non-replaced failures and radiation effects) of SPS power supply per year (%/year)	1
CINTF	Cost per kilowatt for interfacing operational SPS satellite power modules with other operational SPS satellite power modules ($/kW)	--
PCINTF	Percent increase in cost of interfacing operational SPS power modules with demonstration satellite power modules (%)	Assumed to be zero

The results of the analysis are illustrated in Figure 3.4 where the present value of the demonstration satellite is indicated as a function of transportation cost ($/kg) and the time interval between the initial operations dates of the full-scale operational satellite and the demonstration satellite. The basic conclusion that may be reached from the data presented in Figure 3.4 is that the salvage value ($1.1-$1.7 billion) of the demonstration satellite may be a large percentage of the demonstration satellite on-orbit cost (first unit plus transportation cost). The salvage value may be in the range of 60-90 percent of the on-orbit cost of the demonstration satellite depending upon transportation cost achieved and the time interval from demonstration satellite operations to operation of the first full-scale SPS satellite.

3.2 Demonstration Satellite Use as a Power Supply for Non-SPS Space Activities

If the demonstration satellite is not utilized as an initial element of a full-scale operational SPS satellite, it may serve as a source of power (335 MW) and major subsystems for other space activities. When used in this manner its value is a function of the demand for space power and other major subsystems and the timing of this demand. The value of the demonstration satellite when used as a power supply for non-SPS space activities is the value of the power supplies and

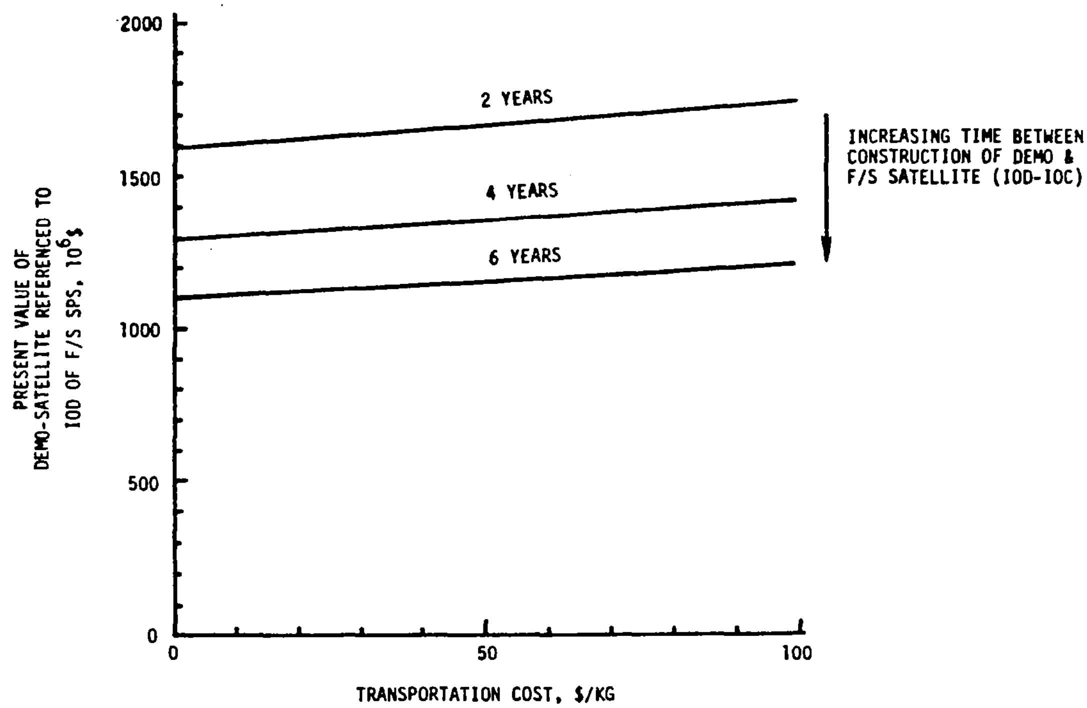


FIGURE 3.4 PRESENT VALUE OF DEMONSTRATION SATELLITE WHEN USED AS AN INITIAL ELEMENT IN A FULL-SCALE SATELLITE

major subsystems that would not have to be procured and transported for the other space activities less the specific costs associated with segmenting the demonstration satellite into the useful power modules and other major subsystems and the incremental costs of installing these on other mission spacecraft.

Since it is not possible to accurately forecast the demand for space power in the 2000 to 2030 time frame, the demand has been treated parametrically in terms of MW required per year. This demand has been considered in the range of 1 to 15 MW/yr as illustrated by the solid lines in Figure 3.5. The dashed curve in Figure 3.5 indicates the available supply taking into account a 1%/yr degradation in power and an assumed inefficiency (25% salvage loss) or loss resulting from the salvage segmentation process. The intersection of the supply and cumulative demand curves yields the number of years that the demonstration satellite power

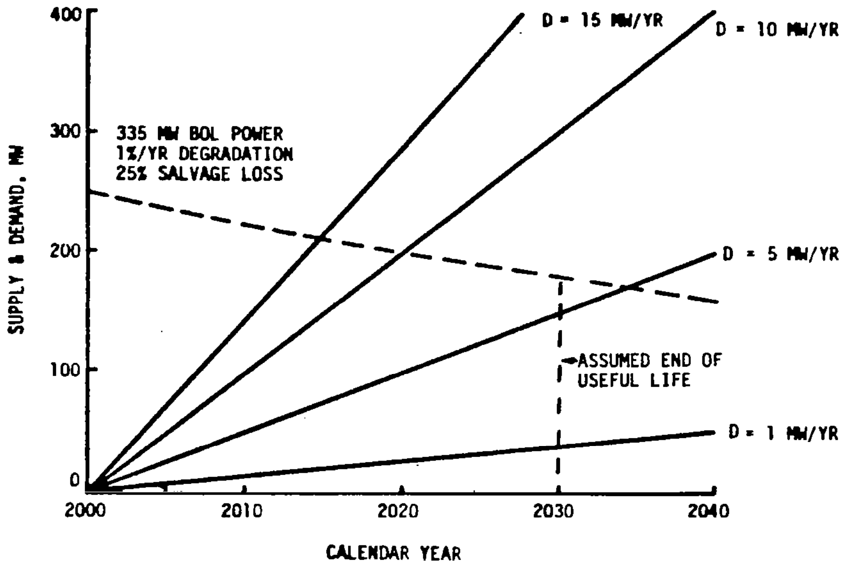


FIGURE 3.5 SUPPLY & DEMAND FOR POWER FROM DEMONSTRATION SPS SATELLITE

supply will last (for example, at demand rates of 15, 10, 5 and 1 MW/yr, the demonstration satellite power supply will last 12, 20, 33 and 96 years respectively). It was assumed for the analyses reported in the following paragraphs that the demonstration satellite would have a maximum life of 30 years for being able to remove portions of the power supply.

The salvage value of the demonstration satellite when used as a source of power and other major subsystems for other space activities is summarized in Figure 3.6 and discussed below. The salvage value, SV, is

$$SV = PV1 - PV2 - PV3 - PV4 - PV5$$

where PV1 is the present value of the non-SPS mission investment costs that may be foregone because of the utilization of the SPS demonstration satellite hardware. The costs that may be foregone include both the space hardware costs and the

SV ← {VALUE OF SPS DEMO SATELLITE} =

{PRESENT VALUE OF NON-SPS MISSION INVESTMENT COSTS FOREGONE
- SPACE HARDWARE COSTS (POWER & OTHER SUBSYSTEMS)
- TRANSPORTATION COSTS FOR SPACE HARDWARE} ← PV1

− {PRESENT VALUE OF INCREMENTAL MISSION MAINTENANCE COSTS
- RANDOM FAILURES
- WEAROUT FAILURES} ← PV2

− {PRESENT VALUE OF INCREMENTAL DEMONSTRATION SATELLITE OPERATION COSTS
- CONTINUING OPERATIONS & MAINTENANCE OF DEMONSTRATION SATELLITE} ← PV3

− {PRESENT VALUE OF INCREASE IN MISSION OPERATIONS COSTS
- SEGMENTING OF DEMONSTRATION SATELLITE POWER SYSTEM
- INSTALLING SEGMENTED DEMONSTRATION SATELLITE POWER SYSTEM ON MISSION SPACECRAFT} ← PV4

− {PRESENT VALUE OF DISPOSING OF UNUSED PORTION OF DEMONSTRATION SATELLITE} ← PV5

FIGURE 3.6 SALVAGE VALUE--SPS DEMONSTRATION SATELLITE USED AS A SOURCE OF POWER AND OTHER SUBSYSTEMS FOR OTHER ACTIVITIES

transportation costs incurred in placing the hardware in the desired orbit. PV2 is the present value of incremental mission maintenance costs incurred as a result of using the demonstration satellite hardware in lieu of mission specific hardware. For this analysis PV2 has been assumed to be zero. PV3 is the present value of incremental demonstration satellite operations costs incurred as a result of continuing the SPS demonstration satellite operations throughout the salvage period and providing the necessary maintenance. PV4 is the present value of the increase in mission operations costs and includes those costs incurred to segment the demonstration satellite power system and to install the segmented power system on the other mission spacecraft. PV5 is the present value of the costs associated with disposing of the unused portion of the demonstration satellite. The detailed value model is indicated below with the definition of variables and nominal values for the variables also indicated.

$$PV1 = CFAC * \Delta T^{L\emptyset} (1+\frac{DR}{100})^{-\Delta T} + CKG * MFAC * \Delta T^{L1} * (1+\frac{DR}{100})^{-\Delta T}$$

$$+ \sum_{i=1}^{t} CKG * KGKW * 10^3 * M * i^{(L1+L4)} * (1+\frac{DR}{100})^{-i}$$

$$+ \sum_{i=1}^{t} CKW * 10^3 * M * i^{L2} * (1+\frac{DR}{100})^{-i} - \sum_{i=1}^{t} CKGSG * KGKW * 10^3 * M *$$

$$(1-\frac{D}{100})^{i} * i^{(L3+L4)} * (1+\frac{DR}{100})^{-1}$$

where $L\emptyset = (\log_{10}LCCF-2.0)/\log_{10}2.$

$L1 = (\log_{10}LCKG-2.0)/\log_{10}2.$

$L2 = (\log_{10}LCKW-2.0)/\log_{10}2.$

$L3 = (\log_{10}LCKGSG-2.0)/\log_{10}2.$

$L4 = (\log_{10}LKGKW-2.0)/\log_{10}2.$

$PV2 = 0$

$$PV3 = 10^3 * M * \sum_{i=1}^{t} \left\{(CKWS * i^{L5} + CKWSI * i^{L6}) * (1-\frac{D}{100})^{-i} - CKWMI * i^{L7}\right\} *$$

$$(1+\frac{DR}{100})^{i}$$

where $L5 = (\log_{10}LCKWS-2.0)/\log_{10}2.$

$L6 = (\log_{10}LCKWSI-2.0)/\log_{10}2.$

$L7 = (\log_{10}LCKWMI-2.0)/\log_{10}2.$

$$PV4 = \sum_{i=1}^{t} SPSCOC * i^{L8} * (1+\frac{DR}{100})^{i}$$

where $L8 = (\log_{10}LSPSCO-2.0)/\log_{10}2.$

$$PV5 = CDIS * \left\{ INMASS-MFAC-KGKW * 10^3 * M * \left[\frac{1-e^{-t\ln(1-\frac{D}{100})}}{\ln(1-D/100)}\right] \right\} * (1+\frac{DR}{100})^{t}$$

$$t * \ln(1-\frac{D}{100}) - \ln(t) = \ln\left(\frac{100 * M}{P*DELTA}\right)$$

Variable	Definition	Nominal Value
i	Time subscript referenced to year 2000 (years)	
t	The time at which demonstration satellite power is consumed (years)	See Figure 3.5
M	Rate of increase in the demand for space power (MW/year)	Treated Parametrically
P	Power available from the demonstration satellite in 2000 for space operations (W)	335×10^6
D	Percent power degradation (due to both random nonreplaced failures and radiation effects) (%/year)	1
DELTA	Percentage of the demonstration satellite power that may be efficiently utilized for other missions (%)	75
DR	Discount rate (%)	4
CKGSG	Cost per kilogram for transporting power subsystem from the demonstration satellite orbit to mission orbit ($/kg)	Negligible
CKWS	Cost per kilowatt for segmenting the demonstration satellite into useful size power modules ($/kW)	152 (See Appendix A)
CKWSI	Cost per kilowatt for installing the demonstration satellite system segment on a mission spacecraft ($/kW)	30 (See Appendix A)
CKWMI	Cost per kilowatt for installing non-SPS power system on a mission spacecraft ($/kW)	15
SPSCOC	Demonstration satellite continuing operations costs (during salvage operations) ($/year)	0.6×10^6
INMASS	Initial mass of demonstration satellite just prior to start of salvage operations (kg)	1.618×10^6
KGKW	Achievable power density of power system (kg/kW)	.825 (See Appendix A)

Variable	Definition	Nominal Value
T	Time, measured from year 2000, when nonpower salvageable pieces are removed (years)	Treated Parametrically
CKW	Cost per kilowatt of power not including delivery costs (it is assumed that the cost of SPS and mission power are equal) ($/kW)	$1.67X10^3$ (See Appendix A)
CKG	Cost per kilogram delivered to GEO from Earth ($/kg)	Treated Parametrically
CDIS	Cost per kilogram of disposing of nonsalvageable mass of the demonstration satellite ($/kg)	Small Compared to CKG
MFAC	Mass of usable demonstration satellite facilities (kg)	87600 KG
CFAC	Cost of usable demonstration satellite facilities ($)	$134X10^6$
LCCF	Cumulative average learning rate for cost of other salvagaeble pieces of the demonstration satellite (%)	90
LCKG	Cumulative average learning rate for cost per kilogram delivered to GEO from Earth (%)	90
LCKW	Cumulative average learning rate for cost per kilowatt of power not including delivery costs (%)	90
LCKGSG	Cumulative average learning rate for cost per kilogram for transporting power subsystem from the demonstration satellite orbit to mission orbit (%)	90
LKGKW	Cumulative average learning rate for achievable power density of power system (%)	90
LCKWS	Cumulative average learning rate for cost per kilowatt for segmenting the demonstration satellite into power modules (%)	90
LCKWSI	Cumulative average learning rate for cost per kilowatt for installing SPS segmented power module on mission spacecraft (%)	90

Variable	Definition	Nominal Value
LCKWMI	Cumulative average learning rate for installing non-SPS power system on mission spacecraft (%)	90
LSPSCO	Cumulative average learning rate for the annual cost of operating the demonstration satellite (%)	90

The results of the analysis are summarized in Figures 3.7 and 3.8. Figure 3.7 indicates the salvage value (present value) of the demonstration satellite when the demonstration satellite is used as a source of power for other space activities such as GEO platforms, manufacturing bases, OTV or space exploration vehicles. The salvage value is shown as a function of the annual demand for space power and the cost of earth to GEO transportation. It can be seen that the salvage value is not materially impacted by transportation costs but is directly related to demand (MW/yr). At very high demand levels the salvage value can approach $150 - 170 million and at a demand level of less than 1.5 MW/yr the salvage value is zero.

It is possible that other major (nonpower) subsystems such as slip-rings, mechanisms, transmitter subarray and switchgear and converters will be salvageable for other space missions. Figure 3.8 illustrates the salvage value of the SPS demonstration satellite when the power supply and several other major subsystems are salvageable. The salvage value is shown as a function of annual demand for power, the cost of earth-GEO transportation and the time (relative to 2000) at which the nonpower subsystems are salvaged.* Salvage value may approach $400 million when other subsystems are salvaged and the demand for

*It should be noted that certain of these curves terminate abruptly. For example, the curves for 20 year time delay terminate at a demand of 10 MW/yr indicating that the power subsystem would be completely segmented at the end of 20 years. It is assumed that other subsystems are not salvageable after the power supply is completely segmented.

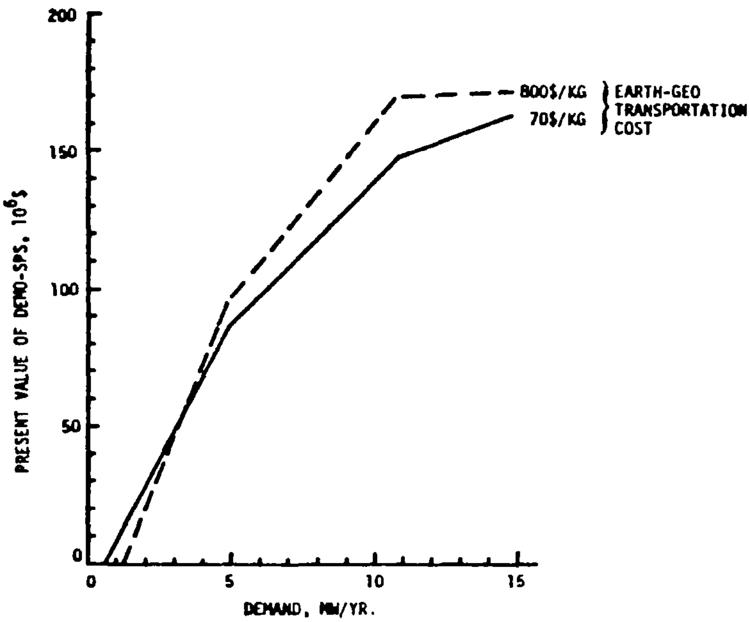


FIGURE 3.7 SALVAGE VALUE OF THE SPS DEMONSTRATION SATELLITE WHEN USED AS A SOURCE OF POWER FOR OTHER ACTIVITIES (GEO PLATFORMS, MANUFACTURING BASE, OTV OR SPACE EXPLORATION VEHICLES)

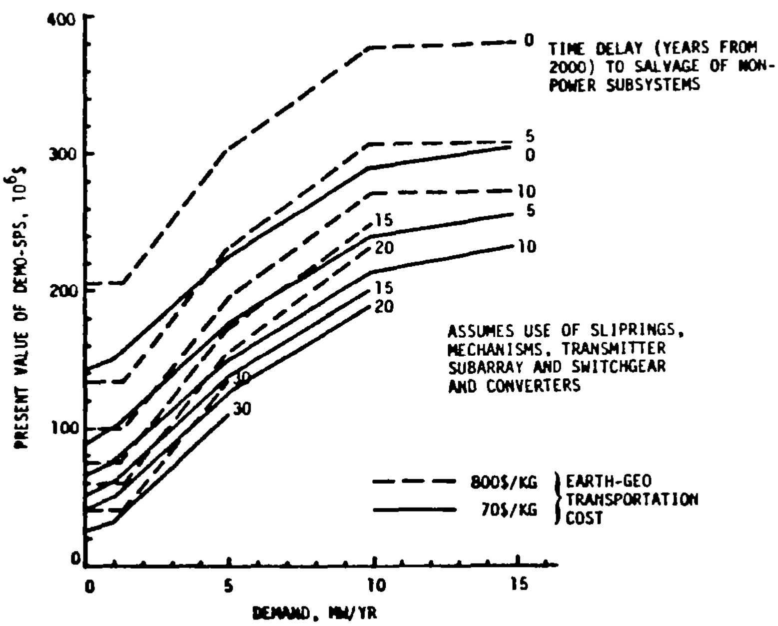


FIGURE 3.8 SALVAGE VALUE OF SPS DEMONSTRATION SATELLITE WHEN USED AS A SOURCE OF POWER AND OTHER SUBSYSTEMS FOR OTHER ACTIVITIES (GEO PLATFORMS, MANUFACTURING BASE, OTV OR SPACE EXPLORATION VEHICLES)

power is high. Salvage value may approach as much as $200 million when other subsystems are salvaged and the demand for power is low.

3.3 Power Supply for a Laser Orbit-to-Orbit Transportation System

Table 2.1 shows that whether or not the SPS program moves into an implementation phase, there is likely to be a substantial level of LEO to GEO traffic. A considerable fraction of this traffic will include man and logistics and must be transported relatively quickly, thus prohibiting the use of low thrust, electrically propelled orbit transfer vehicles. The presently planned mode for providing LEO to GEO transportation of personnel and logistics is to use a chemical rocket personnel orbit transfer vehicle (POTV). As Table 2.1 shows, the propellant requirements for the chemical POTV are considerable. These propellants must be transported from earth to LEO. The implementation of a laser space transportation system with a specific impulse of 2,000 s could reduce the propellant mass requirements by about 72 percent.*

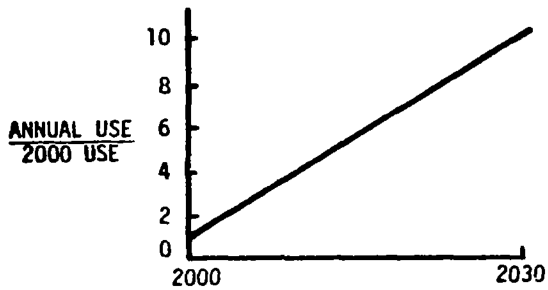
Assuming that propellant costs remain constant, and that the POTV capital cost and per flight maintenance costs are approximately equal for both the chemical and laser configurations, the principal benefit attributable to a laser space transportation system will be derived by means of cost savings in earth to LEO transportation of propellants. Furthermore, it is likely that the cost of transportation from earth to LEO will depend upon whether or not the SPS program proceeds into an implementation phase. Since transportation costs are a major fraction of total SPS capital costs, the transportation costs are likely to be low if forced by SPS technology development. They are likely to be significantly higher if SPS is not implemented thus alleviating much of the need to achieve low

*Laser Rocket System Analysis, Final Report, Lockheed Missiles and Space Company, Inc., NASA CR-159521, September 1978.

transportation costs. At the same time, the demand placed upon a laser space transportation system will be very much higher if the SPS program proceeds into an implementation phase than if it does not. Thus the fact that the SPS program is likely to result in technologies leading to reduced launch costs, and thus to reduce benefits for a laser space transportation system, is substantially offset by the increased traffic that implementation of the SPS would cause. Accordingly the benefits of a laser space transportation system are evaluated using as a baseline the LEO to GEO POTV traffic model identified in Table 2.1. Earth to LEO transportation costs are assumed to be $70 per kg. A second case is also considered using an earth to LEO transportation cost of $800 per kg representative of an advanced Space Shuttle or Shuttle derivative vehicle.

To compute a salvage value for this use it is necessary to determine year-by-year savings achieved by the laser space transportation system. To obtain a LEO to GEO traffic model year by year during the period 2000 to 2030, it is assumed that the lower bound of the transportation requirements given in Table 2.1 apply to the year 2000 and the upper bound apply to the year 2030, and that traffic growth between these years is linear as shown in Figure 3.9. The present value of savings obtained by this traffic model, at a 4 percent discount rate, is equal to 83.8 times the year 2000 savings.

The present value of the demonstration satellite in this use for the baseline case with transportation costs of $70 per kg is $1.68 billion, and at $800 per kg transportation costs to LEO is $19.27 billion. These numbers, of course, are likely to apply if the SPS program does not proceed into an implementation phase. If the SPS program proceeds into an implementation phase, the benefit from this salvage value would be very much larger. Thus it is clear that it is desirable to devleop and implement the laser space transportation system independent of the SPS program.



$$\begin{pmatrix}\text{PRESENT VALUE}\\ \text{OF SAVINGS}\end{pmatrix} = 83.8 \times \begin{pmatrix}\text{YEAR 2000}\\ \text{SAVINGS}\end{pmatrix}$$

FIGURE 3.9 LEO TO GEO TRAFFIC GROWTH

Since the laser SPS configuration is presently under consideration, it would appear an interesting option to include a laser power transmitter on the demonstration satellite such that demonstration tests for both the microwave and laser SPS configurations could be performed with the demonstration satellite and such that, upon completion of these tests, the satellite could be easily converted to use as a power supply and laser power transmitter for a laser space transportation system. These arguments are reinforced by the fact that the benefits of a laser space transportation system are of sufficient magnitude to warrant its development even if an SPS demonstration satellite is not constructed.

Since the benefits of a laser space transportation system are likely to exceed the costs of the SPS demonstration, the salvage value of the demonstration satellite in this use is equal to the present value of a power supply for a laser space transportation system, discounted from the initial date of operation of the laser space transportation system to the initial operation date of the SPS demonstration satellite. If this time period is very short, the salvage value of the demonstration satellite becomes approximately equal to the cost of the demonstration program less the cost of the microwave transmitting antenna and associated systems. These equipments, however, could be salvaged for use on the first full-scale SPS satellite, provided that the program enters an implementation phase.

3.4 Source of Space-Based Materials

A potential use of the SPS demonstration satellite is as a source of materials conveniently located in geosynchronous orbit. In this salvage use the demonstration satellite would be cut up into small sections, possibly melted down and reused as raw materials for space-based manufacturing processes. This salvage use is considered in more detail in Section 4.6 relative to full-scale SPS satellites. It is found that the value of the raw materials which make up the demonstration satellite is relatively small, roughly on the order of \$157 million. The fact that these materials are located in geosynchronous orbit, however, adds an incremental value of about \$50 million (at SPS transportation costs, 50,080\$/MT), bringing their on-orbit value up to approximately \$217 million. Unfortunately not all of the materials contained in the demonstration satellite would be salvageable. The major items in question include sapphire and GaAs. These materials alone constitute about 63 percent of the total on-orbit value. Thus if they are not salvageable, the on-orbit value of the SPS materials decreases to about \$81 million. Even so, much of this value is made up of materials which are not likely to be easily salvaged for use as raw materials in manufacturing processes.

Because of the relatively low value that the demonstration satellite has as a source of raw materials in space, this is not a very desirable salvage option. Furthermore, the return of these materials to earth for reuse would, in all likelihood, cost substantially more than their value on earth.

4. FULL-SCALE SPS SATELLITE SALVAGE ALTERNATIVES

Starting in the year 2001 and continuing through the year 2030, two full-scale SPS satellites will become operational each year in addition to a full-scale SPS satellite becomming operational in the year 2000. The full-scale satellite characteristics are summarized in Tables 1.1 and 3.2. Current plans call for these satellites remaining in operation for a period of 30 years at which time they will be taken out of service. When this occurs it is likely that major portions of the full-scale satellites will prove useful in other space activities. The full-scale SPS satellites will thus have a salvage value that is related to their value when used in other space activities. The salvage value, as measured by costs that will be foregone because of the use of full-scale SPS satellites, will derive from the use of the full-scale satellites:

1. In a continuing SPS program (termed "SPS reuse")
2. As a source of power for non-SPS space activities
3. As a power supply for a laser orbit-to-orbit transportation system
4. As a power supply for laser propelled aircraft
5. As a source of power for accomplishing asteroid capture and mining
6. As a source of space-based materials.

These potential uses and the derived salvage value of the full-scale satellites are discussed in the following paragraphs.

4.1 Salvage for SPS Reuse

The full-scale operational satellite consists of a power generation system utilizing gallium aluminum arsenide (GaAlAs) solar cells with a concentration ratio of two; an attitude control/station keeping system utilizing argon ion thrusters; a power distribution system consisting of switchgear and converters; conductors and insulation; structure; a microwave power transmission system including waveguides and klystrons for converting DC to RF energy; a structure system comprised of aluminum and graphite fiber reinforced thermal plastic and an information management system. The components, subsystems and systems are designed such that 5 GW of power are delivered at the utility interface. To accomplish this in an economic manner, certain systems are designed to achieve a life of 30 years (for example, the graphite structure), whereas other systems may achieve shorter useful lives and must be maintained and/or replaced periodically during the 30 year life of the full-scale satellite (for example, the klystrons will be replaced at ten year intervals). It is obvious that such a complex system will not completely deteriorate instantaneously at the end of 30 years but will continue to function in a degrading fashion for some time beyond its design life. Thus certain systems may be salvageable for use in other full-scale SPS operational satellites or a full-scale satellite may continue to be utilized beyond its 30 year nominal life. The actual life, including specific maintenance/replacement policies, will be determined as a result of the overall system economics, evolving design and design philosophy, and operational procedures all of which have been considered in insufficient detail at this time to specifically establish which components/subsystem/system maintenance/repair procedures and policies* will be accomplished and which components/subsystems/systems will be economically salvageable.

*It should be noted that these policies and procedures will be a function of technology and improvements in reliability. For example, if klystrons have a ten-year life, then they will be replaced twice and have little salvage value at the end of 30 years. If, however, klystrons achieve a 14-year life, the SPS satellite may have a 28-year life with one klystron replacement, or it may have a 30-year life with economically salvageable klystrons (for other SPS satellites).

The salvage value of reuse of components of a full-scale SPS satellite depends upon which specific components, subsystems and systems are available for reuse at the end of the 30-year life of the satellite. To determine specifically which "pieces" will be available requires a detailed reliability/replacement/repair analysis which has not yet been accomplished.

In the absence of such an analysis only a rough estimate of value may be accomplished by considering the value of extending the useful life of a full-scale satellite. The value of extending the useful life may be established as the difference in the present value of the cost of a series of full-scale satellites which become operational at 30-year intervals and the present value of the cost of a series of full-scale satellites which become operational at 30 + ΔT year intervals. With a real discount rate of 4 percent, a one year ($\Delta T = 1$) increase in life corresponds to a salvage value of 2-3 percent of the satellite cost. This increases to 17 percent of the satellite cost when $\Delta T = 10$ years.

4.2 Power Supply for Non-SPS Space Activities

In the same manner that the demonstration SPS satellite was viewed as a potential source of power (335 MW) for other space activities, so may the full-scale satellite be considered as a potential source of power (9.52 GW) for other space activities. The salvage value will depend upon the demand for power created by other space activities. The supply of power will be incremented by up to 19 GW per year, starting in the year 2030, and decremented by the rate of degradation of the power supplies. Since a mission model for non-SPS activities cannot be established for the mid-21st century, it is not reasonable to compare supply and demand (as was done for the demonstration SPS satellite--see Section 3.2) to establish the salvage value in terms of the demand for space power satisfied by the SPS satelites. It is likely, however, that the supply will far exceed the demand. At an annual (new capacity) demand growth of 15 MW/yr, a maximum of 450 MW will be supplied by an SPS satellite if it lasts 30 years beyond its useful life. Since this is but a small percentage of the design power level of the full-scale satellite, it may be concluded that the salvage value derived from this use will be a small percentage of the cost of one full-scale SPS satellite.

4.3 Power Supply for a Laser Orbit-to-Orbit Transportation System

As in the case of the demonstration satellite, an interesting potential salvage use of full-scale SPS satellites is as a power supply for a laser orbit-to-orbit transportation system. The economics of this use are quite similar to the demonstration satellite case; however, the full-scale satellite provides some 30 times more power and would thus be appropriate for use with much larger and higher payload vehicles. The benefits of this salvage use are strongly dependent upon geocentric traffic in the post-2030 period. They could be considerable if there are massive manned activities in space, such as large manufacturing bases, space habitats and so on. Alternatively the benefits could be quite small if the traffic remains relatively small. At this point in time the only traffic that would clearly exist beyond that noted in Table 2.1 is the traffic necessary to support the construction and maintenance of the SPS fleet. This traffic, as envisioned by Rockwell International, would involve on the order of 150 POTV flights per year or one every other day. This level of traffic can be supported by a power supply which is on the order of hundreds of megawatts rather than gigawatts. The advantage of a multi-gigawatt system would be to allow higher thrust levels, possibly higher specific impulse and possibly to provide power for ascent from earth-to-LEO. Unless the earth to LEO traffic becomes a major factor, or unless it becomes desirable to station satellites to provide a capability for continuous or unconstrained thrusting, it does not appear that this salvage use will require more than one full-scale SPS satellite. Because of the speculative nature of the benefits resulting from this salvage use, they are not quantified further.

4.4 Power Supply for Laser-Propelled Aircraft

It has been proposed by researchers at the University of Washington and Lockheed Missiles and Space Company that space-based lasers be used to power aircraft on transoceanic flights.* Conceptually, oceanic flights would be conducted by means of conventional kerosene-powered jet engines for takeoff and climb to altitude. Upon reaching altitude, at some point over the ocean, the kerosene combustors would be shut down and the aircraft provided energy from a laser beam originating in space. Energy in the laser beam would be intercepted by a laser receiver mounted on the top of the aircraft and used as thermal energy to power turbofan engines. Upon descent the laser power would be discontinued and the use of kerosene resumed.

It seems reasonable to base projections of the demand for power by oceanic aircraft on the assumption that the number of oceanic flights beyond the year 2030 is equal to the current number of oceanic flights. It is furthermore reasonable to assume that all aircraft in the oceanic regions at that point in time will be comparable to current heavy aircraft such as the DC-10 and 747. Table 4.1 summarizes the current oceanic air traffic. There are presently about 3000 aircraft-hours spent in the oceanic sectors each day.

The power requirements of a wide-bodied aircraft are typified by the 747 and DC-10. The 747 burns an average of about 24,000 pounds per hour of fuel at cruise and the DC-10 17,000 pounds per hour. These numbers correspond to power levels of 133.6 MW thermal and 94.6 MW thermal respectively. Thus the average energy

*Hertzberg, Abraham, Kenneth Sun and Wayne Jones, Laser Aircraft, Astronautics and Aeronautics, March 1979, pp. 41-49.

TABLE 4.1 CURRENT OCEANIC AIR TRAFFIC		
REGION	FLIGHTS/DAY	HRS/FLIGHT
NORTH ATLANTIC (NAT)	500	3.5
CENTRAL EAST PACIFIC (CEP)	120	3.5
NORTH PACIFIC (NOPAC)	60	6.0
CARRIBEAN	100	2.0
SOUTH ATLANTIC	75	2.0
SOUTH PACIFIC	10	3.0
WEST PACIFIC	25	3.5
TOTAL ~3000 OCEANIC FLIGHT HOURS/DAY		

consumption across the day is at the rate of about 15 GW. Assuming a peak to average power ratio of 2, it follows that the peak energy consumption rate is about 30 GW. Further assuming an "end-to-end" efficiency (power into the jet engine divided by power into the laser power transmission system) of 20 percent, 30 GW of thermal energy at the aircraft requires an input of 150 GW to the laser power transmission systems in space. Thus to service this level of traffic will require 17 or more full-scale SPS satellites, depending upon the extent to which they have degraded at the time of salvage.

The next step is to consider the economics of this salvage use. Taking the cost of jet fuel to be $1.00 per gallon (roughly the present price paid by oceanic aircraft), the cost of the thermal energy derived from this fuel is 23.5 mills/kWh. It is this number which must be compared to the cost of SPS-supplied energy. Taking the operation and maintenance cost for the SPS, in the salvage mode, to be $200 million per year (note that in this salvage mode it is not necessary to continue to refurbish the microwave power transmission system) and assuming that each satellite is used at 50 percent of capacity (corresponding to a peak to average load ratio of 2), each satellite provides roughly 40.3×10^9 kWh per year. This results in a marginal cost of energy at the satellite bus bar of 5.0 mills/kWh. Again, using the 20 percent conversion/transmission efficiency, the cost of laser-delivered energy is about 25.0 mills/kWh. Thus it appears that, at the present price of jet fuel, this salvage use does not have economic benefit.

On the other hand, however, it is likely that the cost of jet fuel will continue to inflate at a rate which is somewhat above the level of general inflation. Thus it becomes interesting to consider the potential benefit of this salvage use at inflated jet fuel costs. If all oceanic aircraft shown in Table 4.1 made use of laser energy on the oceanic segment, a total 1.3×10^{11} kWh of energy would be supplied each year to these aircraft from SPS satellites. Taking an infinite horizon benefit approach and a 4 percent discount rate, this would yield a cost saving benefit of $3.3 billion (net present value referenced to the date at which the system is fully operational) per mill/kWh cost savings obtained by the use of SPS power over jet fuel. This breaks down to a benefit of $193 million per satellite.

To continue the above example, if the price of jet fuel escalates to a level of $2 per gallon (1977 dollars), the benefit becomes $4.2 billion per satellite. Assuming that salvage to this use would occur at the end of the satellite's nominal 30-year lifetime, the salvage value thus becomes this $4.2 billion amount discounted back to the initial operation date of the satellite (30 years). Accordingly the salvage value for this use, assuming $2 per gallon jet fuel, is $1.3 billion per satellite.

It is interesting to note as an aside that this SPS satellite salvage use would make use of orbital positions over the ocean as opposed to over the continents and thus would not conflict with operational SPS satellites.

4.5 Asteroid Capture and Mining

It has been proposed by Brian O'Leary* that Amor and Apollo asteroids could be captured and placed into earth orbit to provide a source of raw materials for various space activities. Typical characteristics of Amor and Apollo asteroids are shown in Table 4.2. The estimated population of these asteroids greater than 100 m in diameter is about 150,000. They are presently being discovered at the rate of 2 to 3 per year. The Apollo and Amor asteroids appear to be typical of ordinary and carbonaceous chondrites and contain a number of free metals including nickle, iron, gold, silver, platinum and so on. They are located in orbits close to that of the earth and require only about 3 km/s velocity increment for capture.

O'Leary proposes the use of a mass driver that is capable of using asteroidial material to provide the necessary impulse for asteroid capture. This mode of capture would consume a significant fraction of the asteroid. Another mode, that examined here, proposes the use of argon propellant at 10,000 s specific impulse and the use of the SPS satellite as a power supply to effect asteroid capture. Taking a ΔV of 3 km/s each way and a 100 m diameter asteroid, 1.25 million MT, the propellant requirements are 2,300 MT outbound and 39,100 MT inbound for a total of 41,400 MT. Using this trajectory mode, a thrust duration of somewhat in excess of one year is required to impart the ΔV with the asteroid in tow.

The economics of asteroid recovery depend strongly on the materials contained in the asteroid and the demand for these materials in space. Typical values of iron and nickle contained in a 100 m diameter asteroid are as follows: A 10 percent yield of iron would provide 0.125 million MT with a gross value, at $210

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*O'Leary, Brian, Mass Driver Retrieval of Earth-Approaching Asteroids, presented at the Third Princeton/AIAA Conference on Space Manufacturing Facilities, Princeton, NJ, May 9-12, 1977.

TABLE 4.2 CHARATERISTICS OF AMOR AND APOLLO ASTEROIDS

- POPULATION BY DIAMETER

> 100m	~150,000
> 500m	~ 6,000
> 1000m	1,600 ± 800

DISCOVERY RATE 2-3/YR
NUMBER OF KNOWN APOLLO/AMOR ASTEROIDS 37 (AS OF 1977)

- COMPOSITION, % (TYPICAL OF ORDINARY AND CARBONACEOUS CHONDRITES)

SILICATES	75-90
WATER	0-20
FREE METALS	0-20
CARBON MATERIALS	0-7.5
NITROGEN	0-0.3

FREE METALS INCLUDE NICKLE, IRON AND LESSER QUANTITIES OF GOLD, PLATINUM, SILVER, ETC.

- TYPICAL ΔV REQUIRED FOR CAPTURE ~ 3KM/SEC

- ASTEROID MASS BY DIAMETER

100m	1.25×10^6 MT
500m	150×10^6 MT
1000m	1.25×10^9 MT

per MT for pig iron, of \$26 million equivalent value on earth or \$6.286 billion at geosynchronous orbit. A one percent yield of nickle would yield 12,500 MT with a gross value at \$4,590 per MT of \$57 million on the earth or \$683 million at geosynchronous orbit. Beyond iron and nickle the total value of an asteroid will depend strongly on the quantities of rare materials which it contains. Sizeable deposits of silver, gold, platinum, rhodium, osmium, etc. could drive the total value of the asteroid up substantially. But the quantities of these materials likely to be found in any particular asteroid are highly uncertain at the present time. Conceivably, the value of a 100 m diameter asteroid in geosynchronous orbit could be as high as \$10 billion. However, much lower values are likely, especially due to the fact that there would not exist an on-orbit demand for all of the metals which the asteroid contains.

The value of the materials contained in an asteroid located in geosynchronous orbit must be compared to the cost of recovering the asteroid. The cost of providing sufficient propellants (assuming the trajectory mode stated) at geosynchronous orbit, is approximately \$2.1 billion. It follows that the total cost of an asteroid recovery mission would be on the order of \$2.5 billion to \$3 billion. Consequently, if the net on-orbit value of the minerals recovered from the asteroid is on the order of \$7 billion to \$8 billion, the net salvage value of SPS used for an asteroid recovery mission would be on the order of \$1 billion to \$2 billion (after discounting).

4.6 Source of Space-Based Materials

If no salvage uses can be found for a particular SPS satellite, its subsystems or components, that satellite may nonetheless be salvaged as raw materials for use in space-based manufacturing processes. Table 4.3 summarizes the materials contained in a full-scale SPS satellite. While the total value of these materials is approximately \$4.5 billion on the earth, most of this value is contained in the sapphire and GaAs which make up the solar array blanket. The major metals contained in the satellite have a value on earth of only \$205 million. In geosynchronous orbit, accounting for cost of transportation, these materials would have a value of approximately \$1 billion. Thus, depending upon the demand for their use in space, these materials could have reasonably significant salvage value. However it is unlikely that any but very special materials such as silver could be economically transported back to earth for terrestrial reuse.

Two satellite materials, sapphire and GaAs, which contain over 60 percent of the total on-orbit value of SPS satellite materials, present an interesting salvage possibility. Thus if there is a demand for them and if they can be economically processed for reuse in space, they would be of considerable salvage value. If such

TABLE 4.3 VALUE OF SPS SATELLITE MATERIALS--GaAs, CR=2

	MATERIAL	MASS METRIC TONS (MT)	UNIT COST $/MT	VALUE $ MILLIONS	VALUE AT GEO* $ MILLIONS
	GFRTP	7,680	57,200	439	824
●	STAINLESS STEEL	5,305	1,370	7	273
●	COPPER	4,834	1,570	8	250
▶	SAPPHIRE	3,376	800,000	2,701	2,870
●	ALUMINUM	4,122	1,170	5	211
▶	GaAs (DEP)	1,354	700,000	948	1,016
	TEFLON	1,152	6,820	8	66
	KAPTON	2,719	66,000	179	315
●	SILVER	928	196,000	182	228
	MERCURY	89	4,500	0	4
●	TUNGSTEN	646	32,400	3	35
	MISC.	1,947	-	-	98**
		34,152		4,480	6,190

* EARTH-TO-GEO TRANSPORTATION COST = 50,080 $/MT
** TRANSPORTATION COST ONLY

● SALVAGE OF MAJOR METALS--$205M ON EARTH, $997M AT GEO--COST TO RECOVER AND RETURN MAJOR METALS TO EARTH ~ $1B ($793M FOR TRANSPORTATION ALONE)

▶ SAPPHIRE AND GaAs PRESENT AN INTERESTING SALVAGE POSSIBILITY

reuse is economically viable it would probably be for the purpose of making new solar arrays both for new SPS satellites and for other space power requirements.

4.7 Miscellaneous Salvage Uses

It is likely that there will be other potential applications of decommissioned full-scale SPS satellites. In the mid-21st century, space industrialization will come into its own with the need for large space stations, high power and raw materials. It is also likely that there will be large laboratory facilities (for example, a high energy physics laboratory) in geosynchronous orbit. It is hard to establish a value for salvage use of SPS satellites for these activities because they do not lead to economic activities that can be easily evaluated. For example, salvage of an SPS satellite may make the establishment of a high energy physics laboratory in space viable, but the salvage value of the SPS satellite in this use would not equal the cost savings afforded since the availability of the SPS satellite would enable this mission, not merely benefit it. Accordingly estimates of salvage value for these uses would be highly speculative and are not included here.

4.8 Continued Use

An obvious potential use of a 30 year old SPS satellite is to simply continue to use it as an SPS satellite. Since the satellite would be fully depreciated at this time, its continued use would provide, in essence, a salvage value. The only thing which would prevent a satellite from obtaining salvage value from continued use would be if there is a wearout failure mode for the satellite which occurs shortly after it has been in use for 30 years. If, on the other hand, the satellite degrades exponentially with time at a rate δ then the net salvage value (net of disposal costs at the end of its economic life) is approximately given by the following equation:

$$V_S = \frac{E_0 r}{\rho+\delta}\left[(1+\rho+\delta)^{1-t} - (1+\rho+\delta)^{1-T}\right] - \frac{C_{OM}}{\rho}\left[(1+\rho)^{1-t} - (1+\rho)^{1-T}\right] - C_D\,(1+\rho)^{-T}$$

where E_0 is the beginning-of-life energy produced by the satellite per year, r is the revenue generated in mills/kWh, t is system age when salvaged in years, C_{OM} is the annual operation and maintenance cost, C_D, is the disposal cost and ρ is the discount rate. T is the satellite age at the end of its economic life (when revenues equal marginal operating costs):

$$T = \frac{\ln(E_0 r/C_{OM})}{\ln(1+\delta)}$$

For typical values of these parameters, Figure 4.1 shows the continued-use SPS salvage value. Clearly, for degradation rates between 0 and 2 percent, this salvage use produces a considerable salvage value at t = 30 years. It is also clear, however,

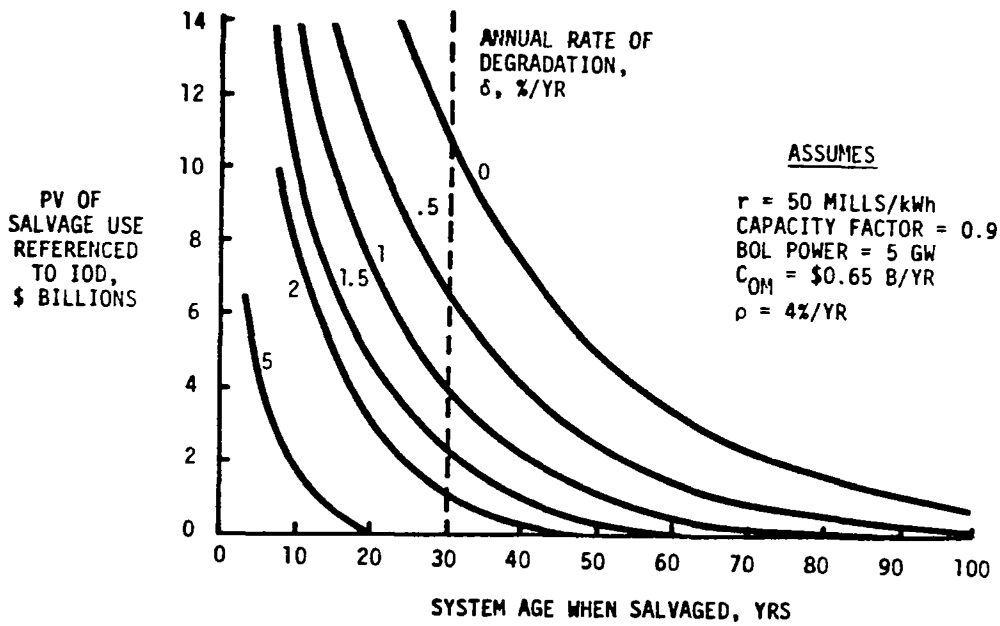
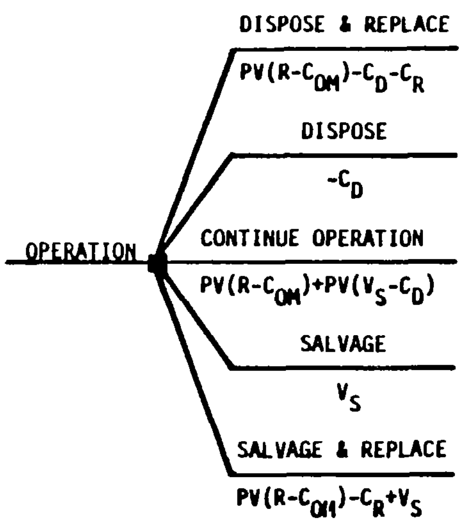


FIGURE 4.1 CONTINUED USE SPS SALVAGE VALUE

that for degradation rates approaching 5 percent, the SPS system will not have an economic lifetime of 30 years. Since Rockwell International projects the degradation rate to be on the order of 0.5 percent per year, the present value of continued use of the SPS, referenced to the initial operation date, will be in excess of $6 billion (conditioned on the assumption that there are no sudden wearout failure modes).

The notion of continued use can be expanded to verify estimates of salvage value obtained by direct estimation techniques, such as those employed in the sections above. This can be done by examining the decision to decommission an SPS satellite. At any point in time there are essentially five options: to continue operation of the satellite; to discontinue operation and dispose of the satellite; to discontinue operation, dispose of the satellite and replace it with a new satellite; to discontinue operation and salvage the satellite; or to discontinue operation, salvage the satellite and replace it with a new satellite. This decision and the values associated with each alternative are shown in Figure 4.2. R refers to the annual revenues generated by continued use of the satellite, C_{OM} is the annual operation and maintenance cost as above, C_D is the cost of disposal, C_R is the cost of replacing the satellite, V_S is the salvage value of the satellite and PV(•) refers to present value. It is desirable to take the choice which has the highest present value at the date of the decision. The resulting decision rules are shown on the right side of Figure 4.2. Thus it becomes apparent that if a decision is made to salvage the SPS satellite, its salvage value should be greater than its continued use value. This notion, once again, argues for relatively substantial salvage values associated with annual degradation rates in the range of 0 to 1 percent per year, so long as there exist no wearout failure modes that will occur shortly after 30 years of system use.



- DISPOSE IF

  $R < C_{OM}, \; -C_D > V_S$

- SALVAGE IF

  $R < C_{OM} + \frac{\rho}{1+\rho} V_S, \; V_S > 0$

  OR IF

  $R < C_{OM}, \; V_S > -C_D$

- REPLACE IF

  $PV(R - C_{OM}) - C_R > 0$

FIGURE 4.2 THE DECISION TO DECOMMISSION AN SPS SATELLITE

5. SPS SALVAGE VALUE

5.1 SPS Demonstration Satellite Salvage Value

Section 3 developed the salvage value for the demonstration satellite that will result from its use as part of a full-scale operational SPS satellite, as a source of power for non-SPS space activities, as a power supply for a laser orbit-to-orbit transportation system and as a source of space-based materials. These applications of the demonstration satellite are summarized in Figure 5.1 which indicates their relative timing and salvage value.

The laser orbit-to-orbit transportation system utilizes the demonstration satellite as a power source for a laser space transportation system. The microwave power transmission system is not needed in this salvage use and is thus available for use by the first full-scale SPS satellite. The salvage value derives primarily from cost savings in the cost of transporting chemical propellants from earth to LEO for use in LEO to GEO transportation of personnel and logistics. The considerably higher specific impulse of a laser rocket permits about a 70 percent reduction in the mass of propellant that must be transported to LEO compared to chemical rockets. The value of the demonstration satellite when used in this manner is in excess of $1.7 billion.

If the demonstration program is successful, that is if it is found desirable to continue the SPS program beyond the demonstration phase, the demonstration satellite can be used as a component of the first full-scale SPS satellite. In this application the demonstration satellite has a salvage value of slightly less than $1.7 billion.

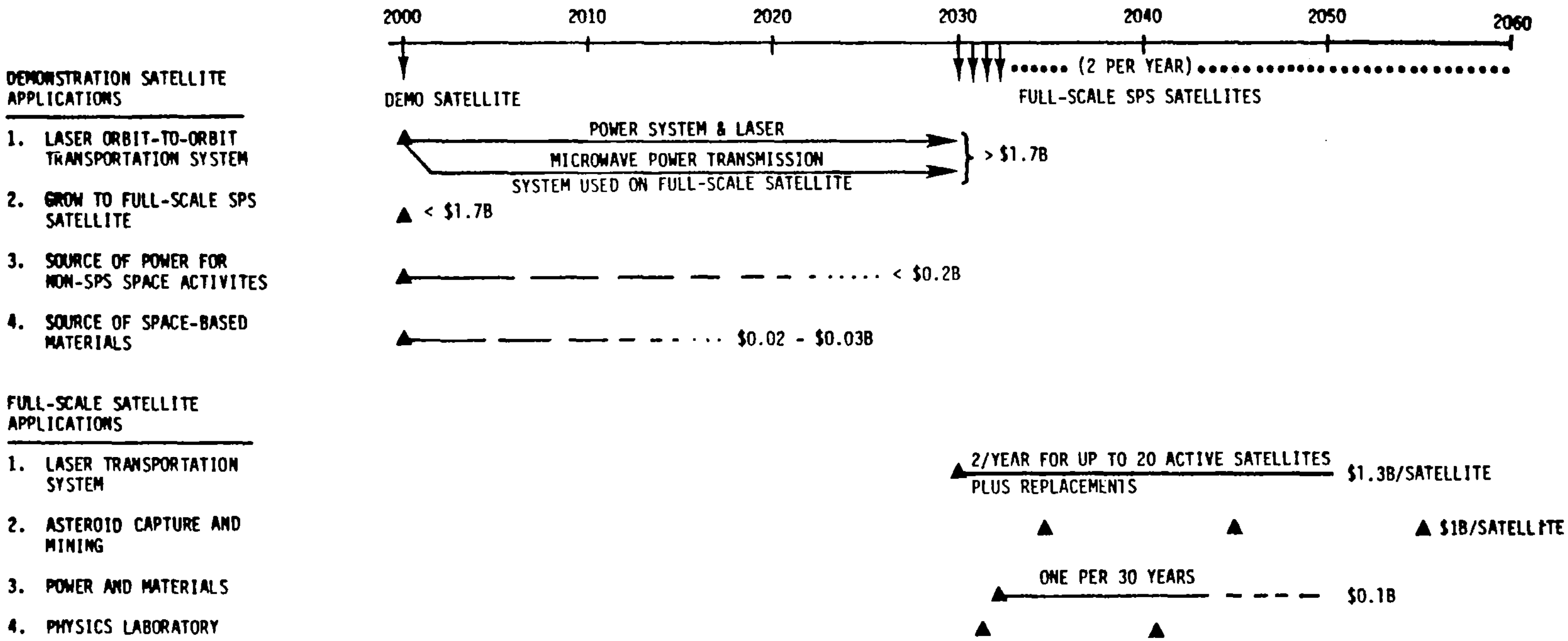


FIGURE 5.1 SUMMARY OF DEMONSTRATION AND FULL-SCALE SATELLITE SALVAGE APPLICATIONS

If the demonstration program is not successful, and if it is not desirable to use the demonstration satellite as a power source for a laser space transportation system, it will be available as a source of power and subsystems for non-SPS space activities or as a source of space-based raw materials. Both of these applications of the demonstration satellite require the segmenting of the satellite and the utilization of the segments over extended periods of time depending upon the non-SPS space activities' demands for power, subsystems and raw materials. When the demonstration satellite is used as a source of power and subsystems for other space activities, its salvage value is on the order of \$0.2 billion. This value derives from costs (both hardware and transportation) that would be foregone by the other space activities because of the use of the demonstration satellite subsystems. When the demonstration satellite is used as a source of raw materials, its salvage value is relatively small, being on the order of \$0.1 billion. A large part of this value is the result of transportation costs that may be foregone since the materials are already in geosynchronous orbit. Clearly these salvage uses are less preferred than the former uses.

5.2 Full-Scale SPS Satellite Salvage Value

Section 4 developed the salvage value for a full-scale SPS satellite relative to its date of initial operation. The salvage value was developed for continued use of the satellites in the SPS program, as a power supply for non-SPS space activities, as a power supply for laser transportation (orbit-to-orbit and aircraft) systems, as a facility for asteroid capture and mining and as a source of space-based materials. These applications of the full-scale SPS satellites are summarized in Figure 5.1. The salvage value of the SPS satellites for these uses occur 50 to 80 years in the future. The uses which appear to be most attractive include laser transportation systems, both space-to-space and for aircraft on oceanic routes, as a power supply to recover Amor and Apollo asteroids and, although not quantitatively evaluated, as a power supply for a high-energy, high-vacuum physics laboratory in space. It is conceivable that these uses, plus other uses such as power for space manufacturing, could provide sufficient demand for salvage use of an entire fleet of 60 5 GW SPS satellites.

The relative timing of the salvage use of full-scale SPS satellites is indicated in Figure 5.1. The bulk of the salvageable full-scale satellites (20) will be used for the laser transportation system with three additional satellites used for asteroid capture and mining, one additional satellite used for providing power and materials for other space activities and two additional satellites used for high energy physics laboratories. The remaining 34 satellites are disposed of at a disposal cost of $100 million ($30 million present value at the initial operation date). The salvage value is taken at $1.3 billion for each full-scale satellite used in the laser transportation system with this figure based upon infinite horizon discounting. It should be noted, however, that if the satellite must be replaced periodically, the replacement satellite does not have to be disposed of but the replaced satellite must be disposed of instead. Thus replacement considerations do not alter the computed average satellite salvage value. The salvage value associated with asteroid capture and mining is taken to be $1.0 billion per satellite. The maximum possible salvage value associated with the use of the satellite as a source of space-based materials is on the order of $0.3 billion for the major metals (not including nonsalvageable items such as sapphire and GaAs). Assuming that one-third of the available major metals are actually salvaged, the salvage value is on the order of $0.1 billion.

All of the above numbers are per satellite salvage values and disposal costs, and are referenced to the time of initial operation of each satellite. It is desired next to combine all salvage uses and disposals to estimate the average salvage value per satellite. This is accomplished by disounting the salvage value and disposal "cash flow" stream back to the date of initial operation of the first full-scale satellite yielding a present value of the net program salvage values. (A component of this cash flow stream is the present value of the disposal cost, of \$0.03 billion, associated with each satellite that is not salvaged.) There are 26 full-scale satellites that are salvaged over a 30-year period in the indicated scenario and 34 full-scale satellites that have to be disposed of. The present value of the "salvage value cash flow stream" (at a 4% discount rate) is approximately \$22 billion. An equivalent annuity may be established which over the 30-year time period (60 satellites) has the same present value as the salvage value cash flow stream. This annuity, approximately \$0.64 billion per satellite or about 6 percent of the satellite capital cost, corresponds to the average net salvage value per satellite. It should be noted that this value could increase substantially if salvage uses are found for the 34 satellites that are disposed of in the scenario presented.

5.3 Programmatic Implications

There are two significant programmatic implications of positive SPS demonstration satellite and full-scale satellite salvage values. The first deals with the salvage value of the demonstration satellite. Although the salvage value of the demonstration satellite is very much smaller than the salvage value of the full-scale SPS satellites, it is probably a more important consideration from a programmatic standpoint. The second programmatic implication deals with the effects of salvage value upon the cost of SPS-generated electricity and hence on the perceived benefits that development of the SPS concept would provide.

The implications of the demonstration satellite salvage value are shown in Figure 5.2. In advance of performing the demonstration research phase, it cannot be known that this effort will be successful; that is, that upon completion of the

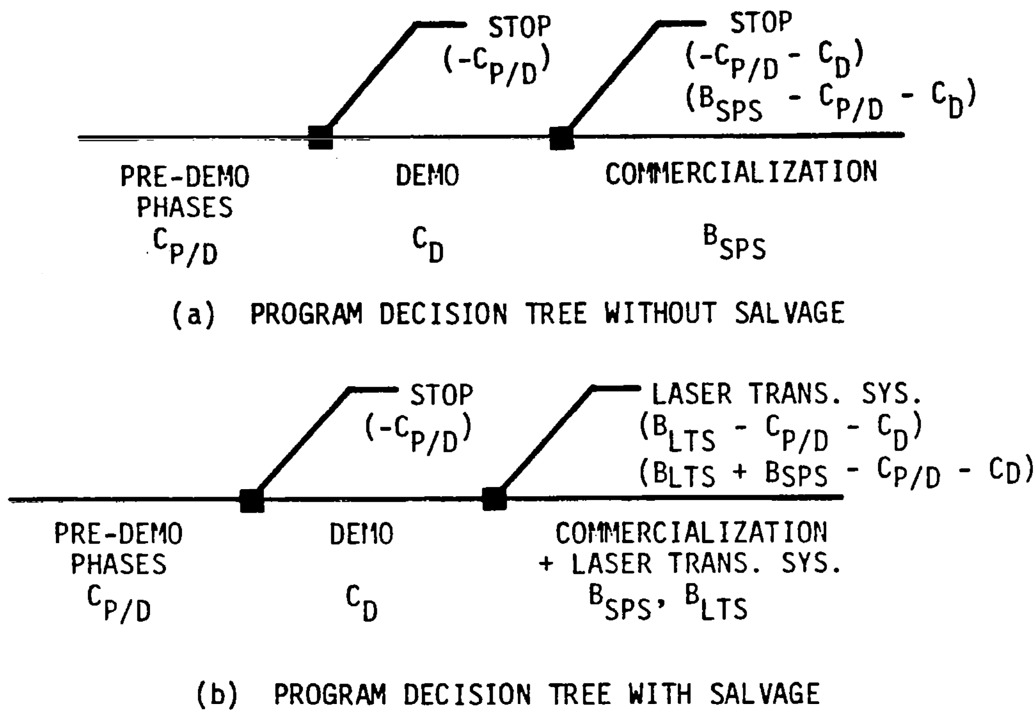


FIGURE 5.2 PROGRAMMATIC IMPLICATION OF DEMONSTRATION SATELLITE SALVAGE VALUE

demonstration phase it will be decided to commercialize or implement the SPS technology. Thus two options may be considered to exist upon completion of the demonstration phase. These are termination of the SPS program and commercialization or continuation of the SPS program into an implementation phase. The consequences of a termination or stop decision would be that the costs sunk in the SPS program, $C_{P/D}$ and C_D in Figure 5.2, would be lost and the beneifts of commerialization, B_{SPS}, would not be realized. It is only through the commercialization phase that the SPS development costs would in any way be recovered (Figure 5.2(a)).

On the other hand if the demonstration satellite can be salvaged say, for example, for use as a power supply for a laser space transportation system, this salvage use provides a benefit, B_{LTS} in Figure 5.2(b), that directly offsets the SPS development costs, even in the event that the SPS program does not continue into an implementation phase. This effect becomes very dramatic when one reaches the decision to proceed with the demonstration phase. At this point the net cost of the demonstration is $C_D - B_{LTS}$ rather than C_D. The difference which the term B_{LTS} makes in the decision to pursue the SPS concept through the demonstration phase is profound indeed, especially as the magnitude of B_{LTS} is on the order of 80 percent of the magnitude of C_D.

Finally, the salvage value of full-scale SPS satellites can have a strong impact on the perceived benefits of development of the SPS concept. For example, assume that without salvage the levelized cost of power from an SPS is 50 mills/kWh. Assume also that the cost of power from alternative energy sources is 55 mills/kWh. One would then perceive that a cost savings benefit to society would obtain from the use of SPS-generated energy versus alternative sources with a magnitude of 5 mills/kWh.

If, however, the SPS has a salvage value equal to 10 percent of its capital cost, this salvage value will reduce the levelized generation costs for the SPS system by about 5 percent, resulting in a net 50 percent increase in the perceived benefit of the SPS. Although it may not be prudent from the point of view of a regulated utility to reduce its energy rates in accordance with the expected salvage value for SPS, incorporation of this value in the federal government's planning process is entirely appropriate.

6. SPS DISPOSAL

The principal articles considered for disposal in this study include the SPS demonstration satellite and full-scale satellites. These satellites may be disposed of either intact or in varying states of disassembly depending upon the extent to which they are salvaged prior to disposal. The demonstration satellite or sections of it, if any, will require disposal somewhere in the time period 2000 to 2030. Unsalvaged full-scale SPS satellites will require disposal beyond the year 2030.

It is important to consider disposal of SPS satellites upon completion of their useful life and salvage for further use due to the fact that the geosynchronous orbit is a limited natural resource and must be conserved for important uses. It is prudent in consideration of SPS life cycle costs to acknowledge costs associated with satellite disposal and consider them as a part of the capital investment in the SPS system. Although SPS differs from many electric energy systems in that there appear to be a number of relatively valuable salvage uses, once it has reached the end of its useful life there is little doubt that at least some of the SPS hardware will require disposal. Placing a value on SPS disposal costs is in essence a matter of placing a lower bound on net salvage value. The data presented in this section should be interpreted accordingly.

6.1 Disposal Alternatives

Unlike terrestrial power plants where disposal infers physical disassembly of the plant, structures and equipment and recovery of land for alternative uses, disposal of SPS satellites may infer simple removal of those satellites from geosynchronous orbit to another orbit or location in space where they will not interfere with other space activities. A number of interesting possibilities exist.

First, however, it is worth noting that not all disposal options are clearly distinguishable from salvage. For example, it may be desirable to collect SPS satellites that have reached the end of their useful life at a repository location in geosynchronous orbit. This location might be co-located with a manufacturing base that, over an extended period of time, would make use of the SPS material. Disposal of SPS satellites to a common geosynchronous location is a trivial matter requiring only a few m/s of velocity increment and which could be accomplished over a period of one to a few months at very little cost. This disposal option has been discussed in part in Section 4.6 and is not considered further here. The major disposal options considered here include those shown in Table 1.3; L_4 or L_5, supra-GEO, moon, heliocentric orbit and earth reentry.

The L_4 or L_5 disposal option is illustrated in Figure 6.1. There exists in a two body gravitational system five points at which gravitational forces and accelerations cancel each other such that an object placed at these positions remains stationary with respect to both of the major bodies. The five points are referred to as libration or Lagrangian points. Points L_1, L_2 and L_3 are unstable in the sense that if the body placed there is subjected to a small perturbation from the precise position of the Lagrangian point, it will drift away or assume an orbit which diverges from the Lagrangian point. Points L_4 and L_5, sometimes referred to as the equilatoral Lagrangian points, however, are stable. That is to say if an object is placed near these points, it will tend to orbit stably around the Lagrangian point, at least for extremely long periods of time. Thus if SPS satellites were disposed of in these locations, one could expect that they would remain there unattended, essentially forever. The only qualification to this mode of disposal would be that it might become desirable to lash together all of the satellites located at each of these points in order to keep them from bumping violently into each other. Since

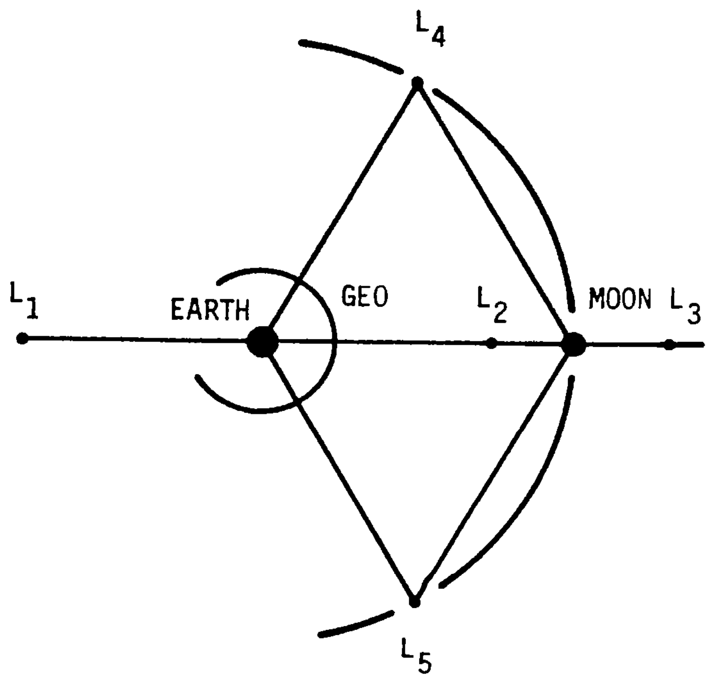


FIGURE 6.1 LAGRANGIAN POINTS IN THE EARTH-MOON SYSTEM

L_4 and L_5 are located in the orbit of the moon, the energy required to reach these points is essentially equal to the energy required to reach the moon.

In the supra-GEO disposal option it is envisioned that the SPS satellite would be removed from geosynchronous orbit to an orbit which is somewhat higher than geosynchronous and from which decay or perturbation resulting in interference with the geosynchronous would require a vast period of time (say greater than 10,000 years). Orbits lower than GEO were not considered as a viable disposal option because of the fact that they would result in disposed SPS satellites shadowing operational SPS satellites. Any of a variety of supra-GEO orbits, however, are open for consideration. The orbit proposed here is two times GEO. This is an orbit which is substantially removed from GEO but yet one for which the energy requirements to reach it are modest.

The third option is considered as a means for removing the SPS satellite permanently from space. In this option the satellite is impacted on the lunar surface. Naturally any such impact would have to be carefully coordinated with lunar activities at the time of impact. Although it might be possible to recover some of the SPS materials after impact, this is not accepted as a realistic benefit of this mode of disposal at this time.

The fourth disposal option considered is removal of SPS satellites to a heliocentric orbit such as 0.8 AU. This option removes the SPS satellites sufficiently far from the earth that they are effectively gone forever. The energy requirement for this mode of disposal is, of course, dependent upon the heliocentric orbit into which the satellite is placed.

The final disposal option considered is earth reentry. This disposal option arouses some amount of interest because of the possibility of recovering some SPS materials for reuse on earth if the reentry can be sufficiently wellcontrolled. Unfortunately, however, this mode of disposal not only requires the highest energy increment and is, thus, the most expensive disposal option, it probably is not acceptable due to environmental and risk considerations, especially in light of the absurd extent to which the Skylab reentry risks were escalated in the media.

Within each of the above disposal options there exists several suboptions. The principal suboptions include the trajectory mode and thrust level for the disposal mission. It is envisioned that the disposal would occur using argon thrusters at a 10,000 s specific impulse. Disposal could be by means of the last flight of a COTV. The COTV could use its own power supply or it could be augmented by power provided from the SPS satellite. In the event that it uses its own power, the SPS satellite could be disposed of in varying states of salvage incuding one in which essentially all of the solar arrays have been removed. In the event that the satellites are disposed intact, power from the SPS satellite can be used and propellant tankage, controls and thrusters from the COTV could be placed on the SPS satellite to provide the necessary thrust and control. In this mode it is likely that one would choose to use equipment that was essentially at the end of its useful life and was salvaged from a COTV.

The Rockwell International cargo orbit transfer vehicle is referred to in their study* as an electric orbit transfer vehicle (EOTV), Figure 6.2. It has a dry mass of 1,000 MT and carries 670 MT of propellant. This amount of propellant is sufficient to impart a velocity increment of 1.9 km/s to the SPS satellite. Thus, for the higher energy disposal option, additional propellant tankage will be required. The Rockwell International EOTV configuration includes 144 thrusters of which 20 percent are spares. The present specification on these thrusters is a lifetime of 8,000 hours. This is not sufficient to complete a disposal mission that requires more than 333 days of thrusting time. Thus, for some dispsal options, longer lifetime thrusters or additional spares may be necessary. An alternative to the use of the EOTV thrusters is the use of the attitude control and stationkeeping thrusters of the SPS satellite. Sixteen thrusters are located on each corner of the SPS satellite making a total of 64 thrusters. These thrusters provide a total thrust of 832 newtons at a specific impulse of 13,000 s. Combined, these thrusters can impart an acceleration of about 23×10^{-6} m/s^2 to the SPS satellite. At this acceleration it requires 503 days to obtain a velocity increment of 1 km/s. At this rate it would require several years to dispose of an SPS satellite by means of the disposal options presented. However, with augmentation from the EOTV thrusters, this period of time is dramatically reduced.

*Satellite Power Systems (SPS) Concept Definition Study, Final Report, Vol. I, Executive Summary, Rockwell International Report No. SSD-79-0010-1, March 1979.

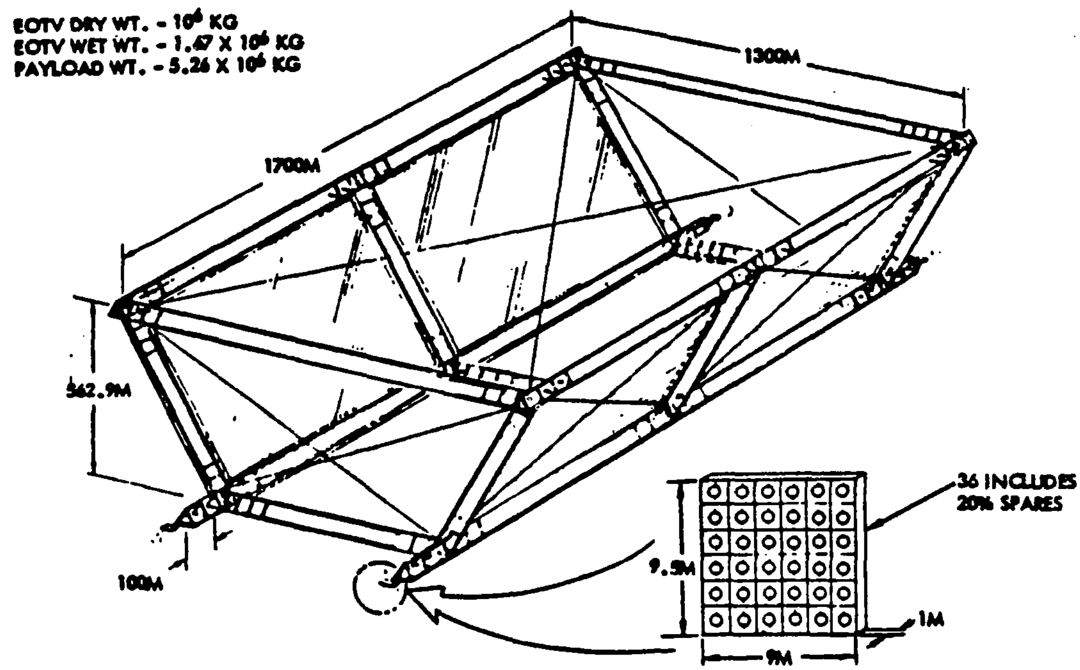
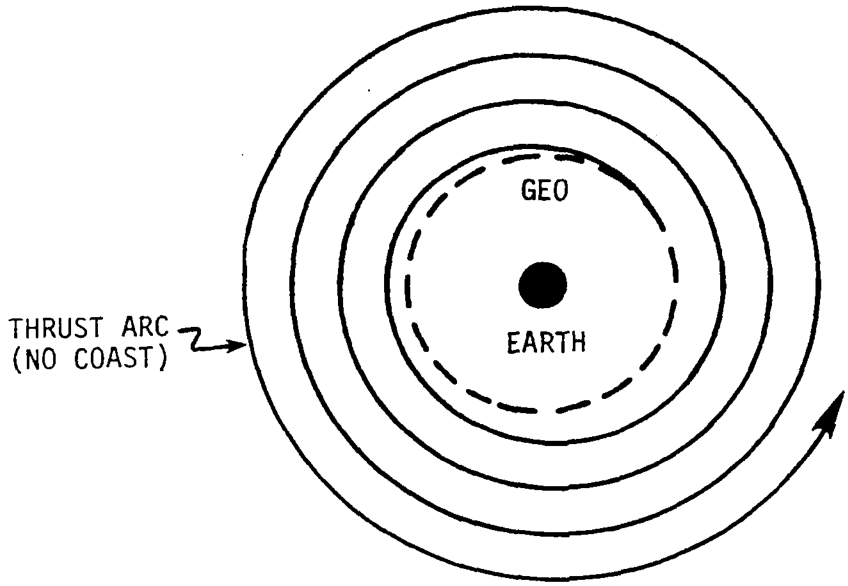
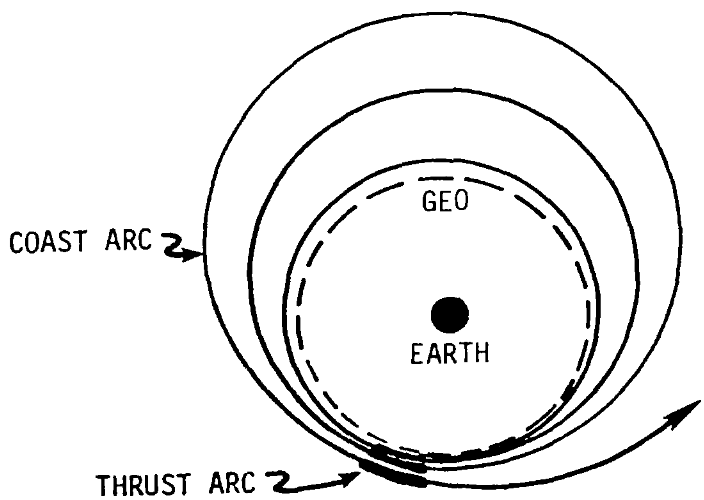


FIGURE 6.2 EOTV CONFIGURATION

The use of very low thrusts also raises an issue as to specifically which trajectory mode should be used. Due to the very low thrust levels and long thrusting periods required of electrically propelled vehicles, the trajectory mode selected for their use generally entails continuous thrusting in geosynchronous space, resulting in spiral trajectories as those shown in Figure 6.3(a). The velocity increment for such a trajectory is approximately twice that of the optimal, high thrust or impulsive trajectory mode. By lengthening the mission timing, however, as shown in Figure 6.3(b), thrusting only in the vicinity of periapse and apoapse of the transfer orbit, it is possible to devise trajectory modes where the velocity increments required of a low thrust vehicle approach that of the optimal high thrust transfer. Thus one cannot choose a specific velocity increment for the disposal options presented here as these require further analysis and cost optimiza-



(a) CONTINUOUS THRUST SPIRAL TRAJECTORY MODE



(b) INTERMITTENT THRUST, QUASI IMPULSIVE TRAJECTORY MODE

FIGURE 6.3 ALTERNATIVE TRAJECTORY MODES

tion. The numbers chosen were conservatively selected at two times the velocity increment required for an impulsive transfer. Thus the velocity increment or ΔV numbers shown in Table 1.3, and subsequently the propellant requirements to provide those velocity increments, are probably somewhat higher than the amounts which will be ultimately decided upon. However, this overestimate in cost will be somewhat offset by the increase in mission operations cost due to the lengthened disposal mission time resulting from the cost optimization of the trajectory mode.

6.2 Disposal Costs

There are four principal elements of dispoal costs:

1. The cost of modifications to the SPS satellite to ready it for the disposal mission. These costs include added thrusters, propellant tankage, controls and so on. Depending upon the state of salvage of the satellite, some structural modifications for adaptation of an EOTV may be necessary.

2. The cost of propellants.

3. The cost of transporting propellants to the SPS satellite in geosynchronous orbit.

4. The cost of mission operations.

Assuming argon to be the propellant and a specific impulse of 10,000 s, 342 MT of propellant is required for each km/s of velocity increment imparted to a full-scale SPS satellite. The cost of argon is presently $240 per MT thus resulting in a cost of propellant of $81,960 per km/s of velocity increment imparted to the satellite.

Taking the cost of cargo transportation from earth to GEO to be $50,080 per MT, the cost of transporting propellants to the SPS satellite in GEO is $17,102,000 per km/s of velocity increment imparted to the satellite.

The cost of modifications to the SPS satellite in preparation for the disposal mission is obviously somewhat variable. A reasonable estimate for this cost can be obtained from the assumption that the entire EOTV vehicle is used on its last or 20th flight to carry out disposal missions. Thus taking one twentieth of the cost of an EOTV, \$690 million, an estimate of \$34.5 million is obtained for satellite modifications.

The final cost, that of mission operations, is a time dependent cost. It is assumed here that the mission operations costs for the disposal mission are equal to mission operations costs for EOTV flights. This amount is \$4.8 million per year. Using the EOTV thruster packs, it requires about 62 days to impart a velocity increment of 1 km/s to the SPS satellite. Thus the mission operations costs, assuming continuous thrust operation, amount to about \$818,000 per kilometer per second of velocity increment.

Combining the above costs leads to a velocity-dependent cost estimating relationship for SPS disposal cost as follows:

$$\text{Disposal cost} = \$(34.5 + 18.0\ \Delta V)\ \text{million}.$$

This cost is given in 1977 dollars, comparable to the SPS cost estimates. It is the cost presented in Table 1.3. In order to compare these costs to the satellite capital investment cost, they must be discounted back to the initial operation date of the satellite. This discount factor is $(1+\rho)^{-L}$ where is the discount rate and L is the satellite lifetime. Taking $\rho = 0.04$ and L = 30 years, $(1+\rho)^{-L} = 0.308$. Thus the present value of disposal costs referenced to the initial operation date of the satellite are on the order of \$30 million or 0.3 percent of the capital cost of the satellite.

APPENDIX A

Supporting Data for Value of the Demonstration Satellite Used as a Power Source for Other Activities

A.1 Cost of Segmenting the Demonstration Satellite-CKWS

The SPS demonstration satellite is constructed at LEO and then flown up to GEO. The construction requires 120 men in orbit for 15 months with 5-6 months required for blanket construction. Crews are changed every three months. It is thus necessary to transport 600 men to accomplish the construction.

It is assumed that the major cost associated with segmenting the demonstration satellite is the transportation cost (Earth-GEO-Earth) for men and supplies. It is further assumed that the segmenting can be accomplished at GEO without transporting the construction facilities from LEO to GEO. The efficiency of segmentation will depend upon the size of the components/subsystems/systems that are salvaged. Since the solar blanket will be constructed in about six months it is assumed that a total of 240 man-trips will be required to segment the power supply. Therefore:

$$\text{CKWS} \doteq \frac{\text{Transportation cost for 240 men plus supplies}}{\text{335,000 KW}}$$

Trans. Cost = Cost from Earth to LEO + Cost from LEO to GEO

- Unit Cost of POTV = 63 X 10^6\$
- Design Life of POTV = 300 flights
- Cost per POTV Flight = .09 X 10^6\$
- No. of People/POTV Flight = 48
- Number of HLLV Flights/POTV Flight = 3
- Unit Cost of HLLV = 611 X 10^6\$
- Design Life of HLLV = 300 flights

- Cost per HLLV Flight = 1.25×10^6\$
- HLLV Load Factor = .9
- HLLV Payload (to LEO) = 91000 kg

$\left.\begin{matrix} \\ \\ \end{matrix}\right\}$ 81900 kg

$$\text{CKWS} \doteq \left\{\left[\frac{\text{Unit Cost of POTV}}{\text{Design Life of POTV}} + \text{POTV Cost/flight}\right] \times \frac{240 \text{ men}}{48 \text{ men/flt}}\right.$$

$$+ \left[\frac{\text{Unit Cost of HLLV}}{\text{Design Life of HLLV}} + \text{HLLV Cost/flight}\right] \times \frac{240 \text{ men}}{48 \text{ men/flt}} \times$$

$$\left.\text{no. of HLVV Flights/POTV Flight}\right\} / \text{Demo-SPS Power}$$

$$\doteq \left\{\left[\frac{63 \times 10^6}{300} + .09 \times 10^6\right] \times \frac{240}{48} + \left[\frac{611 \times 10^6}{300} + 1.25 \times 10^6\right] \times \frac{240 \times 3}{48}\right\} / 335{,}000$$

$$\text{CKWS} \doteq 152\$/\text{kW}$$

A.2 Cost of Installing Segmented Demonstration Satellite Power-CKWSI

It is assumed that since the installation will probably be accomplished at the time of segmentation that this cost may be somewhat less than the segmentation cost. It is assumed (more or less arbitrarily) that the installation cost is on the order of 20 percent of the segmentation cost.

CKWSI $\doteq$ 30\$/kW

A.3 Initial Mass of Demonstration Satellite (Just Prior to Start of Salvage)-INMASS

Extrapolated from the data presented in the Rockwell Report SPS Concept Def. Study, Vol. VII, March 1979, the initial mass of the demonstration satellite is obtained as indicated in Table 3.2 and summarized below:

Solar Array	$.464 \times 10^6$ kg
Antenna	$.683 \times 10^6$ kg
Array/Antenna Interfaces	$.147 \times 10^6$ kg
Subtotal	1.294×10^6 kg
Contingency (25%)	0.324×10^6 kg
Total	1.618×10^6 kg

INMASS = 1.618×10^6 kg.

A.4 Achievable Power Density of Power Systems-KGKW

From Table 3.1-2 Rockwell Report, SPS Concept Def. Study, Vol. VII, March 1979.

Solar Cell and blanket & reflector mass = 7.855×10^6kg

Array output to Distribution Bus (EOL) = 9520 MW.

$$KGKW = \frac{7.855 \times 10^6 \text{kg}}{9.520 \times 10^6 \text{kW}} = .825 \text{ kg/kW}$$

A.5 Cost Per kW of Power (not including delivery costs)-CKW

From Table B-5 Rockwell Report, SPS Concept Def. Study, Vol. VII, March 1979.

1.1.9.1.1	Primary Structure	1.5×10^6\$
1.1.9.1.2	Secondary Structure $(69.5 \times \frac{335}{9520})$	2.4×10^6\$
1.1.9.1.3	Concentrator	2.8×10^6\$
1.1.9.1.4	Solar Blanket	60.3×10^6\$
1.1.9.1.5	Switchgear & Converters	1.7×10^6\$
1.1.9.1.6	Conductors & Insulation	1.4×10^6\$
1.1.9.1.7	ACS Hardware $(72.5 \times \frac{335}{9520})$	2.6×10^6\$
1.1.9.1.8	Sliprings $(27.6 \times \frac{335}{9520})$	1.0×10^6\$
1.1.9.1.9	Primary Structure-Interface	.
1.1.9.1.10	Secondary Structure-Interface	.
.		.
.		.
1.1.9.1.23		$.5 \times 10^6$\$
		558.6×10^6\$

$$CKW \doteq \frac{558.6 \times 10^6 \$}{335 kW \times 10^3} = 1.67 \times 10^3 \$/kW$$