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SURVIVABILITY CONSIDERATIONS IN THE DESIGN OF SPACE POWER SYSTEMS

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ABSTRACT

Mission requirements for planned NASA and DOD spacecraft often include designing for survivability. The threats to the survivability of a spacecraft can be either manmade (e.g., ASATs, space debris) or natural (e.g., radiation belts, micrometeoroids). An overview of the principal kinds of manmade threats and the implications on the design of space power systems are discussed. In general, it is concluded that for survivability space power systems should be compact with high thermodynamic conversion efficiencies and appropriate intrinsic hardness.

INTRODUCTION

As many analysts have noted, the United States is very dependent upon its space assets -- early warning satellites, communications satellites, navigation satellites, meteorology satellites, and surveillance systems. To be useful and credible these space assets must be survivable against natural and manmade threats.

Survivability is a measure of the capability of a space asset to perform its mission during and after exposure to a given threat or combination of threats. Within this definition is the implied concept of an acceptable although degraded performance. Achieving survivability depends upon a number of factors, including the size and placement of the constellation of satellites; the signature, mobility, and other defensive capabilities of the satellites themselves, and, not the least, the degree of the intrinsic ability of the individual satellites to withstand particular threat components ("hardness"). A certain measure of passive hardness can be built into a satellite through designing the system and its various componentry to survive postulated threats.

The subject of survivability is important to civilian as well as military spacecraft. Already NASA spacecraft have been sent through the severe radiation belts of Jupiter and more spacecraft will go there in the future. Civilian satellites in Earth-orbit are subjected to natural radiation doses from the Sun and the particles trapped by the Earth's magnetic field.

From a practical standpoint an individual satellite is only as survivable (or "hard") as its weakest critical component. A spacecraft's power subsystem is critical to its generic functioning; thus, it is important that the power subsystem not represent the weak link. This paper will review the U.S. policy on survivability, discuss postulated threats and then qualitatively consider how spacecraft power subsystems can contribute to survivability against these postulated threats.

Since the focus of this paper is on power sources for spacecraft, some manmade threats such as electronic jamming, blinding, spoofing (the giving of false commands and information), and takeover (unauthorized use by an adversary), which primarily affect spacecraft control subsystems and sensors, will not be discussed. This paper is based on unclassified, publicly available documents and makes no pretense to being either an exhaustive survey or an official document.

SURVIVABILITY POLICY

One of the overall goals of the national space policy approved by the President on 5 January 1988 is "to strengthen the security of the United States". The national space policy provides policies ensuring that "Survivability and endurance of national security space systems, including all necessary system elements, will be pursued commensurate with their planned use in crisis and conflict, with the threat, and with the availability of other assets to perform the mission"(1).

The Presidential Directive on national space policy states that "DOD will also continue to enhance the robustness of its satellite control capability through an appropriate mix of satellite autonomy and survivable command and control, processing, and data dissemination systems". The directive also states (1)

- "The DoD will develop, operate, and maintain enduring space systems to ensure its freedom of action in space. This requires an integrated combination of antisatellite, survivability, and surveillance capabilities".
- "DoD space programs will pursue a survivability enhancement program with long-term planning for future requirements. The DoD must provide for the survivability of selected, critical national security space assets (including associated terrestrial components) to a degree commensurate with the value and utility of the support they provide to national-level decision functions, and military operational forces across the spectrum of conflict."

From the Department of Defense Space Policy, which was signed by the Secretary of Defense on 4 February 1987, the general policy was stated that "DoD space policy supports and amplifies U.S. national space policy". Under DoD space goals, it was stated that DoD space "efforts include protecting the peace and decreasing the incentives for attack and enemy escalation by providing secure, survivable means for collecting and transmitting information, and by providing the means to counter enemy advantages through U.S.

space-related and strategic defense operational capabilities." Under space control policy it was stated that "DoD space systems will be designed, developed and operated to ensure the survivability and endurability of their critical functions at designated levels of conflict. DoD will develop and operate space systems which balance capability and survivability to deter attacks by creating a dilemma for adversary attack planners by responding to these attacks with both space and terrestrial force responses"(2).

The national space policy and the derivative DoD space policy are further implemented in specific regulations, e.g., Air Force Regulation (AFR) 80-38 which states (3)

- "Sufficient numbers of each U.S. Air Force system must be capable of surviving manmade hostile environments to carry out their designated mission."
- "Survivability must be considered in developing the requirements for, and the tradeoffs leading to, the basic design of a US Air Force system."

It is clear that U.S. policy requires survivable space systems and that designers are to consider survivability in their tradeoffs.

THREATS TO SPACE SYSTEMS

The DoD lists the following current antisatellite (ASAT) capabilities for the Soviet Union (4):

- Co-orbital antisatellite interceptor
- Nuclear-armed Galosh antiballistic missile (ABM) interceptor (a direct ascent ASAT)
- Ground-based lasers

The DoD also lists the following new ASAT systems as likely to be developed and deployed in the next 10 years (4):

- Particle beam weapons
- Radio-frequency weapons
- Kinetic energy weapons
- Space-based lasers

Another ASAT system often cited in the literature is the space mine, which in this paper will be discussed with the co-orbital ASAT interceptor.

The following subsections elaborate on these different types of threats. The focus in these subsections is on capabilities - no attempt is made to assess intent or threat scenarios.

Co-orbital ASAT Interceptor

The currently operational Soviet ASAT system, known as the co-orbital ASAT interceptor, was introduced in 1968. In tests to date, it has been launched into an orbit similar to that of its target atop an SS-9 modified Scarp ICBM. This ASAT has been tested over 20 times using an active radar or a passive optical/infrared sensor. In all tests the ASAT has been launched from Tyuratam into orbits with inclinations in the range of 62 to 66 degrees. The highest altitude reportedly reached in the tests has been about 2400 km but a higher energy booster could increase this altitude. With a closing speed of about 400 m/s, the interceptor comes within range (generally assumed to be within 1-2 km) and, on command from ground controllers, explodes and showers the target with shrapnel. At best, a target may have only a few hours of warning that it will be attacked (5,6,7).

The space mine represents a variation on the co-orbital ASAT. The mine can be launched and maneuvered in the vicinity of the target where it remains dormant awaiting the signal to attack. When activated, the mine would lock onto the target satellite, maneuver within range and explode its conventional or nuclear charge. The space mine is a particular threat in geostationary orbits (GSO) where it can be disguised as a spent rocket body or a dead payload and allowed to drift by its target (8,9). If fully developed and deployed, the x-ray laser, which would be activated by a detonating nuclear weapon, could be used as a space mine capable of killing multiple satellites thousands of kilometers distant (10,11).

Direct Ascent ASAT

The nuclear-armed Galosh ABM interceptor has been cited by a number of sources as having the capability to be a direct ascent ASAT against satellites in low Earth orbit (LEO). With 100 modified Galosh interceptors planned for the Moscow ABM system and a possible 3-megaton warhead, the Galosh could conceivably kill or damage satellites over a range of hundreds of kilometers. The use of higher energy boosters could extend this altitude considerably (4,5,10,12,13,14).

The direct-ascent nuclear-armed ASAT system could attack satellites in LEO in a few minutes while an attack on satellites in geosynchronous Earth Orbit (GEO) might take several hours (see Figure 1) (11). (Traveling at Earth escape velocity such an ASAT could reach GEO in less than one hour.)

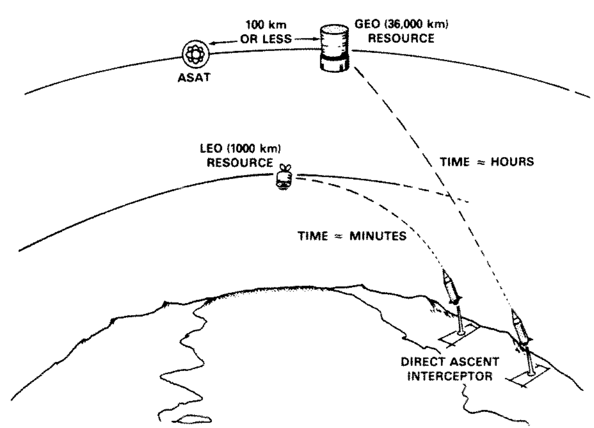


Figure 1. Potential ASAT Systems in Space and on the Ground (after reference 11).

Ground-Based Lasers

The DoD has reported that at the Sary-Shagan Missile Test Center near Lake Balkhash "the Soviets are estimated to have several lasers for air defense and two lasers probably capable of damaging some components of satellites in orbit . . ." Three types of lasers are reportedly being explored: the gas-dynamic, the electric discharge, and the chemical. The DoD reports that the Soviets "have achieved impressive output power levels with these lasers. The Soviets are possibly exploring the potential of visible and very-short-wave-length lasers. They are investigating the excimer, free-electron, and x-ray lasers, and they have been developing argon-ion lasers." The DoD report also noted that the Soviets have "produced a 1.2-meter segmented mirror for an astrophysical telescope in 1978 and claimed that this reflector was a prototype for a 25-meter mirror"(4). (Note: If several lasers can be operated in phase they could achieve the desired total power from smaller mirrors).

At least four more laser systems may exist atop a 2,290-m mountain at Nurek, about 40 km southeast of the city of Dushanbe, near the Soviet border with Afghanistan. The Nurek site is reportedly linked to the 2,700-MW Brezhnev hydroelectric dam only about 16 km away. Also tied in with Nurek are the directed energy weapon (DEW) sites at Semipalatinsk and the ASAT launch sites at Tyuratam (15).

Gen. John Piotrowski, commander-in-chief of the U.S. Space Command, has said Sary-Shagan's twin ground-based lasers are capable of killing U.S. satellites below 400 km and damaging satellites up to 1,200 km. He has also said that these lasers, if transmitted over certain frequencies, can cause in-band damage to sensors and solar panels on satellites in GSO (16). It has been noted that the "longitudinal spacing of Tyuratam, Dushanbe, Sary Shagan and Semipalatinsk ensures that no low altitude satellite can avoid at least two attack opportunities each day"(17).

Figure 2 shows some capabilities of ground-based and space-based lasers.

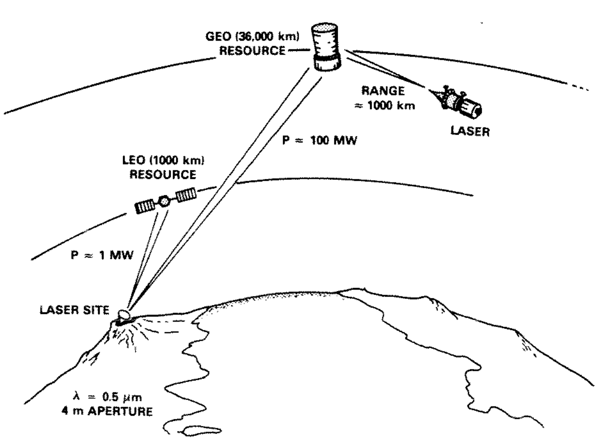


Figure 2. Potential Laser ASAT Systems in Space and on the Ground (after reference 11).

Particle Beam Weapons

The DOD has reported that the Soviets "may be able to test a prototype space-based particle beam weapon intended to disrupt the electronics of satellites in the 1990s. An operational system designed to destroy satellites could follow later. . ."(4).

Radio-Frequency Weapons

The DOD has reported that the "USSR has conducted research in the use of strong radio-frequency (high-power microwave) signals that have the potential to interfere with or destroy critical electronic components of . . . satellites. The Soviets could test a ground-based radio-frequency weapon capable of damaging satellites in the 1990s"(4).

Kinetic Energy Weapons

The Soviets reportedly developed in the 1960s "an experimental 'gun' that could shoot streams of particles of a heavy metal such as tungsten or molybdenum, at speeds of nearly 25 kilometers per second in air and more than 60 kilometers per second in a vacuum." Furthermore, it has been reported that "the Soviets could deploy in the near term a short-range, space-based system . . . for close-in attack by a maneuvering satellite. Current Soviet guidance and control systems are probably adequate for effective kinetic energy weapons use against some objects in space, such as satellites"(4).

Space-Based Lasers

The DoD has stated that the "development of a space-based laser ASAT that can disable several satellites is probably a high-priority Soviet objective." The DoD has reported the USSR "could have a prototype space-based antisatellite laser weapon by the end of the decade" and that the "Soviets may deploy space-based lasers for antisatellite purposes in the 1990s, if their technological developments prove successful."

The DoD has noted that "Space-based laser ASATs could be launched on demand, or maintained in orbit, or both. By storing a laser ASAT in orbit, the Soviets could reduce the time required to attack a target. This option would decrease the warning time available to the target needed to attempt countermeasures. The Soviets are also developing an airborne laser whose missions could include ASAT, and limited deployment could begin in the early 1990s"(4).

Weapon Kill Mechanisms

The ASAT threats described in the preceding subsections can neutralize target satellites by one of three types of kill mechanisms: (1) functional kill, (2) thermal kill, and (3) impulse kill (18).

The functional kill mechanism, pertinent to nuclear weapons, particle beam weapons or radio-frequency weapons, prevents the satellite from operating correctly without necessarily destroying it (18). For example, the gamma rays from a nuclear weapon detonation can induce damaging high voltages or currents through an internal electromagnetic pulse (IEMP) and/or system-generated EMP (SGEMP) (19). So-called "hot" x-rays (~15 keV) can pass through most materials (unless the atomic number is high) and damage (or kill) electronics. Not only can the deposition of nuclear radiation affect the satellite but the rate of deposition can be a significant threat. Furthermore, charged particles can induce single-event upsets (SEUs) in electronic circuits. If the immediate effects of the nuclear weapon detonation do not destroy the target satellite, the intense, long-lasting radiation belts from the detonation may eventually kill the satellite (20). The particles from a particle beam weapon, if given energies on the order of a few hundred MeV, can penetrate at least several centimeters of dense materials or tens of centimeters of typical aerospace materials. This, too, would be sufficient to alter or destroy sensitive electronic components deep inside the target (18).

The thermal kill mechanism involves delivering a lethal amount of energy (nominally 1 to 100 kJ/cm^2) in a very short period of time (nominally a few seconds or less) so that the target surface is melted or vaporized to the point of catastrophic failure. As an example, a 25-MW hydrogen-fluoride laser operating at a wavelength of 2.7 μm with a 10-m-diameter mirror could deliver 20 kJ/cm^2 over 400 km. This would be more than enough to cross the damage threshold for most space systems (estimated to be 0.4 to 2 kJ/cm^2) (18,21,22).

The impulse kill occurs when sufficient energy is deposited by mechanical or thermal means to create a destructive mechanical shock wave in the target. It has been noted that, given satellite orbital velocities (3.6 km/s in GEO to about 8 km/s in LEO) a 1-g projectile in the path of an unprotected satellite can cause its destruction. Lasers and x-rays can cause spallation and thermal stress failures (18,21). For example, the so-called "cold" x-rays (~ 1 keV) will have only a superficial energy deposition on the surface (with perhaps microns of material being vaporized) but they will produce a shock wave through the structure causing spalling and cracking on the backside.

POWER SOURCE CONSIDERATIONS

Maj. Gen. Robert R. Rankine, Jr., Deputy Commander of USAF Space Division, has written: "A major program will identify effective counters to such threats as direct-ascent antisatellite weapons, ground- or air-based lasers, orbital antisatellites (both conventional and directed-energy), space mines, and fragment clouds. In surface and air warfare, classic approaches such as hardening, evasion, proliferation, deception, active defense, and tactics have been used to help aircraft and surface ships survive. The SDI program is designed to identify a similar set of defenses for space-based systems"(23).

A similar statement was given in 1984 by Dr. Gerold Yonas, then Chief Scientist of the Strategic Defense Initiative Organization (SDIO): "The strength of any defensive system rests on its ability to survive a direct attack, and to continue to function effectively even if degraded by attack. Space-based components that must orbit directly over the Soviet Union will face a host of possible threats, including direct-ascent ASAT weapons, ground- or space-based lasers, space mines, particle-beam weapons, and the effects of nuclear explosions. The tactics of survivability are familiar ones - hardening, active self-defense, concealment, proliferation, maneuvering . . ."(24).

Table 1 summarizes the various threats and lists possible techniques to enhance survivability.

Table 1

Threats to Satellites and Protective Countermeasures (8,18,25)

Threat	Protective Countermeasures
Nuclear Weapon Threat (NWT)	EMP Shielding Neutron Hardening Very high orbits Maneuvers Proliferation (in-orbit spares) Deception Concealment
Kinetic Energy Weapon(KEW)	Armor Higher Orbits Maneuvers Proliferation Deception Concealment
Directed Energy Weapon(DEW)	Reflective Coatings/ Shielding Higher orbits Maneuvers Proliferation Deception Concealment

In designing a power subsystem for a spacecraft, the designer must consider first the requirements as derived from the System Threat Assessment Report (STAR) and the Threat Environment Description (TED). It is clear from Table 1 that a survivable spacecraft should be difficult to detect, easy to maneuver and decoy, and very difficult to destroy. This means the power subsystem designer must consider packaging concepts for spacecraft maneuverability, surface materials and coatings, filters, electronic/electrical parts selection and shield materials. Figure 3 summarizes this process.

Considering the protective countermeasures listed in Table 1, the power subsystem for a survivable satellite should, as a general rule, meet these criteria

- small optical cross section
- low infrared signature
- small radar cross section
- easy to maneuver (and minimal jitter)
- simple to model for decoys

- high DEW hardening
- high NWT hardening
- high KEW hardening

Obviously, the power subsystem and its power processing and control subsystem should be appropriately hardened consistent with the overall spacecraft requirements. Ideally, the power subsystem should be mounted closely to or inside the spacecraft (or perhaps be able to be so structured as part of the attack response) in order to meet the foregoing criteria. Figure 4 illustrates qualitatively the survivability characteristics of some candidate generic types of power sources compared against these criteria. In general, the power subsystem should be compact (preferably with both a low mass and a small exposed surface area) with high thermodynamic conversion efficiencies (low heat rejection rates).

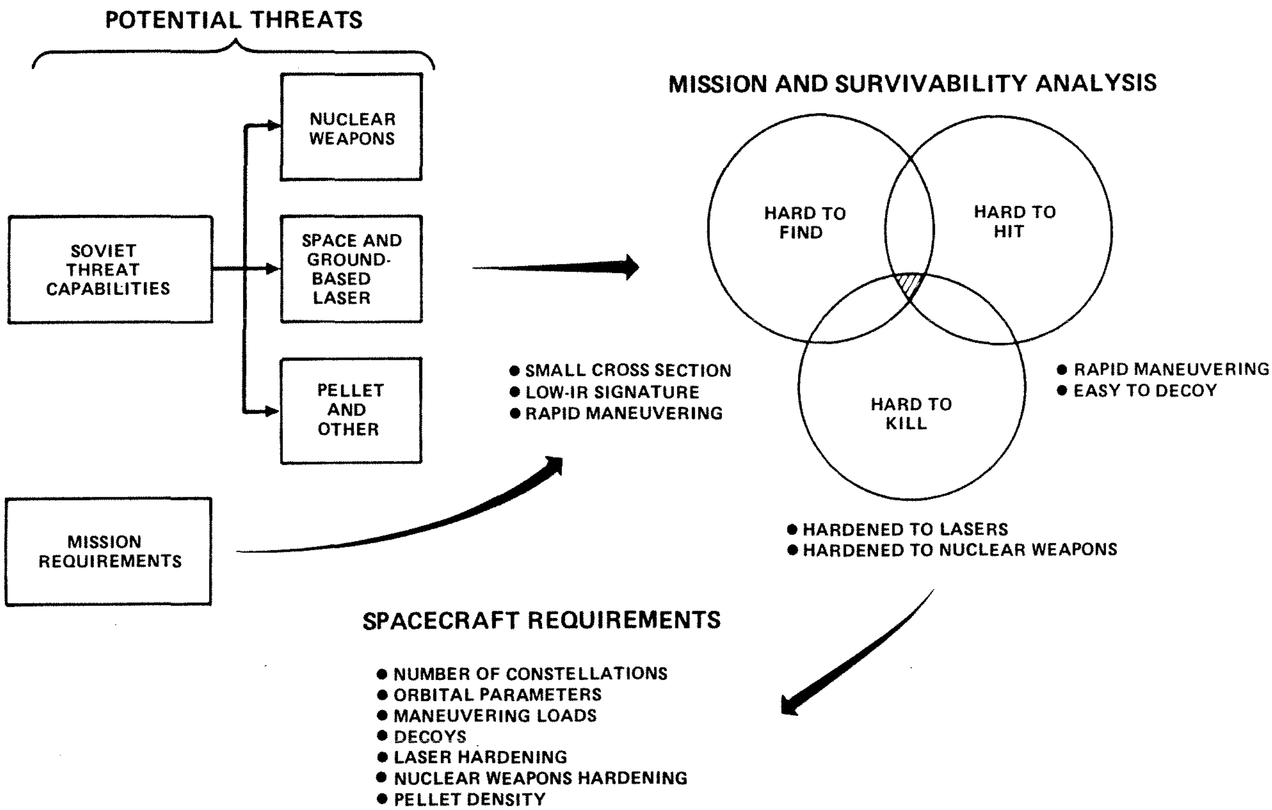
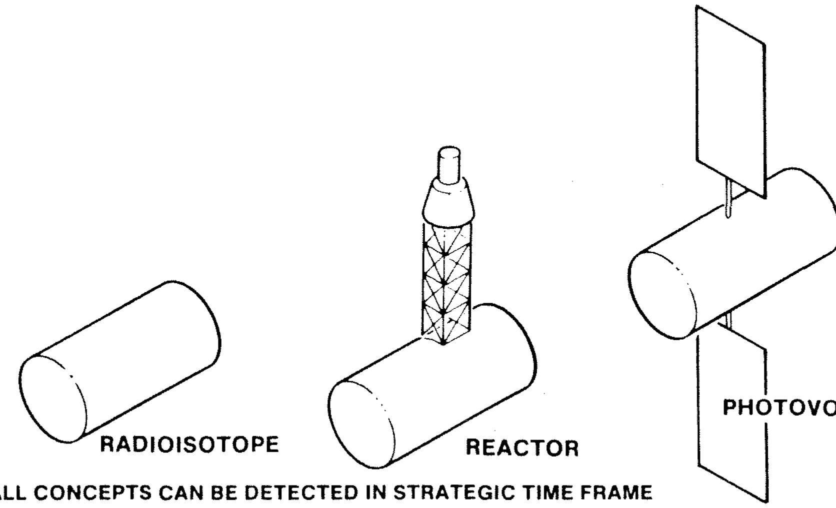


Figure 3. Systems Approach to the Determination of Survivability



ATTRIBUTE	RADIOISOTOPE	REACTOR	PHOTOVOLTAIC
STRATEGIC DETECTION	ALL CONCEPTS CAN BE DETECTED IN STRATEGIC TIME FRAME		
TACTICAL DETECTION			
OPTICAL	• SMALL CROSS SECTION	• MODERATE CROSS SECTION	• LARGE CROSS SECTION
INFRARED	• MODERATE SIGNATURE	• MODERAGE SIGNATURE	• LOW SIGNATURE
RADAR	• SMALL CROSS SECTION	• MODERATE CROSS SECTION	• LARGE CROSS SECTION
MANEUVERING	• EASY	• DIFFICULT (ON A BOOM)	• MUST RETRACT PANELS
DECOYING	• EASY/SIMPLE SHAPE	• DIFFICULT/COMPLEX SHAPE (ON A BOOM)	• DIFFICULT/COMPLEX SHAPE
LASER HARDENING	• HIGH	• HIGH	• LOW
NUCLEAR WEAPON HARDENING	• HIGH	• HIGH	• LOW

Figure 4. Qualitative Comparison of the Survivability Characteristics of Some Candidate Generic Types of Power Sources.

SUMMARY

U.S. space policy calls upon the DoD to pursue a survivability enhancement program. Currently, threats to survivability include co-orbital ASAT interceptors, direct ascent ASATs, and ground-based lasers. Various DEW and KEW ASATs may become operational in the 1990s. Through proper selection and design, the power subsystem can, at a minimum, avoid being the weakest element of the satellite and, at a maximum, be an enhancer of satellite survivability.

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