ON THE MILITARY IMPLICATIONS
OF A SATELLITE POWER SYSTEM
A WORKING PAPER

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Just as a person speaking in a language he has not fully mastered sometimes says things he did not intend, so policy can order things not in accord with its intention. This has happened often, and it is the lesson of history that a certain knowledge of military affairs is essential to the management of political matters.

--Karl von Clausewitz--
(Vom Kriege, 1830)

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FOREWORD

The Satellite Power System (SPS) is a potential energy technology for the turn of the century and beyond. This report on the military implications of the SPS is one of a large number of studies performed under the auspices of the Department of Energy and the National Aeronautics and Space Administration which cover every major issue concerning the SPS concept.

In the past few years, public awareness of the military implications of space technology has grown considerably. Thus the question of the potential military implications of the SPS has attracted a great deal of public discussion and debate. Could the power transmission beam from a power satellite be modified for use as a weapon? Given the huge size and the large investment required for each power satellite, wouldn't they become highly attractive and vulnerable targets for attack by hostile countries or terrorists? Might the SPS represent a further escalation of an expensive armaments race into newer and more lethal means of destruction? This report provides a detailed and comprehensive discussion of the military implications of the SPS.

Internationalization of ownership, management, and control for initial development of SPS may be feasible. Experience to date with large-scale international projects, however, suggests that funding difficulties and management and control questions (particularly when great sums of money are involved) might delay or even stifle development of the system. In addition, a number of salient U.S. foreign policy concerns, including technology transfer and dependence on foreign energy sources, would tend to weaken arguments for internationalization. Therefore, although this study addresses multinational program arrangements and implications, the preponderant orientation is toward a unilateral United States program.

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GLOSSARY OF ABBREVIATIONS AND ACRONYMS

ABM	Ballistic missile defense
ABRES	Aeroballistic Reentry Systems
AC	Alternating current
AC	ASAT carrier
ACS	Attitude control system
ADIZ	Air Defense Identification Zone
Agr.	International agreement(s)
ALS	Alternate launch site
ASAT	Antisatellite weapon
BCI	Baggage and cargo inspection
BMD	Ballistic missile defense
BT	Booby trap
C^1	Communications
C^2	Command and control
C^3	Command, control, and communications
C^3I	Command, control, communications, and intelligence
CBW	Chemical/biological warfare
CDEP	(SPS) Concept Development and Evaluation Program
CE+I	Counterespionage and intelligence
CIA	Central Intelligence Agency
CMOS	Complementary metal oxide semiconductor
CO_2	Carbon dioxide
COMINT	Electronic intelligence to analyze a communications network (See also ELINT and SIGINT)
Comm.	Communications
COMSAT	Communications Satellite Corporation (U.S.)
CONUS	Airspace over the continental U.S.
COTV	Cargo orbital transfer vehicle
CW	Continuous wave (Applied to a transmitter, this term implies continuous rather than pulsed operation.)
DB	Direct broadcast
DC	Direct current
DDT&E	Design, development, test, and engineering
DEW	Directed energy weapons
DF	Deuterium flouride
DK	Dual key enabling system
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOS	U.S. Department of State
DRMR	Satellite deployment, replacement, maintenance, or repair
ΔV ("delta-vee")	Maneuvering to change orbit or trajectory; magnitude of change in orbital velocity

e^-	Electrons (Negatively charged particles.)
EB	Earth bombardment
ECM	Electronic countermeasures
EC/LSS	Environmental control and life support system
EDL	Electric discharge laser
EEC	European Economic Community (Common Market)
ELF	Extremely low frequency radio signals
ELINT	Electronic intelligence to analyze characteristics of a transmitter, especially radar (See also COMINT and SIGINT)
EMP	Electromagnetic pulse (specifically, from a nuclear explosion)
EOB	Electronic order of battle
ER	Earth irradiation
ESA	European Space Agency
EW	Electronic Warfare
FAA	Federal Aviation Administration
FBI	Federal Bureau of Investigation
FCS	Fire control system
FEL	Free electron laser
FOBS	Fractional-orbit bombardment system
GEO	Geosynchronous Earth orbit
GFRTP	Graphite fiber reinforced thermoplastic
GHz	Gigaherts (10^9 cycles per second)
GNP	Gross National Product
GPS	Global Positioning System
GW	Gigawatt (10^9 watts)
γ	Gamma rays
H^+	Positive hydrogen ions
Hard.	Hardening
HE	Conventional high explosives
HEL	High energy laser
HF	Hydrogen flouride
HF	High frequency
HFDF	High frequency direction finder
HLLV	Heavy lift launch vehicle
ICBM	Intercontinental ballistic missile
INTELSAT	International Telecommunications Satellite Organization
IR	Infrared
IS	Industrial security measures
ITU	International Telecommunications Union
keV	10^3 electron volts
kV	Kilovolt
kW	Kilowatt

LANDSAT	Earth resources satellite
LEO	Low Earth orbit
LOS	Line-of-sight
LPRE	Laser-powered rocket engine
LRSS	(Comprehensive) long-range space surveillance
LTV	Lunar transfer vehicle
MAD	Mutual assured destruction
MCC	Mission control center
MDRE	Mass driver reaction engine
MeV	10^6 electron volts
MHD	Magnetohydrodynamics
MHz	Megahertz
MOS	Metal oxide semiconductor
MR	Maintenance and repair
MUF	Maximum usable frequencies
mW	Milliwatt
MW	Megawatt
µrad	Microradian (10^{-6} radian)
n	Neutrons
NaK	Sodium/potassium, used as a coolant
NASA	U.S. National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAV	Navigation
NAVSTAR	U.S. (military) navigation satellite system
NCA	National Command Authority
NEARSAT	Hostile satellite maintained close to a given satellite or space station
NORAD	North American Air Defense Command
NTM	Nonterrestrial materials
NTMV	"National technical means of verification" (SALT euphemism for surveillance and reconnaissance satellites)
OAS	Organization of American States
OI	Orbital interceptor
O&M	Operations and maintenance
O-O	Orbit-to-orbit
OPEC	Organization of Petroleum Exporting Countries
OTEC	Ocean thermal energy conversion
OTV	Orbital transfer vehicle
PBW	Particle beam weapon
PLV	Personnel launch vehicle
PM	Personnel management
POTV	Personnel orbital transfer vehicle
PRC	People's Republic of China
Prox.	International agreements on proximity rules in space

PS	Personnel screening and selection procedures
Psychwar	Psychological warfare
Pub. ed.	Public education (to counter misperceptions and deliberate misinformation)
R&D	Research and development
Red. obs.	Reduced observables
RF	Radio frequency
RFI	Radio frequency interference
RIO	(International) Resident Inspection Organization
ROE	Rules of engagement
RV	Reentry vehicles
S^3	Shelter, supplies, and services
S&R	Surveillance and reconnaissance
SAC	U.S. Air Force Strategic Air Command
SALT	Strategic Arms Limitation Treaty
SAM	Surface-to-air missile
SATMUT	Damage or mutilation of a satellite by grapplers
SATNAP	Seizure ("kidnapping") of a satellite
SD	Self-destruction
SDF	Self-defense
SGEMP	System-generated electromagnetic pulse
SIGINT	Electronic intelligence, generically (See also COMINT and ELINT.)
SMAT	Sabotage, mutiny, attack, and/or terrorism
SMF	Space manufacturing facility
SOLARES	Space Orbiting Light Augmentation Reflector Energy System
SPS	Satellite Power System
SSME	Space Shuttle Main Engine
SSTO	Single-stage-to-orbit vehicle
SV	Sortie vehicle
T	Metric ton (1000 kilograms)
TREE	Transient radiation environment effects
UHF	Ultrahigh frequency
UN, UNO	United Nations Organization
UV	Ultraviolet
VHF	Very high frequency
VLF	Very low frequency
VTOHL	Vertical-takeoff, horizontal-landing
WXM	Weather modification
XMTR	Transmitter

1.0 INTRODUCTION AND CONCLUSIONS

1.1 Background and Motivation for this Study

The concept of harvesting renewable solar energy in space for transmission to Earth for terrestrial use has attracted increasing interest and study in recent years. Satellite Power Systems (SPS)* were first proposed in 1968 by Peter E. Glaser as a possible long-term solution for the world's future energy needs. The continued advancement of solid state technology, space technology, and materials science in general, combined with more urgent attention to the energy issues in the political arena, have made the SPS concept more attractive and perhaps nearer in time than was the case in 1968.

If a Satellite Power System such as is described in the NASA Reference Design Report[1]** were to be undertaken to provide significant quantities of power to the United States and perhaps to other countries as well, significant military implications would ensue. These would arise, first, from the possible uses of such satellites and supporting systems (perhaps with enhanced military capabilities) as weapons or as supportive elements of other military systems (threat issues) and, second, from the necessity of ensuring the security of such important economic assets in space (vulnerability issues).

Questions about the military implications of an SPS program arise regardless of which nation or group of nations deploys such satellites. The specific details of the questions raised would vary, but the underlying questions of threat, vulnerability and means of safeguarding the program would remain just as important.

These questions about the military implications of an SPS program are very important domestically as well as internationally. Should power satellites prove to be economically, technologically, and environmentally desirable as new sources of power for the United States, their political acceptability would depend on satisfactory resolution of some of these questions concerning the possible military uses (or misuses) of SPS or its supporting and implementing program.[2] The principal aim of the present study is to investigate means by which convincing

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* A glossary of abbreviations and acronyms used in this report appears near the front of this volume.

** References for each section of this report are included at the end of the section.

assurances could be provided during implementation of an SPS program and during routine operations of a network of power satellites that the system is NOT being used, overtly or covertly, for military purposes and that the system is no more vulnerable to attack than more conventional electrical power sources.

Under the auspices of the Department of Energy's (DOE) SPS Concept Development and Evaluation Program (CDEP),[3] these military implications questions were studied briefly in 1978.[4,5] Table 1-1 lists the possible threat and vulnerability issues which were identified in those two studies, and possible methods of forestalling any real concerns about military uses of power satellites. In this study, these and additional issues have been addressed in greater depth and breadth to develop specific proposals of safeguards for the SPS.

1.2 Scenarios for SPS Programs

Any discussion of the military implications of Satellite Power Systems must recognize that the research and development effort and the construction and operation of power satellites will not be carried out as a single, monolithic project. During different phases of an overall program spanning fifty years or more, different types of organizations will be involved in a variety of roles, each interacting with different sets of actors on the national and international scenes in diverse arrangements having significantly different military, political, and social implications.

Five distinct phases can be identified in an overall program geared to commercial* operation of a significant number of solar power satellites. First, the research and development (R&D) phase may last up to ten years to prove the validity of the SPS concept and to provide a reasonably high degree of confidence that the following phases will be successful.

If the R&D effort continues to demonstrate the viability and desirability of SPS, a commitment could be made to proceed toward SPS deployment by initiating an eight to ten year design, development, test, and engineering (DDT&E) phase, possibly overlapping the R&D phase. (The Reference System report[1] assumes this phase would run from the late 1980's to the late 1990's.)

* In this context, we use the term "commercial" to mean widespread use in commerce, not to imply that SPS will be (or should be) exclusively a private sector affair.

Table 1-1.
SUMMARY OF KEY ISSUES IDENTIFIED IN PREVIOUS STUDIES

REAL OR PERCEIVED THREATS

SPS AS A WEAPON

- Power for beam weapons used as ABM
- Power for beam weapons used as ASAT
- Power for beam weapons used as incendiary device
- Microwave beam used as psychological weapon against enemy troops
- Microwave beam used to disable or degrade enemy satellites by overheating
- Microwave beam used for hostile weather modification

SPS AS A SUPPORT SYSTEM

- Power for remote military installations
- Power for other military satellites
- Laser power transmission to allow military aircraft indefinite loiter times at high altitudes
- SPS as platform for:
  - Manned inspection of other satellites
  - Repair and maintenance of military satellites
  - Advanced sensor systems for surveillance and early warning
  - Alternate communications channels using laser or microwave power transmission beams
  - Advanced military navigations sytsems
  - Electronic jamming techniques
  - Meteorological, geographic, and geological mapping
  - ELF communications link to submarines
- Civilian use of SPS power to free up portable fuels for military use

REAL OR PERCEIVED VULNERABILITIES

- Sabotage during on-orbit assembly phase
- Sabotage during orbital operations
- Sensitivity of solar cells to radiation from nuclear explosives
- Sensitivity of life support systems for personnel on SPS to overt military assault
- Seizure of control of pilot beam by insurgency or sabotage at receiver array on the ground
- Disruption of pilot or control signals by insugency or sabotage
- Rectenna becomes a key military target in time of war
- RF interference with enemy military systems may provide excuse for action against SPS in time of hostilities

SAFEGUARDS

- Hardening of critical electronic components
- Self-defense of satellite segment by beam weapons
- Internationalization of entire program

If the DDT&E phase runs smoothly, commitment to proceed with SPS construction on a commercial scale would require a four-year startup phase of procurement and deployment of launch facilities, launch vehicles, orbit-to-orbit vehicles, and space bases. Extensive launch and orbital operations would be involved in this phase, including major expansions of launch facilities.

In the fourth phase, routine production of several power satellites and rectennas would take place each year. In the Reference System, two units of 5 GW electrical output would be completed each year until a total of sixty 5 GW units are in place.

A fifth phase, decommissioning the entire system, is presumed to lie far in the future and has not been considered in this study. Most of the effort in this study focused on the third and fourth phases of the overall SPS program.

It is also necessary to consider three distinct phases in the life cycle of a particular power satellite and rectenna:

(1) the construction phase, when the power satellite and rectenna are being built;

(2) the routine operations and maintenance (O&M) phase, lasting through the useful lifetime of a power satellite and rectenna, which is expected to be thirty years or more;

(3) the decommissioning phase, when further repairs or modifications of the power satellite and/or rectenna are no longer economically advantageous, and the power satellite and/or rectenna is shut down and scrapped or salvaged for totally different purposes. (Note that the power satellite and the rectenna might be decommissioned at different times.)

From the viewpoint of an individual power satellite and rectenna, we have considered only the first two phases in this study since the third phase lies too far in the future, although decommissioning could have significant military implications.

Various types of organizational arrangements for the different phases of an overall SPS program have been discussed in previous studies.[6,7,8] Obviously, the nature and national composition of the legal entities controlling, financing, owning, managing, or operating various segments of a Satellite Power System will have important effects on perceptions of threats posed by SPS and on perceptions of vulnerabilities of SPS.

The International Telecommunications Satellite Organization (INTELSAT) has been suggested as a model for international arrangements for SPS.[6,7,8] Whatever the relative merits of setting up an analogous international arrangement for SPS, it is necessary for the purposes of examining the military implications of SPS to focus attention elsewhere, not on the legal entity or entities controlling, funding, and managing the DDT&E, startup, and routine construction and operations phases of the program. Our focus here will be on the operational entities which design, build, and maintain the power satellites and which design, control, and operate the launch facilities, the launch vehicles, the orbital bases in low Earth orbit and in geosynchronous Earth orbit, the orbital transfer vehicles, and any other facilities in space.

This focus on the operational organizations results from the following considerations:

(1) These operational entities will have continuous "hands on" access to space vehicles and space facilities, including the power satellites themselves, from DDT&E through decommissioning, whether or not they own these devices. Therefore these entities will be in a unique position to be co-opted by military interests of their own national government(s) or of the government(s) of allied nation(s), and to covertly deploy military adaptors for the SPS.

(2) These entities will have primary responsibility for implementing any technological means for reducing or eliminating vulnerabilities of the power satellites and other SPS elements in space. Thus these organizations would be in a unique position to be subverted in such a manner as to increase the vulnerability of the power satellites and other system elements, or to install "Trojan horse" devices aboard power satellites to be sold to other countries which would permit disabling the power satellite upon command of a hostile entity at a later date.

Short of thorough audit and inspection procedures by other organizations, it is difficult to see how legal and institutional arrangements analogous to those of INTELSAT, *per se*, could provide protection against the dangers suggested above.

1.3 Assumptions

The subject of the military implications of a Satellite Power System planned for deployment in the period 20 to 50 years in the future is vast. Certain assumptions had to be made to guide the directions of inquiry, to limit the scope of the problem, and to provide a background context for the SPS program. The assumptions of this study are discussed in this section. In some instances, consideration was given briefly to alternative possibilities where our assumptions might be considered controversial or where interesting differences in implications could be expected.

1. Civilian Nature of the Program. We have assumed that the national policy decision by the United States to participate in a full-scale SPS program is motivated by the nation's domestic need for energy rather than by strategic considerations regarding national defense. Under this assumption, SPS is considered to be designed as a civilian system only. The U.S. portions of the program are then operated by the private sector, by civilian branches of the government, or by some combination of these. (See References 6 and 7 for discussions of possible financing and management alternatives for SPS.) In case of a national emergency, however, equipment and facilities owned by U.S. entities may come under direct control of, or even direct use by, the National Command Authorities, as is the case today for certain major private sector activities such as the commercial airlines.

2. U.S. Role in the SPS Program. Although substantial interest has been expressed in the SPS concept by government and business leaders in many other countries, most of the R&D effort on SPS to date has been provided by the United States. Should the R&D program conclude that it is definitely worth pursuing the DDT&E phase, we have assumed that the United States would be among the first to make a significant committment to that phase.

Once a system for construction of power satellites is in place (following completion of the startup phase), power satellites built by the United States and its partners could be sold, leased, or otherwise made available to nonparticipating countries on a commercial basis or on an international development aid basis. We do not assume that power satellites would be owned and operated exclusively by the United States. (The Reference Design report[1] assumes that power satellites are built by the U.S. solely for domestic energy production.)

Many of the military issues of SPS would seem to be largely moot if the operational entities for SPS were fully multilateral from the very beginning of the DDT&E phase (if not sooner). It is certainly a more difficult task to devise means to defuse the military issues of threat and vulnerability for a unilateral SPS program. For the purpose of this study, then, we have focused our attention on this most difficult case; an internationalized SPS would certainly be easier to safeguard in a manner acceptable to most national governments.

3. Utility Ownership of Power Satellites and Rectennas. We have assumed that, upon completion of construction of a power satellite and rectenna, the SPS construction organization(s) will sell them outright to utility companies or government agencies, whether in the United States or abroad, rather than retaining ownership of the hardware and selling the power.

Once a power satellite and rectenna is sold outright to a foreign entity, the SPS construction entity would have no further control over it, although the builders may continue to provide maintenance and repair services to the owners on a contract basis, as is the case today for the builders of nuclear powerplants. While the U.S. commitment to participation in building power satellites may be purely civilian in nature, the same cannot be assumed for all foreign purchasers of power satellites.

Given this assumption of ownership of power satellites and ancillary facilities by many different nations, it is perhaps even more difficult to provide credible safeguards against military adaptations of portions of the SPS than if only one nation (e.g., the United States) owned such facilities. It will clearly be necessary to look outside the operational entities for means to assure the non-military nature of SPS elements, and additional actors (including utility companies, foreign owners, and national governments abroad) must also be considered in devising safeguards for SPS.

4. Plural Presence in Space. In the time period after about 1990, we assume the presence in space of spacecraft and personnel from many nations, not just the U.S. and the U.S.S.R. Both the People's Republic of China and Japan have declared their intentions of achieving manned capabilities in space by the end of the century. At least another dozen countries will have the capability of launching satellites to LEO and GEO in the late 1980's and 1990's. One or more private enterprise ventures (such as OTRAG in West Germany[10]) are likely to succeed in bringing new launch vehicles into operational use by that time.

Extensive manned operations in space imply the possible access of terrorists to space systems as well as to ground facilities, especially if the costs of transportation become low enough (less than $20-40 per kilogram) to permit development of space tourism. Such tourists-turned-terrorists, however, would have to be technically highly trained to be very effective.

5. Diffusion of Advanced Technologies. In discussing the potential threats which the SPS could wield under a United States program, we made projections of certain technologies to obtain some idea of the capabilities space weaponry may achieve in the next 20 to 50 years. Over such a time span, we must assume that anything which U.S. technology could devise will be matched by that of other countries, with no more than a few years delay.

6. Normal Technology Growth. While unimaginable breakthroughs could occur in the next fifty years, leading to whole new transporation systems, communications systems, and weapons systems, we have assumed that anything actually deployable in the next five decades will already exist today, at least in conceptual form with a reasonable technical basis. We thus admit high energy lasers, laser propulsion, and microelectronic technologies advanced by several orders of magnitude in capability beyond those available today.

1.4 Method of Approach

Threat and vulnerability, whether potentially real or only imagined because of some misperceptions, are the most basic of considerations in assessing military implications of the SPS concept. That some threat possibilities can be perceived rather than real is shown by the common misconception about the Reference Design that if the microwave power beam to the ground were to wander away from its designated receiver antenna array (rectenna), it would leave in its wake countless "cooked" people, wildlife, and vegetation, along with "scorched" cities should it cross any. (Such misconceptions can only be countered by public discussion about SPS.)

More realistic threats include the addition of directed energy weapons (either laser or particle beam devices) to the power satellite, or substitution of laser power transmission for microwave power transmission to the ground.[14,15] The possibility that a network of SPS facilities was being covertly equipped with a high energy laser ballistic missile defense (ABM) system of high efficiency would be viewed with considerable alarm by any other nation whose strategic military doctrine depended heavily on intercontinental ballistic missiles (ICBM).[15]

On the vulnerability side, the right of free passage in space of vehicles launched by states which are parties to the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies could be invoked to allow a hostile or potentially hostile nation to deploy NEARSATs ("killer" satellites or even remotely controlled mines) in close proximity to a solar power satellite.[16]

The actual degree of military involvement in an SPS program will naturally have a significant impact on threat and vulnerability issues. Any source of energy, of course, plays an indirect supporting role in national security and military preparedness. Such use of the SPS would not be considered directly military, unless the receiver antenna arrays were located predominantly or exclusively on military bases or defense-oriented installations such as uranium enrichment plants.

Conversely, should each power satellite be equipped with long-range beam weapons, or with additional electronic equipment permitting the use of the microwave transmitting array as a deep space surveillance radar, or with laser communications equipment permitting the SPS to act as a relay to and from military communications, reconnaissance, or surveillance satellites, the significance of the SPS as a target for attack in time of hostilities would be altered drastically as might the ability of the SPS to protect itself from certain types of attacks. We must thus consider, at a minimum, the two extreme cases of a SPS with enhanced military capabilities and of a SPS with minimized military support capabilities.

Once the potential threats and vulnerabilities of a SPS have been developed, various methods of safeguarding the system must be developed, and it is the aim of this study to identify and discuss potential safeguards. Safeguards in the most general sense could include preventive measures (i.e., action taken to forestall concerns about SPS threats and to inhibit other nations or terrorist groups from attacking the SPS) and neutralizing measures (i.e., actions taken to allow the SPS to survive attack, or to prevent an SPS with enhanced military capabilities from using those capabilities for aggression.)

Safeguards can be purely technological (such as hardening of electronic components against radiation from nuclear explosions, laser beams, particle beams, or induced surge currents), or institutional (such as international treaties on just how close space vehicles or satellites of different nations may come to one another without prior mutual consent).

The vulnerability and threat issues associated with SPS are to a significant extent shaped by the hardware itself. A thorough analysis of military implications then requires consideration of all the factors mentioned above with respect to each of the major <u>systems and subsystems of the SPS</u>. Insofar as enhanced military capabilities may be added to the system, such military capabilities must also be considered as major system and subsystem elements of SPS in the analysis.

For each subsystem element, we consider the specific threats that element could pose to ground or space systems of another nation, including both technological and institutional means afforded by the SPS. For each threat posed by a subsystem, one or more safeguards are identified and examined. We then consider for each subsystem element of the SPS (but not of military adapters to the SPS) the specific ways in which a threat could be deployed against it by a hostile institutional means. Again, for each such vulnerability of the SPS or any subelement, one or more safeguards are identified and examined.

This analysis results in two matrices, one of threats and safeguards versus subsystem elements of the SPS, with and without military adapters; the other, of vulnerabilities and safeguards versus subsystem elements of the SPS itself, without military adapters. (It is not within the scope of this study to consider the vulnerabilities of military hardware which might be attached to SPS elements.)

The study approach, then, is as follows:

(1) Define the system and subsystem elements of the SPS and of military adapters which might be added to it, either overtly or covertly.

(2) Examine likely technological developments in key areas over the next twenty to fifty years (when the Reference Design SPS is assumed to be deployed) to permit definition of likely threats or vulnerabilities of SPS elements.

(3) Element by element, examine the applicability of these technologies to providing the SPS with significant military capabilities or to providing hostile forces with means of attacking SPS elements. Using the same data base, examine possible safeguards against each potentially real threat or vulnerability identified.

The system and subsystem elements of the SPS for the purposes of this study are described in Section 2. Section 3 discusses the threat issues we have identified and considered. Section 4 discusses the vulnerability issues, primarily of the Reference Design, with occasional comments on differences in vulnerabilities among alternative SPS designs.

Section 5 then identifies and analyzes safeguards against the threats and vulnerabilities identified in the preceding two sections.

Appendix A discusses the Resident Inspection Operations at greater length. Appendix B discusses some multilateral agreements which bear on the military implications of SPS. Appendix C discusses a variety of technical topics, including technological projections in some key areas.

1.5 Conclusions

Several principles and themes have emerged in this study:

(1) Military implications clearly depend on the arrangements under which one or more nations pursue the implementation of a SPS program. It could be conducted as a unilateral program, a multilateral program including only friendly partners, or a multilateral program, including potential adversaries. Military implications further depend on whether SPS development and operation is monitored by international resident inspection operations.

(2) The Unmodified Reference Design SPS has no capability for military force delivery or for military C^3I functions. It does have some modest military support capabilities. Most significant here is the inherent capacity of the system to transport large quantities of equipment and large numbers of people (compared to present standards) between the surface of the Earth and high Earth orbit (past GEO, at least). The detailed nature of military activities in space which could then be carried out independent of the rest of SPS is beyond the scope of this study. Power satellites, the LEO base, the GEO base, and many of the vehicles used for SPS could all be used as platforms for various communications, reconnaissance, and surveillance functions. These facilities and vehicles could also be used to support maintenance and repair of military satellites and vehicles.

(3) Weapons modules having tactical and strategic significance could be added to a Satellite Power System. The more significant military capabilities which could be added are as follows:

a) A ballistic missile defense (ABM) system based on directed energy weapons (DEW's), most likely high energy lasers. Depending on the rate of technological advance, such weapons might ultimately achieve the capability of neutralizing low-altitude aircraft and cruise missiles. Unilateral deployment of such a system could be considered provocative by other nations.. On the other hand, with proper safeguards, multilateral deployment of such defensive systems could be internationally stabilizing.

b) A variety of antisatellite (ASAT) systems. These could include DEW's, space-to-space missiles (either rockets or projectiles), space mines, and grapplers (either manned or remotely operated). Except for DEW's and small projectile weapons, a comprehensive space surveillance system should be able to detect and track such weapons, making it difficult to attack without warning.

c) Reentry vehicles for Earth bombardment with either conventional high explosives or nuclear warheads. Although it would be difficult to defend against such weapons, comprehensive space surveillance should be able to detect such vehicles upon launch.

Any foreseeable non-nuclear weapons which could be added to SPS would be less threatening than the strategic nuclear arsenals already deployed on Earth.

(4) C^3I modules having tactical and strategic significance could be added to a Satellite Power System but would require engineering modifications. The most significant such additions which are unique to SPS (due to the availability of large quantities of electrical power) are EW jammers and direct broadcast to the population of a hostile country.

(5) The power satellites could be used as a power source (with laser transmission) for military satellites or to allow long-duration flight of military aricraft at high altitudes.

(6) The power satellites themselves, in the Reference Design SPS, are vulnerable to system-generated electromagnetic pulse (SGEMP) effects resulting from the gamma-ray and x-ray emissions of nuclear explosions. Use of nuclear weapons for this purpose, however, may result in damage ranging from slight to extensive to other spacecraft (including those of the attacker) at comparable range from the explosion. The Reference Design was not intended to consider these vulnerabilities, and it may be possible to incorporate adequate hardening features. Various design alternatives for SPS may be less sensitive or may be more easily hardened against this threat.

(7) The various system and subsystem elements of the SPS are vulnerable to a variety of types of attack, but are inherently no more vulnerable than existing elements of the civilian economic infrastructure, including electrical generating plants, petroleum refineries, electrical power transmission and distribution networks, pipeline systems, railroads, aircraft and airports, and communications networks. The survivability of each system and subsystem element is sensitive to design details and survivability considerations for SPS would be integrated with other engineering design and program management design from the start.

(8) Military implications of SPS are concept dependent. Therefore, appraisal of the military implications of SPS generically requires that alternative SPS system concepts be evaluated to the same depth as the photovoltaic SPS Reference Design considered in the bulk of this study.

(9) Certain issues have been raised about the capability of a Satellite Power System to effect military force delivery or to survive military attack. Several of these issues are based on misperceptions about the SPS concept. These misperceptions may be overcome, but only if discussions about SPS are carried on in an atmosphere of openness and candor.

(10) Numerous safeguards have been identified against the threats which a SPS with enhanced military capabilities might pose to other countries, and

8. Henry G. Elder, "Satellite Power System: An Overview of Prospective Organizational Structures in the Solar Power Satellite Field," TID-29094, DOE/NASA, October 1978.

9. "First Private Launch Vehicle Successful," The Foundation Institute Report 1(1), 1-2 (September 1977).

10. Krafft A. Ehricke, "Space Industrial Productivity: New Options for the Future," pp. 66-245 in Vol. II Future Space Programs 1975, Committee on Science and Technology, U.S. House of Representatives, September 1975.

11. Krafft, A. Ehricke, "Extraterrestrial Imperative," Bulletin of the Atomic Scientists, pp. 18-26, November 1971.

12. William P. Gilbreath and Kenneth W. Billman, "A Search for Space Energy Alternatives," in: Radiation Energy Conversion in Space, Kenneth W. Billman, ed., Vol. 61, Progress in Astronautics and Aeronautics, American Institute of Aeronautics and Astronautics, New York, 1978.

13. Claud N. Bain, "Potential of Laser for SPS Power Transmission," HCP/R-4024-07, DOE/NASA, October 1978.

14. Claud N. Bain, "Power From Space by Laser," Astronautics and Aeronautics, 17(3), 28-40, (March 1979).

15. Maxwell W. Hunter, "Strategic Dynamics and Space-Laser Weaponry," October 31, 1977, 3165 La Mesa Drive, San Carlos, California 94070.

16. Article I of the treaty states:

> The exploration and use of outer space...shall be carried out for the benefit and in the interests of all countries...and shall be the province of all mankind.
>
> Outer space, including the moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies.

The full text of the Treaty on Principles appears as Appendix A in Carl Q. Christol, "Satellite Power Systems (SPS): International Agreements," HCP/R-4024-08, DOE/NASA, October 1978.

2.0 SYSTEM DEFINITION

The breakdown of SPS into system and subsystem elements presented below differs somewhat from other SPS documentation. We have, however, used the NASA Reference System Report[1] for basic information on the Reference Design whenever possible.

The Reference Design SPS was divided into seven major systems: (1) transportation system; (2) low Earth orbit (LEO) base; (3) geosynchronous Earth orbit (GEO) base; (4) power satellites themselves; (5) receiver antenna arrays (rectennas) and associated facilities on the ground; (6) command and control system; and (7) communications system. In general, whenever we refer to "SPS" or "Satellite Power System" in this report, we mean the entire system including all of the above elements. If we refer to just the power satellites themselves, we use the term "power satellite."

As discussed in Section 1.4 before, it is necessary to consider two extreme cases: a SPS with enhanced military capabilities, and a SPS with minimized military support capabilities. (The Reference Design SPS represents the latter case.) To enhance the military usefulness of SPS, various adapters or modules would be added to, or incorporated into, SPS elements in order to carry out any of the three major missions of military organizations: (1) force delivery; (2) command, control, communications, and intelligence (C^3I); and (3) military support. A Satellite Power System with fully enhanced military capabilities would then have ten major systems, namely, the seven listed above for the Reference Design, plus adapters for each of the three major military missions just mentioned. These ten systems and their refinements into subsystem elements are shown in Table 2-1.

Each of the system elements of the Reference Design in Table 2-1 will be described briefly in this section. We defer discussion of military systems and subsystems which might be added to SPS until Section 3.

2.1 Transportation Systems

Brief descriptions of SPS transportation systems and operations are given here. A more quantitative summary of transportation parameters is presented in Table 2-2 which views the program at the midpoint of total system buildup, that is, when thirty 5 GW units are in place and operational, and construction is proceeding

Table 2-1
SPS SYSTEM AND SUBSYSTEM ELEMENTS

A. SPS REFERENCE DESIGN

TRANSPORTATION SYSTEM
- Earth launch facilities
- Earth-to-LEO vehicles
- Orbit-to-orbit and sortie vehicles

LEO BASE
- Living/working quarters
- Materials stockpile
- Propellant depot
- Power System

GEO BASE
- Living/working quarters
- Construction equipment
- Materials stockpile
- Propellant depot
- Power system

POWER SATELLITE
- Photovoltaic array
- Power collection and distribution
- Power conditioning and conversion
- Power transmitter and microwave beam
- Support structures
- Rotary joint
- Attitude control system
- Living/working quarters

COMMUNICATION SYSTEM
- RF and laser links

COMMAND AND CONTROL SYSTEM
- C^2 centers (at power satellites and rectennas)
- C^2 centers (all others)

RECTENNA
- Pilot beam and associated equipment
- Power collection antennas
- Power conversion and conditioning
- Support structures
- Power distribution and interface

B. POSSIBLE MILITARY ADAPTERS

WEAPON MODULES
- Projectile weapons
- Manipulators/grapplers
- Directed energy weapons

C^3I MODULES
- Communications packages
- Wide area broadcast transmitter
- Radar
- Lidar
- Telescopes and cameras
- RF receivers

MILITARY SUPPORT MODULES
- Navigation beacons
- Power beam diverters
- CBW laboratory and/or stockpiles
- Augmented manning

at the rate of two additional power satellites annually. The Reference Design system includes two alternative power satellite configurations, based upon either silicon (Si) photovoltaic cells or gallium aluminum arsenide (GaAlAs) photovoltaic cells.* Since the construction equipment, the manpower requirements for construction, and the gross mass for each power satellite are different for each of these options, the transportation systems required for each option also differ. Both options are discussed below and are summarized in Table 2-2.

Earth Launch Facilities. All Earth launch operations are conducted from expanded facilities at Cape Canaveral, Florida. These facilities must include at least two launch pads for Heavy-Lift Launch Vehicles (HLLV) and four launch pads for Personnel Launch Vehicles (PLV). These facilities must also support a fleet of three to five HLLVs; five or six PLVs; 9 to 23 Cargo-Orbital Transfer Vehicles; five to seven Personnel Orbital Transfer Vehicles; and 80 sortie vehicles. Assuming 75% use factors, the launch facilities must be capable of handling annual propellant masses on the order of 4×10^6 metric tons of liquid oxygen, 1×10^6 T of liquid methane, and 0.2×10^6 T of liquid hydrogen. This translates to a daily handling capacity of about 10^4 cubic meters of cryogenic propellants, or enough to fill a sphere 25 meters in diameter.

Earth-to-LEO Vehicles. Cargo is transported from Earth to LEO by two-stage winged HLLVs in a vertical-takeoff-horizontal-landing (VTOHL) configuration. The booster is propelled by 16 high-pressure oxygen-methane engines (vacuum thrust = 9.6×10^6 newtons each) and the orbiter by 14 Space Shuttle main engines (SSME; vacuum thrust = 2.1×10^6 newtons each). The HLLV at takeoff stands 161.1 meters high. The landing weights of the booster and orbiter are 934 and 453 T, respectively.

Personnel are transported from Earth to LEO by two-stage winged PLVs, also in a VTOHL configuration, the booster propelled by four high-pressure oxygen-methane engines (vacuum thrust = 9.6×10^6 newtons each) and the orbiter by 3 SSME. The orbiter expends on each flight an external oxygen-hydrogen tank weighing about 25 T. The PLV at takeoff stands 93.6 meters high. The landing weights of the booster and orbiter are 259 and 179 T, respectively. Passenger capacity is 75 per

*See Section 2.4 below for descriptions of the alternative power satellite configurations.

Table 2-2. REFERENCE SPS TRANSPORTATION SYSTEMS AND OPERATIONS

(Fleet size and operations are shown at the mid-point of the Reference SPS program, when 30 units (5 GW each) are in place, and two additional units are being built each year.)

Parameters / Vehicles		Payload Weight (T)	Gross Weight (T)	Fleet Size[a] SPS	Fleet Size[a] RIO*	Flights/Yr SPS	Flights/Yr RIO*	Launch Pads[b] SPS	Launch Pads[b] RIO*	Propellant Use/Year (10^3 T - No Use Factor) O_2	CH_4	H_2	Ar
HLLV	Si	424 up 63.5 dn	11,040	5	0	375	0	2	0	2,711	646	128	0
	Ga			3		225		2		1,627	388	77	
PLV	Si	88.7	2,714	3	2	46	15	2	2	110	22	5	0
	Ga			4		54	15	2	2	124	25	6	
COTV	Si	4,000	6,191	23	0	30	0	0	0	12	0	2	30
	Ga	3,469	4,396	9		22				6		1	5
POTV	Si	151 up 55 dn	890	5	2	20	10	0	0	12	0	2	0
	Ga			3		25	10			15		2	
SV	Si	267 $(= \frac{4000}{15})$	404[c]	70	10	120[d]	180[e]	0	0	12	0	2	0
	Ga	231 $(= \frac{4000}{15})$	351[c]	70	10	120[d]	180[e]			12		2	
TOTAL	Si	---						4	2	2,857	668	139	30
	Ga							4	2	1,784	413	88	5

* RIO (Resident Inspection Operations) is a possible safeguard for SPS discussed in Section 5.

a Vehicle turnaround time = 4 days (HLLV) and 14 days (PLV).

b Pad turnaround = 4 days; one contingency pad.

c Sortie vehicle parameters postulated are Δv = 50 m/sec for construction missions or 500 m/sec for maintenance and for RIO operations, with I_{sp} = 450 sec. Ten missions are assumed to be flown between refuelings.

d 60 for construction; 60 for maintenance.

[redacted]120 [redacted] cr[redacted]rota[redacted]n; [redacted]or [redacted] ch[redacted].

PLV. Flight time from liftoff to docking at the LEO base is one to several hours, depending primarily on the orbital inclination chosen for the LEO base. The return flight duration would be comparable.

Orbit-to-Orbit and Sortie Vehicles. Cargo is transported between LEO and GEO by solar-electric-propelled Cargo Orbital Transfer Vehicles (COTV) using photovoltaic cells (either silicon or gallium aluminum arsenide) as the primary power source and argon as a propellant. The vehicles are 1140 x 1140 x 164 meters and 2250 x 1300 x 1300 meters in dimension for the silicon and gallium options, respectively.

Personnel are transported between LEO and GEO by two-stage Personnel Orbital Transfer Vehicles (POTV), the first stage propelled by four high-pressure oxygen-hydrogen engines (vacuum thrust - 0.47×10^6 newtons each) and the second stage by two of the same engines. The POTV is 81 meters long and carries 160 passengers. Flight time from LEO base to GEO base (or vice versa) is about 10.6 hours, assuming Hohmann transfer. If the LEO base is in an equatorial orbit, launch windows occur about every 100 minutes. If the LEO base is in an inclined orbit, launch windows occur only twice a day.

In space, small sortie vehicles (SV) or "tugs" are used to conduct construction, maintenance, and miscellaneous transfer operations. Characteristics of SV are estimated here as extensions from the NASA Reference System Report[1], in which SV is mentioned only qualitatively. The SVs are assumed to weigh 10 T (20 T carrying maintenance and repair equipment) and to carry four passengers in addition to a crew of two. It is assumed that the LEO base has four SVs (including two for RIO); the GEO base has ten (including two for RIO); each operational power satellite has two; and RIO has six other operating around GEO for RIO crew rotations and spot checks. Transfer time (with minimum fuel consumption) between GEO base and any given power satellite could be as long as 24 hours.

2.2 Low Earth Orbit Base

No real design yet exists for the low Earth orbit (LEO) base of operations necessary during SPS construction and operations. Some initial construction and assembly of SPS support components or systems (such as COTV) can be anticipated at the LEO base. Transfers of people will also use such a base to simplify logistics.

The LEO base can be broken down to the following subsystem elements: (1) living/working quarters, (2) materials stockpile, (3) propellant depot, and (4) power systems. The LEO base is in a circular orbit at an altitude of 477 km.

Living/Working Quarters. Living quarters are postulated to be adequate to sustain crew morale for a three month tour of duty. During the startup phase, the maximum crew required for the silicon option is estimated at 225 people* for a period of two years during which the LEO base itself and 23 COTVs are built, and components and supplies for construction of the GEO base at geosynchronous orbit must be transshipped. For the gallium option, the GEO base is assembled at LEO and provides living quarters for the additional crew needed to build both the GEO base and COTVs.

During power satellite construction, the LEO base provides crew quarters for 75 people for the silicon option or 35 people for the gallium option. Short-term quarters are also provided for 160 people transferring from the Personnel Launch Vehicles (75 passengers each) to the Personel Orbital Transfer Vehciles (160 passengers each) and vice versa for crew rotation at the GEO base. The additional crew-space provided in the silicon option during the startup phase would be more than ample for this purpose. In the LEO base for the gallium option, transferring passengers would presumably have to use common space of the base (such as mess halls), or transfer directly between the PLVs and POTVs.

The living and working quarters consist of one or more pressure shells; an environmental control and life support system (EC/LSS); internal compartments and furnishings including plumbing, wiring, and air ducts; an access system (airlocks and docking ports); information systems (sensors, computers, controllers, communications); an attitude control system (ACS); and a thermal control system. The power system will be treated separately below.

Materials Stockpile. This facility is envisioned largely as an open framework structure with a large variety of "bins" capable of receiving and dispensing crates, boxes, or other objects. This structure (or some portion of it) must also be capable of assembling the COTVs and portions of the GEO construction base during

*All numbers given here for crew sizes are only estimates.

the startup phase. SVs will probably be used extensively for assembly work and for cargo handling.

The onboard systems will be support structures; information systems; materials handling equipment; an attitude control system; and a thermal control system. As before, power will be treated separately.

Propellant Depot. Principal variables are types of propellants, storage time, acceptable losses, and peak quantitites to be stored. The basic systems required are essentially fixed, however, and include storage tanks, onloading and offloading docks, pressurization systems, pumping systems, information systems, attitude control, and thermal control. Power is treated in the following section.

Power Systems. All of the above subsystems of the LEO Base require electrical energy to operate their individual systems. Whether distributed or central, the required power systems have several features in common. The fundamental energy source may be either solar, nuclear, or chemical. Past studies have shown solar and nuclear to be superior under such circumstances, and only these two will be considered further here.

About forty of every ninety minutes will be spent in the Earth's shadow. For a system with high power consumption, this results in very demanding storage constraints, roughly doubling the size of solar array required, in turn affecting radiator size requirements. Studies in the late 1960s and early 1970s of conceptual designs for LEO bases of various sizes showed a strong preference for nuclear power sources when the population size exceeded about twenty people.

2.3 Geosynchronous Earth Orbit Base

The GEO base for SPS will, in many respects, have great commonality with the LEO base in the living/working quarters, materials stockpile, and propellant depot. A notable exception is the radiation protection of crew quarters which may in turn affect other systems. The radiation environment of GEO will require more structural full-time shielding and a solar flare shelter.

The living quarters provide for 480 (silicon option) to 680 people (gallium option), who are rotated in groups of 160 passengers after a three-month tour of duty.

The most dramatic difference between the LEO base and the GEO base may be the power system. Since the GEO base gets continuous sunlight with only brief Earth eclipsing (maximum 72 minutes of darkness daily) during the spring and fall months, it seems likely that solar arrays will be the preferred source.

2.4 Power Satellites

The Reference Design system envisions large power satellites located in geosynchronous Earth orbit (GEO) at zero inclination with zero eccentricity. Two alternative versions of the power satellite are included in the Reference Design system. One of these is based on photovoltaic cells made of single crystal silicon (Si), while the other uses photovoltaic cells made of single crystal gallium aluminum aresnide (GaAlAs), with thin reflectors providing 2-to-1 concentration of sunlight on the photovoltaic cells.

Photovoltaic array (silicon option). Silicon solar cells 6.55 cm by 7.44 cm in size are assembled into panels with overall dimensions of 1.0687 m by 1.059 m, with the cells interconnected in a series/parallel manner, 16 cells in series, 14 cells in parallel across the entire panel. (Thin copper tabs 0.75 cm by 4 cm in size are soldered to the corners of the backs of four adjacent cells, providing both electrical and mechanical interconnection.)

These panels of 224 cells are then assembled into blanket segments 15 m across by 656 m long by welding electrical interconnect tabs between ends of adjacent panels in series, and mechanically taping parallel strings together, with tape reinforcing the electrical interconnect tabs as well. A total of 44 blanket segments, side by side, then fill up a square bay (667.5 m on an edge) of the power satellite. The blanket segments are attached to catenary tension cables running across each end of the trusswork structure of the bay, holding the blanket segments taut.

A power satellite designed to deliver 5 GW of busbar electrical power on the ground then requires 128 bays (8 by 16), with a total active solar cell area of 50.9 km^2 and a total photovoltaic blanket mass of 22,051 metric tons.

Photovoltaic array (gallium option). The general scheme for assembly into panels, blankets, and bays is similar to the silicon option. The solar cells operate at 125°C at an efficiency of 18.2%, with sunlight concentrated by thin membranes of aluminized Kapton forming the sides of 3 to 5 large "V"-shaped troughs, with the solar blankets at the bottoms of the troughs. With the walls of the troughs inclined at 60° from the floor, the concentration ratio is 2, so that only 30.6 km^2 of active solar cell area is necessary. The total inclined area of the reflectors is 61.2 km^2. The reflectors and solar cells together intercept 61.2 km^2 of sunlight and have a total mass of 7,651 metric tons, a major saving in mass compared to the silicon option.

Because of the concentration of sunlight on the solar cells, the operating temperature is sufficiently high to provide continuous annealing of lattice defects produced by the radiation environment at geosynchronous orbit.

Power Collection and Distribution. The electrical output of the solar arrays is collected together, transported across the rotary joint, and distributed to the microwave transmitting elements across the face of the transmitter array. The solar cells and their interconnecting tabs form the major portion of the power collection system, with strings of cells connected in series to provide 38.7 to 45 kilovolts (DC) to three main power buses of sheet aluminum 1 mm thick. For the silicon option, strings of solar panels about 1 m in width and up to about 5 km in length are ganged in parallel to produce 228 independently switched power sectors, each providing about 2000 amperes of current. In the gallium option, each of the 36 bays is switched separately, providing 6085 to 6638 amperes at 45.5 kilovolts.

On the microwave transmitter antenna, most of the power is distributed directly (except for switching) to two of the electron collector plates in each of the klystrons. The remaining power elements of the klystrons are provided with regulated power and voltage.

Power conditioning and conversion. Conversion from DC power to microwave power is done by approximately 100,000 to 140,000 klystron tubes, each converting about 85% of the input DC power (50 to 70 kW per tube) into microwave power. The remaining power is dissipated by heat pipes transferring waste heat to passive radiator fins or to the aluminium faceplate of the transmitter subarrays (see below). To keep the klystron filaments heated during eclipses and other power outages, batteries capable of storing up to 12 MW-hours of electrical energy are installed on the transmitter array.

Power transmitter and microwave beam. The microwave transmitter antenna is a planar phased array system approximately 1 km in diameter composed of 7220 subarrays, each 10.4 m by 10.4 m across. Aluminum slotted waveguides form the radiating surface of each subarray, while the klystron tubes are mounted on the back. Near the center of the array, each subarray has 36 klystrons (70 kW each), while subarrays near the edge have only 4, with varying numbers of tubes per subarray between, providing a 10-step tapered profile in the emitted power density, decreasing from 22.1 kW per square meter at the center to 2.46 kW/m^2 at the edge. (An alternative configuration, using 50 kW klystrons, has 50 tubes per subarray at the center, decreasing to 6 per subarray at the edge.)

Each subarray has a RF receiver and phasing electronics to process the pilot beam signal returned from the rectenna on the ground. The phasing signals provide the subarrays with the necessary information to form a single coherent beam focused at the center of the rectenna. The operating frequency of the microwave transmitter array is 2.45 GHz for the Reference Design.

Rotary joint. Since the photovoltaic array must face the Sun at all times while the transmitter array must face the Earth at all times, relative motion amounting to one revolution per day must be provided between the two major segments of the power satellite. In order to minimize gravity gradient torques on the power satellite, its long axis is oriented normal to the orbital plane and parallel to the Earth's axis of rotation. The transmitter array is then located at either the north or south end of the photovoltaic array and connected to it by the rotary joint.

The rotary joint consists of a turntable made up of two concentric rings about 350 meters in diameter separated by roller bearings. Electrical power is carried through the rotary joint by brushes sliding along three slip rings (one for each of the main power buses). The slip rings range from about 8 meters to 15 meters in diameter, and have a cross section of about 30 cm (radial thickness) by about 50 cm (height). Both the outer and inner faces of each ring are coated about 1 cm thick with coin silver (90% Ag. 10% Cu). Caliper-like structures support pairs of brush assemblies (each about 50 cm wide) distributed around each slip ring to transfer electrical power to or from both sides of each slip ring. Steel springs provide the necessary pressure on the brushes to minimize arcing problems without excessive wear. Total contact area for all the brushes, which are made of silver molybdenum disulfide with 3% graphite, is about 2×10^4 cm^2, so the current density in the brushes is about 20 amperes per square centimeter. The brushes slide along the slip rings at speeds of about 1 to 2 meters per hour.

Attitude control system (ACS). The attitude control system provides thrusters, sensors, and computers to perform station-keeping and orientation control for the power satellite. For the gallium option satellite, a total of 35 operating argon ion thrusters are needed (100 for the silicon option power satellite, since it is more massive); to provide the necessary redundancy (assuming once-a-year maintenance), the Reference Design provides 64 thrusters (160 for the silicon option), 16 at each corner of the photovoltaic array. Each thruster is independently gimballed and controlled. Chemical thrusters are also installed to provide control during eclipse by the Earth.

Th attitude control system uses 34 MW of power (average), mainly for the ion thrusters, in the gallium option, somewhat more for the silicon option. Propellant requirements for the ion thrusters are on the order of 40 to 100 tons of argon per year, along with 1.5-5 tons of liquid oxygen and liquid hydrogen for the chemical thrusters. Propellants are stored cryogenically, with electric refrigeration and (possibly) reliquefaction.

Living/working quarters. The Reference Design system does not provide any living quarters or working facilities aboard the power satellites. Maintenance is assumed to be done by annual visits of maintenance crews visiting from the GEO base. Addition of living and working quarters for both inspection teams and a small permanent maintenance team (5 to 20 people) may be cost-effective. Further, if the owners of the power satellite are concerned about saboteurs infiltrating inspection teams, they may wish to have their own security personnel aboard the power satellites to monitor the inspectors. No additional DDT&E costs would be incurred, since the quarters could be identical (except for total size) to those provided at the GEO base, including a solar flare shelter. These living quarters would most likely be placed near the middle of the photovoltaic array, either directly behind it or at one side, to provide a constant thermal balance (except during eclipses), minimal travel times and distances to all parts of the power satellite, and a safe distance from the microwave transmitter array. (The klystrons emit significant levels of x-rays since electrons of up to 45 keV are constantly bombarding the metal collector plates.)

Access to all parts of the power satellite would probably have to be provided by electric crawlers running along the support structures. The crawlers could carry enough shielding to shelter the crews from solar flares.

2.5 Rectenna

The receiving antenna array (rectenna) on the ground converts the microwave beam into DC electrical power. The Reference Design system assumes that the DC power will be converted to high voltage alternating current for distribution via existing transmission systems in industrialized countries, including the United States.

Power collection antennas. At the surface of the Earth the circular cross-section of the microwave power beam contains 88% of the total power within a 5 km radius of the centerline. At a latitude of 34°, the "footprint" of the beam is an ellipse 10 km wide (east-west) and 13 km long (north-south). The microwave power is collected by half-wave dipoles feeding Schottky barrier diodes (a kind of solid-state rectifier). Dipole panels arranged in east-west rows covering the 10 km by 13 km footprint of the power beam provide a total active area of 78.5 km^2. A total of nearly 11 billion dipoles is required for each 5 GW rectenna site.

Power conversion and conditioning. Power from a few dozen dipoles is gathered together and fed to the Schottky barrier diodes through two-stage low-pass filters to suppress reradiation of harmonics by the dipoles.

Support structures. The dipoles and diodes are mounted on panels of steel mesh and lightweight steel framing. Panels are mounted, inclined, in rows aligned east-to-west, supported by steel posts implanted in concrete footings in the ground. For ease of access, the panels should be as low as possible; for alternate land use beneath the rectenna, it would be advantageous to elevate the panels several meters above the ground.

Power distribution and utility interface. Panels of collectors are ganged together into 1 MW units at a DC voltage of ± 2 kV. These are again arrayed into 125 larger units of 40 MW each, still at the same voltage. Each of these units has its own local DC-to-AC converter, providing output at whatever line voltage is desirable for integration with the transmission network.

Assuming high voltage AC is to be the end product, the rectenna interface with the electric utility system would include one or more electrical transformer yards of conventional type, including circuit breakers and switching gear. If various chemical forms of output are desired, the necessary synthesis plants and transportation or pipeline interfaces would probably be located on, or very near, the rectenna site.

Pilot beam and associated equipment. The phased array microwave power transmission system is designed to rely on a pilot beam from the rectenna to provide the necessary information for phase control. The pilot beam is transmitted by double sideband carrier at frequencies symmetrically displaced from the power beam frequency. To avoid intermodulation effects in the ionosphere between the power beam and the pilot beam, the frequency split between the sidebands must be at least 20 Mhz. The pilot beam (in the Reference Design) is transmitted from the geometric center of the rectenna. Measurements of microwave intensity at perhaps one or two dozen locations around the perimeter and scattered in the interior of the rectenna site provide information necessary to control transmitter array phases in such a way as to keep the power beam centered on the rectenna and its profile nearly constant despite ionospheric distortions. This information is encrypted in such a way that it is decipherable only to the power satellite corresponding to a particular rectenna. The system must also allow the transmission of a shutdown signal to the power satellite.

2.6 Command and Control (C^2) System

The Reference System Report discusses the subject of integrated operations management for SPS very briefly, but the discussion there is not sufficiently detailed for our purposes. Figure 2-1 presents our concept of the command, control, and communication (C^3) system for SPS during the routine construction and operation phase of the program. We will discuss C^2 centers in this section, and communications (the third "C") in the next section.

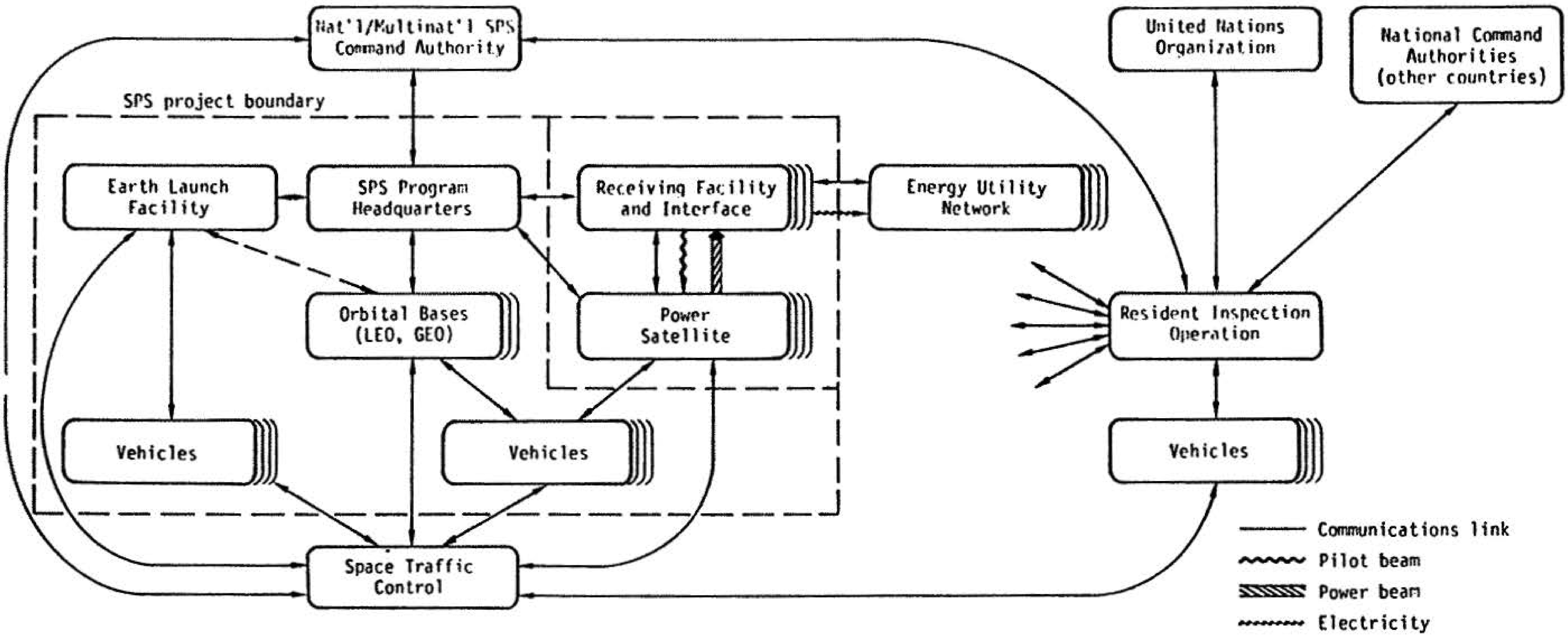

Figure 2-1. Command, control, and communications (C^3) system for the SPS during the routine construction and operation phase of the SPS program.

The nodes of the diagram (shown as balloons) represent C^2 centers, while solid lines betwen nodes represent communications links. The wavy line between each power satellite and its corresponding receiving facility (rectenna) on the Earth represents the pilot beam, while the heavy crosshatched line is the power transmission beam. The jagged line between each rectenna and an energy utility network represents the electrical power supplied by the rectenna.

C^2 nodes in the Satellite Power System (whether or not owned by the legal entities managing the SPS program) include the SPS Program Headquarters,* Earth launch facilities, launch vehicles, the LEO and GEO bases, orbit-to-orbit and sortie vehicles, the power satellites, and the rectennas. All of these have been discussed before. C^2 centers at each of these SPS elements typically include a variety of sensors (e.g., radars), data processing and display equipment, and communications equipment. Each C^2 center is manned by people who are trained and responsible for decisionmaking germane to the functions of that element.

<u>SPS C^2 Centers (Typical)</u>. The C^2 centers at each SPS facility have responsibility for normal SPS operations (including power generation on board the power satellites, control of the power beam at the power satellite and at the rectenna, and general communications management); for construction operations; for maintenance operations; for control of space traffic in the immediate vicinity of the SPS element; and for command and control of military equipment (if any) at the SPS element, including operation of surveillance systems, self-defensive weaponry, and offensive weaponry.

<u>C^2 Centers at the Power Satellites and at the Rectennas</u>. The C^2 centers at each power satellite and at each rectenna have the same kinds of equipment and the same scope of authority as other C^2 centers, except for the addition of the pilot beam controlling the microwave power beam. Since the pilot beam is a key element in the fail-safe design of the SPS, additional protection and precautions must be implemented to prevent unauthorized interference with, or deliberate military misuses of, the pilot beam.

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*The term "Program Headquarters" includes offices of the legal entities controlling SPS as well as offices, laboratories, and Earth-based facilities of the operating entities.

What is specifically new about Figure 2-1 is the identification of interfaces between the SPS and various C^3 nodes external to SPS which are critical to an understanding of the military implications of the program. These external nodes are the various power grids operated by utility companies which are SPS customers; a space traffic control center; the international Resident Inspection Operation, a safeguard for the Satellite Power System, discussed in Section 5; and the (military) National Command Authorities (NCA) of the countries sponsoring the SPS program in either a legal or an operational manner. The functions of each of these external nodes are discussed below.

The boundaries of the SPS are indicated by the dashed lines in the figure. Whether the rectennas and power satellites are owned by the SPS organization or by the utility companies is an important question from the financing and legal viewpoints, but of little relevance from the operational viewpoint which is key to examination of the military implications.

Utility Power Grid C^2 Centers. As was mentioned earlier, individual segments of the power satellite solar cell array can be switched separately, allowing the total power delivered by a power satellite to its rectenna to vary to match load demand of the utility grid. A C^2 center in the utility grid exercises this control over the power satellite, manages load shifting in anticipation of power satellite eclipses and power satellite outages for scheduled maintenance, and manages load shifting in response to unscheduled interruptions (for any reason) of power from the rectenna. Control of power satellite output may be transmitted to the satellite via the pilot beam or by a separate communications link. Personnel operating these C^2 centers are likely to be utility company employees.

Space Traffic Control Center. In the 1990 to 2030 time frame, it is very likely that some sort of centralized space traffic control will be in operation, serving a role analogous to that of the Federal Aviation Administration's Air Traffic Control. The space traffic control center would keep up-to-date information on orbital parameters, masses, and ownership of all sizeable objects in Earth orbit. Parameters of proposed launches or orbit-to-orbit transfers would be examined by computer for possible conflict with existing objects in space, and suitable clearances issued before launch. Such a space traffic control center may be operated by the United States as an extension of the space tracking now performed by the Air Force's North American Air Defense Command (NORAD), or may be operated under international agreements* by an entirely new international entity.

National Command Authorities (NCA). It is the policy of the United States today that, in time of national emergency, all space facilities belonging to U.S. government agencies or to corporations domiciled in the United States may be taken over by the NCA for its use in dealing with the emergency. We assume that this policy would also apply to SPS facilities, and that other countries will adopt similar policies.

For simplicity in understanding the implications of Figure 2-1, assume at first that the entire SPS is owned and operated by the United States. In a national emergency, the NCA would communicate command and control directives for various SPS facilities, whether on Earth or in space, via SPS Program Headquarters. The NCA would also communicate directly with the space traffic control center, especially if it is operated by the United States, to obtain appropriate clearances for military launches or launches of civilian spacecraft supporting military activities in the emergency. The space traffic control center would then provide alternate communication paths between the NCA, SPS facilities in space, and the launch facilities on Earth.

Assume now that the SPS is a cooperative undertaking involving several or many nations. If specific elements of the SPS are owned and operated by particular countries, and if each country has a policy with respect to space assets similar to that of the United States, the respective space facilities would come under the command and control of the respective National Command Authorities in emergencies.

To avoid disruption of the entire system due to an emergency involving only one or a few of the SPS participants, however, it may be desirable for all participants (including the United States) to exempt SPS facilities from such a policy on space assets.

*Air traffic in international airspace (over the oceans) is provided by the air traffic control systems of individual countries bordering the international air space under specific agreements with the International Civil Aeronautics Organization (ICAO).

The Resident Inspection Operation. The Resident Inspection Operation has a C^3 network similar to that of the SPS, which can be envisioned as overlying the SPS C^3 network shown in the major portion of Figure 2-1. The C^3 system for RIO, however, differs in that RIO headquarters must interface with three additional sets of nodes: (1) the United Nations Organization (UNO); (2) the NCAs of all the countries participating in SPS or in RIO; and (3) the space vehicles belonging to RIO. These interfaces are necessary for RIO to perform its purpose effectively and reliably. In order to disseminate information gathered by resident inspection teams, RIO must have assured communications directly to the UNO and the NCAs involved in SPS and in RIO. In order to maintain the capability of independent space travel for inspection purposes, especially in times of international tension or crisis, RIO must have its own fleet of space vehicles and thus must have assured direct communications between headquarters and each vehicle. (This is in addition to the communications required between RIO vehicles and various launch facilities, orbital bases, and the space traffic control center.)

Figure 2-1 shows the C^3 system for the routine construction and operations phase of the SPS program. A C^3 system will also be an essential part of SPS during the DDT&E phase. Since many of the components of the SPS will not yet have been constructed, the network would be considerably simpler but the international Resident Inspection Operation would already be in place to protect against military adaptation of the SPS and to assure that appropriate safeguards are designed into the system from the start.

2.7 Communications System

The full C^3 system shown in Figure 2-1 requires a great many long-distance links between various facilities, both within and outside of the Satellite Power System. Communications on Earth are assumed to use commercial telephone land lines and microwave nets, commercial communications satellites, and conventional radio. Space communications may be conventional RF channels or laser links, the latter providing greater security and privacy.

Figure 2-1 suggests that space vehicles would communicate only with space traffic control and with C^2 centers at the point of departure and at destination. Messages from SPS Program Headquarters would be relayed via the departure or destination facilities, if necessary. If a space traffic control system were in operation, the Earth launch facilities would have no need to communicate directly with the LEO or GEO bases, since space traffic control would coordinate departure and arrival traffic flows with the local traffic controllers at the launch site and at the orbital bases, as well as at individual power satellites.

Communications which must be private can be provided by digitizing the messages and encrypting the digital stream by any one of a wide variety of algorithms, including some which are presently believed to be essentially unbreakable.[2]

2.8 References

1. "Satellite Power System (SPS): Reference System Report," DOE/ER-0023, DOE/NASA, January 1979.

2. Martin E. Hellman, "The Mathematics of Public-Key Cryptography," Scientific American, pp. 146-157, August 1979.

3.0 THREAT ANALYSIS

Numerous satellites in Earth orbit presently perform military missions of surveillance, reconnaissance, communications, navigation, and weather observation. Unmodified elements of the Satellite Power System such as the transport vehicles, the LEO base, or the power satellite itself could offer advantages for some military support functions. In view of the size and scope of SPS we consider what possible military adaptors, if such a decision were made, could be attached to a SPS to enhance its ability to perform military missions.

Potential military uses of SPS would be to support military operations in space. The LEO base, for instance, could be used to provide shelter, supplies, and services such as propellant stockpiles and maintenance and repair facilities. Similarly, OTVs could be used to provide transport for military personnel and equipment.

If decisions were made to add to, or modify, the Reference Design SPS, then space-based elements of the SPS could become platforms for various weapon systems including antisatellite missiles (ASAT), high energy lasers (HEL), and particle beam weapons (PBW). With deliberate hardware modifications, the SPS microwave power beam could be used for electronic warfare (EW).

In this section, we assess the threat potential of the Reference Design Satellite Power System and the threat potential of an SPS with deliberately enhanced military capabilities.

3.1 Methodology

A matrix formulation was used to provide a convenient framework for presenting the results of our analysis.* Each row of the matrix represents a subsystem element of the SPS, while two main columns identify, respectively, the potential threats posed by each subsystem element and the corresponding safeguards for neutralizing or mitigating each potential threat.

Threats were subdivided into technological threats and institutional threats. By technological threats, we mean capabilities to perform the functions of force delivery, C^3I, and military support. By institutional threats, we mean use of subelements of the SPS system as tools to coerce unfriendly nations into particular

*The completed matrix is given later as Table 3-9.

political actions. As an example, if the United States were supplying electrical power to a foreign nation and desired to apply pressure to that nation, the United States could threaten to shut off power from the SPS. Similarly, economic warfare might be conducted by controlling the price of electrical power, much as the price of oil is controlled by OPEC.

Safeguards, like threats, were subdivided into technological and institutional categories. Technological safeguards involve methods of force delivery or surveillance. Institutional safeguards encompass such means as international agreements and treaties, and international inspection. Potential safeguards will be discussed in Section 5.

3.2 Potential Military Uses of the Reference Design SPS

Implementation of the Satellite Power System would result in a large expansion of basic capabilities in space. Could those capabilities inherent in the Reference Design SPS be used for military purposes, without any modifications of SPS hardware, if a deliberate decision were made to use SPS elements militarily? In this section, we assess the capabilities of the unmodified elements of SPS for such potential uses.

Transportation System. The Earth launch facilities used for SPS could be used for launch of military vehicles or for transportation of military cargo and personnel aboard launch vehicles belonging to the SPS. The Earth-to-LEO vehicles, the orbital transfer vehicles, and the sortie vehicles belonging to SPS could all be used for military transport purposes, including deployment, retrieval, and on-orbit maintenance and repair (DRMR) of military satellites, with no modifications of the hardware. These military support applications of the SPS transportation systems are no different in kind from the use of the civilian highway system, railroads, airlines, and ships for transportation of military personnel and cargo on Earth.

The Personnel Launch Vehicle, the Personnel Orbital Transfer Vehicle, and the Sortie Vehicles, however, could all be used (to a limited extent) to "kidnap" satellites belonging to hostile countries (SATNAP). To use the civilian SPS vehicles for this purpose, however, requires a deliberate decision to do so, and if the seized satellites were in operation at the time of capture, the act would be detected immediately.

The LEO and GEO Bases. Both bases in the Reference Design could be used in certain military support roles without any hardware modifications, including shelter for military personnel; supplies (life support consumables and propellants); and such services as medical treatment, repair of military equipment and spacecraft, data processing support, and communications. In an emergency, many of these support activities would be provided to civilian or military personnel in space from any nation under provisions of the 1968 Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched Into Outer Space. Such uses of the SPS on a sustained basis, however, would require deliberate expansion of SPS facilities to accommodate these military missions without reducing SPS productivity.

Power Satellites. The living and working quarters aboard the power satellites would offer shelter, support, and services (including electrical power) similar to those afforded by the LEO and GEO bases, but on a smaller scale.

Since the 1967 Treaty on Principles declares that outer space "shall be free for exploration and use by all States wihout discrimination of any kind," military spacecraft belonging to a friendly nation could find sanctuary by flying in close proximity to various SPS facilities in orbit or, indeed, even between the girders of a power satellite. Hostile forces might be reluctant to attack military spacecraft so close to a civilian space asset for fear of incurring retaliation from a third party. The owners of an SPS facility being used as a sanctuary could publicly deny any cooperation or consent since the Treaty on Principles permits such close flight.

Rectenna. The electrical power supplied by a rectenna can be used for both civilian and military purposes. In this sense, the rectenna would serve a military support function, especially if located near major military facilities.

Command and Control System. C^2 centers at power satellites and rectennas could be used to shut down the power satellite, denying power to the utility network.

Communication System. The communications links throughout the SPS could be used, with no modification of hardware, to relay messages for military purposes.

In summary, the threats which an unaltered Satellite Power System can pose to other nations are modest in scope, even if deliberate policy decisions are made to use the SPS for such purposes. We now turn to consideration of threats posed by a SPS which has been modified to incorporate military adapters.

Technological Threats

Table 3-1 lists the three main mission areas in which the military capabilities of the SPS, if such a decision were made, could be enhanced by technological means to pose threats to non-SPS nations and indicates possible adapters which would have to be installed in order to provide those enhancements.

Table 3-1. Possible Military Adapters for SPS

MISSION AREA	POSSIBLE ADAPTERS
Force Delivery	Projectile weapons Manipulators Directed energy weapons
C^3I	Communications packages Wide area broadcast transmitter Radar Lidar Telescopes (optical/IR) RF receivers
Military Support	Navigation beacons Power beam diverter CBW laboratory and/or stockpiles Augmented manning

3.2 Force Delivery

With suitable adapters, elements of a Satellite Power System offer new possibilities for force delivery in the space environment. First, the power satellites can supply approximately 8 GW of electrical power; the COTVs can suply 260 to 610 MW; and the LEO and GEO bases can provide lesser amounts. Second, SPS elements offer a number of orbital platforms which have complete sets of built-in housekeeping functions (station-keeping, attitude control, C^2 center, utility power, etc.). Third, LEO and GEO bases (and perhaps the power satellites) are permanently manned facilities.

Adapters which could be used for force delivery when combined with elements of the SPS can be divided into three categories listed in Table 3-1. Projectile weapons could be used against targets in space or on Earth. Manipulators could be attached to orbital transfer vehicles or to sortie vehicles and used to seize satellites ("satnapping") or to damage or destroy enemy satellites (satellite mutilation, "satmut"). Various types of directed energy weapons (DEW) could be developed and attached to SPS elements having abundant power onboard.

3.2.1.1 Force Delivery Adapters for SPS. Projectile weapons for use against space targets (space-to-space missiles) can be categorized in several different ways. It is useful to consider the means of propulsion (rocket propelled or impulsively propelled) and the velocity change the projectile or its launcher is capable of achieving ("low velocity"--Δv of order, say 300 m/sec. suitable for co-orbital missions; "high velocity"--Δv of order 3000 m/sec, suitable for targets at significantly different altitudes, eccentricities, or inclinations).

Both rockets and projectiles can be used for co-orbital missions. Rockets allow the possibility of midcourse and terminal correction maneuvers and thus are applicable to orbital intercept (OI), but they may be relatively costly and can probably be detected and tracked unless special measures are taken. These measures include "reduced observables" (techniques such as antireflective paint or suitable shaping to reduce radar cross sections); decoys; and propulsion using cold gases to avoid the strong infrared (IR) signature characteristic of a hot exhaust.[1] Impulsively propelled projectiles (bullets, fusillades of pellets, or shaped charge explosives) are very difficult if not impossible to detect and track. In most cases, such projectiles would be easy to launch from small platforms in space. (Note that conventional high velocity rifles attain muzzle velocities on the order of 300 m/sec.)

At greater distances from the Earth, small velocity changes can result in large changes in orbital parameters, including inclination, apogee, perigee, and eccentricity. (The orbital speed of the Moon around the Earth is less than 1 km/sec.) Small launch platforms for space-to-space missiles, deployed beyond geosynchronous orbit, could thus be very difficult to detect, track, and monitor since modest supplies of propellants could make their orbits essentially unpredictable for months at a time. Projectiles launched on command from such "hidden" platforms could then attack targets anywhere in the Earth-Moon system from virtually any direction.

Transorbital missiles (requiring velocity changes of several thousand meters per second) are limited to rockets, shaped-charge particles, and other projectiles. Using standard solid propellants, a single stage rocket can accelerate a warhead of 0.2 metric tons (T) to 3000 m/sec with a gross ignition mass of only 1 T. If the warhead were nuclear, its yield would be of over 1 megaton.[2] Such a warhead and rocket combination corresponds to a missile having a diameter of 0.5 meter and a length of 3-4 meters. Shaped charge projectiles can typically attain speeds on the order of many thousands of meters per second, but present significant aiming problems. Since they are simple and cheap, however, they would seem to be suitable for "shotgun" attacks at great distances.

Projectile weapons for use against Earth targets are commonly known as reentry vehicles (RV). The technology for high speed warhead reentry has been demonstrated by the Soviet Union in the Fractional Orbit Bombardment System (FOBS) program, and for suborbital speeds in intercontinental ballistic missile (ICBM) programs in several countries. The 1 T missile described above as a space-to-space missile could be used as an Earth bombardment (EB) weapon from the LEO base or from the COTVs during the large portion of their round trip time between LEO and GEO which is spent at low altitudes. If the warhead weight were increased by 50% to allow for reentry systems, the rocket's Δv would decrease from 3000 m/sec to 2600 m/sec, still more than adequate for deorbit and reentry maneuvers.

Furthermore, if two of the same solid propellant rockets were strapped together and used as a boost stage for a third rocket with warhead, this would form a 2.7 T two-stage missile. Launched from geosynchronous orbit (either from the GEO base or from a power satellite), such a missile could deliver the reentry vehicle to any target on Earth from any point in GEO at any time, with a transit time of little more than 5 hours. If the launch were clandestine, with the missile designed for minimal IR signature and radar cross section, the first warning of attack might be reentry streaks in the sky no more than 30 seconds before impact.

The effectiveness of such attacks can be enhanced by use of reentry vehicles designed for controlled aerodynamic maneuvering during reentry, as developed during the 1970s in the U.S. Air Force's Aeroballistic Reentry Systems (ABRES) program.

(Article IV of the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Clestial Bodies states:

> State Parties to the Treaty undertake not to place in orbit around the earth any objects carrying nuclear weapons or any other kind of weapon of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner.

The strength of this treaty provision has perhaps been eroded by the failure of the United States to protest the Soviet FOBS program both publicly and vigorously, shortly after the treaty entered into force; by recent U.S. studies of placing Minuteman warheads in orbit for survivability during periods of increased tension; and by the open question of whether unassembled nuclear warhead components can be considered to be "weapons."

The potential effectiveness of both first-strike and second-strike attacks against targets in low orbits and on the Earth by strategic weapons deployed in far orbits (GEO and beyond) has been stressed previously.[3] Defense against this kind of attack, once launched, appears to be difficult, if at all possible. This case points up the critical need for effective and credible safeguards for SPS to assure the international community that military adapters could not be added to the SPS.

The technology of robotics (as exemplified by remote manipulation equipment in nuclear laboratories, the Space Shuttle payload deployment arms and manipulators, and a host of related developments in automation) will enable many SPS construction and operational functions to be accomplished by remote control. These developments will also lead to the possibility of small automated vehicles, equipped with grapplers, which would be capable of approaching foreign spacecraft to inspect them, to capture and retrieve them, or to negate them by weapon fire or by physical breakage by direct contact (satellite mutilation). Grapplers might also be incorporated in sortie vehicles for special missions, but the risk of possible boobytraps in foreign spacecraft make remotely operated grapplers more attractive.

Grappler-equipped vehicles could be based at maintenance and repair facilities at the LEO and GEO bases, or at the power satellites where periodic servicing would be available.

A great deal has been written about directed energy weapons (DEWs) in the popular press,[4,5] especially high energy lasers (HELs) and particle beam weapons (PBWs).* However, directed energy from a power satellite or other SPS element having a sizable power supply can be delivered in a number of other ways as well. One such way would be to utilize the microwave power beam itself for electronic warfare directed against satellites or against Earth-based targets. At lower power levels, it is conceivable that an RF transmitter could be attached to the SPS and utilized for electronic warfare (EW) or electronic countermeasures (ECM). Lastly, the SPS power beam itself could be utilized for Earth irradiation (ER) if it were captured by a "Pied Piper box." Such a box would emit a pilot beam suitably encoded to capture a specific power beam. Covert placement of the box in an enemy location (such as a major population center) would direct the power beam wherever desired. If many beams could be captured simultaneously, the total microwave flux could reach incendiary levels. If the beam from a single SPS were captured, the power level would be rather low but could conceivably be utilized for psychological warfare against civilian populations in which misperceptions about biological effects of microwave irradition were prevalent. No biologically harmful effects of the SPS microwave beam are known.

3.2.1.2 Force Delivery Missions for a SPS With Military Enhancements. Table 3-2 lists possible missions or uses for force delivery devices which could be mounted on SPS elements or for SPS elements themselves when adapted or modified for force delivery. The table also lists acronyms or abbreviations for these missions and indicates the SPS adapters or elements which could perform each mission.

For the silicon photovoltaic cell option, each of the 23 COTVs has some 260 MW of electrical power onboard; for the gallium option, each of the 9 COTVs has 610 MW, adequate for either PBWs or HELs of significant threat potential. The COTVs take about six months to make a round trip between the LEO base and the GEO base; most of that time is spent in the lower altitude regions, so that the range to

*Particle beam weapons and high energy lasers are discussed in detail in Appendices C.2 and C.3, respectively.

Table 3-2. Uses of Force Delivery Devices

POSSIBLE MISSION OR USE	ABBREVIATION	SPS ADAPTER OR ELEMENT
Ballistic missile defense	ABM	PBW, HEL
ASAT carrier	AC	COTV, POTV, SV
Satellite attack	ASAT	OI, PBW, HEL, SPS power beam, EW
Satellite seizure	SATNAP	SV with grapplers
Satellite mutilation	SATMUT	SV with grapplers
Earth bombardment	EB	RV
Earth irradiation	ER	HEL, SPS power beams
Electronic warfare	EW	SPS power beam
Weather modification	WXM	SPS power beam, special RF transmitter
Physical attack	--	Armed military troops

significant targets (LEO satellites, ICBMs, high altitude aircraft, foreign Earth-to-LEO vehicles, etc.) is characteristically 1000 to 5000 km, not 35,000 km or more as for the power satellites themselves. Furthermore, the ground track of a COTV encircles the globe instead of remaining at fixed longitudes as is the case for the power satellites. Some provision would have to be made for energy storage aboard the COTV if the weapons were to be usable even when the COTV is in the Earth's shadow, but given the payload of 3500-4000 T available, a modest decrease in useful payload could be compensated by adding a few more COTVs to the fleet.

The term ASAT carrier (AC) refers to the use of a transport vehicle to carry antisatellite weapons such as space-to-space missiles or space lasers.

In the Reference Design, the power density at the center of the microwave beam exceeds the solar constant at distances less than about 12,000 km from the transmitter array, reaching 4 solar constants at a range of about 5000 km.[5] Unless spacecraft intended to pass through these regions of space are properly designed, significant thermal overloading may occur, whether or not the microwave beam is aimed at them deliberately.

High energy lasers and possibly particle beam weapons could be used for irradiation of Earth-based targets (ET). However, the characteristics of PBWs may make it impossible for their beams to penetrate the Earth's atmosphere. (Refer to the discussion in Appendix C.2.) The SPS power beam itself could be used to irradiate areas on the Earth. While one beam does not supply a high level of intensity, focusing the power beams of, say, twenty power satellites upon the same location would result in a power level of 460 mW/cm^2 at the center. This is approximately 3.3 times larger than the peak incident solar flux at the Earth's surface (~140 mW/cm^2). Such diversion of SPS power could be used only against targets in the same hemisphere as the intended recipient of the power. Regardless of the means used, the term "Earth irradiation" is intended to denote levels of radiation which are sufficiently high to cause physical damage to the intended target.

Another category of radiation weapon is electronic warfare. This involves the jamming of enemy communications links, radars, or navigation signals by the SPS power beam itself or by special transmitters operating on military frequencies. (See Appendix C.4 for a discussion of electronic warfare possibilities.)

A third category of radiation weapon is deliberate weather modification. As discussed in Appendix C.6, it is unlikely that weather modification could be achieved with the SPS power beam operating at 2.45 GHz. At the least, it would be necessary to install a high-power RF transmitter operating at approximately 22.2 GHz. Even with such a transmitter, weather modification appears to be of doubtful feasibility.

The last force delivery mission shown in Table 3-2 involves the actual physical attack of space-based facilities by armed military troops. Such troops could be used as boarding parties to inspect an enemy space station or possibly even to seize it (SATNAP).

3.2.2 Command, Control, Communications, and Intelligence (C^3I)

The Satellite Power System appears to offer few new possibilities for performance of C^3I missions beyond those expected to be available during the 1980s and 1990s in the absence of SPS. Nonetheless, the sheer scale of SPS suggests that military C^3I functions might be performed in conjunction with SPS on a larger scale and, perhaps, with some economies.

3.2.2.1. C^3I Adapters for SPS. Various electronic devices could be attached to SPS elements to facilitate communications relays, both ground-to-space and space-to-space. The ability to relay communications between spacecraft would be particularly useful for communicating in a covert manner with silent satellites, using a tightly focused laser beam. The SPS element could then relay the signals down to Earth. Similarly, adapters could be provided for wide area broadcast to earth to disseminate propaganda.

Active sensors (such as radars and lidars*) or passive sensors (which could be used to obtain optical and/or infrared imagery or to detect radio and microwave signals emitted by space-based and ground-based military transmitters) could be readily added to SPS elements. Such sensors could perform surveillance of both space and Earth for the purpose of attack warning, tracking of spacecraft, tracking of vehicles on the Earth's surface or in the Earth's atmosphere, and gathering of electronic intelligence.

3.2.2.2 C^3I Missions for a SPS with Military Enhancements. Table 3-3 lists the possible military missions or uses of various C^3I devices and facilities. Command and control (C^2) consists primarily of receiving sensor data, making decisions based on that data, and communicating the results of these decisions to other units which will execute suitable responses. These functions are typically performed in a command post where decisionmakers have access to data processing equipment and communications equipment. Most elements of the SPS system will have some sort of command center to direct local operations and to perform space traffic control in their immediate vicinity. Such command centers thus could be used readily to perform military command and control functions.

Various types of sensor technologies can be used for surveillance and reconnaissance. All current sensing methods utilize some type of electromagnetic phenomenon. Optical and infrared systems (telescopes, cameras, and lidars) can be used to look at objects in space, as well as to view objects located upon the Earth from a space platform. Various types of radio receivers and radars are also widely used for S&R.

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*Just as "radar" is an acronym for RAdio Direction And Range finder, so "lidar" is an acronym for LIght Direction And Range finder which uses a laser beam (usually infrared to avoid visual detection of its use) to track targets.

Table 3-3. Uses of C^3I Devices and Facilities

POSSIBLE MISSION OR USE	ABBREVIATION	DEVICE/FACILITY
Command and control	C^2	Space traffic control center C^2 center at launch facility C^2 center at LEO base C^2 center at GEO base C^2 center at power satellites C^2 center at rectennas
Communications	Comm.	Radio links Laser links
Surveillance and reconnaissance	S&R	Cameras Telescopes Radars Lidars
Signal intelligence	SIGINT	Radio receivers

A special category of S&R use of radio receivers is the collection of signal intelligence (SIGINT). Two types of intelligence data can be obtained from SIGINT collection: electronic intelligence (ELINT) and communications intelligence (COMINT). ELINT provides data on the characteristics of RF emitters such as radars (e.g., frequency, power, and waveform) and on noncommunications transmissions (e.g., telemetry). COMINT is obtained from analysis of communications patterns between various nodes in a C^3 network (traffic analysis) and the reading of messages transmitted between the nodes. If these messages are not transmitted in plain language (which is the usual case), analysis of the system used to encipher or encrypt the messages is required before the messages can be read.

All of the possible uses outlined in Table 3-3 are considered to be real threats. All can be performed given currently existing technology. Except perhaps for use of SPS C^2 centers for military C^2 purposes, none of these uses of SPS appear to offer great advantages over dedicated space systems independent of the SPS.

3.2.3 Military Support

Virtually any large-scale addition to the civilian economic infrastructure can be used in some way to enable or to assist military forces in performing their principal missions of force delivery and C^3I. The Interstate Highway system in the United States, for example, is one of the largest civilian projects ever undertaken by the federal government,* but one of the arguments used in the 1950s to justify it was its potential use in deployment of mobile ICBM launchers. Similarly, we anticipate that SPS elements could be used, or modified, to perform a wide variety of military support roles.

3.2.3.1 Military Support Adapters for SPS. Table 3-1 indicates possible adapters which could be added to SPS elements to provide enhanced capabilities for military support. Beacons or transponders could be installed aboard space segments of the SPS to provide navigational services for land and sea forces, for aircraft, for spacecraft, and for ballistic missiles during boost phase or terminal maneuvering. In view of the anticipated capabilities of independent navigational satellite systems such as the NAVSTAR Global Positioning System (GPS), which will provide geographic coordinates anywhere on Earth accurate to 10 meters in all three coordinates by about 1990,[6] and velocity measurement accurate to 0.03 meters per second in all three directions, it is difficult to foresee any real advantage to attaching such navigational devices to SPS elements.

It would also be possible to install phase control circuits on the power satellites which could divert the microwave power beam (or a portion of the beam energy) to different locations on the Earth in order to provide substantial amounts of electrical power to remote military installations. Similarly, the diverted power beam(s) could supply power to other spacecraft, although large receiver antennae would be required. Such spacecraft, especially if located in low orbits, could field directed energy weapons to good advantage. Depending on technological advances, it might also be possible to transmit power by laser beam to armed spacecraft or to military aircraft at high altitudes, permitting almost unlimited loiter.[7,8]

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*The federal govenrment has thus far spent about $175 billion (1978 dollars) for construction of the Interstate Highway system.

Since orbital stations can be kept isolated from the Earth's biosphere, they may offer attractive locations to develop or store chemical and biological weapons (CBW). A CBW lab is thus a possible military adapter for the SPS system.* Such a lab would be placed in a separate structure to minimize the possibility of inadvertent vectoring of agents to other orbital facilities. Physical separation of the lab would also restrict physical access by uncleared personnel and thus improve security.

The last type of "adapter" to enhance military support capabilities is augmented manning. The LEO base, the GEO base, and perhaps the power satellites, all have the necessary life support and communications facilities to serve as alternate command posts, with minimal modifications needed except to supply trained military personnel. These facilities could also serve as operational bases for trained military troops.

3.2.3.2 Military Support Missions for a SPS with Military Enhancements. Table 3-4 lists possible missions and uses of military adapters and SPS elements for military support. These support missions can be grouped in a few broad categories as discussed below.

The first such category is transportation. This includes the use of SPS launch facilities as alternate launch sites for military spacecraft, the use of SPS orbital structures as docking platforms, and the use of Earth-to-LEO and orbit-to-orbit vehicles to transport military troops or supplies.

The second broad category involves the supply of military material. This includes propellants, life support consumables, electrical power, and beamed power for military satellites or remote ground installations. For example, the materials stockpiles located in LEO and GEO could be utilized to support a wide range of military activities in space.

SPS facilities could also be used to provide a much broader range of support. We refer to such support as shelter, services, and supplies (S^3). This category is particularly applicable to the living/working quarters which are present at the LEO and GEO bases, as well as at the SPS. Shelter would provide life support and

*See Appendix C.5 for further discussion of CBW and SPS.

Table 3-4. Uses of Military Support Devices

POSSIBLE MISSION OR USE	ABBREVIATION	SPS ADAPTER OR ELEMENT
Propellant supply	--	Attitude control systems at LEO base, GEO base, and power satellites; propellant depots
Electrical power	--	LEO base, GEO base, COTV, power satellite
Remote (beamed) power	--	Microwave power beam, laser power beam
Supplies	--	Materials stockpiles at LEO, GEO
Shelter, services, and supplies	S^3	LEO living/working quarters GEO living/working quarters
Manpower	--	SPS (civilian) personnel, military troops
Deployment, retrieval, maintenance, and repair	DRMR	OTV, SV
Maintenance and repair	MR	GEO construction base
Navigation	NAV	Beacons, transponders

sleeping quarters. Examples of services which could be provided to military personnel include medical treatment, repair of military equipment and satellites, data processing support, and communications. Supplies which would be readily available include oxygen, water, food, power, and perhaps additional manpower.

Although repair is also included in the S^3 category, other elements of the SPS system could also be used to deploy, retrieve, maintain, and repair (DRMR) various military spacecraft. One facility ideally suited to perform this function would be the orbital transfer vehicles (OTVs) or the sortie vehicles (SVs) used for on-orbit construction work. Similarly, the GEO construction base would have many facilities to maintain and repair (MR) spacecraft which had been retrieved by the OTVs.

Various elements of the SPS system could be modified to enable them to serve as navigational aids by installing beacons or transponders. Such aids could support the operations of spacecraft, aircraft, ships, and land vehicles. In addition, they could be used for in-flight trajectory updates for ballistic and cruise missiles.

In contrast to modifying the SPS for force delivery, the addition of military support modules to the SPS would be easier, making these adaptions more likely.

3.3 Institutional Threats

Table 3-5 lists possible institutional threats which could be implemented using SPS elements. We note that institutional threats are based upon a real or perceived capability to deliver some type of force. For example, a government could not threaten a credible blockade of an enemy space station unless it possessed a demonstrated (or at least credible) antisatellite capability such as an HEL, a PBW, or an OI. Obviously, such weapons would be necessary to prevent enemy spacecraft from running the blockade and reaching the blockaded space station.

Table 3-5. Institutional Threats

POSSIBLE THREAT	DEVICE/METHOD
Blockade	HEL, PBW, OI
Direct broadcast (DB)	RF transmitters
Denial of power	Pilot beam shutoff, power satellite shutdown by command
Theft of power	Divert power beam
Military presence	Station troops at LEO base or GEO base
Second strike	DEWs, RV launchers
Survivability of decision-makers	Install military command post on SPS

Similar to the blockade function is that of denying access to various facilities. NASA has made the launch facilities at Cape Canaveral available to other countries on a contract basis, but the United States could refuse such services at any time. In orbit, enemy astronauts could be denied access to a space station by securing and defending its airlock. Alternately, enemy astronauts could be denied access to transport vehicles by "hijacking" such vehicles. The distinction between "blockade" and "denial of access" is that the latter uses less force.

Orbital facilities provide convenient platforms for installing RF transmitters which could be utilized for direct broadcast to enemy nations, that is, for disseminating propaganda.

The electrical power supplied by a power satellite to a foreign nation could be denied by shutting off the power beam. Alternately, power could be stolen from power satellites owned by foreign nations by diverting the power beam.

Modified SPS facilities might project an image of increased military strength. This could include showing a "military presence" in space by stationing troops at the LEO base or the GEO base. A credible second strike capability could be claimed if directed energy weapons (DEWs) were installed aboard power satellites and the COTVs, or if RV launchers were installed aboard SPS facilities in space. Enhanced survivability of the military command and control apparatus would be a credible claim if a military command post were actually installed aboard the GEO base or a power satellite.

3.4 Credibility of Threats

We now want to examine the extent to which the various threats discussed above are credible. The credibility of a particular postulated threat depends upon the level of technology available to both the attacker and defender, and on the proposed use of that technology to accomplish military goals. The available technology is a function of time. For the current study, the following periods are of interest:

PERIOD	ABBREVIATION	TIME
Near-term	N	1980's
Mid-term	M	1990's
Far-term	F	2000 and beyond
Infeasible	I	Basic physical laws and scaling relationships indicate such a capability could never be constructed.

We consider a threat as real or potentially real in a particular time period if it could be deployed then. This assessment will depend on the availability of any SPS elements needed to support the deployment and/or operation of the threat. The SPS Reference Design indicates that the first powersat and rectenna might be deployed in the year 2000. Other supporting elements of the SPS would be deployed sooner, from about 1995 on. Thus, threats which depend upon SPS elements for their actualization cannot become feasible, at the earliest, until the "M" time period.

The availability of technology alone does not make a particular threat feasible. Even though a military goal could be accomplished using a particular technology, other methods may accomplish the same mission more cheaply and effectively, and/or with less risk. For example, POTVs or SVs could be used to inspect enemy satellites at close range. However, long-range space sensors might do this job almost as well for less cost, more covertly, and with less risk to personnel. We have indicated such potential but implausible threats by, for example, "M but I", i.e., the technology to create the threat could be available in the "M" time period but the threat would not be implemented for other reasons. Such threats may thus be perceived by a casual observer, but are not credible on closer examination.

The area of operation affects the feasibility of a proposed weapon directed at a particular target. For this study, three arenas for military encounters are relevant: Earth-to-space (ExS), space-to-Earth (SxE), and space-to-space (SxS). Here, "Earth" refers to ground-based or airborne weapons or targets. Ballistic misiles can have apogee altitudes of hundreds of kilometers. Thus we consider them as being located in LEO (except during the early phases of boost). The "space-to-space" areas refer to engagements where the attacker and target are in fairly close proximity, that is within 1000 kilometers of each other.

The credibility of various postulated threats has been indicated using three tables, one each for ExS, SxE, and SxS (Tables 3-6, 3-7, and 3-8, at the end of this section. Each row of the tables is a "threat." The columns of the tables indicate weapons, possible targets, time period, and remarks. In the SxE table, the term "vehicle" encompasses ground vehicles, ships, aircraft, and cruise missiles. In the SxS table, the term "spacecraft" refers to satellites, OTVs, and space bases (stations). If necessary to distinguish particular members of either set (vehicles or spacecraft), we refer to them specifically by name.

3.5 Threat/Safeguard Matrix

The final step in the threat analysis was to examine each subsystem element of the SPS system and to identify the threats and corresponding safeguards applicable to that subelement. (For greater coherence of this discussion of military implications of SPS, we defer analysis of safeguards against SPS threats until Section 5.) The resulting threat/safeguard matrix for the SPS is shown in Table 3-9.

Modification of Earth-to-LEO vehicles to enable them to be operated as hypersonic bombers or long-range military transports might be relatively easy if the space transportation system utilized single-state-to-orbit vehicles or vehicles with a flyback first stage. The small numbers of launch vehicles available, however, would prohibit their effective use in a significant strategic strike or to support a rapid deployment force.

The LEO base and GEO construction bases could serve as ASAT carriers (AC) and as platforms to support Earth bombardment (EB). These potential force delivery capabilities apply to all subelements of both of these bases because these subelements may be individual structures which are merely colocated with one another.

Considering the various military adapters in Table 3-9 which could be added to the basic SPS, we observe a range of enhanced military capabilities. We comment on only a few of these here. One simple type of weapon module which could be added to the power satellite is a phase control box which could control the SPS power beam, without a pilot beam from the ground, like a conventional phased array radar. This would make it possible to direct the beam toward enemy spacecraft or against Earth targets. Depending upon the actual design selected for the power satellites, it may or may not be feasible to actually construct such a phase control box.

Another type of weapon module which could be added would be a moderate power radio frequency transmitter. Such a device could be utilized for jamming enemy radio links (EW) or for communications, including direct broadcast to Earth (DB).

Many kinds of sensing devices could be used to perform surveillance and reconnaissance. These have all been lumped into a single entry in our matrix. Note that "S&R" appears in both the "C^3I" and "military support" columns. This is intended to indicate that sensors can provide either tactical or strategic information.

Augmented manning includes both the operation of command posts and establishment of troop bases. This differs from personnel employed in the various SPS C^2 centers and in the living/working quarters because specially trained troops could be used to physically attack enemy spacecraft or space stations, boarding them to conduct inspections or to seize them. These troops could also be used for a variety of military support activities, including deployment, retrieval, maintenance, and repair (DRMR) of military space systems, and operation of military adapters installed aboard various civilian space systems.

3.6 Summary

The Reference Design SPS, with no modifications, has some military support capabilities. These include transportation of military cargos and personnel between the surface of the Earth and high Earth orbit. The space transportation systems could also be used to support maintenance and repair of military spacecraft. The LEO base, the GEO base, and the power satellites can provide limited shelter, supplies, and services to military operations in space.

The only overt threat posed by elements of the Reference Design is the seizure of satellites belonging to other nations, using unmodified vehicles belonging to the SPS.

Weapons modules having tactical and strategic significance could be added to a Satellite Power System. The more significant military capabilites which could thus be added are as follows:

a) A ballistic missile defense (ABM) system based on directed energy weapons (DEW's), most likely high energy lasers. Depending on the rate of technological advance, such weapons might ultimately achieve the capability of neutralizing low-altitude aircraft and cruise missiles. Unilateral deployment of such a system could be considered provocative by other nations. On the hand, with proper safeguards, multilateral deployment of such defensive systems could be internationally stabilizing.

b) A variety of antisatellite (ASAT) systems. These include DEW's, space-to-space missiles (either rockets or projectiles), space mines, and grapplers (either manned or remotely operated). Except for DEW's and small projectile weapons, a comprehensive space surveillance system should be able to detect and track such weapons, making it difficult to attack without warning.

c) Reentry vehicles for Earth bombardment with either conventional high explosives or nuclear warheads. Although it would be difficult to defend against such weapons, comprehensive space surveillance should be able to detect such vehicles upon launch. Any foreseeable non-nuclear weapons which could be added to SPS would be less threatening than the strategic nuclear arsenals already deployed on Earth.

With certain engineering modifications, C^3I modules having tactical and strategic significance could be added to a Satellite Power System. The most significant such additions which are unique to SPS (due to the availability of large quantities of electrical power) are EW jammers and direct broadcast to the population of a hostile country.

Given the necessary technological advances, the power satellites could be used as a power source (with laser transmission) for military satellites or to allow long-duration flight of military aircraft at high altitudes. Depending on technology advancement and on range, relay satellites might be necessary.

3.7 References and Notes

1. The full text of the Treaty on Principles appears as Appendix A in Carl Q. Christol, "Satellite Power System (SPS): International Agreements," HCP/R-4024-08, ODE/NASA, October 1978.

2. Robert J. Salkeld, "Space Intercepters: An Investigation of Seven Main Parameters," J. Spacecraft 8, 541-543 (1971).

3. Robert Salkeld, War and Space, Prentice-Hall, New York, 1970.

4. Particle Beam Weapons, collected reprints from Aviation Week and Space Technology issues of May 2, 1977; October 2, 9, & 16, 1978; and November 6 & 13, 1978. McGraw Hill, Inc., New York, 1978.

5. "ABM Promise Seen in Space-Based Lasers," Aviation Week and Space Technology, p. 15, October 8, 1979.

6. "NAVSTAR GLobal Positioning System," Deputy for Space Navigation Systems, Headquarters, U.S. Air Force Space and Missile System Organization, Los Angeles, June 22, 1976.

7. Claud N. Bain, "Power From Space by Laser," Astronautics and Aeronautics 17(3), 28-40 (March 1979).

8. Abraham Hertzberg, Kenneth Sun, and Wayne S. Jones, "Laser Aircraft," Astronautics and Aeronautics 17(3), 41-49 (March 1979).

TABLE 3-6. EARTH-TO-SPACE THREATS

WEAPON	TARGET	PERIOD	REMARKS
HEL	Spacecraft	N-M	Level of capability increases with time.
PBW (neutral beam or pulsed charged beam)	Spacecraft	I	The difference in exo- and endo-atmospheric propagation mechanisms make it unlikely that ground-to-space or space-to-ground attacks can be mounted.
Orbital interceptor	Spacecraft	N	Range beyond GEO. Conventional or nuclear warhead.
Pilot beam	Power satellite	F(I?)	Covert communications relay to other military facilities in space. Probably infeasible since cheaper, more effective means exist.
RF transmitter	Power satellite	F(I?)	Jamming, pied piper box. Feasibility depends on design of beam steering equipment.
RF/Laser communication	Spacecraft	N	
Launch vehicles used for support	Non-specific	N	Transportation of men and materiel, including ASAT weapons.
Launch site used for support	Non-specific	N	Alternate launch site for military vehicles--existing facilities presently used for both purposes. Thus, this is not a new threat which could cause concern and we ignore it.

TABLE 3-7. SPACE-TO-EARTH THREATS

WEAPON	TARGET	PERIOD	REMARKS
HEL	Structures, vehicles	M but I	HF chemical lasers could be deployed in space by the late 1980's. Deployment in GEO is impractical due to the long ranges involved. (Electric discharge and free electron lasers would be more likely candidates for GEO deployment since large amounts of electrical power would be available.
PBW (neutral beam or pulsed charged beam)	Structures, vehicles	I	The difference in exo- and endo-atmospheric propagation mechanisms make it unlikely that ground-to-space or space-to-ground attacks can be mounted.
RV	Structures	N	Earth bombardment, second strike capability.
SPS beam	Structures People Elec. equip. WXM Customers	I F(I?) F I F	Insufficient power for incendiary attacks. Psychwar (possible but implausible) Jamming (near 2.45 GHz) Requires too much power. Denial of power is possible.
RF transmitter	RF equip. People WXM	M M I	EW (any desired frequency) Wide area broadcast Requires too much power (at 22 GHz).
RF sensors	RF emanations	M	SIGINT collection
Optical/infrared sensors	Structures and vehicles	N	Photoreconnaissance, surveillance
Radars	Structures and vehicles	N	Surveillance and reconnaissance
RF/laser communications	People	N	Military communications

TABLE 3-8. SPACE-TO-SPACE THREATS

WEAPON	TARGET	PERIOD	REMARKS
HEL	Spacecraft, missiles	N-M	Level of capability increases with time. HF chemical lasers could be deployed in space by the late 1980's. EDL's and FEL's are likely candidates for deployment in GEO since large amounts of electrical power would be available. LEO deployment would enable use of such lasers for ABM defense, but the relay of electrical power from SPS's in GEO would be required to make ABM defense feasible with electrically-driven lasers.
PBW (neutral hydrogen)	Spacecraft, missiles	F(M?)	Power relay from GEO to LEO would be required for ABM defense.
Orbital interceptors	Spacecraft	N	Space missiles and mines. Conventional or nuclear warheads.
Nuclear weapons	Spacecraft	N	Weapons exist but deployment in space is banned by treaty. Use may pose fratricide problems for attacker.
Spacecraft Spacecraft used as support	Spacecraft Non-specific	N N	ASAT carrier Shelter, services, supplies
Troops	Spacecraft DRMR C^2	M but I N N	Physical occupation or seizure (SATNAP). Unlikely because booby traps and self-defense devices could be installed easily. Also, cheaper, better ways exist to accomplish the desired goals. Important mission for the Space Shuttle.
SPS beam	Spacecraft	F	Insufficient power for physical damage against moderately shielded targets, even at close range. EW is feasible.

TABLE 3-8. SPACE-TO-SPACE THREATS (continued)

WEAPON	TARGET	PERIOD	REMARKS
RF transmitter	Spacecraft	N	EW only.
RF sensors	Spacecraft RF emanations	N	SIGINT collection. Capabilities depend on receiver sensitivity at the desired frequency and on signal processing capability.
Optical/infrared sensors	Spacecraft	N	Surveillance and reconnaissance. (Resolution depends on range and detector sensitivity.)
Radars, lidars	Spacecraft	N	Surveillance, reconnaissance, tracking. Maximum range is a function of transmitter power, receiver sensitivity, and target size.
RF/laser comm.	Spacecraft	N	Military communications
Space bases used as support	Non-specific	M	Shelter, services, supplies, docking platform, power
Space bases used for C^2 functions	Non-specific	M	Alternate command post
Space bases used for CBW support	People	M but I(?)	CBW labs could be constructed. Such orbital CBW labs may or may not offer advantages over ground-based labs. We are unable to assess their feasibility.
SPS	Spacecraft	I	Effective shadowing of enemy spacecraft precluded due to relative orbital motion.
SPS used as support	Non-specific	F	Electrical power at GEO, relay to LEO or high altitude aircraft.
OTV used as support	Non-specific	M	Transport of troops and materiel.
OTV	Spacecraft	M but I	Inspection.
OTV	Spacecraft	I	SATNAP, SATMUT. Propellant is not a limiting factor. Booby traps and self-defense devices make such actions too risky to be credible.

TABLE 3-9. THREAT/SAFEGUARDS MATRIX FOR THE SPS

System Element	Subsystem Element	THREATS: Technological: Force Delivery	THREATS: Technological: C^3I	THREATS: Technological: Military Support	THREATS: Institutional	SAFEGUARDS: Technological	SAFEGUARDS: Institutional
Transportation	Earth-launch facilities	0	0	Alternate military launch site	0	Physical attack	RIO
	Earth-to-LEO vehicles	0	0	Transport, Sat. DRMR	0	LRSS, SDF + BT (SATNAP only)	Agr., Prox., RIO
	Space tugs + O-O vehicles	0	0	Transport, Sat. DRMR	0	LRSS, SDF + BT (SATNAP only)	Agr., Prox., RIO
LEO Base	Living/working quarters	0	0	S^3	0	LRSS	Agr., RIO, Pub. disc.
	Materials stockpile	0	0	Supplies	Sanctuary	LRSS	Agr., RIO
	Propellant depot	0	0	Supplies	0	LRSS	Agr., RIO
	Power system	0	0	Power	0	S&R	Agr., RIO
GEO Construction Base	Living/working quarters	0	0	S^3	0	LRSS	Agr., RIO, Pub. disc.
	Construction equipment	0	0	Sat. M&R, S^3	Sanctuary	LRSS	Agr., RIO, Pub. disc.

TABLE 3-9. THREAT/SAFEGUARDS MATRIX FOR THE SPS (continued)

System Element	Subsystem Element	THREATS				SAFEGUARDS	
		Technological			Institutional	Technological	Institutional
		Force Delivery	C^3I	Military Support			
GEO Construction Base (cont'd)	Materials stockpile	0	0	Supplies	Sanctuary	LRSS	Agr., RIO
	Propellant depot	0	0	Supplies	Sanctuary	LRSS	Agr., RIO
	Power system	0	0	Power	Sanctuary	S&R	Agr., RIO
Power Satellite	Photovoltaic array	0	0	0	0	0	0
	Power coll. & distribution	0	0	0	0	0	0
	Power cond. & conv.	0	0	Power	0	LRSS	Agr., RIO
	Power transmission (XMTR & beam itself)	0	0	0	0	0	0
	Support structures	0	0	0	Sanctuary	LRSS	Agr., RIO
	Rotary joint	0	0	0	0	0	0
	Attitude control system	0	0	Propellant supply	0	LRSS	Agr., RIO
	Living/working quarters	0	0	S^3	0	LRSS	Agr., RIO

TABLE 3-9. THREAT/SAFEGUARDS MATRIX FOR THE SPS (continued)

System Element	Subsystem Element	THREATS: Technological: Force Delivery	THREATS: Technological: C^3I	THREATS: Technological: Military Support	THREATS: Institutional	SAFEGUARDS: Techno-logical	SAFEGUARDS: Institutional
Rectenna	Pilot beam & associated equipment	0	0	0	0	0	0
	Power collection antennas	0	0	0	0	0	0
	Power conver. & conditioning	0	0	0	0	0	0
	Support struct.	0	0	0	0	0	0
	Power distrib. & interface	0	0	Power	0	Physical attack	Agr., RIO
Command and Control System	C^2 centers (SPS & rectenna)	0	0	0	Deny power	0	Agr., RIO, Pub. disc.
	C^2 centers (other)	0	0	0	0	0	0
Communication System	RF & laser links	0	Communications	0	0	ECM, EW, SIGINT	RIO
Weapon Modules	ASAT projectiles	ASAT	0	0	Second strike, blockade	Red.obs., decoys, counter-ASAT	Agr., RIO
	Earth projectiles	EB	0	0	Second strike, blockade	ABM(?)	Agr., RIO
	Manipulators	SATMUT, SATNAP	0	0	Blockade	Red.obs., decoys, ASAT, SDF, SD, BT	Agr. RIO

TABLE 3-9. THREAT/SAFEGUARDS MATRIX FOR THE SPS (continued)

System Element	Subsystem Element	THREATS: Technological: Force Delivery	THREATS: Technological: C^3I	THREATS: Technological: Military Support	THREATS: Institutional	SAFEGUARDS: Technological	SAFEGUARDS: Institutional
Weapon Modules (cont'd)	PBW, HEL	ASAT, ABM, ER, WXM	0	Power, WXM	Blockade, second strike	Red.obs., hardening, decoys, reflectors (HEL only), counter-ASAT	Agr., RIO
	Power beam + phase control box	EW, ASAT, ER, WXM	Communication	Power, WXM	Deny power	ASAT, ECM, dual keys, SIGINT	Agr., RIO, Pub. disc.
	RF transmitter (moderate power)	EW (jamming)	Communication	0	Direct broadcast	ECM, ASAT, SIGINT (for comm. & DB)	Agr., RIO
	"Pied Piper" box	ER, EW	0	0	Steal power, deny power	ECM, pilot beam override, redundant pilot beams	Agr., RIO
C^3I Modules	Communications equipment	0	Communication	0	Direct broadcast	LRSS, EW, ASAT, SIGINT	Agr.
	S&R (Earth & space)	0	S&R	S&R	0	Red.obs., decoys, ECM, ASAT	Agr., RIO
	Trained military command personnel	0	C^2	0	Survivability of decision makers	Monitor crew movements, SIGINT	Agr., RIO

TABLE 3-9. THREAT/SAFEGUARDS MATRIX FOR THE SPS (continued)

System Element	Subsystem Element	THREATS				SAFEGUARDS	
		Technological			Institutional	Technological	Institutional
		Force Delivery	C^3I	Military Support			
Military Support Modules	Navigation package	0	0	Navigation	0	LRSS, EW, ASAT, SIGINT	Agr., RIO
	Power beaming equipment	ER(?), EW	0	Power	Steal power	LRSS, ASAT, dual keys	Agr., RIO
	Modify Earth-LEO vehicles	AC, EB (bomber)	0	Earth-Earth transport	0	ABM, SAM, ASAT ?	Agr., RIO
	Trained military troops	Physical attack	0	Manpower	Military "presence"	SDF, SD (phys. attack only), monitor crew movements	Agr., RIO
	CBW labs	0	0	CB agent development, production, storage	0	S&R	Agr., RIO

4.0 VULNERABILITY ANALYSIS

In considering the potential vulnerability of the Satellite Power System we must consider not only the vulnerability issues of a highly concentrated generating capacity (5 GW at a single rectenna site) but also the vulnerability issues of placing very expensive elements of the system (the power satellites themselves, the LEO and GEO bases, and fleets of space vehicles) outside the presumably defensible territorial limits of the nations which own, operate, and/or use these valuable assets.

The potential for loss of power at the utility grid interface is a function of SPS vulnerability in the broadest sense of the term. Issues such as component reliability, random accidents, natural disasters, and hostile actions represent categories of vulnerability. We are concerned here only with the last of these categories.

Vulnerability as a military issue seems, on the surface, relatively simple to address. Sabotage or attack as part of a military operation by one nation against another would be the simplest definition to accept. We found it necessary to widen this definition considerably to address in a reasonably complete fashion the breadth of system vulnerabilities germane to <u>all</u> military considerations. For example, actions by terrorist groups, mutiny by established crews, espionage by hostile countries, and nuclear weapons tests in space by other nations must all be considered to get a well-rounded picture of the whole range of vulnerability issues.

4.1 Methodology

The matrix approach to structuring the assessment outlined in Section 3 was also used in this portion of the study. The two major issues addressed in column format were vulnerabilities and safeguards. Vulnerabilities were divided into technological and institutional types, with the former further broken down to Force Delivery and C^3I. (Military support systems are used either to enable or to assist Force Delivery or C^3I missions; the enemy's military support systems thus do not pose any direct threat to SPS and are not included in the discussion here.) Safeguards were also divided into technological and institutional types, with technological safeguards further resolved as either active or passive measures.

Drawing on the material developed in Section 3, we approached the vulnerability issues of the SPS by examining the generic categories of threats which would be technically feasible to mount against SPS elements in the time frame of interest here.

In analyzing the potential vulnerabilities of the SPS, we consider the system from two different perspectives:

(1) From the viewpoint of defending the SPS against hostile forces:

- o What generic types of assaults would have to be mounted against SPS elements?
- o How effective might such assaults be in degrading, disabling, or destroying each element?

(2) From the viewpoint of attacking the SPS:

- o What are the "soft spots" in each system element, where the application of a given force is most likely to produce significant damage?

In following sections, we will discuss generic types of assaults, discuss likely effectiveness of such assaults against the SPS, explore apparent weaknesses of the Reference Design SPS, and compare the vulnerability of SPS to the vulnerabilities of other systems in the economic infrastructures of industrialized nations.

4.2 Generic Types of Assaults

A system such as the Satellite Power System is subject to the following generic types of assaults:

1. sabotage;
2. mutiny;
3. overt attack by military or paramilitary forces;
4. terrorism and insurrection;
5. harassment, using legal or quasi-legal means;
6. espionage; and
7. strikes.

One indirect form of assault (abuse of sanctuary) will also be discussed below.

Sabotage is always a serious consideration in complex systems because of the potential for disrupting significant system elements by interrupting a relatively small but critical component. Given the panoply of complex systems involved in deployment and operation of the Satellite Power System, sabotage could be effective and difficult to guard against completely. Small quantities of gases, liquids, or fibers (such as chopped, high-modulus graphite) released in the right place could wreak havoc in sophisticated vehicles, orbital facilities, or fabrication plants. More overt attacks by saboteurs, using plastic explosives, for example, have obvious destructive potential.

In the context of the Satellite Power System, mutiny means rebellion against established authority by some portion of a trained crew who take control of part or all of their assigned system or subsystem element.

Mutiny differs significantly from other types of assaults in that the mutineers are thoroughly familiar with the system itself and with its built-in safeguards. Such a crew has most likely been on station long enough before overt mutiny to have had ample opportunity to study the safeguard systems and to nullify at least some of them surreptitiously.

Attack includes any explicit action which might be taken by hostile nations or groups to disable some portion or all of the Satellite Power System, including its supporting elements.

At least in the DDT&E phase of the SPS program and probably in the early years of SPS deployment and operations, the threat from terrorists can be confined to Earthside elements of the SPS. However, the commandeering or hijacking of launch vehicles, whether manned or unmanned, and of manned OTVs, cannot be entirely ruled out as a possibility, especially if the hijackers are willing to carry out a suicidal mission.

A system as complex and as extensive as the SPS can also be harassed by a wide range of legal and quasi-legal means short of actual violence. Recent history provides a number of examples which could be replayed in analogous forms against the SPS in various stages of the program.

A country determined to harass the SPS might deliberately place inexpensive unmanned satellites on trajectories or in orbits passing close to SPS facilities. Deliberate misinformation and adverse propaganda can also serve to harass a program such as SPS. In the extreme case, a hostile power could mount a covert campaign to deliberately misinform the public about hazards and costs of SPS or to deliberately impugn the motivations of SPS advocates to such an extent as to make SPS politically impossible to implement. Such harassment, at the least, distracts SPS managers and workers from constructive efforts on the system, requiring them to respond publicly to the misinformation.

If the SPS program were a purely civilian undertaking, none of the technical or operational details of the system would fall under military security classification. Nonetheless, the legal and operating entities for SPS will protect information about certain details of the system if knowledge of those details (e.g., the encryption algorithms used in the pilot beams from the rectennas to the power satellites) would make it easier to attack the system.

Hostile interests may then be expected to resort to espionage to obtain sensitive information of this kind. Because the international Resident Inspection Operation (RIO) would have unrestricted access to all phases of SPS operations and engineering designs from the inception of the DDT&E phase, hostile groups would be tempted to infiltrate RIO for both espionage and sabotage purposes.

Elements of the SPS could be subject to shutdown by local or general strikes. The military implications of the sensitivity of the system to strikes would depend on the degree to which the production or operation of military systems becomes dependent on SPS hardware elements or on power from SPS.

A further vulnerability of the space-based elements of the SPS should be discussed at this point. We noted in Section 3.3 that the 1967 Treaty on Principles allows any nation to place a satellite arbitrarily close to an SPS facility in space without the consent of the SPS owners, as long as their satellite does not directly interfere with the operations of the SPS facility. Suppose countries A and B (neither of which is aligned with the owner of a given SPS facility in space) have very poor relations with each other. Country A might then place one or more of its military satellites close to a power satellite, the LEO base, or the GEO base, in "sanctuary." Country B, presumably, would be reluctant to attack A's military satellites in sanctuary for fear of damaging the adjacent SPS facilities and thus provoking the owning nation. Should open hostilities break out between A and B, such considerations may become secondary. Thus, the risk of damage to the SPS would have been increased by A's action in seeking sanctuary.

If country A is hostile to the nation owning the SPS facility it might deliberately provoke an attack on its military satellite in the hope that the SPS facility would be damaged and that the SPS owners would retaliate against B.

4.3 Scenarios for Assaults Against SPS

Since the geopolitics of the next century are unknowable today, it seems instructive to consider the following questions:

> If the SPS were in place today, and if we were to ignore the enormous differences between the present geopolitical environment and that which would result from the SPS having been deployed, from what quarters could we anticipate assaults against the SPS? What kinds of economic, ideological, or political goals would motivate assaults on the SPS?

Such an exercise can suggest a number of alternative scenarios for assaults against SPS elements.

Random assaults could be expected either from dictators able to muster significant resources or from sociopathic individuals. A demagogic leader in a Third World country beset with international turmoil and international trade deficits could decide to enhance national prestige and regain popular support at home by putting a team of engineers and technicians to work building a sounding rocket capable of reaching the altitude of the LEO base and throwing up a cloud of nails directly in the path of the case, thus striking a blow for the "freedom of oppressed peoples everywhere" against the "neoimperialism" of the SPS owners and builders.

Alternatively, individuals could telephone a bomb threat against a rectenna installation, claiming that the pilot beam transmitter facility would be demolished unless a large ransom were paid for information on the device.

Given the growing technical sophistication of the general population in industrialized countries, terrorist groups in the next century could be expected to attempt assaults against rectennas, launch sites, launch vehicles, SPS communications facilities, SPS offices and laboratories, and factories manufacturing SPS components. Harassing SPS executives, workers, and their families could also be included in their tactics.

Should any of the nations actively participating in a multilateral SPS program become involved in a brushfire war, SPS elements which it owns or operates could become targets for attack. While attacks might be carried out ostensibly by a surrogate small country, motivation and technical support could come from the opposing superpower behind the scenes.

During a conventional theater war on Earth, assets of any of the belligerent countries would be fair game for attack, especially if they contributed to the economic and industrial strength of an opposing nation. SPS facilities, ground-based electrical generating plants, petroleum refineries, pipelines, highways, railroads, and airfields would all be subject to attack, and our concern in this context must be the relative vulnerability of the SPS in comparison with alternative energy systems.

Thus far, the major spacefaring nations have been the opposing superpowers of terrestrial politics, the United States and the Soviet Union. Both nations have deployed extensive military systems in space, ranging from communications, weather observation, and navigation satellites to surveillance and reconnaissance (spy) satellites. Both nations are actively pursuing development of antisatellite weaponry. Reportedly, the U.S.S.R. has the capability with ground-based lasers to damage and incapacitate sensitive optical sensor elements in U.S. spy satellites.*

Most spacefaring nations can be expected to deploy military satellites of their own in the next few decades. As the strategic value of military assets in space increases, as the number of participants in military space grows, and as the level of capabilities in space rises, warfare in space could break out as a prelude to warfare on Earth; SPS elements in space could then expect to come under attack along with overtly military satellites.

4.4 Technological Vulnerabilities

From the above discussions of generic vulnerabilities, it is evident that assaults against the SPS by sabotage, mutiny, attack, and terrorism or insurrection will rely upon various technological means to inflict damage or injury upon SPS facilities, vehicles, or personnel. While assaults by harassment, espionage, strikes, or expropriation may occasionally resort to the use of force, these assaults by their very nature tend to use institutional means.

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* Weather imaging and Earth resources satellites have cameras with lens apertures of 12-15 cm or more. Since a lens of aperture 5-8 cm can easily achieve flux concentration ratios of 100 or more, sensor elements behind the still larger lenses of high-resolution spy satellites can be damaged by flux levels far too low to damage solar cells, let along structural components or thin metal skins.

Technological means of delivering injurious physical effects to a target include Force Delivery and C^3I techniques. For purposes of this discussion, it is convenient to classify these according to the scheme shown in Table 4-1. Each of the items in Table 4-1 will be discussed briefly below in relation to the SPS to give a preliminary indication of the likely effectiveness of such assaults. A later section will highlight those subsystem elements of the Reference Design SPS which are most sensitive to damage by hostile actions.

4.4.1 Physical Contact

Sophisticated mechanical and electronic systems can be damaged by mutilation, in which key components are mechanically broken, electrical circuits are shorted or physically interrupted, or key fluids are allowed to escape. The immediate tools used for mutilation can often be far smaller in mass than the systems they damage, potentially affording the assailant a significant advantage over the defender when the targets are objects in space.

At remote target sites, mutilation of communications systems may be the initial action of terrorists or guerrillas, heightening their psychological advantage over the defenders. Successful mutilation requires the ability to place either a person or a fairly sophisticated machine in close proximity to the target without triggering defensive reactions.

Explosives are a time-honored tool for destruction. On Earth, their effectiveness often depends on the propagation of shock waves through the ambient medium (air or water) to the target. In vacuum, blast effects are imperceptible except at extreme proximity between the explosives and the target. Conventional explosives would then be used in space only in space mines with proximity fuses, with vehicles capable of rendezvous and attachment to their targets, with inside pressure vessels if they can be surreptitiously introduced by saboteurs or inside baggage or cargo, or for explosives-driven projectiles (shrapnel bombs).

Nuclear explosives rely on radiation as well as on blast effects for their lethality. Due to the absence of an absorbing medium in space, the zone of lethality by radiation for a given nuclear warhead is greater in space than on Earth. A one-megaton nuclear warhead at a range of 5 kilometers in space, for example, would deposit a few thousand calories per gram of spacecraft structure facing the explosion, an energy density sufficient to melt or even vaporize at least the outer

Table 4-1.
Possible Technological Means of Assault Against SPS

MISSION AREA	TECHNOLOGICAL ASSAULTS
Force Delivery	Physical contact o system mutilation o explosives (chemical and nuclear) o chemical and biological warfare (CBW) agents o radiological agents o boarding and takeover
	Standoff weapons o shadowing and beam blocking o nonexplosive projectiles o lasers o particle beam weapons o nuclear weapon effects
C^3I	Electronic warfare
	Chaff deployment

layers of the satellite. In thicker structures, shock waves initiated by this rapid energy deposition can propagate extensively, causing additional mechanical damage similar to that from blast effects. The term "extreme proximity" for nuclear warheads thus means distances of less than 10 or 20 kilometers in space. Obviously, any single space-based element of the Reference Design SPS can be totally destroyed by a nuclear warhead with a yield of less than one megaton, since the maximum length of the power satellite is 10.5 km.

Chemical, biological, and radiological agents could be used to damage or incapacitate space-based elements of the SPS. They would be released in a confined space such as living and working quarters or inside electronic "black boxes," thus requiring surreptitious introduction of these agents. Since the radiation environment in space-based facilities would be monitored for purposes of personnel dosimetry, radiological agents would not remain undetected long enough to do much damage. It would be difficult to smuggle such agents through inspection inside shielding canisters without attracting attention to the high density of the shielding. Biological and chemical agents would thus be more likely to be used to attack SPS elements.

Boarding and takeover of space facilities has already been discussed in Section 3. It is difficult to envision groups other than regular military or paramilitary forces attempting such a mission, since the occupation forces would have to have their own capability for resupply. Seizure of manned facilities or space vehicles would thus be a clear-cut act of war.

4.4.2 Standoff Weapons

Standoff weapons offer several advantages to a potential assailant. First, personnel and equipment remain far from the target, minimizing risks of damage or loss of these assets. Second, it may be easier to conceal the origin of the attack and the identity of the assailant. Third, since most of these means of assault rely on rapid motion from weapon to target, it can be easier to achieve surprise. On the other hand, the greater distance may require more sophisticated and expensive equipment than close-in attacks with large numbers of relatively "dumb" devices, both to permit the necessary precision and stability of aiming and to provide higher power levels required to overcome increased dispersion.

The power satellites, GEO base, Cargo Orbital Transfer Vehicles (COTVs), and LEO base (unless it has a nuclear power plant) all depend on a predictable stream of raw sunlight for their power. One might thus consider interrupting the power supply of one or more of these SPS elements by deploying large, lightweight, thin-film structures in space to cast large shadows on the solar collectors of these SPS elements.

For the power satellites and the GEO base, such an orbital shade could be placed in a 24-hour equatorial orbit of small eccentricity, with perigree perhaps 100 km lower than GEO and apogee as much higher. The shade would then execute a circular trajectory of radius 100 km about its target every 24 hours, with the shadow remaining centered on its target at all times. Similarly, an orbital shade could immobilize a COTV in high orbit once its shadow fell on the COTV's solar collectors long enough for the COTV's batteries to run too low to operate the chemical thrusters. (The COTV's ion thrusters could not operate as long as the shade was in the way.)

In order to use orbital shades against targets in low Earth orbit, however, it would be necessary to provide a continuously operating propulsion system to maintain oribital altitude to counteract atmospheric drag on such a lightweight structure. Even in high orbits, large quantities of propellants or sophisticated lightsailing techniques would have to be used to correct for the perturbing effects of solar radiation pressure. The scale of the effort required to deploy an orbital shade, especially one large enough to block the sunlight shining on a power satellite, would be large compared to the limited injury it would inflict. Since a shade would have to be lightweight to be worth deploying at all, it could be very easily removed from its original placement by any of the SPS's OTVs.

Similar techniques might be imagined for blocking the microwave power beam from the power satellite to the ground. In this case, however, in order to block the beam full time, the microwave shade would have to remain in a 24-hour orbit at an altitude lower than the power satellite. At best, then, a series of microwave shades would have to be placed in circular trajectories around each power satellite in order to repeatedly eclipse its beam throughout its daily orbit around the Earth. Although microwave shades could be made of lightweight wire mesh and would thus experience little solar radiation pressure, the scale of effort required to deploy them would be greater than that required for the SPS owners to remove such shades.

Nonexplosive projectile weapons were discussed briefly in Section 3. These would be particularly effective against targets in low Earth orbit where orbital speeds are highest, within reach of relatively simple sounding rockets. Dozens of nations and terrorist groups would be capable of fielding such rockets in the next few decades. In rather prosaic terms, a sounding rocket capable of reaching 477 km altitude (275 miles) could disperse 100 kg of 5-cm nails (about 6,000 nails) in a cloud with a radius of 35 meters in the path of the LEO base.

With a closing speed of 11 km/sec (28,000 ft/sec), each nail with a mass of 16.5 gm would have a kinetic energy upon impact with the LEO base of 2×10^6 joules, equivalent to the explosive yield of 480 gm of TNT. (In contrast to TNT explosions, however, the kinetic energy of the nail is directed entirely along the relative velocity of the nail and the LEO base, so that the damage inflicted by each nail would be considerably greater than that due to 480 gm of TNT exploding against the hull of the LEO base.) In effect, the LEO base would be peppered with 1.6 hypervelocity bullets per square meter. Since flight time for the sounding rocket from liftoff on the ground to impact with the LEO base could be as little as 5 minutes, even an armed LEO base would have difficulty in destroying the rocket before it released its nails.

Space-to-space missiles can also be used to lay down clouds of flechettes on collision course with space-based elements of the SPS. Attacks of this kind could only be made by nations or groups with fairly extensive spacefaring capabilities, but it could be very difficult for a defender to identify the origin of the attack and the identity of the assailant, especially if the missile were launched from a hidden platform high above GEO. The use of nonexplosive projectile clouds against targets in high orbit, however, has an important drawback for a spacefaring assailant: unless all the projectiles in the cloud actually strike their intended target, large numbers of hypervelocity bullets would be inserted into long-lived orbits in the Earth-Moon system, where they would plague the attackers as much as their victims. This consideration would be a strong deterrent to the use of projectiles against the power satellites themselves, since enormous numbers of projectiles would be needed to inflict significant damage on such an extended target. Because of the very low area density of the power satellite, most projectiles striking a power satellite would pass completely through, with increased dispersion in velocities and thus in orbital elements. Moreover, clouds of fragments from the power satellite would also be scattered about the Earth-Moon system, creating further collision hazards for both the assailants and their victims.

Nuclear weapons effects and the capabilities of particle beam weapons and high energy lasers likely to be developed in the next few decades are discussed in some detail in Appendices C.1, C.2 and C.3, respectively, with further discussion on feasibility of the latter two types of weapons in Section 3.4 above. All of these could be used by spacefaring nations or groups in direct assaults against SPS elements.

As remarked earlier, detonation of a nuclear warhead with a yield comparable to current strategic weapons (up to about one megaton) at distances of less than about ten kilometers could destroy any of the space-based SPS elements. Long-range system-generated electromagnetic pulses (SGEMP), however, would severely damage the power satellites, the COTVs, and perhaps the power systems of the LEO base and the GEO base at distances of up to hundreds of kilometers unless extensive circuit protection is added to the Reference Design. At lesser ranges, prompt radiation (neutrons, gamma rays, and X-rays) could adversely affect performance of electronics systems and could pose threats to personnel.

A direct attack in space upon another nation's satellites or space vehicles with nuclear warheads would be regarded as an act of war. However, a loophole in present treaties leaves a legal opening for legally inflicting severe damage by SGEMP upon multiple elements of the SPS. The 1973 Treaty Banning Nuclear Weapons Tests in the Atmosphere, in Outer Space, and Underwater (often referred to as the "Limited Test Ban Treaty") has not been signed by France, by the People's Republic of China, or by many Third World nations which could join the nuclear club within the next few decades. Many of these nonsignatories (including the PRC) have not signed the 1967 Treaty on Principles Governing the Activities on States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, which would prohibit them from carrying out activities in space which could interfere with peaceful activities of other states. Testing of a very large nuclear warhead in space by such a nonsignatory state would then be "legal," even if it wrought havoc with dozens of power satellites thousands of kilometers away from the detonation.* Note also that a number of nations which have signed neither the Limited Test Ban Treaty nor the Treaty on Principles have not signed the 1970 Treaty on the Nonproliferation of Nuclear Weapons, and thus reserve the right to develop nuclear weapons.

4.4.3 Electronic Warfare

Smooth and efficient operation of the entire Satellite Power System depends on reliable operation of the electronic equipment used for command, control, and communication functions. Short of actual physical damage to the electronic equipment, operation of the C^3 system can be disrupted by electronic warfare (EW) techniques to introduce excessive noise, excessive information, or false information into the C^3 system.

Jamming of radars or communications channels is the classic EW techniques for inserting excessive noise into the system. This requires deployment of high-power transmitters operating in the frequency bands used by the target equipment. In view of the large number of ground transceiver locations, the large number of space-based elements of the SPS, provision of redundant equipment operating at different

*Admittedly, this is farfetched. Should the North-South conflict over international economic issues become more virulent over the next few decades, however, the opportunity such an attack would provide for simultaneously damaging the economic infrastructures of a number of industrialized nations participating in the SPS could become tempting to leaders in Third World countries.

frequencies, and the complexity of orbital motions, it would require a massive undertaking to jam routine C^3 functions of the SPS to a degree sufficient to cause disruption and confusion. At most, jamming could be expected to have some nuisance value in support of more direct attacks.

Electronic equipment (especially digital processing equipment) can also be disrupted by saturation of its information processing capabilities. Thus a conceivable EW attack would attempt to overload C^3 equipment by sending signals mimicking normal SPS communications signals, but at elevated bit rates on a continuous basis. Such an attack could succeed only if the receiving and processing systems were not very selective about message formats and bit rates, and if the attacker had detailed information about the design and operating characteristics of the C^3 systems.

False information inserted into the C^3 system (either by wiretaps into ground-based transmission lines, by clandestine insertion of "Trojan horse" electronic "black boxes" aboard space segments of the SPS, or by hostile transmitters sending such signals during a lull in normal SPS communications traffic) appears to offer a wide range of possibilities for disruption. Erroneous malfunction indications on the launch pad, for instance, could cause long holds during countdown. In some cases, this could cause a scheduled flight to miss its launch window, snarling launch schedules but it is difficult to see how this could imperil SPS crews in orbit or lead to massive physical damage to the system.

False information transmitted by a "Pied Piper" box of sufficiently high power to override the normal pilot beam signal from the rectenna to the power satellite could cause the microwave beam to be aimed away from its assigned rectenna, but this would require successful espionage to determine the pilot beam message formats and the exact encryption algorithm used. Microwave signals from covertly emplaced transmitters around a rectenna could provide anomalously high microwave fluxes at sensors around the periphery of the rectenna, leading the phase control and transmission antenna steering system to believe that the power beam from the satellite had wandered off center.* The control system aboard the satellite might then shut down the power beam inappropriately.

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*This case is examined in detail in Appendix C.4. The hostile transmitters would have to have very high output levels, so they could not remain undetected for long.

While examples of means of inserting false information into the C^3 system are numerous, it appears that one or more of the following preconditions must be met before assaults of this type can succeed:

- The C^3 system would have to be poorly designed, failing to incorporate standard error detection and signal verification techniques.
- Saboteurs would have had to implant "black boxes" or tapped into transmission circuits successfully, with these alterations remaining undetected until used in an assault.
- Hostile espionage activities would need to have obtained detailed design and system operating information, including exact message formats and encrypting algorithms.

In summary, it does not appear that EW techniques <u>by themselves</u> used against the SPS C^3 system pose a serious threat. In concert with other forms of assault, however, EW could doubtless enhance the effectiveness of the attack.

4.4.4 Chaff Deployment

In the Reference System, the pilot beam transmitter antenna is located in the middle of the rectenna and transmits its signal directly to the power satellite providing power to that rectenna. Since the transmitter array aboard the power satellite subtends a very small angle at the pilot beam transmitter (less than one-tenth of a minute of arc), a plume of chaff at an altitude of 10 kilometers (39,000 feet) would have to be only a few meters wide to block the pilot beam totally, provided the chaff dipoles in the beam were sufficiently dense to attenuate the microwave signal from the pilot beam transmitter.

Detailed analysis in Appendix C.4, however, shows that the chaff would spread out and descend toward the ground sufficiently fast that, even in the worst case light-wind conditions, the interruption of the pilot beam would last no more than a few minutes. Chaff dropped in the microwave power beam would, of course, scatter microwave radiation in all directions, and might provide some radio frequency interference in receivers unrelated to the SPS located in the vicinity of the rectenna. Since receivers and other electronic equipment intended for use near the rectenna would be designed for minimum sensitivity to the SPS carrier frequency in any case, the scattered radiation would not be expected to disrupt other equipment.

4.5 Vulnerabilities of Specific SPS Elements

Identification of "soft spots" in the design is a key step in the iterative process of design: once these soft spots have been identified, suitable alterations can be made in the Reference System to overcome these deficiencies. More basically, this exercise illustrates the necessity of including vulnerability analysis as an integral part of the design process for any large, complex, and valuable system. Note that the Reference System was designed for study and analysis only; no attempt was made in its design to protect it from deliberate assault.

4.5.1 The Transportation System

Earth launch facilities at Cape Canaveral are under the umbrella of the national territorial defense of the United States and thus are as safe from overt military attack by other countries as any other economic asset within the territorial limits of the United States. Due to the presence of highly flammable and explosive propellants, launch facilities are designed to withstand large explosions with minimal damage. Potential soft spots, however, are the propellant storage facilities themselves and pipelines delivering propellants to the launch facilities.

Earth launch vehicles are vulnerable to attack by military forces, terrorists, or insurgents during propellant loading and during the early stages of ascent. Perimeter security at the launch facilities during these periods is especially important. Reentry is another critical phase of flight since relatively small injuries to these vehicles could result in total loss of the vehicle. Such injuries could be inflicted by antisatellite weaponry in low Earth orbit just after the vehicle had completed its deorbit burn and was irreversibly committed to reentry. If such an attack were detected, of course, it might constitute an act of war; depending on the international political climate at the time, however, a hostile nation might be willing to take the chance that the attack would remain undetected and that the loss of the vehicle would be attributed to a mechanical failure of unknown origin.

Personnel Launch Vehicles (PLVs), Personnel Orbital Transfer Vehicles (POTVs), and Sortie Vehicles (SVs) are vulnerable to hypervelocity pellets. The Cargo Orbital Transfer Vehicles (COTVs), as pointed out earlier, are highly vulnerable to electromagnetic pulses from nuclear detonations in space. The attitude sensors of all these space vehicles are vulnerable to laser weapons.

4.5.2 The LEO Base

The living and working quarters and the propellant depots at the LEO base are vulnerable to hypervelocity pellets, such as deployed by a sounding rocket from the surface of Earth just in front of the base. Since the Earth's magnetosphere provides significant protection from cosmic radiation and solar flares, the living quarters are unlikely to be heavily shielded. Particle beam weapons or clouds of high energy electrons from distant nuclear explosions in space could thus inflict ionizing radiation on SPS workers at the LEO base. If the power system is based on photovoltaic arrays, the power system would be sensitive to nuclear weapon effects. Chemical or biological agents could be smuggled aboard in cargo or baggage.

4.5.3 The GEO Base

The power system (presumably photovoltaic) is sensitive to nuclear weapon effects. The propellant depots are vulnerable to hypervelocity pellets, and the living and working quarters are sensitive to chemical and biological agents. (Radiation shielding against cosmic rays, solar flares, and the outer fringes of the Van Allen belts would reduce the effectiveness of hypervelocity pellets.)

4.5.4 Power Satellites

The photovoltaic arrays and the transmitter arrays are sensitive to electromagnetic pulse effects resulting from nuclear explosions, even at great distances. The living and working quarters are vulnerable to chemical and biological warfare. The power buses, tension cables supporting the photovoltaic blankets, slip rings in the rotary joint, and brushes in the rotary joint would be fairly easy to damage by mutilation. In the silicon option, gantries carrying annealing lasers would also be attractive targets for mutilation. Mutilation could be carried out by teleoperators equipped with industrial lasers or conventional cutting tools, or by small rockets using conventional high-explosive warheads. Sensors of the attitude control system are vulnerable to laser weapons. These, however, would either have to be near geosynchronous orbit or be of very high power. (In the latter case, they would pose more serious military threats elsewhere.)

The large size of the power satellite makes it very difficult to inflict massive damage by conventional weaponry on supporting structure, transmitter array, or photovoltaic blankets. While high-energy lasers or particle beam weapons could deliver sufficiently high energy densities to photovoltaic blankets to destroy the solar cells, the time required for such a weapon to scan a significant portion of the blankets would be prohibitively long. (Assuming a high-energy laser consuming 100 MW to produce 16 MW of laser power, and assuming the laser beam covers a spot 160 m^2 in area on the power satellite, so that significant damage is inflicted on the solar cells within 1 second,* the time required to scan the entire blanket would be 45 hours for the gallium option and twice as long for the silicon option.)

4.5.5 Rectenna

Due to the distributed nature of the rectenna, it is difficult to inflict massive damage on it short of using a nuclear weapon. On the other hand, its large size would make it vulnerable to damage from electromagnetic pulses generated by high-altitude nuclear explosions (above 50 kilometers altitude) during a nuclear exchange. Commando or terrorist attacks on the rectenna would likely focus on the pilot beam transmitter, beam position sensors and the associated computers, power collection buses, power conditioners, and the utility interface equipment. All of these should be reparable fairly rapidly if spares are available, limiting the effectiveness of such assaults.

4.5.6 Command, Control and Communications System

Any local C^2 centers in the network can be damaged by small conventional explosives, as could transmitters, receivers, antennae, and landlines. Good engineering practice already includes redundancy, limiting the effectiveness of assaults on only one or a few centers. For attacks on the C^3 system to be effective, multiple coordinated assaults would be required, including numerous saboteurs.

4.6 Misperceptions Concerning the SPS Vulnerabilities

A number of misperceptions about the vulnerability of the SPS have become widespread. A common mistake is to underestimate the effort required to carry out a particular assault. For example, some observers consider the power satellites to be highly vulnerable to missiles landed from Earth. The energy required to deorbit a power satellite, however, is enormous, obviating this threat unless the missile has a nuclear warhead. Even then, getting close enough requires a multistage rocket with sophisticated guidance.

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*See Appendix C.3 for details.

One misconception which must be repeatedly addressed is the use of ground-based lasers to "shoot" objects in orbit. It is not now possible to predict how sufficient energy could be transmitted through the dispersive and attenuating effects of the atmosphere to overcome passive defensive measures on spacecraft and inflict structural damage, although it is possible that technological advances in the next two or three decades may overcome this difficulty. Even so, it is likely that ground-based lasers would be unable to damage objects in high orbits, including geosynchronous. Space-based lasers or particle beam weapons would be required to attain the energy levels needed to inflict structural damage at significant range.

These and other misperceptions about the vulnerability of SPS elements are summarized in Table 4-2. This table is not exhaustive, but it presents and refutes the most common misperceptions about vulnerabilities which have arisen during the last few years.

4.7 Vulnerability/Safeguard Matrix

The potential vulnerabilities of the Satellite Power System are summarized in Table 4-3, at the end of this section, along with safeguards to be discussed in Section 5. In contrast to the threat matrix, the vulnerability matrix does not include various military adapters which could be added to the Reference System, since analysis of the vulnerabilities of such military systems is outside the scope and intent of this study.

Several of the potential vulnerabilities listed are followed by a minus sign in parenthesis (-) to indicate that these assaults on SPS are considered either infeasible or so ineffective that they are extremely unlikely to be deployed. As in the threat matrix, a zero ("0") indicates that no plausible vulnerability of the type indicated by the column heading has been identified for that subsystem of the SPS.

Two institutional vulnerabilities (espionage and harassment) and one mixed institutional-technological vulnerability ("strategic" vulnerability of the SPS, discussed in Section 4.8 below) do not appear in this matrix since they apply to the system as a whole rather than to any particular system or subsystem element.

Table 4-2.
Common Misperceptions Regarding SPS Vulnerability

MISPERCEPTIONS	REALITIES
1. A power satellite will decay out of geosynchronous orbit orbit and crash to Earth if its propulsion system is disabled.	1. A disabled power satellite would continue to drift in GEO. Due to small orbital perturbations, it may contact other satellites, but it would take thousands of years to decay from this very high orbit.
2. Any hit on the solar array of a power satellite will result in the entire structure being ripped apart.	2. The solar array and the support structures of power satellites can readily be designed to be highly tolerant to damage.
3. Blast damage in space is similar to that on Earth, so shock waves from a small explosion can have devastating effects on large enclosed structures.	3. In a vacuum, there cannot be a compression-expansion wave emanating from an explosion. Shrapnel is the principal concern for non-nuclear explosions in space, with blast entering into consideration only for extreme proximity.
4. Spacecraft are easy to hit and kill, even with simple non-nuclear tactical rockets.	4. Intercept and kill in space is extremely difficult with non-nuclear warheads. Very sophisticated guidance and/or homing devices would be required, especially at GEO distances. To reach GEO would require staged rockets or launch from an orbital platform. Even in thirty years, only a small number of nations will have will have these capabilities.
5. A single small-caliber projectile, properly placed, can disable any spacecraft or satellite in the Satellite Power System.	5. With proper design, shielding, and redundancy all SPS elements can be made reasonably impervious to small-caliber projectiles. Space vehicles will remain the most vulnerable.
6. All SPS elements (except the rectenna) can be destroyed by a ground-based laser located anywhere on Earth.	6. In the near term, the Earth's atmosphere precludes such Earth-to-space threats because of dispersion and attentuation of high-energy laser beams and because of the relative ease of hardening space systems. Sensors in low Earth orbit, however, may remain vulnerable.
7. Space-based lasers are small objects which would be easy to conceal and use with no advance warning.	7. The power supply and the large focusing mirror required for an operational laser weapon result in a sizeable package with certain characteristic external features. Thus the existence, location, and ownership of such weapons would be well known before they reach operational status.

TABLE 4-3. VULNERABILITIES/SAFEGUARDS MATRIX FOR THE SPS

System Element	Subsystem Element	VULNERABILITIES			SAFEGUARDS		
		Technological		Institutional	Technological		Institutional
		Force Delivery	C^3I		Active	Passive	
Transportation	Earth-launch facilities	SMAT	EW (against computerized equipment)	Strikes, expropriation (if abroad)	National territorial defense	Fence	PS, PM, police, IS
	Earth-to-LEO vehicles	SMAT	0	Strikes, expropriation (if launch site abroad)	Δv, CE+I, SDF, BCI, decoys	Red. obs., spare vehicles, hardening	Agr. (Prox.), PS, PM, IS
	Space tugs & O-O vehicles	SMAT SGEMP (COTV only)	0	Strikes	Δv, CE+I, SDF, BCI, decoys	Red. obs., hardening	Agr. (Prox.), PS, PM, IS
LEO Base	Living/working quarters	SMAT	EW (against computerized equipment)	Strikes	SDF, BCI, CE+I, LRSS	Hardening	Agr. (Prox.), PS, PM, IS
	Materials stockpile	SMAT	0	Sanctuary	SDF, LRSS	Hardening	Agr. (Prox.), PS, IS
	Propellant depot	SMAT	0	0	SDF, LRSS	Hardening	Agr. (Prox.), PS, IS
	Power system	Shadowing(-) (if solar), SMAT, SGEMP	0	Sanctuary	LRSS, SDF	Hardening	Agr. (Prox.), PS, IS

TABLE 4-3. VULNERABILITIES/SAFEGUARDS MATRIX FOR THE SPS (cont'd)

System Element	Subsystem Element	VULNERABILITIES			SAFEGUARDS		
		Technological		Institutional	Technological		Institutional
		Force Delivery	C^3I		Active	Passive	
GEO Construction Base	Living/working quarters	SMAT	0	Strikes	SDF, BCI, CE+I, LRSS	Hardening	Agr. (Prox.), PS, PM, IS
	Construction equipment	SMAT	EW (against computerized equipment)	Strikes, sanctuary	SDF, BCI, CE+I, LRSS LRSS	Hardening	Agr. (Prox.), PS, PM, IS
	Materials stockpile	SMAT	0	Sanctuary	SDF, LRSS	Hardening	Agr. (Prox.), PS, IS
	Propellant depot	SMAT	0	0	SDF, LRSS	Hardening	Agr. (Prox.), PS, IS
	Power system	Shadowing(-) (if solar), SMAT, SGEMP	0	Sanctuary	Δv, SDF, LRSS	Hardening	Agr. (Prox.), PS, IS

TABLE 4-3. VULNERABILITIES/SAFEGUARDS MATRIX FOR THE SPS (cont'd)

System Element	Subsystem Element	VULNERABILITIES			SAFEGUARDS		
		Technological		Institutional	Technological		Institutional
		Force Delivery	C^3I		Active	Passive	
Power Satellite	Photovoltaic array	SMAT, shadowing(-), SGEMP	0	Sanctuary	LRSS, SDF	Hardening, alternative SPS design	Agr. (Prox.), PS, IS
	Power coll. & distribution	SMAT, SGEMP	0	0	LRSS, SDF	Hardening	Agr. (Prox.), PS, IS
	Power cond. & conversion	SMAT, SGEMP	0	0	LRSS, SDF	Hardening	Agr. (Prox.), PS, IS
	Power transmission (XMTR & beam itself)	SMAT, blocking μ-wave beam(-), SGEMP	"Trojan horse" box, "Pied Piper" box	0	LRSS, SDF, pilot beam override	Hardening	Agr. (Prox.), PS, IS, RIO
	Support structures	SMAT	0	Sanctuary	LRSS, SDF	Hardening	Agr. (Prox.), PS, IS
	Rotary joint	SMAT	0	0	LRSS SDF	Alternative SPS design, hardening	Agr. (Prox.), PS, IS
	Attitude control system	SMAT	0	0	LRSS SDF	Hardening	Agr. (Prox.), PS, IS
	Living/working quarters	SMAT	0	Strikes	LRSS, BCI, SDF, CE+I	Hardening	Agr. (Prox.), PS, PM, IS

TABLE 4-3. VULNERABILITIES/SAFEGUARDS MATRIX FOR THE SPS (cont'd)

System Element	Subsystem Element	VULNERABILITIES: Technological: Force Delivery	VULNERABILITIES: Technological: C^3I	VULNERABILITIES: Institutional	SAFEGUARDS: Technological: Active	SAFEGUARDS: Technological: Passive	SAFEGUARDS: Institutional
Rectenna	Pilot beam & associated equipment	SMAT	EW, chaff(-)	Expropriation, strikes	Alternate beams, CE+I, nat'l terr. defense	Redundancy	Agr., police, PS, PM, IS, outright sale
	Power collection antennas	SMAT EMP	0	Expropriation, strikes	Nat'l terr. defense, CE+I	Fence, hardening	Agr., police, PS, PM, IS, outright sale
	Power conver. & conditioning	SMAT EMP	0	Expropriation, strikes	Nat'l terr. defense, CE+I	Fence, hardening	Agr., police, PS, PM, IS, outright sale
	Support structures	SMAT	0	Expropriation, strikes	Nat'l terr. defense, CE+I	Fence, hardening	Agr., police, PS, PM, IS, outright sale
	Power distribution and interface	SMAT EMP	0	Expropriation, strikes	Nat'l terr. defense, CE+I	Fence, hardening	Agr., police, PS, PM, IS, outright sale
Command & Control System	C^2 centers (SPS & rectenna)	SMAT	EW	Strikes	ECM, encryption	ECM, encryption, hardening	Agr., police, PS, PM, IS
	C^2 centers (other)	SMAT	EW	Strikes	ECM, encryption	ECM, encryption, hardening	Agr., police, PS, PM, IS
Communication System	RF & laser links	SMAT, blocking(-)	EW	Strikes	ECM, encryption	ECM, hardening, encryption, redundancy	Agr., PM, IS

4.8 Comparative Vulnerability of the Satellite Power System

We have explored the potential vulnerabilities of the Satellite Power System in some depth. We now turn to a brief consideration of the relative vulnerability of the SPS compared to alternative technologies for electrical power generation and to some of the major transportation systems in use in industrialized countries today in order to place the whole question of vulnerability into perspective.

No complex industrial system is immune to disruption or destruction by hostile groups or nations. In considering whether to proceed with development of a major new energy technology, it is necessary to consider the strengths and weaknesses of that system relative to the strengths and weaknesses of alternative technologies accomplishing the same ends.

Candidate technologies for electrical power generation around the turn of the century and beyond include coal-fired generating plants using conventional boilers and turbines or magnetohydrodynamic (MHD) generators; conventional fission reactors; breeder reactors; fusion reactors; hydroelectric installations; ground-based solar electric conversion; large windmills; and ocean thermal energy conversion (OTEC).

With the exception of OTEC, the hardware associated with each of these technologies would lie entirely within the territorial limits of the country owning it, although both coal and nuclear power plants may rely on fuel sources abroad.

Careful examination of these alternative generating systems shows that they could be disabled for months using conventional explosives in quantities a few individuals could easily transport and emplace.

Some hydroelectric installations have generating capacities comparable to a power satellite. Grand Coulee Dam on the Columbia River in Washington state, for example, presently has an installed generating capacity of about 2.3 GW which could be expanded to more than 9 GW. In the case of Grand Coulee Dam and in the case of numerous hydroelectric facilities proposed for the developing countries, much of the water in the river proposed to be dammed comes across a national boundary. Unless the two countries involved have cordial relations and come to a mutually acceptable agreement regarding water rights, the water supply cannot be assured; the country upstream may choose to divert a significant part (or all) of the river's flow, rendering the hydroelectric plant virtually useless.

The industrialized countries today depend for the survival of their populations on a number of networks of transportation and distribution systems. Largely unthinkingly, we accept the vulnerabilities of these systems as part of the risks of civilization. Nonetheless, it is instructive to examine some of the vulnerabilities of the infrastructures on which we depend both for our standard of living and for our survival itself.

The water supply for most cities in the United States is carried by a very few (sometimes only one) aqueducts from reservoirs at some distance from the city. These acqueducts frequently cross rivers or ravines with little or no restriction of access, so that terrorists could easily interdict the entire water supply for at least a few weeks with a modest supply of conventional explosives. Pumping stations along such aqueducts are also highly vulnerable.

A large fraction of the energy supplied to the populous northeastern states of the United States is delivered from the Gulf of Mexico by two major pipelines transporting crude oil and petroleum distillates. Multiple river crossings and pumping stations are protected only by a chain link fence. One of the pipelines is almost totally controlled by a solitary computer system on the ground floor of an office building with virtually open public access. In many cases, a spare pump at a pumping station is in the same room as the operating pump, so that a single explosion could destroy both. (Most of these pumps are custom-order items, so that months might be required for replacement.)[1]

In a nuclear exchange, the existing electric utility grids in the continental United States would be vulnerable to sizable surge currents induced by electromagnetic pulses (EMP) from a handful of strategic nuclear weapons detonated at high altitudes (about 100 km) at selected points over North America. Such surges in the network would be quite likely to trip a large fraction of the electrical generators across the country simultaneously. Recovery from such a massive blackout would not be routine or straightforward, even if every generating plant should survive intact. (Note that the events at Three Mile Island in March 1979 began with a surge in the electric grid, and that several large generators suffered significant damage in the Northeast blackout of 1966.)

Most of the industrialized countries today depend on petroleum imports for a large fraction of their energy supply. In most cases, the petroleum is transported in tankers and supertankers over thousands of miles of international waters. Most oil from the Middle East must pass through the Strait of Hormuz, an area of some political instability. Regardless of flag shown, tankers would be prime targets in time of war. A recent fictional account[2] suggests the vulnerability of supertankers at sea to total destruction, not only by military forces, but by very determined and technically able individuals.

Obviously, certain safeguards should be implemented to reduce vulnerabilities in any vital system, whether it be the pipeline network, urban aqueducts, or the Satellite Power System. To demand total invulnerability for any of these systems, however, is unreasonable.

In contrast to major alternative energy systems which could be developed for civilian use in the United States in the same time frame as the SPS, the SPS program as a whole is subject to a "strategic" vulnerability which does not affect those alternatives. That vulnerability is the possibility of a major spacefaring nation blockading space against any major initiative in space by other nations. Interdiction of the early stages of an SPS program may be possible today. Intercontinental ballistic missiles armed with conventional high-explosive warheads or shaped charges would be adequate for the task, given some additional guidance and homing equipment. Any such attacks, however, would be viewed as acts of war.

4.9 Summary

The Satellite Power System, like any complex industrial system, is vulnerable to a wide variety of assaults by hostile groups or nations. Any element of the SPS, of course, can be destroyed by nuclear bursts. The most costly portions of the SPS are in space, and it is likely that the military forces of a small number of countries will be able to attack those facilities with sufficient force to inflict severe damage.

The vulnerabilities of SPS elements accessible to ground-based terrorists or commandos are similar in kind and degree to those of alternative energy technologies or of present-day transportation and distribution infrastructures in the industrialized countries.

The power satellites, the COTVs, and the photovoltaic power supplies of the LEO and GEO bases appear to be vulnerable (in the Reference Design system) to electromagnetic pulse effects from nuclear bursts in space at substantial distances. Such bursts, however, may result in damage to other spacecraft including those of the attacker, at comparable distances.

Vulnerability analysis and design for survivability of each component of a Satellite Power System is clearly an essential step in the design process from the start.

4.10 References

1. "Key Crude Oil and Products Pipelines Are Vulnerable to Disruptions," Report to the Congress, Comptroller General of the United States, United States General Accounting Office, EMD-79-63, August 27, 1979.

2. Justin Scott, The Shipkiller, Dial Press, New York, 1978.

5.0 SAFEGUARDS ANALYSIS

The preceding two sections developed a catalog of potential military threats which might be posed by the SPS or its elements, with and without modifications to enhance its military capabilities, and of potential vulnerabilities of the SPS or its elements. We turn now to an analysis of potential safeguards against these threats and vulnerabilities. First we will describe each of the technological and institutional safeguards we have identified, indicating the applicability of each to specific threats or vulnerabilities. We will then discuss in greater depth several safeguards which we consider to be especially important, concluding with a discussion of a possible scenario for the use of the Satellite Power System as a key element in strategic arms control.

The term "safeguard" is used here instead of terms such as "countermeasure" or "protection" since it has a broader meaning. In this discussion, the term "safeguard" encompasses protection of an object from actual assault; means of deterring an enemy from initiating an assault; and methods of preventing or forestalling implementation of a potential threat capability.

Protection of a spacecraft from enemy attack, for example, could be accomplished by passive measures such as hardening or protective coatings, or by active measures such as deployable shields, expulsion of chaff clouds, evasive maneuvering, or active self-defense using various weapons to destroy an incoming orbital interceptor.

Deterrence requires the threatened party to develop and deploy military capabilities which can be used to retaliate against an assailant. For example, attack upon space objects could be deterred by developing suitable capabilities to retaliate against enemy space systems. Deterrence is based on any type of force-delivery capability. In our analysis we have emphasized only safeguards which can be applied specifically against a particular threat. We have not considered the neutralization of a threat by "secondary means," such as threatening to launch an ICBM attack against any nation which attacks a vital space system. The possibilities for such "indirect deterrence" are numerous but are beyond the scope of this study.

Deterrence as defined above includes treaties and agreements to forbid attacks upon space systems. However, such legal documents are peripheral to the force delivery capability required for a credible deterrent. A more purely institutional type of deterrence is the use of various diplomatic means including negotiation, trade embargoes, propaganda, and placing armed forces on military alert. Such safeguards are beyond the scope of this study and will not be discussed further.

The last type of safeguard deals with methods for preventing the actualization of potential threats. For example, the diversion of the SPS power beam could be effectively prevented by encrypting the pilot beam signals and by providing remote or redundant pilot beam transmitters. This class of safeguards--whether technological or institutional--would be factored into the detailed engineering design of any SPS system at an early stage.

5.1 Technological Safeguards

Table 5-1 lists possible technological safeguards and the abbreviations used for these safeguards. It also indicates whether the safeguard would be used against threats, against vulnerabilities, or both.

Alternate SPS designs can safeguard elements of the systems against certain types of assaults which may otherwise be difficult to avert. In the Reference Design configuration of the power satellite, for example, the photovoltaic arrays are sensitive to surge currents induced by ionizing radiations from nuclear explosions at great distances (SGEMP). Redesign of the system to include current-limiting devices distributed throughout the solar cell arrays would significantly reduce the vulnerability of the power satellites to SGEMP. Should the solution result in an excessive cost or weight penalty, a more radical change (such as use of Rankine cycle or Brayton cycle thermal conversion instead of photovoltaics) may be necessary. Similarly, if the rotary joint in the Reference Design appears to be unacceptably vulnerable to mutilation, and hardening the joint is impractical, the power satellite could be redesigned to eliminate the rotary joint, with a fixed transmitter array illuminating a separate passive reflector satellite always aimed at the rectenna.

As is evident in Table 5-1, some of the safeguards using force delivery overlap the threats discussed in Section 3. Antisatellite weapon systems, for example, could be used by the SPS to defend itself, or by a non-SPS nation to protect itself against force delivery adapters attached to an SPS.

Table 5-1 TECHNOLOGICAL SAFEGUARDS FOR SPS

SAFEGUARD	ABBREVIATION	COUNTER THREAT	COUNTER VULNERABILITY
Alternate SPS designs	---	X	X
Antisatellite weapons	ASAT	X	
Baggage and cargo inspection	BCI	X	X
Ballistic missile defense	ABM	X	
Boobytraps	BT	X	
Chaff, decoys	---	X	X
Counter-ASAT	---		X
Counterespionage and intelligence	CE+I		X
Design for survivability	---		X
Dual key (or multikey) enabling systems	DK	X	X
Electronic countermeasures	ECM	X	X
Electronic signal intelligence	SIGINT	X	X
Encryption	---	X	X
Evasive maneuvering	ΔV		X
Fences	---		X
Hardening	Hard.	X	X
Long-range space surveillance	LRSS	X	X
Monitor crew movements	---	X	X
National territorial defense	---		X
Physical attack	---	X	
Pilot beam override	---		X
Reduced observables ("STEALTH" technology)	Red. obs.	X	X
Reflectors (against high energy lasers)	---	X	X
Remote/redundant pilot beams	---	X	
Self-defense	SDF	X	X
Self-destruct	SD	X	
Spare vehicles	---		X
Surface-to-air missiles	SAM	X	
Surveillance and reconnaissance	S&R	X	
Industrial security measures	IS	X	X
International agreements and treaties	Agr.	X	X
International resident inspection operations	RIO	X	
Personnel screening and selection	PS		X
Police and security forces	Police		X
Proximity rules in space (by international agreement)	Prox.	X	X
Public discussion	Pub. disc.	X	X

Baggage and cargo inspection (BCI) would be an important preventive measure against sabotage of, or terrorism against, space-based SPS elements, analogous to current security practices in commercial airline operations. If operated by (or under the supervision of) the Resident Inspection Operation (RIO), BCI would also provide a safeguard against augmented military manning of SPS facilities.

Ballistic missile defense (ABM) systems could be used by non-SPS nations to protect themselves from Earth-bombardment reentry vehicles based aboard SPS elements adapted for military purposes. In addition, such defenses might also be effective against Earth-launch vehicles converted into hypersonic bombers.

Boobytraps (BT) may provide a deterrent against kidnapping or mutilation of unmanned satellites (SATNAP and SATMUT, respectively) or against boarding and takeover of manned facilities in space, although care would be required in their design to ensure that only illegal boarders could be injured by such systems.

Dual key arrangements are similar to those used to control the launch of ICBMs. (Launch cannot occur until two individuals simultaneously turn keys in different locations.) Such techniques could be used to activate self-defense weapons. Similarly, switches wired in series could allow designated individuals to shut off the power beam ("veto privilege"). Such switches could be widely separated (e.g., one in space, one on the ground). Appropriate technological safeguards would, of course, be required to prevent tampering.

Electronic countermeasures (ECM) would be used to counter electronic warfare and signal intelligence activities. Examples of such countermeasures are increasing transmitter power, changing the operating frequency of a transmitter, and the use of various "antijam" techniques such as spread spectrum modulation and frequency hopping. Encryption is a possible safeguard against SIGINT, especially COMINT.

The various types of military support modules listed perform straightforward functions, and technological safeguards should be fairly effective. For example, navigation aids must emit radio signals to function. Thus, SIGINT could be used to detect their presence. Similarly, communications devices could be detected by SIGINT or, assuming they require moderate to large antennae, could be detected by optical means (LRSS). Even if military power beaming adapters were to be installed, dual key control of the main electrical power bus of the power satellite could effectively prevent misuse of the electrical power for military purposes. (This assumes that the amount of power being diverted is sufficiently large to permit detection.)

Hardening and protective coatings could be utilized as passive defenses against weapons such as HELs and PBWs.

Long-range space surveillance (LRSS) is a type of surveillance and reconnaissance. It has been given a unique name to emphasize that it would be used to detect the installation of military adapters aboard orbital facilities or at ground sites.

To safeguard against augmented manning of SPS facilities by military personnel, it would be necessary to monitor the movement of crew personnel to ensure that they were not congregating at a particular location. In addition, the operation of an alternative command post could be detected using COMINT and/or MSGINT.

Physical attack is primarily intended here to denote the use of land forces to prevent the military use of SPS launch facilities.

Pilot beam override could be utilized to overcome the effects of a "Pied Piper box." Such a box is a special type of transmitter which would mimic the pilot beam equipment and serve to draw the power beam to another location, possibly a population center.

Another safeguard against Pied Piper boxes is a robust pilot beam system. At a minimum, this would include encryption of the power beam steering parameters which are sent by the pilot beam. Other approaches include: redundant pilot beams operating on different frequencies, the use of antijam techniques (frequency hopping and spread spectrum modulation), and indirect routing of the pilot beams. Indirect routing means that the beam steering parameters would not be sent directly up from the rectenna site. Rather, they would be conveyed via land lines to one or more transmitter sites, conveyed to relay satellites, and finally reach the SPS via a space-to-space communications link (preferably a lasercom link). Lastly, if all else fails, a dual key design would enable the SPS power beam to be shut off.

Reduced observables involves the use of nonreflective coatings, etc., to make it difficult to detect the object. This would tend to safeguard against surveillance and reconnaissance, as well as against attacks by ASAT weapons.

Reflectors and shields could be used to protect a space system from attacks by HELs and PBWs.

Self-defense primarily deals with intercept or shootback capability but could also include the installation of boobytraps aboard a spacecraft. Intercept capability or directed energy weapons could be installed on the power satellite or deployed some distance away. Under RIO, it would seem possible to deploy such weapons with international assurance that their range and capabilities were adequate for defensive purposes but not for offensive uses. Such self-defense capabilities could be used to safeguard against ASAT attacks as well as satnapping. Similarly, an onboard self-destruct capability could be used to safeguard against satnapping.

5.2 Institutional Safeguards

Table 5-2 lists possible institutional safeguards and the abbreviations used for these safeguards.

Table 5-2. INSTITUTIONAL SAFEGUARDS FOR SPS

SAFEGUARD	ABBREVIATION	COUNTER THREAT	COUNTER VULNERABILITY
Industrial security measures	IS	X	X
International agreements and treaties	Agr.	X	X
International resident inspection operations	RIO	X	
Personnel screening and selection	PS		X
Police and security forces	Police		X
Proximity rules in space (by international agreement)	Prox.	X	X
Public discussion	Pub. disc.	X	X

Various kinds of international treaties and agreements are considered indispensable concomitants of an SPS program, whether multilateral or multinational. These are needed to resolve issues such as the implications of existing treaties (e.g., the 1967 Treaty on Principles) on the use of outer space for orbital power generation, use of geosynchronous orbit, use of SPS in behalf of private sector organizations, and other questions. A discussion of this kind of safeguard is presented in Appendix B.

A prominant candidate institutional safeguard considered in this study is resident inspection. This involves the use of independent observers to monitor and inspect, as required, all space-based and land-based facilities belonging to the SPS project. This concept is discussed further in Section 5.4 below.

A special type of agreement involves proximity rules in space. These can be described by analogy with civil aviation practices in international airspace. Legally, international airspace is not subject to national appropriation and is available to aircraft belonging to any country. However, in order to protect against collisions between aircraft, air traffic control services are provided. Depending on flight altitudes and distances from fixed navigation aids, substantial volumes of airspace surrounding each aircraft are protected from intrusion by other aircraft. Similarly, minimum distances of separation between spacecraft could be specified by international agreement.

Another type of institutional safeguard is public discussion. This is primarily useful in safeguarding against threats and vulnerabilities which are based on misperceptions. For example, the public could fear that a system failure could cause diversion of the SPS power beam over a population center, thereby threatening the population. Open public discussion would counter such unjustified fears by accurately describing the flux density of the SPS power beam, by explaining how the SPS power beam is designed to home in upon a pilot beam located at the rectenna site, and by stressing the design features of the pilot beam system which make it secure and reliable.

5.3 Key Safeguards

Possible safeguards noted in the threat and vulnerability matrices and in preceding discussions can be classed as active or passive, counterthreat or countervulnerability or both, and of varying degrees of provocativeness. Table 5-3 summarizes over thirty possible safeguards according to the above classifications.

Three primary criteria for evaluating possible safeguards, in order of decreasing importance, are: 1) effectiveness; 2) provocativeness or acceptability; and 3) cost. While all safeguards identified in this study are thought to be realistic and potentially effective, total effectiveness is beyond reach in the

Table 5-3. SPS SAFEGUARD SUMMARY

ACTIVE SAFEGUARDS			
Type / Provocativeness	Counter-Threat	Counter-Threat and Counter-Vulnerability	Counter-Vulnerability
"HIGH"	ASAT ABM Physical attack	EW/ECM	
"MODERATE"	RIO Booby-traps Self-destruct SAM	Self-defense Decoys EW/ECM Crew monitoring	Police National territorial defense Counter-ASAT
"LOW"		EW/ECM Public discussion Pilot beam override Industrial security Baggage and cargo inspection	Personnel screening Evasive maneuvering

PASSIVE SAFEGUARDS			
Type / Provocativeness	Counter-Threat	Counter-Threat and Counter-Vulnerability	Counter-Vulnerability
"HIGH"			
"MODERATE"		Reduced observables	
"LOW"	Surveillance and reconnaissance	International agreements Proximity rules (international) Counterespionage and intelligence Long-range space surveillance (LRSS) SIGINT Encryption Hardening Reflectors and shields	Fences Spare vehicles Redundant and/or remote pilot beams Design for survivability

real world. Optimization of individual safeguard means or combinations of safeguards for acceptable effectiveness and comprehensive projections of expected absolute and relative effectiveness require in-depth investigations beyond the scope of this study.

A qualitative impression of relative effectiveness can be conveyed by indicating whether a safeguard appears applicable in only a counterthreat role, in only a countervulnerability role, or in both, and this indication is included in Table 5-3.

Degrees of provocativeness can be estimated qualitatively by informed judgment, and this estimation is incorporated in Table 5-3. Obviously "low" or "moderate" degrees of provocativeness are preferable to "high" provocativeness. Costing of the candidate safeguards identified would require specialized studies, but it is reasonable to assume that, in a general way, cost varies in the same sense as degree of activeness and provocativeness.

Based on these comments, Table 5-3, in conjunction with the threat and vulnerability matrices, provides an initial perspective on the array of possible safeguards. Six kinds of safeguards emerge which appear to be of priority importance. These are shown in Table 5-4.

Table 5-4. PRINCIPAL SAFEGUARDS

	TECHNOLOGICAL	INSTITUTIONAL
ACTIVE	o Self-defense o Electronic warfare/electronic countermeasures	o Resident inspection o Public discussion
PASSIVE	o Space surveillance o Design for survivability	o International agreements

5.4 International Resident Inspection Operation (RIO)

The uses of space stations like SPS for military purposes are so varied that a piecemeal analysis of each potential threat, coupled with detailed steps to counter it, can hardly satisfy the proper doubts and concerns of critics. This is because of the inherent danger of threat potentials that surface only after an initial go-ahead has been obtained. Each new threat possibility, whether real or fancied, could be used as an excuse for cessation of any SPS program. (We have seen this method applied to nuclear power projects in this country and elsewhere.) A general solution is therefore required, that is clearly satisfactory in principle.

It has been suggested that, in accordance with the 1967 Treaty on Principles, nations building power satellites might allow inspection visits at space facilities (including the power satellites themselves) by observers from non-participating countries at random intervals, with minimum advance notice.

While such a proposal has some merit, it is not likely to allay all fears of SPS military threats. In the next few decades, the capabilities of spacefaring nations or consortia will be substantial. It would thus be feasible, for example, for a battery of high-energy lasers (together with the focusing, tracking, and pointing equipment necessary for a ballistic missile defense system) to be concealed in deep space beyond tracking range. In time of impending crisis, such a weapon system could be brought up rapidly for attachment to its power source, a power satellite, without detection by other nations. Only if an international inspection team were in permanent residence aboard each power satellite and each SPS facility in space could every nation on Earth be assured that such military use or conversion of the SPS would not remain undetected.

If an international Resident Inspection Operation (RIO) is to successfully allay reasonable fears about military uses or abuses of SPS, it must be open to participation in the inspection program by any nation which is concerned about potential SPS threats to its national security. International confidence in SPS would then rest on the opportunity for observers designated by a variety of nations to inspect any portion of SPS on a continuing basis and on the ability of RIO inspection teams to report to RIO headquarters on Earth (and thus to the international community) the absence of military activities or hardware aboard SPS elements.

While international observers have played a useful role in a number of cases of potential or actual international conflict, a lesson of history is clear: once open hostilities begin, the presence of international inspection teams will be ignored by all combatants. It is thus likely that SPS, even under international resident inspection, may still have need for self-defensive capabilities. RIO, however, could guarantee that the capabilities of such weapon systems were indeed limited strictly to self-defense. A high energy laser incapable of focusing its beam to incendiary levels for ranges greater than a few hunded kilometers, for example, would hardly constitute a grave threat to other nations if it were deployed on a highly unmaneuverable power satellite in geosynchronous orbit more than 36,000 kilometers above the equator.

For an inspection organization to be effective and credible, it must have assured means of access to all parts of the SPS and assured means of communications between all its operatives and headquarters. If RIO were dependent on the SPS operational entities for these services, a variety of "reasonable" excuses might be invoked by the operational entities to refuse these services at time of international crisis or of national emergency, just when the international community most urgently needs assurances that SPS elements are not being converted or adapted for military use. RIO must thus have its own space transportation capabilities and its own communications systems.

We thus envision RIO teams residing aboard each power satellite, aboard the LEO and GEO bases, and at each rectenna site. At the SPS launch facilities, all baggage and cargo to be loaded aboard SPS launch vehicles would be subject to RIO examination. In addition, RIO teams would have carte blanche access to SPS records and blueprints at offices and facilities of both the legal and operational entities controlling SPS. During the DDT&E phase, RIO would review experimental hardware and blueprints for evidence of military adaptations.

In addition to inspection teams residing at various SPS sites, RIO would also have a number of inspection teams roving at large to perform random spot checks on both RIO teams and SPS to minimize chances of collusion between RIO teams and the SPS operational entities. Fairly frequent rotation of RIO personnel would further minimize this risk. Appendix A discusses RIO further and provides rough estimates of minimum manpower levels for RIO at the midpoint of SPS deployment in the Reference Design, when thirty 5-GW units are in place and two more units are being built each year.

Each power satellite and each rectenna built by the operational entities would then be sold with the understanding that the buyer accepts RIO teams in perpetuity both aboard the power satellite and at the rectenna site. Nations objecting to international inspection of any facilities within their borders but still wishing to use SPS for part of their energy supply would have the options of placing the rectenna offshore or of attempting to lease a rectenna site in a neighboring country which has no objections to such inspection.

Member states of RIO could appeal to Article IX of the 1967 Treaty on Principles which states:

> ....If a State Party to the Treaty has reason to believe that an activity or experiment planned by it...would cause potentially harmful interference with activities of other States' Parties in the peaceful exploration and use of outer space..., it shall undertake appropriate international consultations be fore proceeding with any such activity or experiment. A State Party to the Treaty which has reason to believe that an activity or experiment planned by another State Party...would cause potentially harmful interference with activities in the peaceful exploration and use of outer space...may request consultation concerning the activity or experiment.

Regarding the vulnerability of SPS, defensive weapon systems in space (such as ASAT, PBW, or HEL) could be considered in violation of the 1967 Treaty on Principles and the spirit of the proposed Moon Treaty as infringements on the peaceful uses of outer space by SPS.

If the first power satellite were deployed by the United States for its own energy purposes initially, or deployed in cooperation with such friendly countries as the United Kingdom, Canada, Japan, and members of the European Space Agency, it would clearly fall within the terms of existing treaties regarding scientific research and development for peaceful purposes. This affords another legal institutional safeguard, particularly if subsequent power satellites were planned to be utilized for the benefit of other nations participating in some kind of SPS umbrella organization analogous to INTELSAT. The organization and form of the initial ownership arrangements for SPS will clearly be a very strong determinative factor in the legal institutional safeguards for SPS.

The success of the Apollo-Soyuz Test Program lends some credibility to the proposal that the United States (with private sector participation) and the Soviet

Union join in the planning, design, and construction of the initial SPS to reduce perceived threats. However, because of technology transfer limitations in the United States, the most practical approach may be for the United States, the United Kingdom, Canada, Japan and Western European nations to join and proceed together. Insurance and indemnity for SPS hazards might then be legally obtainable from private and governmental sources. Satellite life insurance, perhaps on a three-year basis with renewals, and with or without war risk exclusions, would be desirable.

Any conversion of SPS facilities into a military weapon capable of damaging the Earth, its environment, other satellites, or SPS facilities may be a violation of the existing treaties, especially if it could be argued that directed energy weapons using a sizeable portion of a power satellite's output constitute "weapon(s) of mass destruction."[1] The RIO appears potentially promising in providing assurances that SPS is not a weapons system or an antiweapons system, and will not become one.

On the basis of the estimated transportation and staffing requirements for RIO given in Tables 2-2 and A-1 respectively, it is evident that capital and recurring costs of RIO would be no more than a modest fraction of total SPS costs.

5.5 Summary

Over thirty distinct possible means can be identified which promise to be credible and effective safeguards against SPS threats and/or vulnerabilities. Comprehensive projections of expected effectiveness require more detailed investigations. Acceptability and cost considerations appear reasonable. Further understanding of the possible mechanisms and implications of international agreements is required.

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1 However, note that the term "weapon of mass destruction" is undefined in international law. Its use in parallel with the term "nuclear weapons" suggests that much greater destruction than could be delivered by PBW's or HEL's was contemplated in drafting the treaty. One should also note that the Soviet development of ASAT's, if protested by the United States under Article IX of the Treaty on Principles, would likely be defended by the U.S.S.R. as posing no threat to peaceful uses of outer space, but only to hostile (military) uses of space, and thus not prohibited by Article IX. Similar arguments could be made to justify active defensive weaponry aboard power satellites and other SPS facilities in Earth orbit.

Resident inspection operations (RIO) appear to be a potentially promising safeguard and its formulation, organization, and implementation poses novel challenges. In addition, RIO's unique position would place it in a position to play a significant role in the maintenance of international stability. Other key candidate safeguards appear to be SPS self-defense, expanded space surveillance, electronic warfare and countermeasures, and public discussion.

APPENDIX A

GUIDELINES FOR RESIDENT INSPECTION OPERATIONS (RIO)

A. GUIDELINES FOR RESIDENT INSPECTION OPERATIONS (RIO)

A key institutional safeguard against potential military threats arising from the SPS is the concept of an international Resident Inspection Operation (RIO). The principal function of RIO would be to detect and report to the international community any attempt to use the SPS as a threatening military weapon, to convert the SPS into a weapon, or to use any of its elements to support offensive military systems in any direct manner.

A.1 General Consideration

In order to perform its intended function, RIO must be both effective and trustworthy. It must be able to carry out its function despite attempts at political, economic, or physical coercion. It must be a trustworthy organization whose activities are above suspicion and whose reports are believable.

Several problems present themselves in organizing and managing RIO in order to ensure its effectiveness, believability, and reporting capabilities.

The first of these is the problem of the independence of the RIO. Regardless of the mechanisms of ownership and management of the SPS systems, the RIO must be organized and managed in such a manner that it is acceptable to the SPS system owners and managers. Although the SPS systems personnel may, in some instances, tend to treat RIO personnel as necessary evils, there must be an agreement between the RIO management and the SPS management permitting the free access of RIO personnel to every aspect of the SPS, with due regard for the safety of both personnel and equipment.

The RIO must also be acceptable and believable to political and military leaders and to the general public in diverse countries of the world. Since it cannot show the slightest hint of conflict of interest, it cannot be organized or staffed by the owners or operators of the SPS system, nor by any government or organization in a position to exert significant political, economic, or ideological leverage on the RIO.

Although this in itself appears to be a very large order, the organization and management of the RIO must be effective. If and when a potentially threatening activity occurs, RIO must be ready, willing, and able to report it on a worldwide basis. RIO must, therefore, possess its own communications systems which are, to all intents and purposes, nonjammable and noninterruptable. These RIO communications systems will be used for intraorganizational secure communications, as well as for communication with world leaders, world news media, or the general public through existing communications networks. Communications is an important and essential element of RIO effectiveness.

Because the organization and management of RIO appears to be solely that of an observational and reporting agency, it may be highly advisable that RIO members not be armed and not carry or be able to operate any sort of weapon, even in self-defense.

RIO must be an apolitical, independent, multinational group with no conflict of interest. It must be an organization designed for immunity to bribes, both monetary and ideological. It must therefore be a highly dedicated organization with esprit de corps, discipline, pride, and a set of unique developing traditions that will help set it apart from social groups. These characteristics are typical of paramilitary organizations, and it is suggested that RIO be considered as one. Similar--albeit not paramilitary--organizations are already in operation in the world; one example is the International Red Cross. Industrial security police forces provided by Brink's, Pinkerton's, Wells Fargo, and Purolator are also analogous. RIO, however, amounts to a new form of social organization and cannot be equated with any existing groups. RIO must be developed on a higher social level than any of these analog examples.

All RIO personnel--especially those on the various Inspection Teams--must be selected using psychological screening such as the current human reliability programs operational in the USAF Strategic Air Command.

A.2 Institutional Arrangements of RIO

A number of "umbrella" organizations might provide the initial roots for RIO. But each presents problems.

The United Nations might serve as an umbrella for RIO. As a paramilitary organization most closely analogous to the pan-national UN Security Force originally proposed in 1946, RIO would most certainly be saddled with constraints impairing its effectiveness. As a UN organization, it might be subject to recall, reorganization, restaffing, or veto of operations by individual UN member nations or by political blocs in the UN.

Operation of the RIO under any national umbrella is unlikely to be acceptable. Virtually any existing political group can be ruled out as an umbrella organization because of the sure and certain perception of military threat by other political bodies around the world. One possible exception is a nation with a long, established history and tradition of neutrality, such as Switzerland, although it is unclear whether such a nation would be willing to undertake RIO even if that were acceptable to the international community as a whole.

One must look carefully to those social organizations which would stand to lose the most should an SPS become, or even be perceived as, a military threat. Not the least of the basic factors involved in a SPS is the capital investment and the attendant high capital risk, especially if the SPS were perceived as a military threat and therefore became an early target in an armed conflict between nations capable of significant assaults against SPS. The elements of the SPS would probably be heavily insured against loss, just as large terrestrial power stations are today.

It would then seem that a possible umbrella organization or foundation for RIO would be the insurance consortiums, financial institutions, and other risk-reduction organizations whose loss would be the greatest if the SPS were perceived as a military threat and therefore came under attack in a general war on Earth. Such risk-reduction organizations will do their utmost to protect the investment of their clients whose risk they have insured. They would certainly wish to establish and insure that the operation of RIO is in concert with the basic needs for RIO: elimination of the risk of the SPS becoming a military target because of perceived threat.

This argument does not apply to the socialist nations of the world such as the USSR or the People's Republic of China in which the state insures itself. It is an open question whether the USSR or the PRC would permit uncontrolled and completely free access by outside organizations to SPS elements which they owned.

Who pays for RIO? Shall the cost be borne by the users and customers? by the SPS owners? by national governments whose concern of the military threat of the SPS system is allayed by the RIO? by the United Nations?

If risk-reduction organizations were the roots for RIO, they would consider RIO as part of their operational costs and would see to it that RIO were suitably funded to remain as effective as possible. The cost would naturally be passed along to their clients, the SPS owners and operators, who, in turn would pass the costs along to the users and customers. This appears to be in concert with the current practice in analogous industries; it is based on the philosophy that the end-user of a product or service must bear its costs, including those associated with assurances that the goods and services which fulfill their needs do not constitute a threat to others.

In view of the difficulties noted above with various umbrella organizations for RIO, it is likely that RIO would have to be established as an entirely new kind of international entity, sui generis. The political difficulties of establishing RIO may be smaller than those of forming a multinational alliance for the DDT&E and startup phases of an SPS program, since even nations ideologically opposed to the United States, to the SPS, or indeed, to international cooperation, would have a strong vested interest in ensuring that SPS did not become a military threat.

A.3 Operational Considerations

Personnel estimates to man and staff the RIO are shown in Table A-1. It should be emphasized that these are estimates and are based on minimal manning of each power satellite. The estimates have been deliberately set low because RIO should be set up as a lean organization; it will have the usual tendency to grow, and this growth must be kept to a minimum consistent with effectiveness.

A Resident Inspection Team may consist of only a few people. Indeed, during the early years of the SPS program, a Resident Inspection Team may consist of only four people, enough to operate three eight-hour shifts plus a supervisor who can step in as supernumerary in case of incapacitation of another member of the Team. A Resident Inspection Team would live with the operations crew aboard each power satellite and each orbital base. They would have their own dedicated and secured communications channel to RIO headquarters. They would not operate on any sort of scheduled inspection routine, but would inspect and observe on a highly random basis. SPS personnel would not know from one shift to the next what the Resident Team would be looking at or for.

Much of the equipment of the Resident Inspection Team would be automated to provide an alarm in case of any change. (For example, should some military hardware have been bolted onto the power satellite girders covertly, the mass and moments-of-inertia of the satellite would change, and the Attitude Control System would require longer burns on the ACS thrusters, providing a computer-detectable change in the system.) Basically, the Team would be watching for changes that would

Table A-1
RIO MANNING REQUIREMENTS (1)

LOCATION		NUMBER	SPS PERSONNEL	RIO PERSONNEL
Power Satellites		30	30 x 4 = 120	30 x 4 = 120
GEO Base		1	680	68
LEO Base		1	35	20
Launch Pads (2)		6	12,000	1,200
Rectenna sites		30	30 x 8 = 240	30 x 4 = 120
Vehicles	SV	70	70 x 8 = 560	70 x 6 = 420
	COTV	9	---	9 x 6 = 54
	HLLV	3	3 x 16 = 48	3 x 12 = 36
	PLV	4	4 x 16 = 64	4 x 12 = 48
	POTV	3	3 x 8 = 24	3 x 12 = 36
SPS Headquarters		1	1,000	16
RIO Headquarters		1	---	100
RIO Liaison Positions		10	---	10 x 4 = 40
RIO Pilots		64	---	64 x 4 = 256
Spot Check Teams		10	---	10 x 4 = 40
TOTALS			~15,000	~2,600

1. Preliminary estimates, based on 30 SPS units in place, 2 per year under construction, for the GaAlAs version of the Reference Design.

2. We assume that RIO will contract for launch operations and maintenance services from the SPS organization or from the same sources the SPS organization uses.

indicate that an SPS facility was being modified for military use. (This presupposes that the SPS is in place and on line; operations during DDT&E would involve close inspection of the design and construction of each SPS element and facility to insure its nonmilitary function or potential.)

Resident Inspection Teams must be rotated on short and irregular intervals to prevent the possibility of team individuals forging friendships, associations, or arrangements with SPS personnel that might result in conflict of interest and abrogation of the function of the RIO.

The question, "Quis custodiet ispos custodes?" arises with respect to an organization such as RIO. Therefore, Spot Check Teams must also be provided to check up on both the SPS system personnel and facilities as well as on the individual Resident Inspection Teams. These Spot Check Teams would make unannounced visits to facilities. No one, not even the Resident Inspection Team, would know what to expect, when to expect it, or what the Spot Check Team would be looking for or at.

In order to maintain RIO independence, the organization must possess its own space transportation system for its personnel. Otherwise, it could be subject to the whims of those who control the space transportation system supporting the SPS. A RIO space transportation system would also be essential to the operation of the Spot Check Teams. RIO might have some launch sites of its own; by and large, however, it would utilize existing launch facilities.

A logistical support function would be essential for maintenance of the RIO space transportation system as well as for secure provision of life support consumables. In a critical situation, reliance on the SPS organization's life support facilities by the Resident Inspection Teams could place them in a difficult if not untenable situation.

Finally, the support functions of the RIO would have to include a separate and secure communications system through which the Resident Inspection Teams and Spot Check Teams could communicate with their headquarters. This communications system would have to be secure and to include fail-safe elements. (For example, coded reports would be made at irregular but scheduled times by each Resident Inspection Team. Failure of a team to report in as scheduled and in the code or with the passwords required would be cause for immediate suspicion, communication of that fact to the SPS management, a report to world leaders, and a prompt inspection visit by a large Spot Check Team, possibly armed.)

Some RIO communications would be made in the clear. Others would be made on secure, scrambled channels. SPS operators and managers, and especially world military personnel, should not know what RIO is doing at all times. A secure channel to RIO headquarters would be necessary to allow the RIO command to work quietly with SPS management to clarify or rectify perceived problems without prematurely bringing them to the full attention of others.

Table A-2 lists a number of operational questions which will arise in the design and implementation of RIO; these are left for further study.

A.4 Conclusion

RIO's trustworthiness ultimately will rest on the inclusion of every nation wishing to have inspection access to the SPS. To the extent that SPS were perceived to have the potential of wielding a significant military threat, other nations would be strongly motivated to participate in RIO even if the SPS program were unilaterally implemented by the U.S. Such motivations should also minimize obstacles to negotiating the structure and implementation of RIO.

RIO's effectiveness would rest primarily on the random nature of its Resident Inspection Teams and Spot Check Teams, on the impermanent nature of its Resident Inspection Teams, and on its ability to communicate at will. Fundamental questions requiring examination in depth include:

(1) Are there existing umbrella organizations that might provide a base for RIO and oversee its operations? Should RIO be created entirely new as a distinct international entity?

(2) RIO appears to be imperative if SPS is to be internationally acceptable. What are some scenarios and their consequences without a RIO? Without RIO, is the military utilization of the SPS system inevitable in view of the sheer size, cost, and complexity of the system as well as the impact on terrestrial users if the SPS output were diverted to military uses?

Table A-2
RIO OPERATIONAL QUESTIONS

1. Where do the RIO teams monitor, what do they look for, what are the critical points for inspection, and what is the level of detail the teams must look for?

2. What are the tradeoffs of personnel vs. automated aids, including the effort that must be expended to check the automated aids? How does this tradeoff affect cost vs. trustworthiness?

3. What manning levels are realistic on the basis of the answers to the above two questions? Is the RIO manning level in any way consistent with similar monitoring and inspection activities, and is this comparison really meaningful in view of the unique nature of the RIO environment?

4. What are the generalized procedures that must be followed by both Resident Teams and Spot Check Teams? What procedures should be followed in the event of a suspected or detected military alteration or use of SPS system equipment or facilities? What are the general policies that must be utilized by SPS Headquarters in dealing with concerned nations and parties?

5. The RIO concept leads to the potential requirement of career personnel for RIO. Will a special training academy eventually be required as it has for other dedicated career organizations? How should RIO be structured to attract and retain highly motivated people of all nations? What are the impacts of these questions on costs? How is RIO phased in during the early years before the dedicated training activities are established and proven?

APPENDIX B

MULTILATERAL AGREEMENTS REGARDING MILITARY IMPLICATIONS OF SPS

B. MULTILATERAL AGREEMENTS REGARDING MILITARY IMPLICATIONS OF SPS

One working premise of the current study on the military implications of a Satellite Power System (SPS) is that international multilateral agreements could serve to minimize potential vulnerabilities of the SPS and could also help to minimize potential SPS threats perceived by foreign States. With the understanding that no agreements are ever absolute assurances against military threats and vulnerabilities, an analysis can be made of the alternative types of multilateral agreements which are available.

Several forms of multilateral agreements involving space-related matters have been utilized in the past, and these options would be available for an SPS multilateral agreement. Specific substantive provisions of such an agreement would evolve in the context of general international law and the law of outer space in accordance with previous multilateral space treaties, as well as in the context of the negotiating positions of the States which participate in the development of the agreement. The resultant agreements would be subject to international norms with regard to enforcement and sanctions.

B.1. Types of Multilateral Agreements

Three general categories of international multilateral agreements are relevant to the development of SPS facilities. These categories consist of binding agreements, nonbinding agreements, and agreements which form the charters of distinct legal entities such as international organizations.

International treaties are agreements, of a contractual nature, creating legal rights and obligations between the parties.[1] Treaties are considered binding in the sense that the sanctity of treaties is an integral part of international law which is based on good faith between States.[2] The Vienna Convention on the Law of Treaties, which is not yet in force in the United States, has codified this principle in Article 26, which states: "Every treaty in force is binding upon the parties to it and must be performed by them in good faith." Likewise, the draft Articles on Treaties Concluded Between States and International Organizations or Between International Organizations would also adopt this same provision.[3] The usefulness of binding agreements to mitigate the threats or the vulnerabilities associated with SPS facilities would be dependent upon the extent to which parties exercised good faith in their observance of the treaty obligations.

Good faith observance of treaties is not always permanently exercised.

> ". . .(t)he circumstances in which a treaty was made may change, and its obligations may become so onerous as to thwart the development to which a state feels itself entitled; and when this happens, it is likely, human nature being what it is, that a state which feels itself strong enough will disregard them, whether it has a legal justification for doing so or not."[4]

Often treaties include provisions by which States can withdraw from their terms and conditions. All four existing multilateral space-related treaties, for example, permit parties to withdraw upon notice.[5] Thus, the concept of "binding" when associated with treaties applies only in a temporary sense.

Certain international agreements are considered nonbinding in the sense that there was never any intention by the parties to be bound by the terms and conditions of such agreements. An important example of this type of agreement is the current effort within the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS) to draft "principles" for the conduct of operational direct broadcast satellite activities and satellite remote sensing activities. Presumably, there is also a good faith obligation to adhere to nonbinding "principles." Thus, the practical distinction between binding and nonbinding multilateral agreements may not be as great as might be supposed.

The difference between binding and nonbinding agreements does not necessarily depend on their title.

> "International compacts which take the form of written contracts are sometimes termed not only agreements or treaties, but acts, conventions, declarations, protocols, and the like. But there is no essential difference between them, and their binding force upon the contracting parties is the same, whatever be their name."[6]

This concept is embodied in the Vienna Convention on the Law of Treaties, which states in Article 2 that a "'treaty' means an international agreement concluded between States in a written form and governed by international law, whether embodied in a single instrument or in two or more related instruments and whatever its particular designation."[7] (Emphasis added.)

Only a State possesses treaty-making powers and thus, in most circumstances, international organizations become parties to treaties by virtue of the collective sovereignty of the member States.[8] Recent international practice has adopted the utilization of intergovernmental and interdepartmental agreements which are negotiated and signed expressly on behalf of the Head of State and which may be, in their legal effect, in the same category as treaties.[9] Examples of these types of agreements are those between governmental departments such as those between postal agencies or ministries of various States.

Private persons or legal entities, such as corporations, are usually not parties to "treaties," but can be parties to subsidiary agreements. For example, the definitive arrangements for the International Telecommunications Satellite Organization (INTELSAT) consists of two basic documents. The first, the Agreement Relating to the International Telecommunications Organization "INTELSAT," is a treaty between States, and the second, the Operating Agreement Relating to the International Telecommunications Satellite Organization "INTELSAT," is a subsidiary agreement which may be signed by a State Party to the Agreement or by a telecommunications entity, public or private, designated by a State Party to the Agreement.[10] Such designated entities, or Signatories, may be private corporations as illustrated by the designation of the Communications Satellite Corporation (COMSAT) as Signatory for the United States to INTELSAT's Operating Agreement.[11]

The INTELSAT definitive arrangements also illustrate the third general category of international agreements, those which create international organizations. While such treaties and the resultant organizations have traditionally been utilized as tools for the coordination of activities between the States for mutual benefit, less developed States have been advocating their use as techniques to force the sharing of benefits between States. For example, with justification derived from concepts such as the "common heritage of mankind" and "New International Economic Order," some States have demanded that an international authority be established to govern the distribution to all States of benefits from the mining of the ocean floor.[12] It is apparent that given the growing predilection by States for preserving their rights with regard to space-related resources such as the radio frequency spectrum, geostationary orbital slots, and Moon resources, there will be an increasing amount of pressure for the creation of administrative international organizations by which to distribute space-related benefits among the nations. This pressure may become apparent with regard to SPS space segment development as well.

Thus, there are a number of forms for multilateral SPS agreements. Since the purpose of the agreements would be to assure against military threats and vulnerabilities associated with SPS facilities, the binding treaty form would be optimal. The principle of good faith adherence to the terms and conditions of binding treaties would afford the maximum assurance to all parties that SPS facilities would not be utilized as a military weapon and that it would not be vulnerable to military action. However, given the fact that the binding nature of treaties is at best temporary, there must be underlying checks and balances which will support the continued good faith adherence of treaty provisions by all parties.

The creation of an international organization for the ownership and operation of SPS facilities has been considered unlikely for the first United States SPS system due to the delays and excessive costs involved in international projects and U.S. foreign policy concerns, including limitations on technology transfer and freedom from dependence on foreign energy sources. Therefore, it would seem unlikely that there would be a promulgation of a multilateral treaty that would create a new international organization with regard to the ownership of the SPS. However, given a tendency among developing States to claim portions of the benefits derived from utilization and exploitation of international resources, and given the view that monitoring of SPS facilities should be conducted by an independent authority, there may be pressure to create an international organization which, although not part of the management or control of SPS facilities, would manage the distribution of benefits from, or otherwise monitor, such facilities.

B.2. Concerns for SPS Multilateral Treaties

Any agreement associated with SPS development must be based upon underlying benefits to all parties or there will be little motivation for continued good faith adherence to treaty provisions. Thus, it is appropriate to assess the relative benefits to, and negotiating positions of, various States with regard to the unilateral development by the United States of a SPS. Any such agreement would contain numerous provisions ranging from standards for environmental protection to prohibition of certain types of weapons systems, and therefore a complete identification of all possible provisions is beyond the scope of this appendix. However, a few salient substantive provisions can be analyzed.

B.2.1 Negotiating Positions

The unilateral development of SPS by the United States would be considered by other nations as an appropriate subject for international accords. They would wish to reduce or eliminate threats which such nations perceive with regard to the satellite. Thus, the major impetus for the creation of an international agreement for SPS development might emanate from foreign nations. The United States would then be in a favorable negotiating position from which to bargain for provisions designed to defuse the vulnerabilities of SPS development in return for provisions intended to forestall perceived threats.

The United States could choose to refrain from including components in the SPS which would produce threats, and any international agreement designed to eliminate such threats would serve to ratify this unilateral U.S. policy. However, from the perspective of foreign nations, it is obvious that once SPS were in existence, few nations would have the practical ability to affect the space segment of the facility in order to prevent perceived or real threats should the United States policy change. Therefore, foreign nations would seek ways in which to achieve leverage _vis-a-vis_ the United States to help ensure the mitigation of threats. For space powers, such leverage may be in the form of the development and implementation of their own SPS or appropriate military systems. For the majority of nations, however, the leverage may come from their combined voting strength within already established international organizations, their united economic strength, and/or their united efforts with regard to allocation of international resources such as the geostationary orbit and radio frequency spectrum. It is likely, therefore, that an international agreement for SPS will be founded on trade-offs between provisions which attempt to eliminate perceived and real threats from a U.S.-developed SPS system and provisions which attempt to eliminate vulnerabilities to the U.S. system.

It is anticipated that, from the perspective of the United States, the value of a multilateral agreement will be significant in reducing certain types of vulnerabilities. Although an international agreement may not be entirely effective in the elimination of military vulnerabilities, just as it may not be entirely effective in the elimination of military threats attributed to SPS, an international agreement would be very useful in eliminating institutional and international legal vulnerabilities. These vulnerabilities may range from claims of right to a portion of the power supplied by the SPS system on the grounds that such benefits are due (because the geostationary orbit and radio spectrum are part of the common heritage of all mankind), to claims that SPS development be banned to avoid interference with the established utilization of the radio frequency spectrum for telecommunications purposes.

Since institutional and international legal vulnerabilities will be most critical during the formative stages of SPS development, the beneficial impact for the United States of an international agreement would necessarily take effect early in the development process. Thus, the early elimination of institutional and international legal barriers would be a tangible benefit that foreign nations could offer in return for assurances that the threats perceived from SPS will not materialize and in return for mechanical and systematic methods to verify, monitor, and enforce such assurances. Consequently, the United States would achieve the elimination of these kinds of vulnerabilities prior to the development of SPS. The result of this situation could be that the United States would have minimized institutional and international legal barriers for SPS development and would retain leverage with which to maintain, in the future, minimization of such vulnerabilities, as long as the United States demonstrates adherence to policies and procedures which reduce or eliminate perceived or real threats.

The bargaining position between the United States and states which possess the capabilities of militarily affecting the SPS space segment is quite different from that between the U.S. and the majority of states. In such cases, bilateral treaties may be adopted between the space powers on the basis of their unique bargaining positions.

B.2.2 Selected Provisions

Two salient subjects for international agreements have been identified in the current study on military implications of Satellite Power Systems. The first involves the concept of proximity rules in space, and the second involves the concept of international resident inspection.

Proximity rules are international agreements under which spacecraft belonging to one nation would not be allowed to approach within an agreed-upon distance of spacecraft belonging to another nation without the advance consent of the latter nation.[13] While parallels can be drawn between this proposal and current practice for ships in international waters and for aircraft in international airspace, where separation between vessels or aircraft is necessitated by the possibility of collisions, the greater distances involved in the case of spacecraft and space facilities attempting to stay out of range of possible weapons systems may be interpreted by some observers as a claim over ascertainable portions of outer space. Proximity rules would thus have to be reconciled with Article II of the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space Including the Moon and Other Celestial Bodies[14] (hereinafter cited as the 1967 Treaty on Principles) which states:

> Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.

In effect, it can be argued, the proximity rules would establish specified regions in space (defined relative to SPS space facilities, including power satellites in geostationary orbit) which are accorded virtually exclusive use by particular States. One commentator has asserted[15] that the concept of "appropriation" in Article II of the 1967 Treaty on Principles suggests the existence of two subsidiary elements: exclusive use and relatively permanent use. To the extent that a power satellite would not be considered a permanent use of a particular portion of space, even though the facility may have a long lifetime, it would follow that the specified zones around such facilities would not be considered a permanent use, either. But since they appear in at least some degree to constitute an exclusive use, they may be construed to constitute an "appropriation" of a portion of outer space. A multilateral agreement on SPS would thus be useful either to exempt such zones from the restrictions posed by Article II or to define the word "appropriation" in such a manner that these zones would fall outside the definition.

The second subject for multilateral agreements regarding SPS is that of international resident inspection. Article XII of the 1967 Treaty on Principles provides that:

> All stations, installations, equipment and space vehicles on the moon and other celestial bodies shall be open to representatives of other State Parties to the Treaty on a basis of reciprocity. Such representatives shall give reasonable advance notice of a projected visit, in order that appropriate consultations may be held and that maximum precautions may be taken to assure safety and to avoid interference with normal operations in the facility to be visited.

Of importance is the fact that Article XII is applicable only to stations, installations, equipment, and space vehicles on the Moon and other celestial bodies, and therefore the Article is not applicable to all facilities in space. However, if the resident inspection concept was included in an international SPS agreement, inspections which would be conceptually analogous to those contemplated in Article XII would apply to SPS space facilities. However, the scope of such SPS inspections could be much broader than those contemplated under Article XII in that they would be conducted by resident inspectors rather than by inspectors visiting upon notice.

The concept of inspection is widely controversial. In the United States Constitution, for example, prohibition of unreasonable searches is a principal freedom which has been ingrained in American political philosophy. In the context of the current discussion with regard to the proposed Agreement Governing Activities of States on the Moon and Other Celestial Bodies[16] (hereinafter cited as the proposed Moon Treaty) which has been approved recently by the United Nations General Assembly and opened for signature and ratification, the issue of inspections has been raised. Article XV(1) of the proposed Moon Treaty states:*

> Each State Party may assure itself that the activities of other State Parties in the exploration and use of the moon are compatible with the provisions of this Agreement. To this end, all space vehicles, equipment, facilities, stations and installations on the moon shall give reasonable advance notice of a projected visit, in order that appropriate consultations may be held and that maximum precautions may be taken to assure safety and to avoid interference with normal operations in the facility to be visited. In pursuance of this article, any State Party may act on its own behalf or with the full or partial assistance of any other State Party or through appropriate international procedures within the framework of the United Nations in accordance with the Charter.

(Note that, unlike the 1967 Treaty on Principles, the proposed Moon Treaty does not make inspection the subject of reciprocity.)

Some critics of the proposed Moon Treaty assert that it would expand the right of foreign governments to inspect U.S. space facilities beyond the right already established in Article XII of the 1967 Treaty on Principles:[17]

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*Article I of the proposed Moon Treaty states that any reference to the "moon" "shall also apply to other celestial bodies within the solar system, other than the earth" and "shall include orbits around or other trajectories to or around it."

> In the interest of verification, the treaty allows any State Party to inspect all facilities in space, whether the facilities are owned by a nation, corporation, or individual. While some form of verification is desirable, this provision makes legal the unrestricted searches of private residences as well as government facilities . . . These are intolerable infringements of human rights.

While the concept of inspection has limited precedent in international space law, the concept is likely to be controversial, notwithstanding arguments that the resident inspection system proposed here entails voluntary consent to inspection a priori by the owners of the facilities, rather than inspection upon demand. Baggage and cargo inspection and passenger screening enroute to SPS space facilities would provide a safeguard against weapon components being smuggled into SPS crew quarters; such inspection and screening is presently accepted by the public in connection with air travel, and is likely to be accepted for space travel, as well, by SPS personnel.

Little precedent can be found in international law, politics, and relations for the formulation of an elite, supranational cadre of international representatives entrusted with inspection of important domestic facilities, but it is conceivable that such criticisms can be overcome. Unprecedented action is always possible, and it appears worthwhile to consider how this can be brought about for the SPS case.

B.3 References and Notes

1. L. Oppenheim, Section 491 in: Vol. 1, International Law, L. Lauterpacht, ed., 8th Edition (London, 1963).

2. J.L. Brierly, p. 331 in: The Law of Nations, Sir Humphrey Waldock, ed., 6th Edition (Oxford, 1963).

3. Article 26

4. Brierly, op. cit.

5. Article XVI, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies; Article XI, Convention on Registration of Objects Launched Into Outer Space; Article XXVII, Convention on International Liability for Damage Caused by Space Objects; and Article 9, Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched Into Outer Space. (The complete texts of the Treaty on Principles and of the Convention on

International Liability appear in Appendices A and C, respectively, in: Carl Q. Christol, "Satellite Power Systems (SPS): International Agreements," DOE/NASA, HCP/R-4024-08, October 1978.)

6. Oppenheim, op. cit., Section 508.

7. However, "a treaty, being a contract, must not be confused with various documents having a relation to treaties but not in themselves treaties--namely a memoire, a proposal, a note verbal, or a proces-verbal." Oppenheim, ibid., Section 491.

8. Oppenheim, ibid., Section 492.

9. Oppenheim, ibid., Section 509a.

10. Richard R. Colino, The INTELSAT Definitive Arrangements: Ushering in a New Era in Satellite Communications, p.1, Monograph No. 9, European Broadcasting Union (1973).

11. Section 301, Communications Satellite Act of 1962, P.L. 624, Eighty-Seventh Congress, Second Session.

12. Article 153, Informal Composite Negotiating Text/Revision 1, United Nations Third Conference on the Law of the Sea, Eighth Session (March 19 -- April 27, 1979).

13. See Section 5.2, in the main text of this report.

14. Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, entered into force with respect to the United States, October 10, 1967.

15. Stephen Gorove, "Interpreting Article II of the Outer Space Treaty," Fordham Law Review 37, 352 (1969).

16. The text to the proposed Moon Treaty is reprinted as an appendix to: Arthur M. Dula, "Free Enterprise and the Proposed Moon Treaty," Houston Journal of International Law 2(1), 3-33 (1980).

17. "The United Nations Moon Treaty," Draft Position Paper, Los Angeles Section, American Institute of Aeronautics and Astronautics, p. 2 (February 14, 1980).

APPENDIX C

TECHNOLOGICAL BACKGROUND PAPERS

Contents

C.1 Nuclear Weapon Effects on Satellite Power Systems

This section discusses the relative nuclear vulnerability and survivability of power satellites and other SPS elements. Nuclear confrontations or even some nuclear weapons tests could damage or destroy elements of the SPS.

C.1.1 Basic Nuclear Effects of Concern

Nuclear weapons produce x-rays and gamma rays, neutrons, and a large electromagnetic pulse (EMP) in addition to the expected thermal radiation and blast. In space, the thermal radiation and blast will not be the main threats. If the weapon is close enough for thermal or blast damage to be significant, the system will have already been killed by other nuclear radiation.

X-rays and gamma rays constitute 60 to 90 percent of the total explosive energy. For example, a one megaton device will produce 10^{15} calories of electromagnetic radiation of very short wavelength. In space, the intensity of this radiation falls off as $1/R^2$ from the burst point. X-rays are photons with energies in the 1 to 100 keV range and gammas are in the 100 to 10,000 keV range. Both can be approximated by a single blackbody spectrum, so the total fluence of gamma rays is about two orders of magnitude lower than for x-rays. Total energy fluence is given in units of cal/cm^2, the total absorbed dose is in rads,* and the transient dose rate is given in rads/sec assuming silicon as the absorber.

As x-rays and gamma rays interact with matter, they deposit energy by ionization (i.e., the creation of hole-electron pairs) and by disturbing the molecular or crystalline structure of the material (i.e., heat). The energy deposited is a strong function of the x-ray/gamma energy and the atomic number of the material. The predominant damage effect, especially in more dense material, is thermal shock due to the rapid heating of materials. Transient radiation environment effects (TREE), due to the sudden change in conductivity resulting from the creation of a large number of excess hole-electron pairs, can induce large transient currents which can be severely damaging in circuits containing semiconductor devices. Total ionization damage can also occur due to charge buildup and crystalline changes. This latter effect is a function of the total accumulated ionization dose.

*Absorbed radiation is usually specified in terms of the energy deposited in a given mass. Thus 1 rad = 100 ergs of absorbed energy per gram of absorber, or 2.39 x 10^{-6} calories per gram.

The intensity of neutrons generated by the weapon also falls off as $1/R^2$ from the burst point. Neutron energies are distributed over the range from 10 keV to 14 MeV, with peaks around 1MeV and 14 MeV. Since neutrons have positive rest mass, they travel slower than light, so the time of arrival for neutrons is later than for x-ray or gamma rays, and the pulse width increases with range. Neutron fluence is measured in units of neutrons/cm^2.

Neutrons collide with atomic nuclei, causing them to be displaced. (Some ionization also occurs, but this can usually be ignored.) This displacement damage can severly degrade the electrical properties of semiconductor devices, especially for large power devices such as power transistors. This material degradation can result in device and circuit malfunctions. There is no practical way to shield against neutrons, but circuit function can be partially restored if the degraded devices are annealed, that is, if they are heated to a high temperature for a period of time (minutes to hours depending upon the initial neutron fluence and the material affected).

Nuclear detonations within even the outer fringes of the Earth's atmosphere produce an electromagnetic pulse (EMP) due to the interactions of gamma rays with the upper regions of the atmosphere and of the resuting Compton (knock-on) electrons with the Earth's magnetic field. The EMP can be transmitted over large distances both on the Earth and in near-Earth space with minimal attenuation. This is the most serious threat to the LEO base and COTVs at lower altitudes from nuclear detonations not aimed directly at these elements of SPS. Energy in the EMP can couple to any antenna, cable, or other conducting structure. The effects are transient but can lead to catastrophic damage due to burnout of electronic devices. The EMP is described by the electric field strength (in volts/meter) as a function of time. (In the frequency domain, EMP signals from high altitude bursts characteristically span 100 KHz to 100 MHz.)

Another indirect nuclear radiation effect is the result of a severe increase in the number of energetic particles, particularly electrons, trapped in the Earth's magnetic field. These can cause significant ionization and atomic displacement in materials. The effect is due to the trapping of beta particles from decay of fission products from weapon debris in the Earth's magnetic field. These negatively charged particles spread around the Earth within minutes after a detonation, with a rapid initial decay followed by a gradual decay over periods of hundreds of days.

Another major nuclear weapon effect is system generated EMP (SGEMP). SGEMP is caused by the interaction of the x-rays with the system under consideration. These x-rays create fairly high energy photoelectrons, which in turn produce electron currents (or displacement currents, in the case of dielectric insulators). The overall system structure can also lose electrons, generating replacement currents on the surface of the system. System cables are especially susceptible to SGEMP effects. SGEMP signals of thousand of volts and/or amperes can be the result, even in circuits internal to spacecraft.

C.1.2 Typical Space System Vulnerability Levels

The nuclear vulnerability levels of space systems are typically controlled by the dominant semiconductor technology used in the circuits of space systems. SGEMP response is more capricious than semiconductor response in that degradation is dependent upon many more factors than just the intrinsic response of the semiconductor devices themselves. In some instances, system vulnerability may be most strongly dependent on the response of the photovoltaic arrays.

The assumptions used to define representative vulnerability levels are as follows:

Unhardened Satellite	-	Semiconductor technology is MOS (metal oxide semiconductor). Degradation at 500 rads.
Satellites with Hardened Circuits	-	Semiconductor technology is hardened bipolar with some selected CMOS (complementary metal oxide semiconductor). Degradation at 10^4 rads.
Hardened Satellites (system level approach to hardening)	-	Semiconductor technology is CMOS. Shielding, circuit level hardening, and captive line semiconductors are employed. Degradation at 10^5 rads.

The term degradation, as used above, denotes permanent damage within the semiconductor integrated circuit devices of sufficient extent to reduce performance seriously. Circuit upset, such as reset of logical states, etc., generally occurs at somewhat lower levels; our estimates of vulnerability levels for both degradation and upset are based upon past experience with integrated circuits of the types specified.

The levels of nuclear radiation rates and of trapped electron fluxes necessary to produce upset and/or degradation were estimated from radiation transport calculations for typical satellite materials and configurations. The resulting estimates of vulnerability appear in Table C.1-1, although there is substantial uncertainty in any vulnerability guidelines such as shown in this table. Any vulnerability assessments which are sensitive to parameters quoted in this table should be used with caution pending detailed analysis of specific designs.

The x-rays and gamma-rays incident on the solar cells also shorten the minority carrier lifetimes, lowering the capabilities of the solar cell both in short circuit current and in open circuit voltage. Simultaneously, high transient rates of ionizing radiation induce enormous transient currents in the solar cells, as shown in Figure C.1-1. Note that 10^{10} rads/sec in silicon produces transient short circuit currents of order 2 amperes/cm^2 in typical solar cells. Under normal operating conditions for the power satellites and COTVs, the solar cells will produce about 0.02 watts/cm^2 for the silicon option and about 0.04 watts/cm^2 for the gallium option, with a potential drop of order 1 volt across each cell. These transient currents would thus be about 100 times normal operating currents for warhead ranges of up to 80 or 100 km, and higher yet for shorter ranges.

Currents generated by x-rays and gamma rays in the power collection and distribution cable networks by EMP effects or by SGEMP would further aggravate the problems with transient currents, since conductors have intrinsic conductivities many orders of magnitude higher than do semiconductors. The lethality range for a one-megaton warhead could thus be multiplied to several hundred kilometers. (These EMP and SGEMP effects cannot be estimated without detailed calculations for specific power satellite or COTV designs.) The Reference Design system includes no provision for current-limiting devices to protect its power collection and conversion circuits from such enormous transient currents. If unimpeded, such transient currents could severely damage the electrical brushes and slip rings at the rotary joint, the power conversion and conditioning equipment at the microwave transmitter antenna, the klystrons which generate the microwave power beam, and the phase control system for the power beam.

Table C.1-1. ESTIMATED VULNERABILITY THRESHOLDS

	X-ray (cal/cm^2)	Total dose (rads) (γ + x-rays)	Neutrons (n/cm^2)	TREE rads/sec	Trapped Electrons (e^-/cm^2)
Unhardened					
o Upset	$3x10^{-7}$	0.1	N/A	10^7	N/A
o Permanent degradation	$3x10^{-7}$ $-9x10^{-6}$	$5x10^2$	10^{10} -10^{11}	10^7 $-3x10^8$	$5x10^{10}$ $-5x10^{11}$
Hardened Circuits					
o Upset	10^{-5}	5	N/A	$5x10^8$	N/A
o Permanent degradation	10^{-2} (1)	10^4	$5x10^{12}$	10^{13} (2)	$5/10^{12}$
Hardened System					
o Upset	(3)	(3)	N/A	(3)	N/A
o Permanent degradation	0.1 (1,4)	10^5	10^{13}	10^{13}	$3x10^{14}$

(1) Controlled by thermomechanical shock, which occurs at about 0.5 cal/gm (Au). Burnout will occur at about $2.5x10^{-2}$ cal/cm^2.

(2) For some integrated circuits, latchup may occur at about $5x10^7$ rads/sec. This is not highly probable.

(3) Circuit can be designed not to upset at any level below permanent damage.

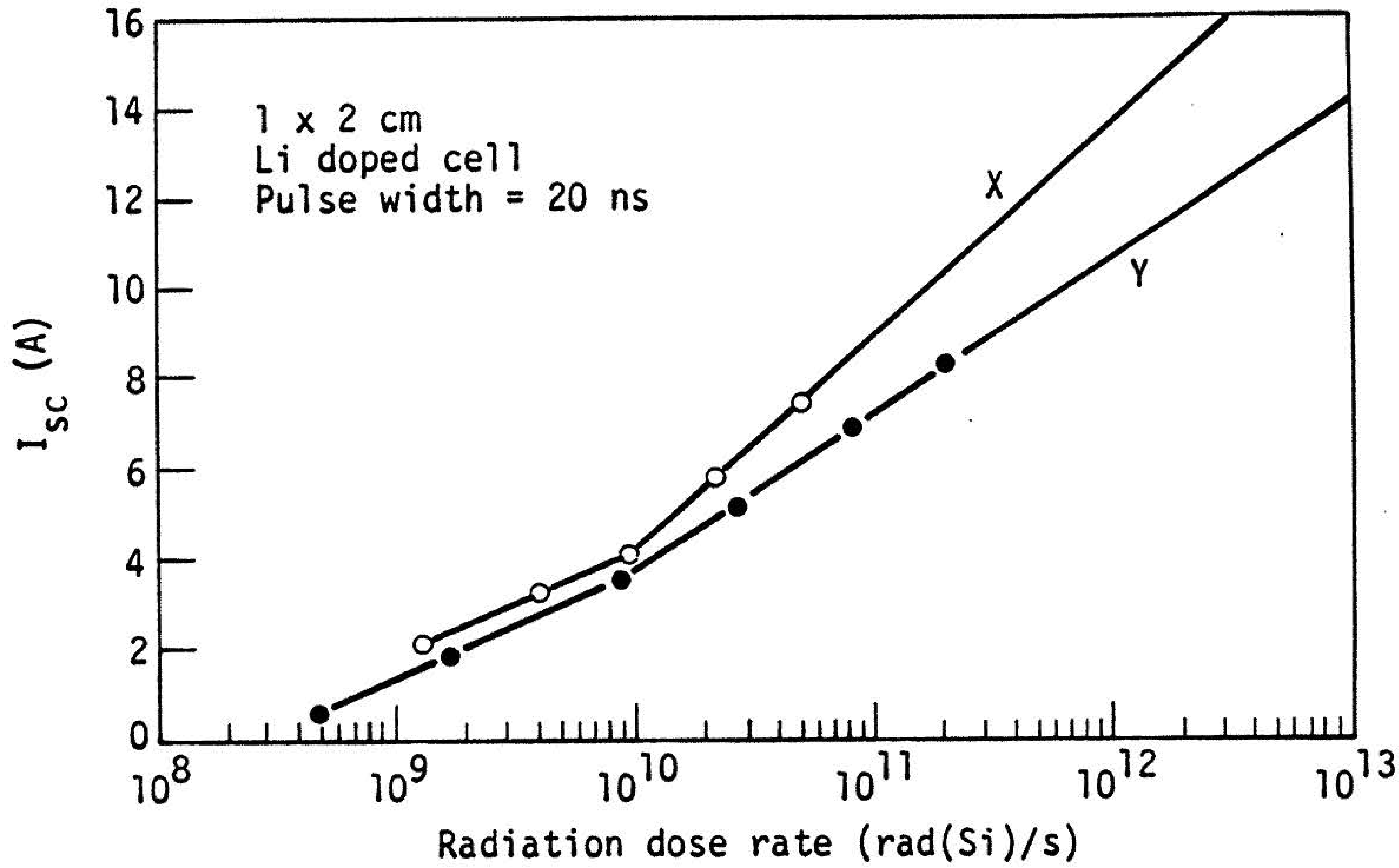

Figure C.1-2. Transient short circuit current (I_{sc}) induced in two typical cells (X and Y) by ionizing radiation at high transient dose rates.

C.1.3 Protecting SPS Elements Against Nuclear Weapon Effects

How can the various elements of SPS be protected against the nuclear weapon effects described above? It is infeasible to harden the space segments of SPS against nuclear detonations within a few kilometers. If friendly military systems in space can defend SPS elements from direct nuclear attacks by hostile forces, or if the SPS has sophisticated defensive capabilities, the problem becomes easier: we would need only to provide protection from nuclear detonation at distances of tens or hundreds of kilometers. Assuming that SPS elements are not of direct strategic significance, decisions about the level of protection to be provided would be based primarily upon the economic costs of temporary or permanent loss of each element in relation to the probabilities of loss and the costs of protection.

X-rays and gamma-ray hardening of the solar panels for SPS will require major advances in the state-of-the-art. Minority carrier lifetimes decrease with accumulated dose, lowering the solar cell short-circuit current and open-circuit voltage output capability. Solar cells can be hardened to some degree against ionizing radiation using gold or lithium doping. Selective doping can reduce both transient and permanent damage radiation susceptibility. (Given the size of the power satellites, however, doping with gold is impractical.)

The silicon option for the power satellite includes annealing lasers which could be used to restore solar cell capabilities degraded by neutrons, x-rays, and gamma rays, provided the system as a whole had survived intact. It is unclear whether the self-annealing feature for the gallium option would allow recovery in a reasonable time under similar circumstances.

Often the most effective and easiest way to harden electronic systems against x-ray and gamma radiation is at the system functional level. By providing ample design margins and overlap between various subsystem/circuit requirements and predicted responses, the engineer automatically allows for some degradation of the subsystems without loss of the system function. Also, by requiring large noise margins, the spurious responses of the system to gamma-ray pulses may be reduced. Another system approach is to design so that the system function can accommodate a few microseconds of upset, that is, the system can "hiccough-and-recover." For example, a radar might lose information from a few of its pulses but the next scan would fill in the loss; or a communications receiver would put out a large "static"-type noise burst, but would recover. (This approach would seem essential for the pilot beam and phase control system for the microwave power transmission system of the SPS.) It is more difficult to design digital logic circuits to hiccough and recover from lost bits, but data checks and redundancies can provide some nuclear hardness.

It is generally impractical to shield against neutrons. The design approach is to use devices which are specifically constructed to be insensitive to neutron displacement effects. Again, due to the enormous size of the devices used and the power handling requirements, solving the neutron degradation problem will require the development of new techniques and significant advances in the state-of-the-art.

By far the biggest problem will be the huge transient currents generated by the radiation pulse and by the electromagnetic pulse (EMP). The system can be protected by shielding to keep all induced currents on the outside of the structure (impractical for the power satellite and the COTVs) or using hardening techniques within the system to reduce the possibilities of upset or burnout. Some of these techniques include current-limiting resistors, clamping circuits, and use of devices designed for far greater power than the system would normally experience. Any of these techniques would require wholesale redesign of the Reference Design power satelites and COTVs, and may impose significant penalties in system mass.*

It is important that the radiation pulse can induce no catastropic phenomena, such as firing of squibs, or power supply burnouts, or arcing across high voltage terminals, etc. The system should be screened for these types of failure modes. Then, if the system can recover and function after transient upset at levels of 10^8 - 10^9 rad(Si)/sec, and if lost information can be reinserted, considerably less detailed circuit design will be necessary. Such design consists of (1) a worst-case analysis to show that the circuit will meet its specifications (with transistors degraded by neutrons, etc.) and will not burn out due to transient currents, or (2) addition of clamping circuits to preclude some catastrophic event during the burst.

Since SGEMP effects could be lethal to power satellites or COTVs at distances of several hundred kilometers from a one megatron warhead (or thousands of kilometers from a 50 megaton detonation), some consideration should be given to spreading out power satellites over as wide a range of GEO arc as possible and to keeping the COTVs as far apart as possible to reduce the chances of losing multiple system elements at once. Short of nuclear holocaust scenarios, large exoatmospheric nuclear tests by hostile nations constitute the major threat.

Protection of SPS personnel in space would depend primarily on sufficient warning time for the crew to reach the solar flare shelter. That much warning time would also be adequate for successful active defense measures to destroy attacking warheads at large ranges, especially using directed energy weapons. The LEO base is not expected to require a solar flare shelter, so a "bomb shelter" would have to be added if the crew is to be protected from nuclear weapon effects.

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*See Section 2.5 for a description of the power satellites.

C.1.4 Summary

The problems associated with hardening the SPS system against nuclear radiation effects are monumental. The technology to harden SPS against peripheral nuclear attacks will require a major development program which must be carefully integrated with the DDT&E phase of a SPS program to ensure that a balanced hardening approach is implemented. Alternative power satellite concepts may be easier to harden against EMP and SGEMP effects than the photovoltaic designs of the Reference System.

C.2 Particle Beam Weapons (PBW) and SPS

C.2.1 General Character of Spaceborne PBW Systems

Exoatmospheric particle-beam weapon (PBW) systems may eventually prove to be useful in a number of roles, including ballistic missile defense and anti-satellite offense.[1,2] The SPS/PBW combination is an interesting one to consider because the extremely large power requirements of PBW systems (typically hundreds of megawatts) are readily satisfied by the power satellites and the cargo orbital transfer vehicles (COTV) of the Reference Design. A PBW directly attached to the SPS would presumably add only marginal additional weight associated with prime power to the total system. A PBW linked at a distance from a power satellite (e.g., in a much lower orbit with laser power transmission) might still benefit in terms of overall weight if the power collection scheme were sufficiently efficient. A PBW system might also be of value directly to the SPS, as a defense system. General considerations involved in these various possible applications include the beam's lethality characteristics, the technology of generating and firing the beam, and the possibilities for countermeasures.

Although one may in principle consider a number of possible beam types for PBW applications, neutral beams of atomic hydrogen isotopes or, conceivably, heavier atoms are by far the most likely candidates for spaceborne applications. The beam would be generated by "conventional" acceleration of charged ions that are neutralized after leaving the accelerator. Other neutral particles, such as neutrons and gamma rays, are not useful, except at quite short ranges, because of the physically inherent divergence of beams produced by any presently foreseeable source. Charged or only partially neutralized beams of electrons or ions are not expected to propagate in near-vacuum (at interesting intensities) to any significant distance from their source, and would probably be subject to moderate-to-severe dispersion by their internal electric fields even if a propagation "window" were found to exist. The geomagnetic field--especially if fluctuations and distortions accompanying a high-altitude nuclear detonation are present--would interact with a charged beam to produce a "bent" beam trajectory that could seriously aggravate an already difficult beam aiming problem. For all these reasons, conceptual exoatmospheric PBW systems are speculative or even completely undefined for many schemes that might be suggested. We will concentrate on neutralized-ion beams as the single exception to this situation, since they would be unaffected by the Earth's magnetic field, are not subject to "self-dispersion" effects, and can be directed with small divergence angles. Such beams can be produced by accelerating negatively charged beams (e.g., H^-) to energies of over 250 MeV and then "stripping" the extra electron after acceleration.

Unlike the endoatmospheric PBW concepts, which typically require pulsed, high-intensity beams, the exoatmospheric neutral beam concept in its present state of conceptual development is based on a rather lower intensity beam that must dwell on the target for some longer period of time. Components of a typical conceptual system (Figure C.2-1) include target acquisition and tracking, beam position, and damage assessment inputs to some overall fire-control function; the charged-beam generator, which includes power, beam injection, and particle acceleration subunits; and beam steering and neutralization functions. The angular dispersion of the neutralized beam, principally determined by the neutralizer, is a critical parameter because of its effects on the lethality characteristics of the system. Basic parameters (based solely on basic physics considerations) for a nominal particle beam weapon are shown in Table C.2-1.

Table C.2-1 Nominal PBW Parameter Summary

Beam Particle Energy	250 MeV protons
Beam Current	100 milliamperes
Beam Power	25 MW
Prime Power	about 50 MW
Accelerator Length	50-75 meters

C.2.2 Basic Exoatmospheric PBW Lethality Considerations

Because of the difference in exo- and endoatmospheric propagation mechanisms, it appears unlikely that ground-to-space or space-to-ground attacks can be mounted. A neutral beam--the most feasible space propagation mode--will rapidly disperse upon encountering a significant amount of atmosphere; and an intense,

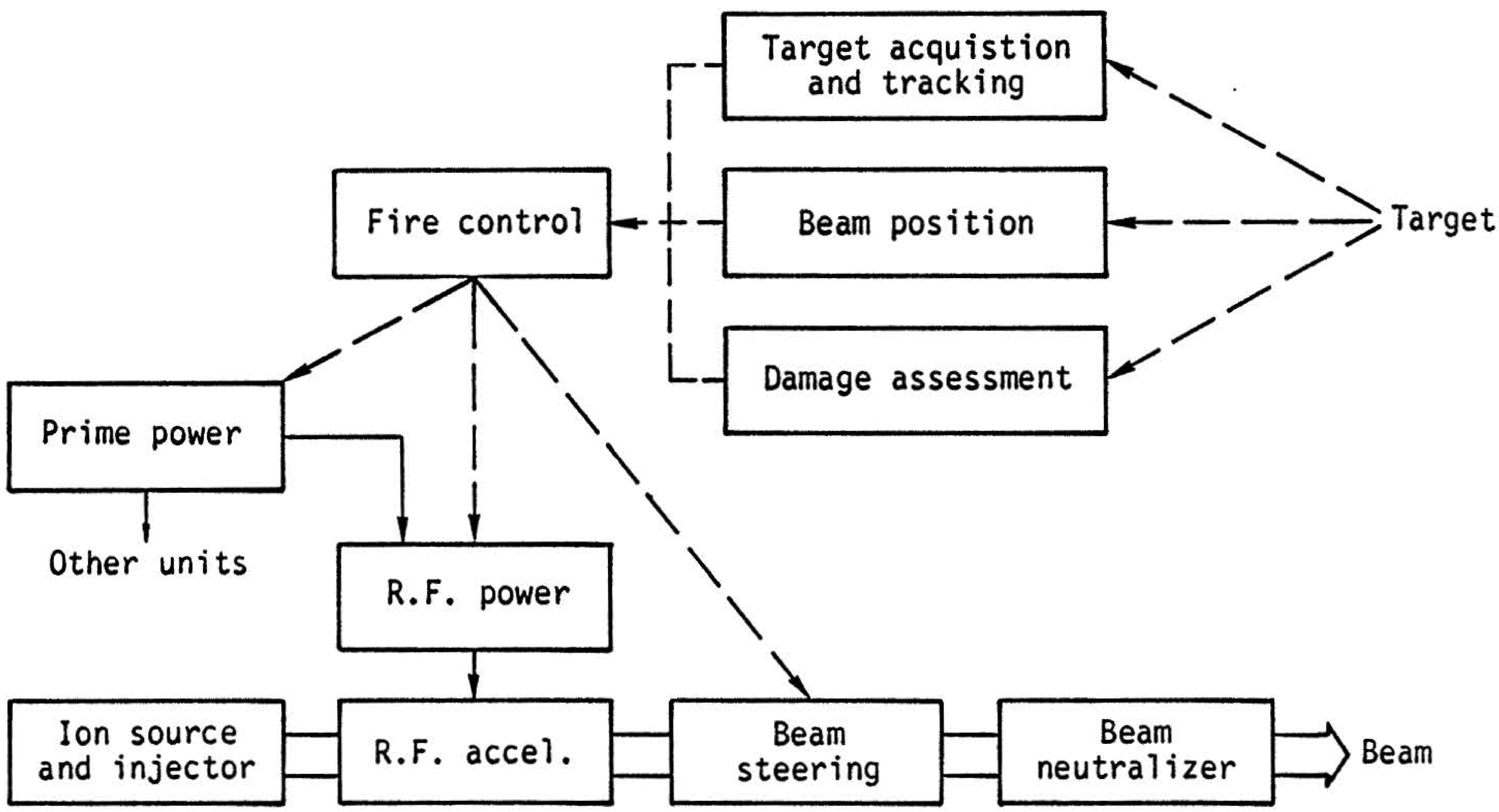

Figure C.2-1. Block diagram of a conceptual exoatmospheric particle beam weapon (PBW) system.

pulsed, chaged-particle beam, needed within the atmosphere, will probably not propagate well in vacuum. We will consequently assume space-space encounters below.

The most basic "kill" process for the exoatmospheric PBW beam is the volume deposition of the beam energy within the target. Typical values of the energy deposition density associated with various kill mechanisms are listed in Table C.2-2. Structural damage by melting can evidently be accomplished for energy deposition densities of about 100 cal/g. Warhead damage might be accomplished either by structural effects or by thermal initiation of the high explosive (HE) content, at somewhat lower temperature rise requirements. Damage to electronic circuitry can also be accomplished structurally--with solder melt at the indicated temperatures as an effective but less demanding criterion than silicon melt--or by heating the components beyond acceptable operating tolerances. Finally, a variety of "microscopic" mechanisms such as lattice damage to semiconductor materials, can also disable electronic circuits. The severity of such damage mechanisms depends in a complicated way on the rate and duration of the exposure and on the temperature history of the components during and after exposure. Without detailed consideration of a particular threat description, the values shown in the table for "microscopic" mechanisms are to be regarded as order-or-magnitude estimates.

C.2.3 Safeguards/Countermeasures

The penetrating character of a particle beam makes it quite difficult, once the target has begun to be irradiated, to shield against it. Indeed, heating and melting damage to the shield may create serious local problems even if integrity of the shield could be maintained. Any adequate shield would be enormously bulky. A nominal beam (250 MeV protons) would penetrate a shield with surface density in the 50-100 g/cm^2 range (500-1000 $kilograms/m^2$), i.e., steel armor 7-14 cm thick. Other countermeasures suggested include artifices to deceive the target acquisition/tracking/fire-control components, such as decoys and chaff; defensive PBWs could be overcome by saturating the system with multiple warheads and decoys.

Table C. 2-2

PBW LETHALITY MECHANISMS SUMMARY

MECHANISM	TEMPERATURE	ε (cal/g)
<u>Structural Damage</u>		
Melt - Al	660° C	~150
- Cu	1080° C	~100
- Si	1420° C	~300
<u>Warhead Damage</u>		
Melt Components	(various)	~50-150
H.E. Thermal Initiation	500° C	~60
<u>Electronics Damage</u>		
Melt Solder	200-400° C	~10-20
Functional Overheating	Δt ~100° C	~20
"Microscopic"	(n.a.)	~ 2-10

C.2.5 Summary

The parameters required for a useful exoatmospheric PBW system are probably attainable. The power required to operate a PBW system could certainly be supplied by either a power satellite with multigigawatt power-generation capability or a COTV with 250-600 MW of onboard electric power. Final judgments, as to practicality and to the time required to actually develop hardware, will depend upon the application and upon the progress of present development efforts. Of the applications of interest to the SPS study, self-defense and antisatellite offense appear most promising to consider because of probable lesser demands on the system. The great range of other possible targets, (e.g., 40,000 km from synchronous orbit to the Earth's surface) and the shielding provided by the Earth's atmosphere, are decisive obstacles for some applications. The number of systems that might need to be deployed depends on the range and coverage demanded. Parmentola and Tsipis have stated, for example, that about 150 satellite-based PBW's would be required to cover potential ICBM launch sites from an altitude of 1000 km.[3] Only a few would be needed in geosynchronous orbits, if the problems associated with a much greater range could be overcome. The time required to destroy a single target could be an important limitation in any event. SPS elements would also be vulnerable to PBW attack from another exoatmospheric system.

C.2.6 References

1. Particle Beam Weapons, collected reprints from Aviation Week and Space Technology issues of May 2, 1977; October 2, 9, & 16, 1978; and November 6 & 13, 1978. McGraw Hill, Inc., New York, 1978.

2. G. Bekefi, B.T. Feld, . Parmentola, and K. Tsipis, "Particle Beam Weapons," in Report No. 4 of the MIT Program in Science and Technology for International Security, Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, Jan. 1978.

3. John Parmentola and Kosta Tsipis, "Particle Beam Weapons," Scientific American 240(4), p. 54 (April 1979).

C.3 High Energy Laser and SPS

The potential of the high energy laser (HEL) is considered from two points of view relative to the SPS. First, the possibility of basing a HEL weapon on the SPS and using it against a variety of targets is considered. These targets include military installations, personnel, ICBMs, SLBMs and satellites. A second possibility is that ground-based HELs would be employed against the SPS systems. The performance of these HEL systems are estimated for the year 2000. It should be clearly understood that these projections are order-of-magnitude estimates for laser performance and target vulnerabilities, based upon theoretical analyses of the basic physical phenomena involved.

C.3.1 System Description

The heart of a HEL is the laser cavity, where an optical resonator is utilized to extract energy from the population inversion in a fast-flowing gas. The power satellites have a unique potential to supply large amounts (8GW) of electrical DC power for indefinite time periods, as do the cargo orbital transfer vehicles (COTV), with 260 to 610 MW of DC power. This suggests that an electrical discharge laser (EDL) could be mated with a power satellite or a COTV. It should operate in a closed-cycle mode, so that the reactant gas supply could be reused. The major parts of the HEL system would be:

- the energy generation system, which in this application is assumed to be DC electrical power in the GW range from the solar arrays of the power satellite or the COTVs;
- the laser beam generator, which would operate as a closed-cycle EDL system on any of several different wavelengths ranging from the mid-IR (10.6 μm) to the UV (0.2 μm); (See Figure C.3-1 for a schematic diagram.)
- the beam control and projection system, which would consist of a large, extremely smooth primary mirror to project the laser beam, and the necessary mirrors to route the beam internally; and
- the fire control system (FCS), which would detect, acquire, and track potential targets. The FCS would also fire the laser weapon, maintain the beam on the target, change targets when appropriate, and assess damage.

Weight and volume scaling laws for the laser system are estimated for the year 2000 and plotted in Figures C.3-2 and C.3-3. Note that the total system weight is a

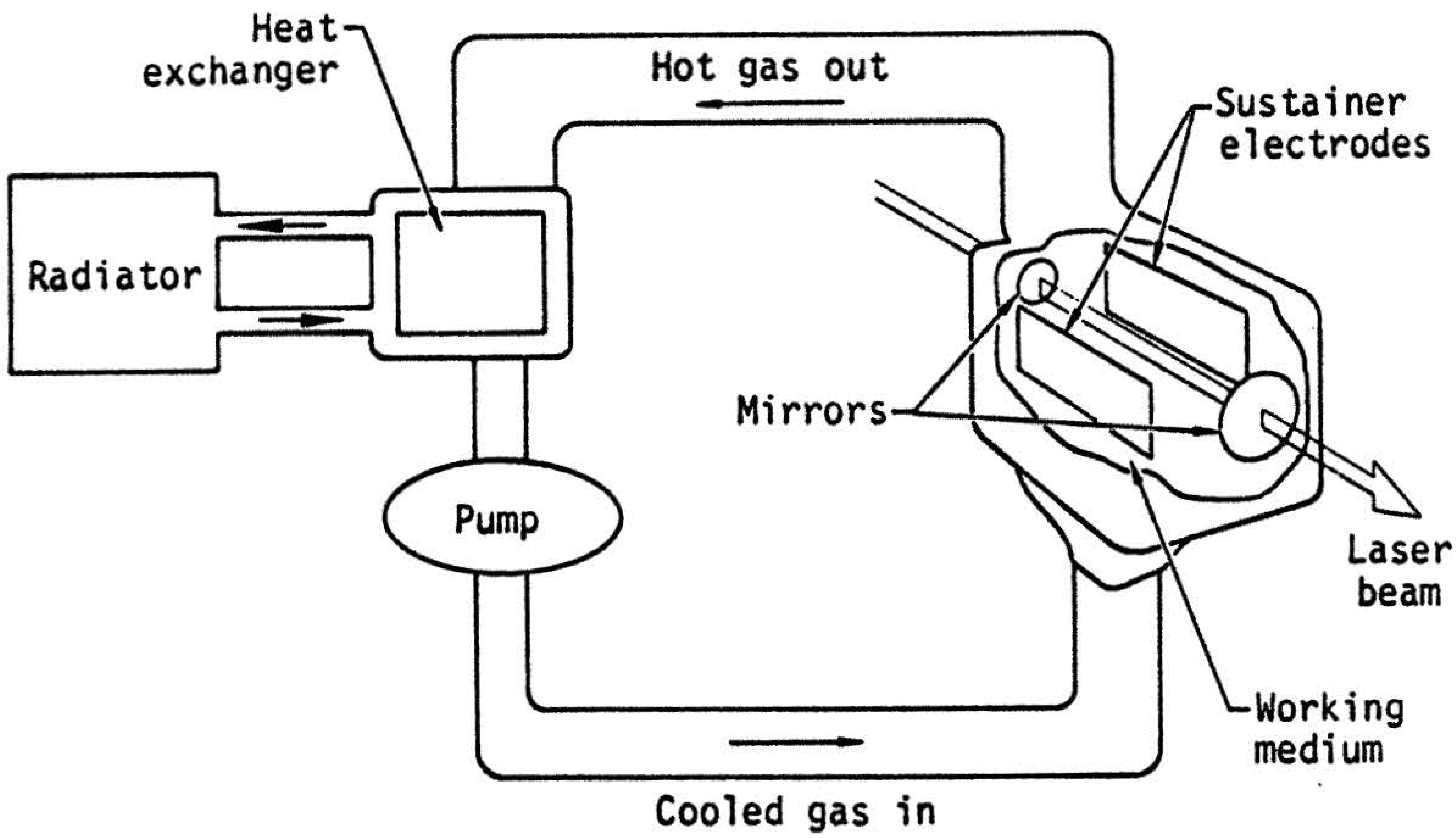

Figure C.3-1. An electric discharge laser (EDL) for space. A closed-cycle subsonic-gas-flow system. (Adapted from Reference (1).)

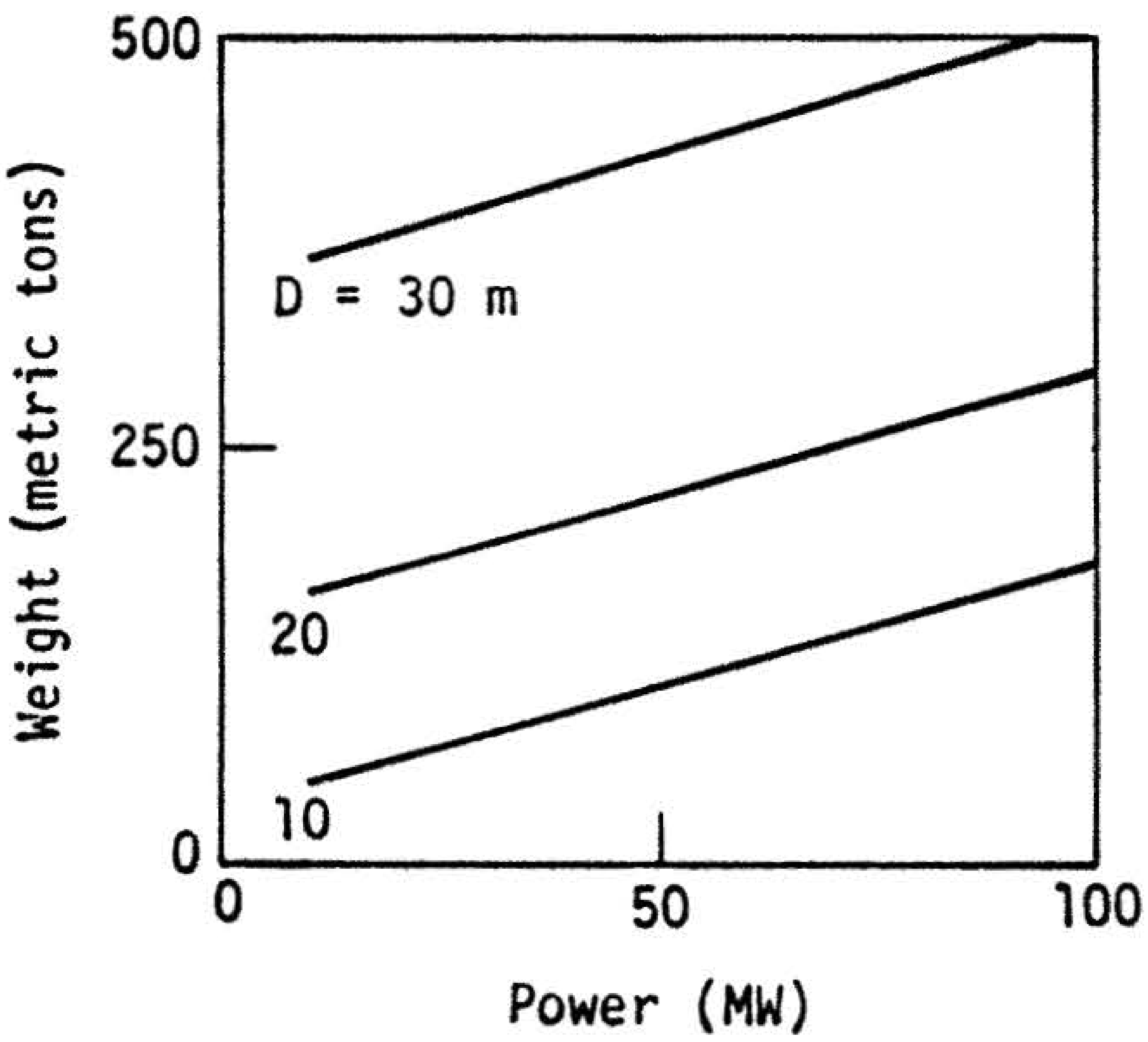

Figure C.3-2. HEL system weight.

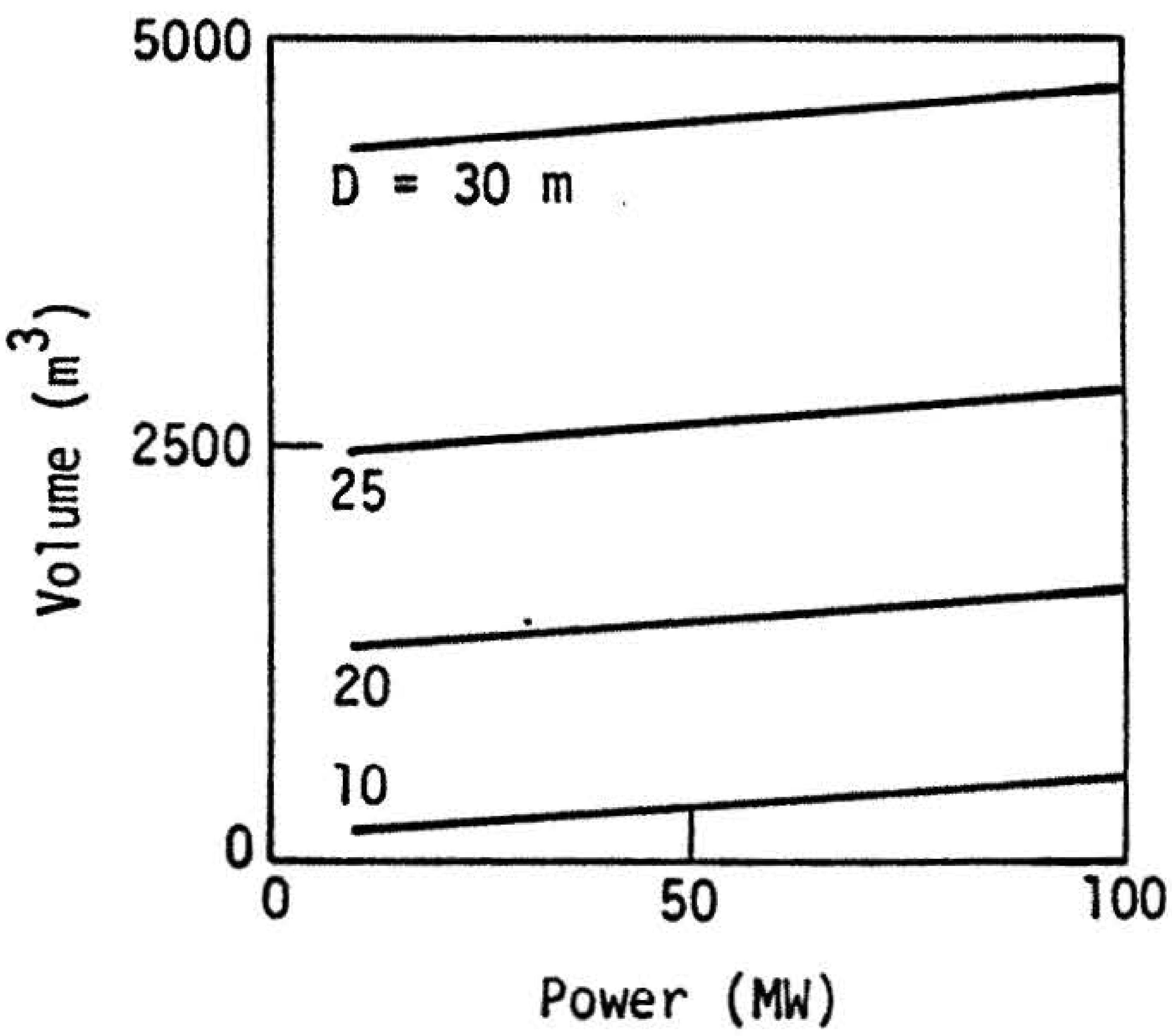

Figure C.3-3. HEL system volume.

strong function of aperture (D) and a weaker function of output power. It is seen that a 100 MW laser with a 30 m primary will have a mass of about 500 T, one percent of the power satellite mass of 5×10^4 T.

The volume of the system is primarily due to the laser device, primary mirror, and the heat rejection equipment to cool the recirculating laser gas. Higher gas temperatures will result in more efficient heat radiation systems and therefore smaller size. This rejection system would be located on the shaded side of the solar array and may not add any overall SPS volume.

The total volume of the laser system is plotted in Figure C.3-3.

C.3.2 Performance Assessment

Based on standard laser performance equations, estimates were made for laser system capabilities for the year 2000, including both SPS-based lasers and ground-based lasers. Two SPS-based laser projections were made, for a "nominal" and an "optimistic" capability. The path length for all of these calculations was the distance from geosynchronous orbit to the Earth.

Table C.3-1 contains "nominal" calculations for a SPS-based laser focused at low Earth orbit (LEO) altitude for the year 2000. Considerable extension of the current state-of-the-art is necessary to achieve some of these values. The values also represent irradiance at the Earth's surface, except at wavelengths at which the atmosphere absorbs strongly (2.7 μm and 0.2 μm).

Table C.3-2 is also for the year 2000, but is called "optimistic," since it assumes a greater advance of the state-of-the-art in laser power, mirror diameter, and jitter accuracy. It might also be regarded as a nominal projection for the year 2020. Irradiances are ten times greater than the nominal performance, except for the 0.2 μm wavelength.

The ground-based laser is considered as a possible threat to the SPS system. Projected performance of such a laser for the year 2000 is displayed in Table C.3-3. Since the path is through the Earth's atmosphere, certain changes have been made to the SPS nominal performance. First, the atmospheric absorption by water vapor has caused a shift in the chemical laser from HF at 2.7 μm to DF at 3.8 μm. Also, the transmittance at 10.6 μm and 5μm is assumed to be 0.5. The UV laser at 0.2 μm is assumed to be entirely attenuated by ozone absorption and scattering. Residual atmospheric turbulence which is uncorrected by adaptive

Table C.3-1. Power Satellite-Based Laser Performance (Nominal)

Laser Wavelength (μm)	10.6	5.0	2.7	1.3	0.5	0.2
Diffraction Angle σ_D (μr)	1.3	0.6	0.3	0.16	0.06	0.024
Spot Diameter D_R (m)	130	60	30	16	6	4
Irradiance E (W/cm^2)	0.15	0.7	2	10	70	70*

*β_2 = 1.5 to reflect mirror figure error.

Assumptions: $D = 10$ m $\quad \sigma_J = \sigma_D \geq 0.05$ μrad
$P = 20$ MW $\quad R = 3.6 \times 10^7$ m
$\beta_1 = 1.2 \quad \beta_2 = 1$

Table C.3-2. Power Satellite-Based Laser Performance (Optimistic)

Laser Wavelength (μm)	10.6	5.0	2.7	1.3	0.5	0.2
Diffraction Angle σ_D (μr)	0.6	0.3	0.16	0.08	0.03	0.12
Spot Diameter D_R (m)	60	30	17	8	3	1.2
Irradiance E (W/cm^2)	1.5	7	20	100	700	4000

Assumptions: $D = 20$ m $\quad \sigma_J = \sigma_D \geq 0.01$ r
$P = 50$ MW $\quad R = 3.6 \times 10^7$ m
$\beta_1 = 1.2 \quad \beta_2 = 1$

Table C.3-3. Earth-to-GEO Performance

Laser Wavelength (μm)	10.6	5.0	3.8	1.3	0.5	0.2
Diffraction Angle σ_D (μr)	1.3	0.6	0.5	0.16	0.06	-
Spot Diameter D_R (m)	150	90	90	70	70	-
Irradiance E (W/cm^2)	0.06	0.14	0.3	0.5	0.5	0

Assumptions: $D = 10$ m $\quad \sigma_J = \sigma_D \geq 0.05$ μrad
$P = 20$ MW $\quad R = 3.6 \times 10^7$ m
$\beta_1 = 1.2 \quad \beta_2 = 1 \quad \sigma_T = 1$ μrad

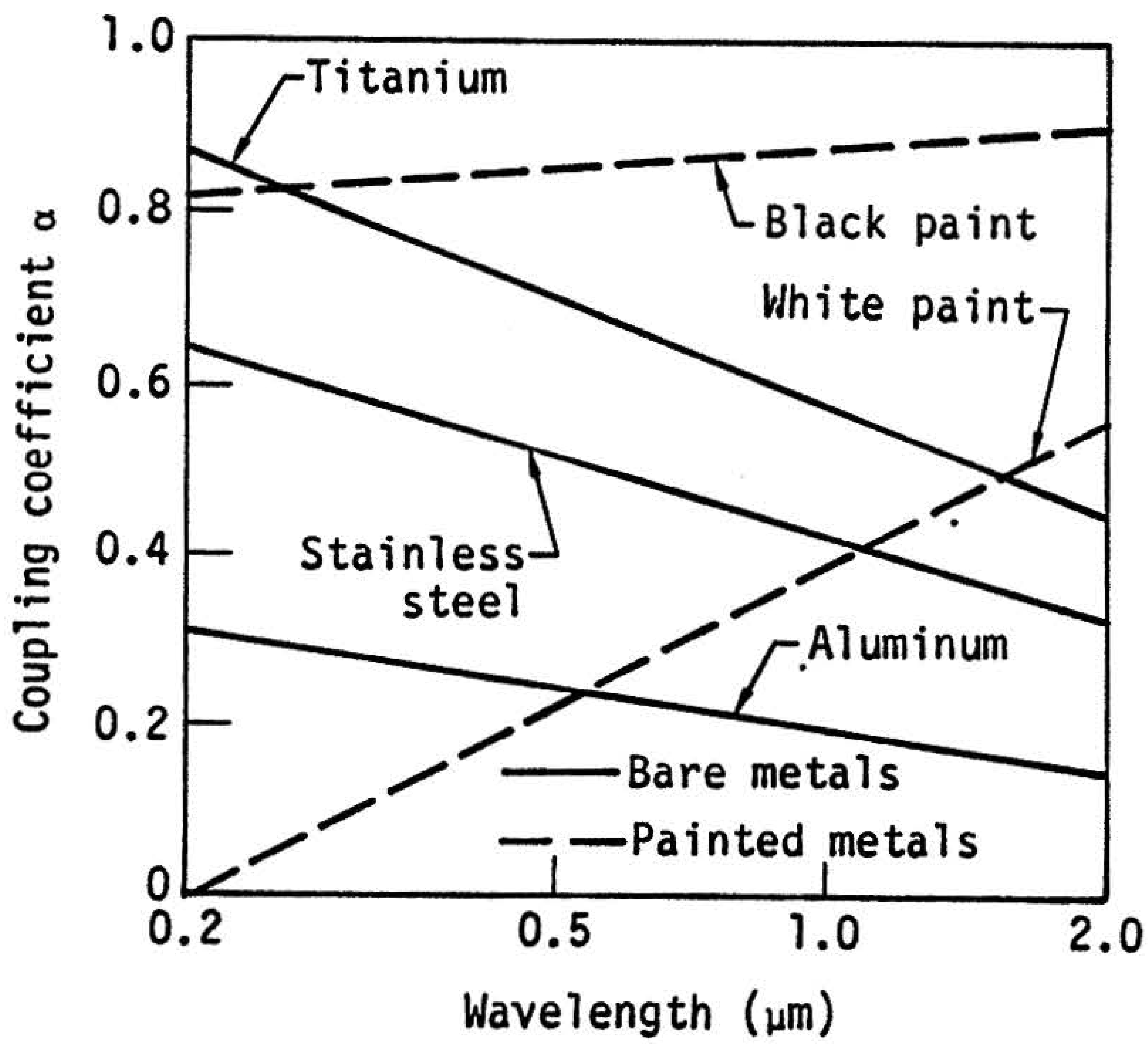

Figure C.3-4. Short wavelength coupling coefficients. (From Reference (2).)

optics is assumed to be 1 μr, which severely degrades the short wavelength systems. Thermal blooming, which may further degrade the irradiance, is ignored.

C.3.3 Strategic Use of an SPS Laser System

Possible targets for an SPS laser based in synchronous orbit include ballistic missiles (both ICBM and SLBM), satellites, aircraft, ships, military installations, and personnel.

The nominal laser threat (see Section C.3.2) would probably not present any significant hazard to targets within the atmosphere. The irradiance values are such that a combination of shielding, convective cooling for moving targets, and time requirements, would severely degrade laser effectiveness. There is some threat, however, to satellites. Analysis on solar cells indicates a threat to low Earth orbit satellites at laser wavelengths of 1.3 micrometers or less. For higher orbit satellites, the threat would extend to higher wavelengths and would be even more pronounced at the lower wavelengths.

The optimistic laser threat extends hazards to atmospheric targets, except where atmospherics degrade propagation. For wavelengths less than about 1 micrometer, the irradiance values are such that metal surfaces could be melted in reasonable times. This could bring the entire spectrum of targets into the hazard category, especially at the shorter wavelengths where, in addition to much higher incident irradiance values, the thermal coupling of radiation into bare metal targets is significant (see Figure C.3-4). There is a definite threat to satellites at wavelengths in the near IR and below. For wavelengths in the visible and UV region, it would be extremely difficult to protect against the irradiance values experienced by satellites.

C.3.4 SPS Vulnerability to HEL

The vulnerability of SPS lasers is assessed here relative to continuous-wave laser irradiation of wavelengths between 0.25 and 2.0 micrometers. The assessment is for thermal damage and is considered to be equally valid for pulsed laser threats within the present state of knowledge of pulsed laser effects and the scenarios under consideration. As the system design is conceptual, and as the vulnerability analyses are based on simplified first order principles, the resulting vulnerability assessments are not intended to establish exact criteria, but rather to provide indications of SPS and component vulnerability.

The massive size of the satellite system and its component parts greatly reduces the number of vulnerable critical components. Three areas of concern are the sensors, the primary power antenna, and the solar cell arrays. The power satellites are relatively invulnerable to a ground-based laser threat but could be vulnerable to a space-based system because of decreased laser-to-target range and the absence of atmospheric absorption.

Sensors. Sensors (in particular, the star and Sun sensors of the attitude control system) are vulnerable to laser attack. However, as these sensors constitute a negligible fraction of the system weight, volume and cost, they can be hardened by prudent design using a variety of passive and active countermeasure schemes to withstand the anticipated threats. Sensor vulnerability is therefore considered an important item which must be evaluated in detail with specific design specifications, but also an item of small system impact.

Primary Power Antenna. The primary power transmitting antenna is a critical component which is easily identifiable as an aimpoint for laser attack. The large size of the antenna, the distributed nature of its power module/klystron transmitters, and the shielding effect of the radiating face, all combine to increase the antenna's survivability. Assuming some redundancy in the power distribution network across the antenna, the large size and distributed nature of the antenna indicate that damage would be localized to the laser-irradiated region. Therefore, significant system degradation would require a large irradiated area. This increases the energy requirements of the incident laser beam. The power module design is such that damage would probably require melting of the aluminum face. The conditions under which melting could occur can be approximated as follows. Neglecting the internal heat source of the module as small compared with the minimum laser irradiance required for melting (it can be shown to be less than 10%), a simple equilibrium energy balance can be written for an antenna section as

$$AE_a = 2\varepsilon A\sigma T^4,$$

where A is the irradiated area, E_a is the absorbed laser irradiance, ε is the emissivity for thermal radiation, σ is the Stefan-Boltzmann constant, and T is the surface temperature in degrees Kelvin. The above assumes a radiation loss surface twice that of the laser-irradiated surace and neglects all conductive losses. Solving the above for the irradiance E_a required to bring the aluminum up to its melting point ($773^{\circ}K$) and setting $\epsilon \approx 0.90$ for a good radiator yields a minimum threshold <u>absorbed</u> irradiance for melting of $E_a \approx 3.6\ W/cm^2$.

The requirement for <u>incident</u> irradiance can be determined from Figure C.3-4, which shows coupling coefficients (ratios of absorbed to incident irradiance) for the wavelength regime of interest. As the antenna face is designed to be a good thermal radiator, its coupling can be approximated by the black paint line for low laser irradiance. Using the high value of 0.9, the minimum threshold incident irradiance for melting is about 4 W/cm^2.

The above minimum irradiance requirement must now be related to energy density (J/cm^2) and time requirements. The incident energy density to melt a typical aluminum alloy is about $3300\ell\ J/cm^2$, where ℓ is the thickness in cm, and the coupling is 0.9. At 4 W/cm^2 the time required for melting of a 0.5-cm-thick aluminum plate is about 400 seconds, which is quite long. More typical times for spacecraft components to reach thermal equilibrium, through a combination of radiation and the conduction neglected in this analysis, are in the range of 50 to 100 seconds. Using this range as a time criterion leads to a minimum incident irradiance requirement of about 15 to 30 W/cm^2 for a front face of 0.5-cm-thick aluminum. This incident irradiance requirement would scale approximately linearly for other thicknesses. A typical SPS antenna system would therefore be invulnerable to the nominal laser threat from an Earth-based laser but could be vulnerable to a space-based laser.

<u>Solar Cell Arrays</u>. The solar cell arrays are a critical portion of the SPS. This section evaluates the vulnerability of the solar cells in terms of expected configurations for commercially available cells. The assessment and resulting vulnerability levels include the assumption of prudent design practices, but do not include the effects of possible countermeasures such as filtering or hardened material development.

A typical solar cell consists of a protective front cover, the cell itself, the attachment of electrical connectors to the cell, a bottom substrate, and adhesives to bond at least one of the interfaces. The vulnerability level of a composite cell is essentially a function of the failure temperature for one or more of these elements. The discussion which follows pertains to both silicon (Si) and gallium-aluminum-arsenide (GaAlAs) cells.

If the electrical connectors are soldered, they are the most vulnerable element of the cell, as typical aerospace solders melt at about 180° C. The assumption is made here that the connectors are welded or otherwise fastened to eliminate this low failure temperature. The next temperature of interest is about 350° C. Here, typical adhesives begin to bubble, lose their adhesiveness, and lose their transparency. In addition, the GaAlAs cells begin to experience contact metalization. As the temperature increases to about 450° C, both cell types experience significant metalization or diffusion of dopants and contact material into the cell body. A reasonable estimate for the upper limit of commercial cell operation for both cell types is about 600° C. The temperature range for failure for either the silicon or the GaAlAs cells is therefore estimated to be 350 to 600° C.

Figure C.3-5 and C.3-6 show equilibration temperatures and times as a function of the incident irradiance E. As indicated, the 600° C failure irradiances of 3.1 and 8.6 W/cm^2 are reached by the GaAlAs and Si cells, respectively, in about 4 and 2 seconds. As with the antenna, the solar cell arrays could be expected to withstand a nominal Earth-based laser attack but could easily be vulnerable to a space-based laser attack.

C.3.5 Implementation

A long lead time is required for the optics and primary mirror system. The polishing of the mirror to the required accuracy may take several years, particularly for the shorter wavelengths. The segmented array concept must be defined, along with the activation method. Most of the technology areas require a concerted effort to significantly advance the state-of-the-art in order to achieve the capabilities in the "nominal" projections by the year 2000. For instance, power must be increased by at least two orders of magnitude, and primary mirror area by a similar factor.

The HEL system development cost is estimated to be less than one billion dollars, with unit cost on the order of one hundred million dollars.

C.3.6 Safeguards

Safeguards to nullify an HEL's effectiveness include reflective paints or coatings and increased mass to moderate thermal effects. Neither of these

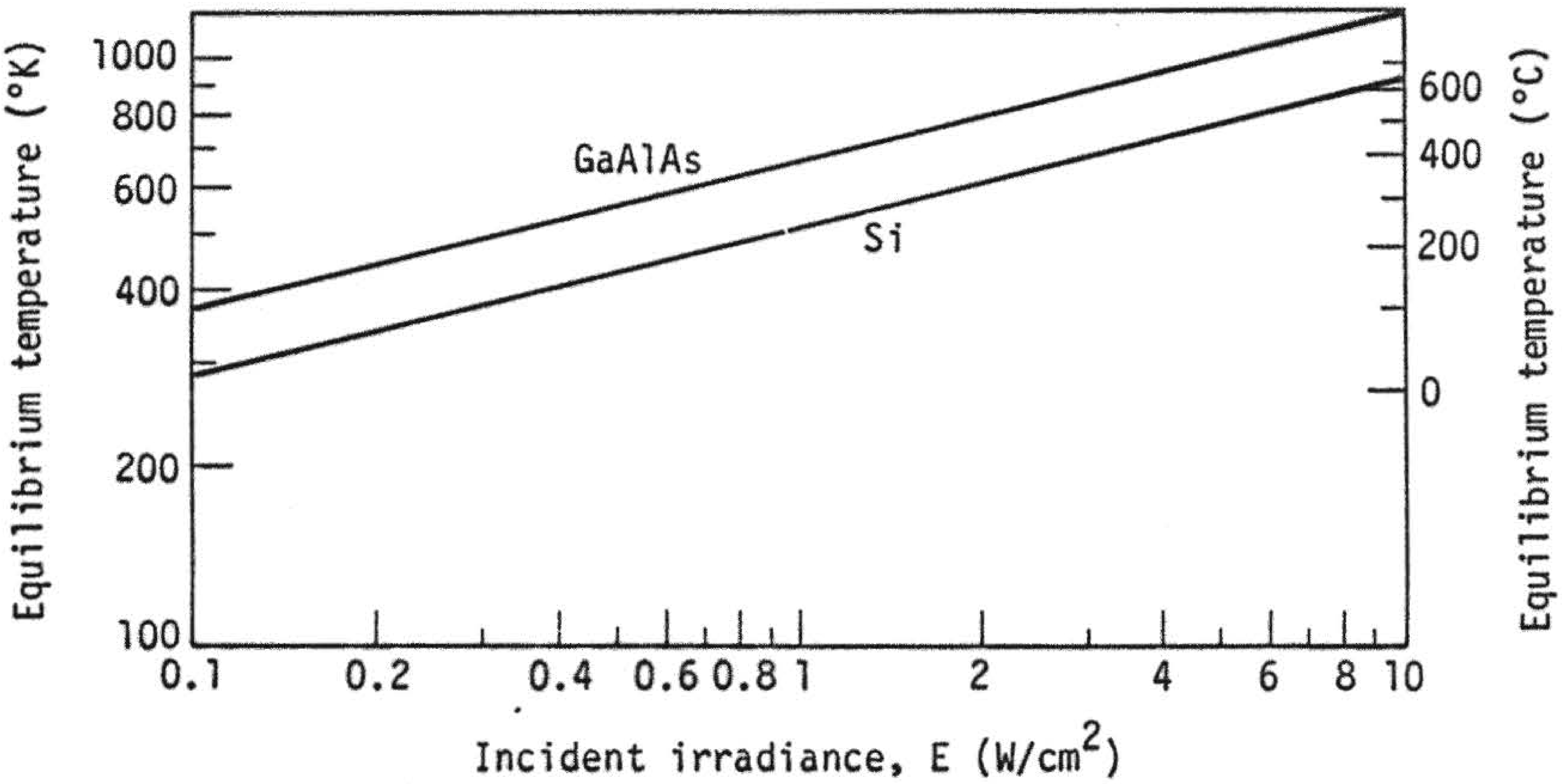

Figure C.3-5. Solar cell equilibrium temperature as a function of incident irradiance.

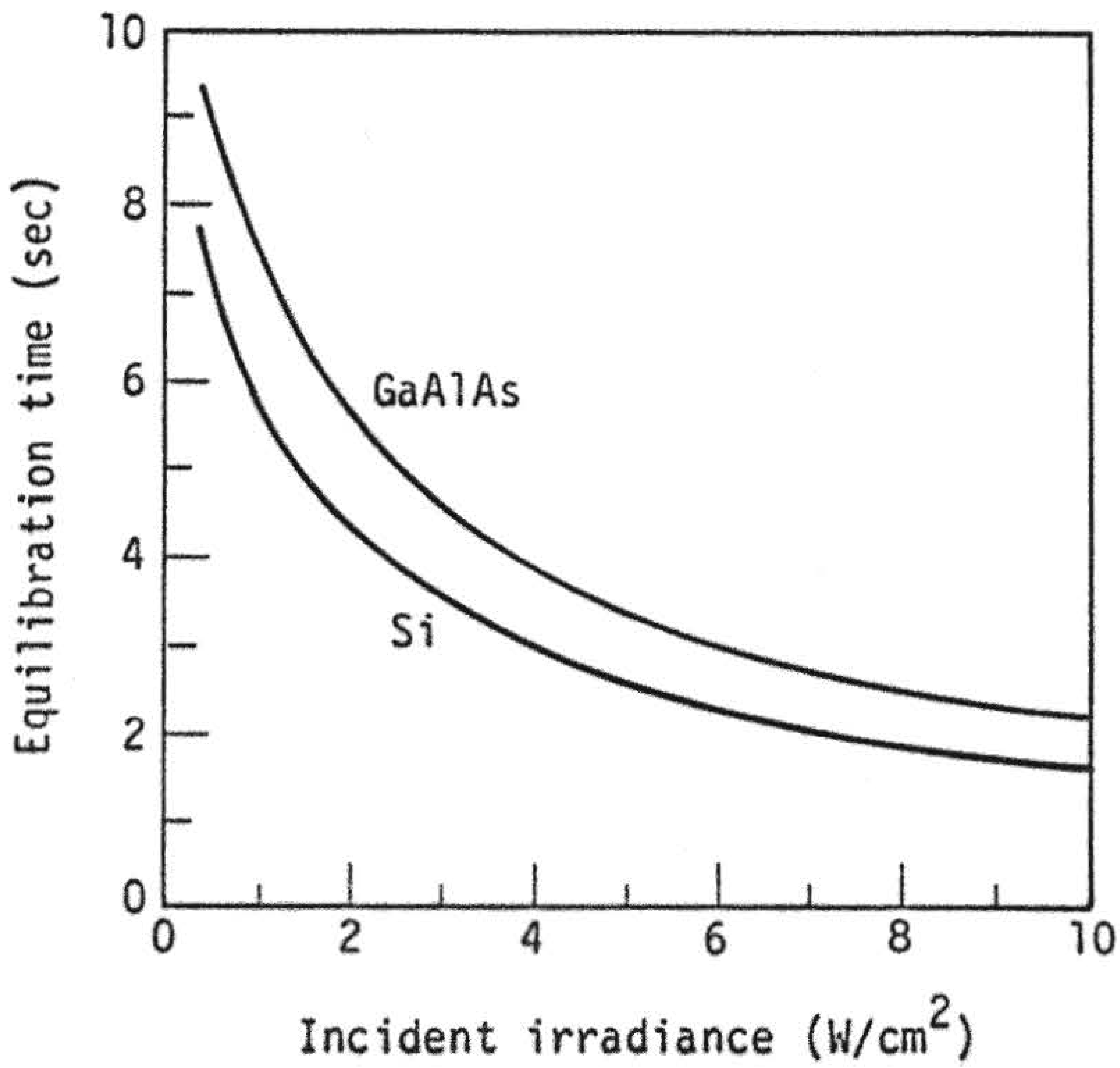

Figure C.3-6. Solar cell equilibration time as a function of incident irradiance.

methods have high probability of success for the power satellite, which must be lightweight and must have a high absorptivity and emissivity in both the solar (0.3 μm to 3 μm) and the thermal (0.6 μm to 20 μm) regions of the spectrum in order to function properly.

C.3.7 References and Notes

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C.4 Electronic Warfare (EW) and Electronic Countermeasures (ECM)

The military use of sophisticated electronics has become so pervasive that, in many instances, modern military organizations cannot accomplish their missions if denied use of their electronic systems. This is particularly true in space where the accomplishment of military activities is predicated on proper functioning of electronic systems and subsystems. Accordingly, electronic warfare will be an important element in all categories of space warfare. Electronic warfare may be used in support of offensive operations, it may pose a significant threat to space activities and it may be used for the mutual or self-protection of space activities. Preliminary considerations of the relevance of these aspects of EW to SPS operations are provided in this appendix.

C.4.1 The SPS as an EW Weapon/Platform

The primary offensive objective of electronic warfare is to prevent effective use of electronic systems by hostile forces. A variety of electronic countermeasures (ECM) and techniques may be applied.[1,2] However, intelligence regarding the characteristics and operational use of hostile systems is a prerequisite for the effective application of ECM to counter their use by hostile forces. Electronic warfare includes both electronic intelligence (ELINT) and ECM activities.

ELINT operations may be conducted to satisfy a variety of requirements. For example, electronic reconnaissance may be used to locate hostile elements, to update hostile force electronic order of battle (EOB) information, to obtain information on specific emitters, to test hostile force response capabilities, or to evaluate hostile command and control procedures. The specific ELINT configuration, such as frequency coverage and resolution, analysis capabilities, etc., are determined by the set of operational capabilities required and the platform characteristics/constraints. The basic SPS includes none of the system capabilities required for the detection, reception, recording, or processing of signals of military interest. Although the SPS may constitute a useful platform for an ELINT capability, the realization of that capability would require the addition of ELINT modules designed to be compatible with the SPS.

A preliminary environmental assessment for the SPS points out that a variety of existing electromagnetic systems would be likely to experience SPS interference. Military communications equipment may be particularly sensitive to SPS interference. A study to characterize the SPS potential microwave interference has been completed and shows that there would be a significant potential interference with national defense requirements as represented by large military operational, test, and evaluation facilities. The performance of radar instruments used at airstrips and on test ranges to acquire and track targets could fall by 10 to 65 percent. The reception and reliability of command and control communications could be reduced by 5 to 30 percent, and tactical systems performance could be reduced greatly.[5] If an SPS program is initiated, modifications or redesign of such equipment would be necessary to avoid degradation.

It seems safe to assume that the SPS potential for interference with electromagnetic systems could be further enhanced with purposeful design to provide a potent ECM device. By way of comparison, a powerful airborne jammer with a directive antenna may be capable of providing an effective radiated power on the order of 50 kW within the SPS frequency range. Such a system may be expected to be effective to ranges on the order of 50 nautical miles or more. The power density at a 50-nautical-mile range from the jammer would be on the order of 4.6×10^{-11} watts/cm^2. This is much less than would be provided by the SPS microwave beam even if directed to locations other than the rectenna site. In addition, a single jammer can simultaneously engage a limited number of hostile systems. Using the SPS, it may be possible to disrupt hostile electronic systems over very large areas.

C.4.2 EW Threats to the SPS

The phase control system for the basic SPS is the most likely candidate for electronic warfare attack. If the phase control system is degraded sufficiently, the transmitter antenna subarrays will no longer be phased together and the SPS microwave power beam will be defocused.

The phase control loop is composed of uplink pilot beam signals transmitted to receivers at each subarray of the SPS power beam transmitter. The SPS power beam constitutes a downlink which is sensed by a ground safety control system with command link capability to the satellite to automatically cease operations if need be.

Possible use of electronic warfare against the SPS may include consideration of any one, or combination, of the following approaches:

- o Jamming the receivers in the SPS transmitting array. If the jamming signals are sufficient to saturate the receiving capability to identify pilot beam coding or process the phase control information, phase control will fail, resulting in power beam defocusing.
- o Injecting false signals into the ground safety control system. If successfully accomplished, this could create the impression of unacceptable changes in power density in the vicinity of the rectenna, resulting in transmission of commands to the satellite to cease operation.
- o Attenuating the uplink pilot beam to prevent detection of control signals by receivers in the satellites. If successfully accomplished this would result in automatic defocusing of the power beam.

The pilot beam provides a double sideband suppressed carrier signal which is symmetrical about the downlink power beam frequency (2.45 GHz). The frequency separation between the sidebands and the downlink frequency is greater than 10 MHz. Both sideband frequencies should be jammed if ECM techniques are directed against the satellite receivers. The SPS receiving system is not highly directional since the phase control system was designed to permit multiple SPS access from one pilot beam transmitter. Accordingly, the constraints on jammer location are not very severe. The jamming signal at the receiver location must be significantly greater than pilot beam signal if receiver saturation is to be achieved. Estimates of the jamming-to-signal ratio requirements are not provided at this time. However, if the requirements are sufficiently high, jamming from surface sites will be precluded even with powerful jammers and high-gain jamming antennas.

If the location of the ground control safety sensor can be determined, it may be possible to illuminate the sensors with microwave energy to generate safety signals associated with unacceptable SPS power density levels. This approach appears impractical if power densities in excess of 0.1 mW/cm^2 are required to activate safety control sensors. The use of a reasonably powered microwave radiator at reasonable ranges simply cannot provide the required power densities.

Chaff use may be considered for attenuation of the pilot beam signal to below the threshold required for maintaining pointing control over the SPS power beam. A signal passing through a cloud of uniformly distributed chaff elements is attenuated by a factor exp $(-n_e \sigma_t \ell)$ where n_e is the number of effective chaff elements per unit volume, σ_t is the total cross section (including absorption) of the individual chaff elements at the signal frequency, and ℓ is the total length of the signal path through the cloud, as illustrated in Figure C.4-1. For aluminum and aluminized-glass chaff dipoles, the absorption cross section is small relative to the scattering cross section, so that $\sigma_t \approx \sigma$ where σ is the scattering radar cross section (RCS) of individual dipoles. For randomly oriented chaff dipoles, the scattering cross section of a single dipole averaged over all orientation is approximately $\sigma \approx 0.153\lambda^2$ where λ is the wavelength (in meters) for the first resonant frequency of the chaff dipole.

It is frequently useful to express attenuation in terms of decibels per unit path length. An attenuation factor, β, for chaff may be expressed in decibels per meter (dB/m) as follows:

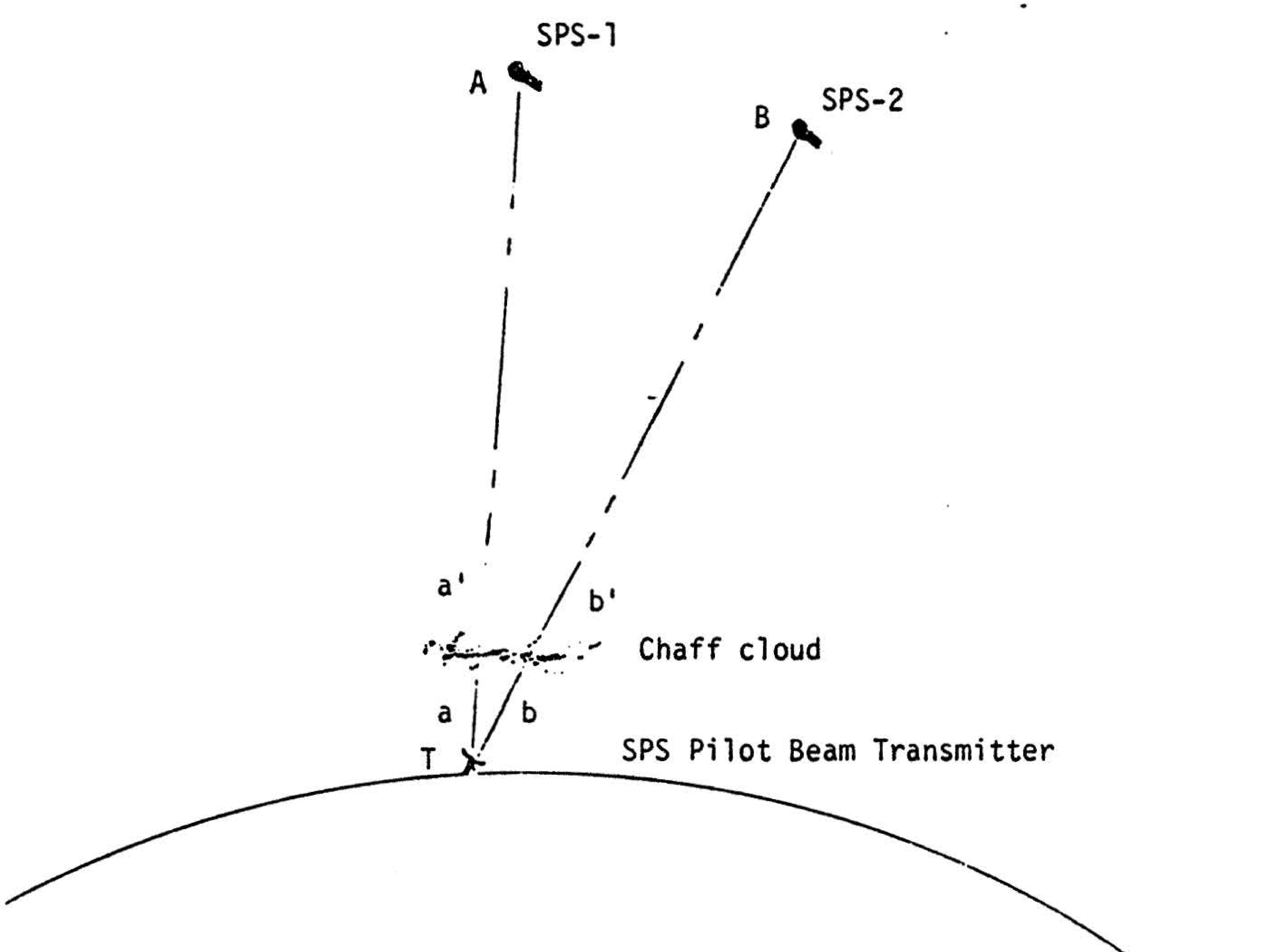
$$\beta = (4.34) n_e \sigma \qquad \text{dB/m} \tag{1}$$

where n_e is the number of effective chaff elements per cubic meter, and σ is the radar cross section in square meters of the individual chaff elements.[4]

Chaff dipoles are frequently fabricated of aluminum coated glass fiber having a nominal coated diameter of one mil. Chaff provides a broad band frequency response so that chaff cut to a dipole length (approximately 2.36 inches long) corresponding to the SPS power beam frequency will provide near maximum RCS response at the sideband frequencies unless the carrier to sideband frequency separation is greater than about 100 MHz.

Individual pod-type chaff dispensers available for Navy and Air Force aircraft can carry approximately 1.5×10^9 aluminized-glass chaff dipoles cut to the SPS frequency of 2.45 GHz. The chaff can be deployed in approximatley 2.5 minutes. Dipole damage, tangling, distortion, etc., associated with the dispensing process may be expected to reduce the effective number of dipoles to something like 60% of the total dipole count. Accordingly only about 9×10^8 dipoles loaded per pod will be effective. The wavelength at 2.45 GHz is 0.122 m so that the random average dipole cross section is

$$\sigma = 0.153\lambda^2 \approx 2.28 \times 10^{-3} \text{ m}^2 \tag{2}$$



Pilot Beam Links		Chaff Attenuation Length (ℓ)
to SPS-1:	$\overline{TA}$	$\overline{aa'}$
to SPS-2:	$\overline{TB}$	$\overline{bb'}$

Figure C.4-1. Representative Chaff Attenuation Path Geometry

The effective number of dipoles per unit volume decreases as the chaff cloud expands with time. Thus the attenuation per unit path length will decrease. (See Equation 1 above.) However, since the cloud size increases with time, the signal path length through the cloud increases and the total signal attenuation will not decrease as rapidly with time as does attenuation per unit path length.

A variety of factors such as variations in chaff dipole dimensions and coating, atmospheric conditions, wind, altitude, etc., can all affect chaff cloud growth and transport. These factors, along with the placement of the chaff cloud relative to the pilot beam and the pilot beam elevation angle, will affect the variation of signal attenuation with time and the length of time the pilot beam will intercept the chaff cloud. The effects of these factors are indicated in Table C.4-1, which considers one pod of chaff deployed at 10,000 ft. altitude by a single small airplane flying from south to north through the pilot beam under very light southerly wind conditions. (This is the worst case from the viewpoint of SPS vulnerability, short of chaff deployment at saturation levels by large squadrons of aircraft arriving in relays a few minutes apart. For a rectenna sited within the territorial limits of the United States or offshore within its Air Defense Identification Zones (ADIZ), military response to penetration of the ADIZ would be a massive scramble of fighter interceptors long before the chaff could be dispensed.)

The fall rate at sea level for one-mil aluminized-glass chaff will vary from approximately 0.6 to 1.0 fps due to variations in chaff mechanical tolerances. The fall rate increases exponentially with altitude and is approximately twice the fall rate at sea level at about 40,000 ft. Wind speeds also tend to increase exponentially with altitude. The wind model used in Table C.4-1 doubles the wind velocity for each 5000-ft. increase in altitude.

The elevation angle for the pilot beam signal path to the SPS in synchronous orbit decreases for transmitter locations at higher latitudes, increasing the path length through the chaff cloud. For the elevation angles of interest, the SPS pilot beam would be most vulnerable under no wind or very light southerly wind conditions. For higher wind velocities, even if from the south, wind transport of the chaff cloud will carry the cloud beyond the signal path before the chaff settles to the ground, as indicated in Part B of Table C.4-1.

The chaff threat to the pilot beam is thus very limited in time and would be almost exclusively from a terrorist group. Any aircraft dispensing chaff in the

Table C.4-2. "WORST CASE" CHAFF DEPLOYMENT AGAINST THE SPS PILOT BEAM

TIME AFTER CHAFF RELEASE (Hr:Min)	CHAFF CLOUD DIMENSIONS			CHAFF CLOUD DENSITY (Effective dipoles per m^3)	LATITUDE 0°	30°	35°	40°
					ELEVATION ANGLE 90°	55°	49°	44°
	Length (km)	Width (m)	Depth (m)		SIGNAL ATTENUATION (dB)	(dB)	(dB)	(dB)
A. Wind Conditions:* At surface: ∿0.21 kts (0.11 m/sec); at 10,000 ft: ∿0.84 kts (0.44 m/sec)								
0:0	7.5	20	20	382	76	92	100	109
0:01.5	7.5	20	33	231	76	92	100	109
0:03	7.5	20	46	166	76	92	100	109
0:05	7.5	21	63	115	72	88	95	104
0:10	7.5	24	106	60	63	77	83	91
0:20	7.5	33	191	24	46	56	61	66
0:30	7.5	47	274	12	32	39	43	46
1:00	7.6	111	513	3	13	16	18	19
1:30	7.7	175	739	1	8	10	11	12
2:00	7.9	288	954	0.5	5	6	7	7
2:30	8.0	382	1157	0.3	4	5	5	5
B. Wind Conditions:* At surface: ∿4.4 kts (2.29 m/sec); at 10,000 ft: ∿17.8 kts (9.14 m/sec)								
0:00	7.5	20	20	382	76	92	100	109
0:01.5	7.5	20	33	231	76	92	100	109
0:03.5	7.5	22	46	151	69	84	91	99
0:05	7.5	27	63	90	56	68	74	81
0:10	7.6	45	106	32	33	40	44	48
0:20	7.9	117	191	6	**	15	16	18
						**	**	**

* All winds assumed to be from the south.
** At this time, the chaff cloud no longer intercepts the pilot beam. Chaff fall rate has been assumed to be 0.6 to 1.0 fps at sea level.

vicinity of the rectenna would be highly visible on radar (especially since flight would have to be at reasonably high altitudes), permitting interception by military aircraft or tracking until it lands, deterring all but the most fanatical of terrorists. The possibility of drones or rockets being used to deploy the chaff remains open, but is most unlikely because of the limited effectiveness of the chaff threat.

C.4.3 EW and SPS Self-Protection

Electronic warfare systems and techniques may constitute part of a mix of systems and techniques required for SPS self-protection against attack. EW could be used to detect and counter those hostile system elements which require the transmission and/or reception of electromagnetic radiation to accomplish their functions. Search/detection, acquisition, tracking, homing, navigation, communication, control, fusing, etc., are all examples of functions which are sometimes accomplished by electromagnetic means.

Threat detection and recognition is a prerequisite for an effective response. Warning receivers, analyzers and direction-finding systems will constitute the EW complement to other threat detection techniques which may be available. Following threat detection, ECM techniques may be directed against hostile systems to prevent the detection or processing of required electromagnetic signals. ECM might also be appropriate for introducing false or deceptive signals into hostile systems. In some instances, antiradiation missiles (ARMs) may be launched to home on and destroy threats which are characterized by signal transmissions.

In many instances, EW in combination with non-EW techniques may be required to effectively defeat threats to the SPS. For example, an EW warning system might detect signals associated with the launch of a nonradiating weapon, and a spray of high velocity pellets might be deployed to destroy the weapon.

It is probably premature at this time to speculate on the nature of an SPS self-protection concept. However, it is almost certain that any concept adopted will feature a high degree of integration and automation even if a manned SPS satellite concept is employed.

C.4.4 References

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C.5 Chemical and Biological Warfare (CBW) and SPS

C.5.1 CBW Vulnerability

CBW appears to be a highly effective means for disabling any portion or all of the SPS system. The vulnerability of the SPS elements to various forms of CBW arises from the fact that each SPS facility in space possesses a separate life support system. These individual life support systems provide highly effective means for vectoring both chemical and biological agents to personnel in space. An exceedingly small amount of CBW agent may be introduced into a life support system with widespread results throughout the facility thus attacked. Since the space transportation system may provide vectors for the agent to other facilities, CBW could be used to attack all space-based SPS facilities by introducing appropriate agents in only one facility.

The CBW agent chosen for application would depend upon whether the aggressor wished to kill or merely temporarily disable the personnel of the facility. Some biological agents, of course, can reproduce themselves, so the effectiveness of the agent need not diminish as it is spread more widely, as is the case with chemical agents.

An additional factor in space CBW is the potential use of agents to attack not the personnel but the highly sophisticated equipment in various facilities. In view of the rapid rate of advance in genetic engineering, specially bred fungi might be used to selectively attack and disable critical components. Again, these agents may be easily vectored into the facility through the life support systems.

No totally effective safeguard against CBW attack is foreseen. The most obvious safeguard is stringent and thorough inspection of both individuals and cargo at Earth-based launch sites and at various transportation hubs such as LEO Base and GEO Base. However, the most thorough inspections would not prevent an immune disease carrier from vectoring a CBW agent into the system and subsequently escaping unscathed, particularly if the agent did not incapacitate all personnel upon first exposure, thus attracting attention to the carrier. Nor could inspection techniques prevent the vectoring of CBW agents into a facility from another space facility if the interfacility transportation does not go through one of the transfer hubs.

CBW is apparently a highly effective means for disabling the SPS system with little or no damage to the physical facilities, a factor that would permit an aggressor to seize the SPS system for his own uses should the CBW agent be time-limited in its action or should the aggressor possess counteragents for each CBW agent in his arsenal.

C.5.2 CBW Threat

A cursory initial look at the military CBW threat posed by the SPS would dismiss the threat as trivial if not inconsequential. This is not necessarily the case: because of the isolation of the life support systems of orbital facilities, it becomes possible to develop and test potent new CBW agents, vectors, and countermeasures in these facilities, and to use them as CBW agent manufacturing, storage, and dispersing (vectoring) centers in space.

The most obvious sites for space-isolated CBW centers would be pharmaceutical and biological space manufacturing modules unrelated to SPS facilities. However, the sheer size of many SPS facilities such as the power satellites and the GEO Base lend themselves to the inclusion of a CBW agent manufacturing or storage module in the facility. Storage modules especially might be very easy to camouflage. These factors, taken into consideration with the SPS space transportation system which offers frequent and relatively inexpensive access to and from orbital space, inevitably make SPS a credible supporting system for CBW.

The basic SPS threat in the area of CBW lies in (a) the biological and chemical isolation of SPS elements from one another, the very factor that renders SPS to vulnerable to CBW; (b) the capability to vector CBW agents to selected space facilities utilizing the space transportation system; and (c) most importantly, the capability for an aggressor using CBW to vector the agents against ground targets with the certainty that some or all of his space facilities would not be affected. An aggressor could use the space segments of the SPS to house his command and control centers while vectoring CBW agents against ground targets, remaining certain that, if he shuts off up-bound traffic to orbit, his space facilities will remain immune and isolated.

One safeguard against the CBW threat--and it cannot be guaranteed absolutely effective--is the Resident Inspection Operation (RIO) whose tasks should include inspection and monitoring of the SPS system for CBW threat.

The delicacy of space facilities in the area of their life support systems will render them continually vulnerable to both deliberate and accidental chemical and biological agents. The magnitude of the CBW vulnerability and threat issues may be blunted by early recognition of these possibilities by spacefaring organizations and the early conclusion of agreements, treaties, and conventions concerning both the deliberate and accidental vectoring of such agents.

C.6 Weather Modification as an Auxiliary Role for the SPS

We consider the possible use of the Satellite Power System to modify weather and the military implications of such a capability. Certain atmospheric processes might be modified by deposition of energy from the microwave power beam. We will consider the feasibility of modifying the weather by using the SPS. In addition, we try to estimate the extent to which such an application could be employed for military benefit--from the creation of drought to the rapid clearing of fog from a runway for military aircraft engaged in interdiction and close-air support. Should weather modification prove to be feasible using the SPS, the SPS must be provided with an effective and credible safeguard against its development and deployment as a military weapon for modifying the weather.

C.6.1 Feasibility

To what extent can one design for SPS for modifying weather, based upon the application of the hydrodynamical equations of meteorology? The nature of the answer is formulated partly by the amount of energy involved in atmospheric processes compared with the amount available from the SPS for altering those processes.

The atmosphere is continually being energized by radiant heat from the Sun. Only two-sevenths of the heat absorbed is made available to increasing the potential energy of the air; five-seventh serves to increase its internal energy. This internal energy, unstable and labile, is readily subject to modification. It is the energy in this part of the atmospheric system that the SPS must seek to release in order to modify atmospheric processes and alter the weather.

Part of the available potential and internal energies will therefore be used up in creating motion. To be effective, the SPS must orchestrate its inputs in such a way as to create the right kind of motion, in the desired amounts, and at the right place and time, in order to produce specific weather changes.

To better appreciate the kinetic energy magnitudes, consider just the tropospheric ring between 10° N and 80° N . For this mass of air, the averaged January surplus of kinetic energy in excess of that for July represents 7.5×10^{14}, W being continuously expended during the half year from January to July, a surplus corresponding to 57 years of electrical energy production by the United States at its generating capability for the year 1978.[1]

Now consider the amount of energy that the SPS could introduce into the atmosphere. The SPS converts sunlight into a 2.45-GHz beam that can pass virtually unattenuated through the atmosphere to Earth. If the power density of the beam is limited to, say, 25 mW/cm^2, the power dissipation at a rectenna site would be comparable with that of a dormitory suburb of equal area: the weather/climate effect of an operating SPS rectenna is small.[2] As presently designed, the SPS could do very little to affect the atmosphere directly and thus to modify the weather.

If the SPS transmitter were retuned from 2.45 GHz to the water vapor absorption line of 22.2 GHz, or if a separate transmission module operating at 22.2 GHz were added, however, the SPS's beam would then be able to transfer to the atmosphere a substantial part (roughly 15%) of the energy being transmitted by the SPS microwave beam.[3]

This power absorption is only enough to increase the temperature of a 10^3 m^3 volume of thermally and radiatively isolated surface-type air by about one Centigrade degree in an hour. Furthermore, if the remaining energy reaching the ground in the SPS beam (about 85% of the total beam energy) is intentionally misdirected away from the receiving platform, it can be absorbed by the ground and increase the near surface air temperature by a few Centigrade degrees.

In comparison with the energies involved in atmospheric processes, the amount available from the SPS for altering the air is meager. It is therefore evident that, in order to modify the weather substantially, the operational SPS must exploit suitable inherent instabilities in the real atmosphere which could be triggered into development. To exploit the small amount of SPS energy transferable to the atmosphere in order to modify the weather to any useful extent (for whatever purposes), the power transmission beam must be physically linked with some process of atmospheric turbulence, a process comparable not only in <u>scale</u> with the cross-sectional size of the SPS beam in the atmosphere but also in <u>power density</u>.

The higher beam frequency of 22.2 GHz required to enable weather modification and control, however, would increase sensitivity of the beam to the intense fluctuations of refractivity caused by clear-air turbulence around the high-level jet-streams and in the vicinity of the tropopause or caused by inversions and stable layers in the lower troposphere. The shift to a higher beam frequency would thus (perhaps seriously) degrade the capability for aiming the microwave beam accurately onto a small weather target as it migrates across the terrain. Disadvantages in control tolerance lost, as well as the increased effects of depolarization, appear to offset (at least in part) the advantages realized in going to the higher beam frequency.

If the motion of small scale atmospheric disturbance is initially unstable, or might be thought to become unstable at some later stage, it may nevertheless be completely altered by even a small change in its initial thermal stage by the heat transferred to it from an SPS beam. A great number of disturbances are always present in the atmosphere. Unfortunately, they are so small in intensity or extent that they completely escape detection within the present weather observation network. When perturbed by SPS heating, however, these disturbances may thereafter exert trigger actions and release large-scale, important new developments. To achieve intended types of weather modification without miscalculation, it would be necessary in principle to determine where, when, and generally also in what way such developments would originate. Therefore, to apply weather modification methods successfully, one must know beforehand the situations in which such trigger actions are present. (In Storm, author George Stewart[4] sized it up in a dramatic way, by suggesting that a sneeze in Szechwan made Alaska snowbound: cyclogenesis from the sneeze in China led irreversibly to an extratropical cyclone named Maria which moved across the North Pacific and Alaska to California.)

If the power density of the SPS beam were increased from 25 up to 100 mW/cm^2, a 22.2-GHz beam could add a sizeable amount of radiant heat directly to the atmosphere traversed, as well as indirectly to the air just above ground heated by the SPS beam. From recent simulations of a tropical atmosphere, a team comprised of the Smithsonian Astrophysical Observatory, the Center for Environment and Man (CEM), and the Massachusetts Institute of Technology found that, for a vertically incident 100-mW/cm^2 beam, heating rates of approximately 7 C^o per day would occur through clouds and a subcloud layer up to 10^3 m above the surface.[5] The SPS power penetrating to the ground or ocean would be double the radiative flux from the atmosphere and five times that from the Sun.

In a wintertime, continental atmosphere, CEM found that a vertically incident 100-mW/cm^2 beam heating the ground for one hour would thus contribute indirectly to a 5 to 10 C^o temperature rise in a 5-m-thick layer of air above the ground. This layer, moreover, would be effective as a storage medium for the SPS radiant heat source for up to half a day after the SPS had been turned off, even after only one hour of irradiance. Even ten hours later, the soil's warming effect, up to 2 C^{o} in air just above the ground, would extend up as high as 60 m above the ground in the form of slightly elevated air temperatures.

Fog dispersal is therefore one obvious possibility for SPS applications. Dispersal would come mainly because of convection triggered by heating the soil, as well as the air aloft, where the heating would contribute to breaking up the thermal inversion that acts as a lid on fog. It would also seem that atmospheric pollution could be reduced by having the SPS break up pollution-trapping thermal inversions aloft by creating chimneys in the atmospheric inversion. For this to happen, wind speeds must be low in the pollution layer, and clouds must be also present in order to enhance the RF energy transferred from the beam.

C.6.2 Possible Other Effects of Microwave Transmission

Meteorological effects other than atmospheric heating, however, may also be related to SPS microwave transmission. How cloud particles interact with one another may be affected by an intervening microwave beam with a powerful CW field similar in frequency to that of the electromagnetically radiating cloud particles. Cloud particle interactions affect the subsequent mechanisms of precipitation; this process must be considered in efforts to stimulate manmade rain.

Interactions among cloud particles lead to electrostatic charging of the particles and a resulting change in ambient electric fields. Summertime precipitation reaching the ground comes after clouds have become strongly electrified. In their charged state and self-altered electrical environment, the electromagnetically radiating cloud particles undergo changed hydrodynamic and aerodynamic interactions and consequent growth. Their growth rate and interactions, however, could be so altered by the SPS beam's electromagnetic field as to trigger cloud growth and rainfall. Electrical forces in the cloud might be so altered by a properly tuned microwave beam as to overcome the natural dynamics normally present, for example, in nonprecipitating cumuli.

These possibilities, nevertheless, are still mere conjectures. No firm physical basis is known today to support the proposition that an altered SPS could modify weather in a useful, practical, or substantial way, even in the distant future (circa 2040). To provide definitive answers regarding the feasibility of SPS-induced weather modification, we will require a far more detailed understanding of atmospheric processes and weather phenomena.

C.6.3 References

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