POST-OPERATIONAL DISPOSAL OF SPACE NUCLEAR REACTORS

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ABSTRACT

As we enter the next millennium, advanced-design 100 kWe-class space nuclear reactors will play a major role in the United States space program. One of the most significant issues facing these future civilian and defense-related applications of nuclear energy in space is the overall question of aerospace nuclear safety. Up until now, the great majority of aerospace nuclear safety efforts have concentrated on pre-launch, launch, and reactor start-up activities. In fact, with the exception of the development of the "safe nuclear orbit" concept, little technical attention has been given to the post-operational disposal or "spent core management" of such future space reactors. This paper discusses the technical alternatives available for the safe, internationally-acceptable post-operational disposal of advanced-design space reactors that could be used in a wide variety of military and civilian missions throughout cislunar space in the 21st Century. Post-operational core radioactivity levels for typical 100 kWe-class advanced-design space reactors are examined as a function of time and contrasted to the spent core inventory of the SNAP-10A reactor system, the only nuclear reactor ever operated in space by the United States (1965). The space technology infrastructure necessary to support various space reactor disposal alternatives is also presented as well as candidate extraterrestrial disposal locations.

INTRODUCTION

Space nuclear reactors represent a major energy option for future U.S. space activities (1-8). Compact, reliable energy supplies are the key to humanity's conquest of the Solar System. Table I, for example, provides a detailed summary of potential civilian applications of advanced space nuclear reactor systems, including operational location, power level, mission duration, and post-operational disposal implications (1-7). As presented in Table I, these future civilian space missions can be divided into five convenient categories: (1) Manned orbital facilities (e.g. the space station in low Earth orbit); (2) Earth science and applications (e.g. a large capacity communications platform); (3) transportation of large payloads; (4) the development and exploitation of extraterrestrial resources; and (5) interplanetary exploration (especially to the outer regions of the Solar System). Electric power requirements for such missions typically range from 50 kWe to well over 1,000 kWe. All of these 21st Century space missions are enhanced or enabled by the availability of space nuclear reactor systems.

The major advantages of advanced space nuclear reactor systems when compared to other energy sources (e.g. solar photovoltaic arrays or solar thermal systems) arise in the nuclear reactor system's compactness, high power density, and lower recurring cost. In addition, space nuclear reactors are also independent of distance from or orientation to the Sun, have an enhanced ability to operate in hostile environments (e.g. in a planet's trapped radiation belts or during the extended lunar night), and greatly simplify spacecraft attitude and control functions for most missions. As a potential lien against these advantages, space nuclear power systems could require additional mass for shielding sensitive payloads and crew members from nuclear reactor radiations. Furthermore, all aspects of aerospace nuclear safety must be assured, not only in ground handling, launch and orbital operations, but also after mission operations have been terminated. Post-operational disposal of a spent space nuclear reactor (or at least its core) is a critical aerospace nuclear safety consideration, which must be properly treated or else another situation could arise similar to the Soviet Union's experience with the reactor-powered COSMOS 954 spacecraft which reentered the terrestrial biosphere over northern Canada in 1978 (9).

U.S. space activities involving nuclear power supplies began in the mid-1950s. The Systems for Nuclear Auxiliary Power (SNAP) program was formed to develop both radioisotope and reactor space power systems. In April, 1965, the United States launched its only space nuclear reactor (to date), called SNAP-10A. This reactor was placed in a 3,800 year lifetime orbit around the Earth and then generated some 500 watts of electrical power continuously for 43 days before a payload voltage regulator malfunction initiated a reactor shutdown. In accordance with aerospace safety design features, once shutdown, the SNAP-10A space reactor could not be made critical (i.e. brought to power) again. Table II provides a summary of the SNAP-10A mission (1,5).

Planning for future space missions that will need hundreds to thousands of kilowatts-electric have revived interest in advanced space nuclear reactor systems both in the 100 kWe-class and in the multimegawatt-class. For example, Fig. 1 presents a contemporary view of the SP-100 space reactor program. The SP-100 Program is a joint Department of Defense/Department of Energy/National Aeronautics & Space Administration (DOD/DOE/NASA) program to develop a safe, dependable, high electric output (100-kWe class) reactor power system for a broad range of military and civilian space missions in the 1990s and beyond (10).

TABLE I

Nuclear Power Applications

(Civil Space Missions 1995-2015)

MISSION	POWER LEVEL (kWe)	DURATION (years)	POWER USE	REGION OF OPERATION	DISPOSAL NEEDED?
MANNED ORBITAL FACILITY					
- Initial Space Stat	75	10	multifunction	LEO	Yes
- Growth Station	300-500	10	multifunction	LEO	Yes
- Advanced Station	500-1,000	10	materials process	LEO	Yes
EARTH SCIENCE & APPLICATIONS					
- Communications plat	100-500	10+	info services	GEO	Yes (possibly)
- Air/Ocean Traffic	100-200	10	info services	GEO	Yes (possibly)
TRANSPORTATION					
-GEO Payload Deliv	100-200	5	multi-sortie (NEP)	LEO-GEO	Yes (use NEP)
- Lunar Cargo Deliv	100-200	5	multi-sortie (NEP)	LEO-lunar orbit	Yes (use NEP)
- Manned Mars Mission	> 1,000	4	NEP/manned	interplanetary	Yes (use NEP)
EXTRATERRESTRIAL RESOURCES					
-Lunar Bases	200-1000+	10+	base ops; multifunct	lunar surface	Yes (in situ)
- Asteroid Mining	200-1000+	5-10	materials processing	cislunar space	Yes (lunar)
SOLAR SYSTEM EXPLORATION					
- Multiasteroid Sample	100-200	8-10	NEP/transportation	interplanetary	Yes (on return)
- Comet Nucleus Sample	100-200	6-8	NEP/transportation	interplanetary	Yes (on return)
- Saturn Ring Rendez	100-200	10	NEP/transportation	interplanetary	No
- Outer Planet Orbiter (Uranus, Neptune)	100-200	10		interplanetary	No

TABLE II

Sanp-10A Mission

LAUNCH	
LAUNCH ON ATLAS-AGENA VEHICLE	3 April 1965 AT 1:24 P.M. PST
ORBIT (km)	
APOGEE	1328
PERIGEE	1295
REACTOR STARTUP	
START COMMAND	5:05 P.M. PST
CRITCALITY	11:15 P.M. PST
FULL POWER	1:45 P.M. PST
DEACTIVATED AUTOMATIC CONTROL	10 April 1965
SHUT DOWN	16 May 1965

However, the development and use of these advanced space reactor systems should not be impaired by the absence of an acceptable post-operational disposal strategy.

AEROSPACE NUCLEAR SAFETY

The principal safety guideline underwriting the beneficial use of nuclear energy in outer space is to minimize the likelihood or potential consequences that might be caused by the interaction of radioactive materials with the terrestrial biosphere. In an effective aerospace nuclear safety program, stringent design factors and well-demonstrated operational procedures are employed to protect human beings and the overall terrestrial environment under both normal flight conditions and any credible accident scenario. In the event of an accidental release of radioactive materials into the biosphere, aerospace design features and operational procedures should keep any potential radiation exposure levels to within the limits of internationally accepted standards.

For space reactors, contemporary U.S. aerospace nuclear safety philosophy requires that the reactor remain subcritical in all credible accident environments (5, 11-14). This guarantees that there is no generation of harmful fission products or the release of radioactivity before the reactor and its payload have been placed in an appropriate, operational orbit. The term "nuclear safe orbit" has sometimes been used to describe an Earth orbital location of sufficiently high altitude (e.g. 1,000 km or more) so as to provide an unattended orbital lifetime of sufficient length, typically tens of thousands of years or more, that the majority of the core's fission products will have decayed to stable isotopes, when the spent reactor eventually reenters the Earth's atmosphere.

The now quiescent SNAP-10A reactor is currently in a typical "nuclear safe orbit" around the Earth. Figure 2 provides the calculated radioactive inventory for the spent SNAP-10A core as a function of time after shutdown (5), while Fig. 3 provides similar data for a generic 100-kWe class advanced-design space reactor. Several millennia from now, the SNAP-10A reactor with its then negligible inventory of radioactive materials, will make a fiery plunge through the Earth's upper atmosphere and, as designed, will harmlessly disperse itself. While this post-operational disposal strategy may be acceptable for a very small number of relatively low power-level reactors, increasing global sensitivity to the overall question of nuclear waste disposal and environmental

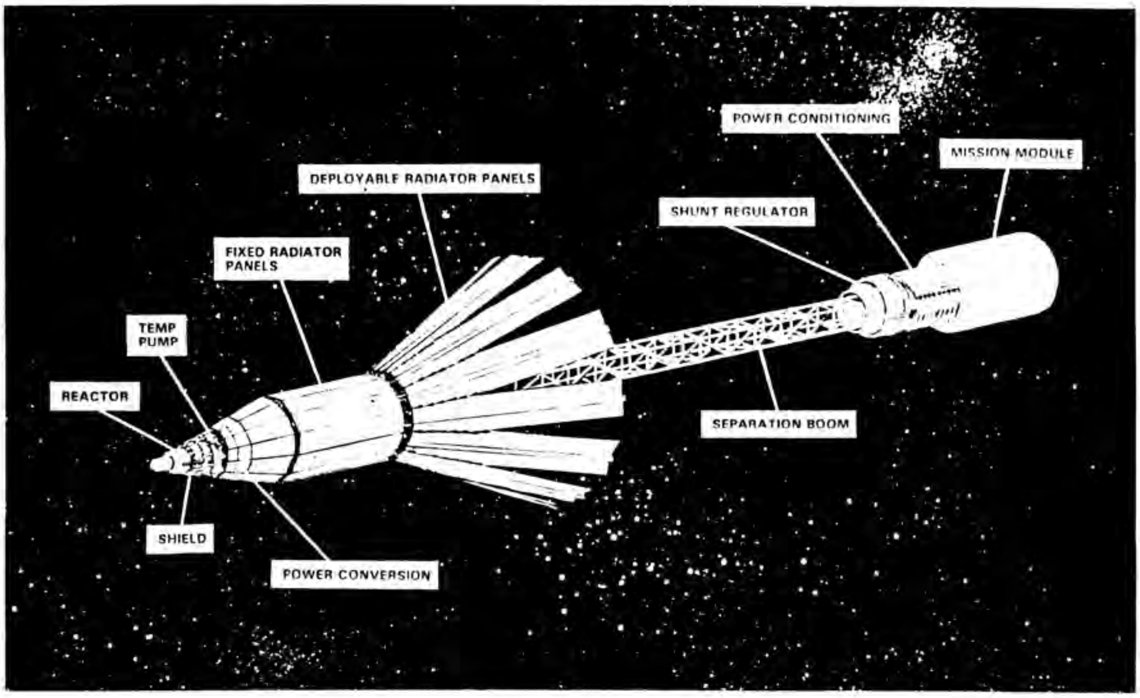
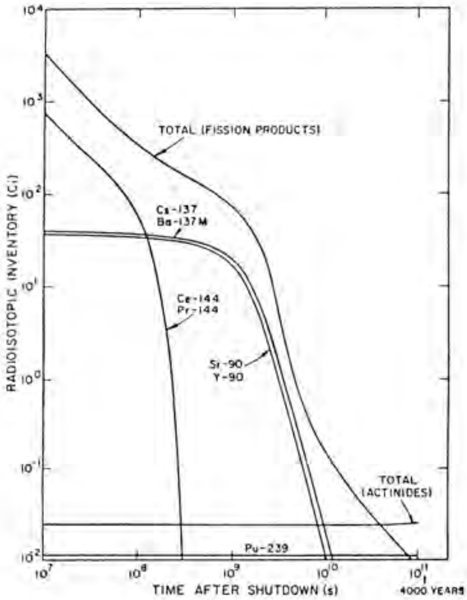


Fig. 1. Contemporary Rendering of the SP-100 Space Reactor System.



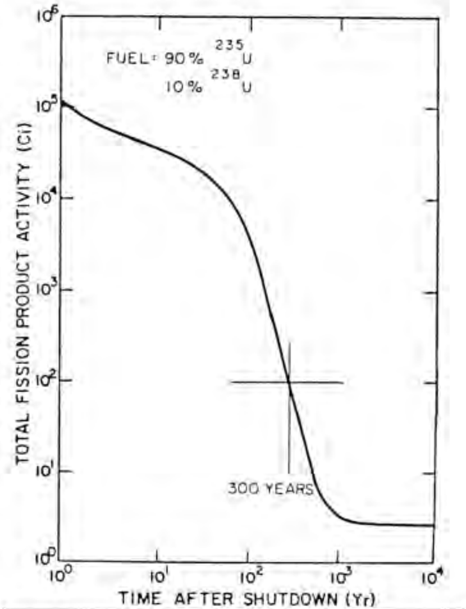


Fig. 2. Calculated Radioisotope inventory of SNAP-10A.

Fig. 3. Calculated Radionuclide Activity of a 1000 MW, Reactor After Continous Operation for 10 Years.

contamination from nuclear accidents (such as the recent Chernobyl disaster in the Soviet Union) now force contemporary space reactor advocates to seriously consider spent core management strategies at the very start of a nuclear system's development. Of course, for some future advanced reactor applications (such as a nuclear electrical propulsion [NEP] mission to Neptune, the successful mission trajectory itself becomes the post-operational disposal strategy. However, for reactors used in cislunar space, and especially for those used in low to moderate altitude Earth orbits, a more definitive strategy to spent reactor core management will be required.

HIGH TECH ANXIETY

Because of the rising level of "high technology anxiety" around the world, stimulated most recently by the loss of the Space Shuttle Challenger and its crew (28 January 1986) and the devastating Chernobyl reactor accident (April 1986), the disposal (or even "backup disposal") of a spent space reactor core, fully charged with fission products, through upper atmosphere dispersion will most likely not be "politically" acceptable, even if technically feasible. Similarly, plans for "intact" reentry and recovery of a spent reactor will also encounter strong opposition.

The international aerospace community is still responding to the globally extensive political shockwaves sent out by the "unprogrammed" and "uncontrolled" reentry of the (nonnuclear) U.S. Skylab Space Station whose debris scattered over Australia in 1979; and, of course, the Soviet COSMOS 954 spacecraft reactor which sprinkled radioactive debris over Canada's Northwest Territories in January 1978, triggering a major U.S.-Canadian cleanup operation, called "Operation Morning Light" (9).

In all likelihood, a "technology anxious" world population will not tolerate any radiological release into the terrestrial environment from an extraterrestrial (manmade) object no matter how slight or insignificant the actual amount. A "radioactive" hunk of space debris would quickly become equated with such inaccurate and inflammatory expressions as: "Orbiting Chernobyls" or "extraterrestrial TMIs." Neither would use of the Earth's upper atmosphere as a "disposal medium" be accepted by a world community which perceived very little direct benefits from an "everthreatening" spent nuclear reactor in Earth orbit. Under such emotionally-charged "safety issues" it is difficult to imagine pure engineering and technical logic governing the decisions of planners and policymakers.

Consider, for example, NASA's recent decision to cancel the Shuttle-compatible liquid hydrogen-liquid oxygen Centaur upper stage rocket. This 674 million dollar Centaur modification program fell victim to heightened aerospace safety issues, following the tragic Challenger accident. Will any future space reactor program remain immune from similar "safety-inspired" termination decisions--especially if a biospheric reentry of a fission product charged core is an integral (albeit backup) portion of the overall aerospace nuclear safety philosophy?

OPERATION MORNING LIGHT

The Soviet Union routinely flies spacecraft in low Earth orbit that use a nuclear reactor as a power source. When the low orbit mission is completed, the Soviets employ a boost system to increase the orbital altitude of the spent reactor. By increasing the orbital altitude and the orbital lifetime of the reactor, sufficient time is permitted before eventual reentry, so that accumulated core radioactivity can decay to acceptable levels. In the event that the reactor falls from its operational (working) orbit after a failure of this orbit boost system, the Soviet aerospace nuclear safety philosophy includes a core dispersal mode. Soviet reactors are reported to be equipped with a backup safety system that will disperse its core in such a way that people living in any potentially contaminated areas of the Earth's surface will not receive radiation dose during the first year after reentry in excess of 0.5 rem (5 mSv) from surface contamination (5,10,15).

Soviet aerospace nuclear safety philosophy was put to a severe test in a major space reactor accident in January 1978. On January 24, 1978, the reactor-powered COSMOS 954 spacecraft plunged into the Earth's atmosphere over Canada's Northwest Territories. In response to this nuclear accident, a massive airborn and underground search and recovery program was undertaken under the direction of the Canadian Atomic Energy Control Board. The Soviets stated that the space reactor was designed to burn up on atmospheric reentry. Although no large fuel particles were found in Canada, several large fragments were discovered with high radioactivity levels. It now appears that most of the debris fell on Great Slave Lake or on unpopulated areas to the northeast. Canadian officials feel reasonably assured that all accessible, significantly-sized radioactive fragments from COSMOS 954 were located and removed in the emergency cleanup operations, called Operation Morning Light. The radioactivity inventory indicated that about 20% (or some 4 kg) of fuel had come back to Earth as of April 1, 1978 (5,10,15,16). The erratic reentry of COSMOS 954 and its radiological contamination of Canadian soil strongly focused world attention on the overall question of space nuclear power. A future uncontrolled reentry of a highly radioactive spent reactor core into a more densely populated region of the Earth may not result in so modest an environmental insult.

POST-OPERATIONAL DISPOSAL STRATEGIES FOR SPENT SPACE REACTORS

Contemporary U.S. aerospace nuclear safety design considerations for future space reactors provide a convenient starting point from which to develop spent core management strategies. Typical reactor design requirements include (5,17): (1) The reactor shall be designed to remain subcritical, if immersed in water or other fluids such as liquid rocket propellants; (2) the reactor shall be designed so that no credible launch pad accident, ascent abort, or reentry from space (involving a terrestrial impact) could result in a critical or supercritical configuration of the core; (3) the reactor shall have a significantly effective negative power coefficient of reactivity; (4) the reactor shall not be operated (except for zero power testing that yields negligible radioactivity at the time of launch) until a stable orbit or flight path is achieved and must have a reboost capability from low Earth orbit, if it is operated in that orbit; (5) two independent systems shall be provided to reduce reactivity to a subcritical state and they shall not be subject to common failure modes; (6) the reactor shall be designed to ensure that sufficiently independent afterheat removal paths are available; (7) the unirradiated fuel shall pose no significant environmental hazard; and (8) the reactor shall remain subcritical under the environmental conditions of postulated launch vehicle explosions or range safety destruct actions.

The reboost capability recommended above can either be an integral part of the advanced reactor/spacecraft design, or be a portion of an overall space technology infrastructure that will emerge in cislunar space in the next few decades. There are three major elements in this emerging space technology infrastructure that could directly influence post-operational disposal strategies for spent space reactors. These are: (1) The Space Station; (2) the development of advanced, spacebased robot systems, including orbital maneuvering vehicles (OMVs); and (3) the establishment and operation of permanent lunar bases. If an advanced space reactor system is properly planned and designed, it would take advantage of this emerging space technology infrastructure as an inherent part of the overall aerospace nuclear safety design philosophy. This would ensure not only safe startup and on orbit operations, but also an acceptable post-operational disposal strategy.

The U.S. Space Station is now being developed to provide a permanent American presence in low Earth orbit as we approach the 21st century. Typical Space Station functions will include: (1) On-orbit laboratories; (2) permanent observatories; (3) transportation node; (4) servising facility (e.g. a space hangar for OMVs, freeflyers, and space platforms); (5) communications and data processing node; (6) manufacturing facility; (7) assembly facility; and (8) storage depot. The Space Station can readily serve as the "management site" for all nuclear reactors being used throughout cislunar space. Emergency robot vehicles could be dispatched to handle operational system malfunctions, while robot transfer vehicles can be teleoperated during spent core management operations. In essence, once an advanced space reactor leaves the Earth's biosphere on its initial launch trajectory, all other space nuclear reactor operations from start up through ultimate disposal could be handled by a special man-machine control team on the Space Station. (Note: Reactors operated on the lunar surface would be controlled by members of the lunar base population.) The permanent Space Station in low Earth orbit with its projected complement of smart, telerobotic devices represents a very powerful adjunct to aerospace nuclear safety designs and procedures. However, these emerging space technologies and their inherent capabilities to support aerospace nuclear safety objectives must be reflected in advanced reactor design concepts from the very beginning (18-20). (See Fig. 4.)

The presence of smart, robotic systems throughout cislunar space in the next century will also provide a supporting technology base for the effective post-operational disposal of spent space reactors. NASA is already exploring the development and use of a first generation space robot, called the orbital maneuvering vehicle or OMV (19-20). (See Fig. 5.) This OMV would be a remotely controlled, freeflying minitug, capable of accomplishing a wide variety of remote servicing and repair operations in space. Second and third generation space robots would be hangared in the Space Station and dispatched to numerous destinations throughout cislunar space on a more or less routine basis. If advanced space reactors are of appropriate design, with the right "hooks and handles," these robot systems under teleoperational human control could be used to separate spent reactor cores from the host space platform and then transport the highly-radioactive core to an ultimate extraterrestrial disposal destination.

And just where in outer space should we dispose of a spent space reactor? Extraterrestrial disposal of terrestrial nuclear wastes has been considered since the early 1970s (21-27). While this paper will not pass technical judgement on the merits of space disposal schemes for terrestrial nuclear wastes, these previous space disposal studies have identified several "extraterrestrial destinations" which also support the post-operational disposal needs of spent space reactors. These destinations include: (1) A circular orbit around the Sun at approximately 0.86 astronomical units (AU); (2) Solar System escape; (3) disposal on the lunar surface via hard or soft landings; (4) placement in high Earth orbit; (5) placement in lunar orbit; and (6) solar impact. Because of gravitational tug-of-war between the Earth-Moon-Sun and even Jupiter, objects orbiting the Earth or the Moon eventually become unstable and require an active, attitude control system. Therefore, neither high Earth orbit nor lunar orbit provide a truly satisfactory ultimate disposal location for spent space reactors. As indicated in Table III, solar impact places severe propulsive requirements on the orbital transfer system, and both solar system escape and the 0.86 AU location require very long transit times to keep the propulsion system requirements reasonable.

Surface disposal on the Moon (via hard landing or soft landing) appears to represent one of the most interesting and advantageous extraterrestrial destinations for spent core disposal. There are several distinct advantages inherent in lunar surface disposal (versus other space disposal locations). First, this approach permanently removes the spent reactor from cislunar space, ending the need for long-term surveillance and monitoring. The spent reactor core would still be accessible and its radionuclide inventory might provide a useful supplement to an emerging lunar nuclear industry. (For example, extracted cesium-137 might prove very useful in treating waste streams as part of a lunar base controlled environment life support system or CELSS.) Third, the implementation time (i.e. transit in space) would be on the order of a few days (with chemical propulsion) or perhaps a few months (with nuclear electric propulsion), minimizing the need for very long transportation system lifetimes or for extended human control and tracking. (By comparison, shipment to a heliocentric destination such as 0.86 AU might require several years transit time, while solar impact via a Jupiter swingby could approach a decade if minimal propulsive system requirements are desired.) Finally, nuclear energy will play an integral role in the development of lunar bases and settlements in the 21st Century (1-5,26-27). As nuclear wastes are generated by a lunar-based nuclear power grid, it is reasonable to assume that such spent reactor cores would be disposed of in a lunar repository. The absence of "flowing water" and an atmosphere on the Moon, in fact, make it an ideal geological repository for the permanent storage of radioactive waste materials. The only negative factor associated with lunar surface disposal (when compared with other space disposal options for spent reactors) appears to be a socio-political one involving "public acceptance." By properly selecting (through international agreement) one or more remote crater sites, we can avoid any significant interference with the scientific or industrial development of the Moon in the 21st Century. Perhaps future lunar inhabitants may even view the post-operational disposal of spent space reactors as a profitable service industry (27).

CONCLUSION

Space nuclear reactors will provide many enabling options for 21st Century space missions. However, this use of nuclear energy in space will ultimately be tempered and controlled by aerospace nuclear safety

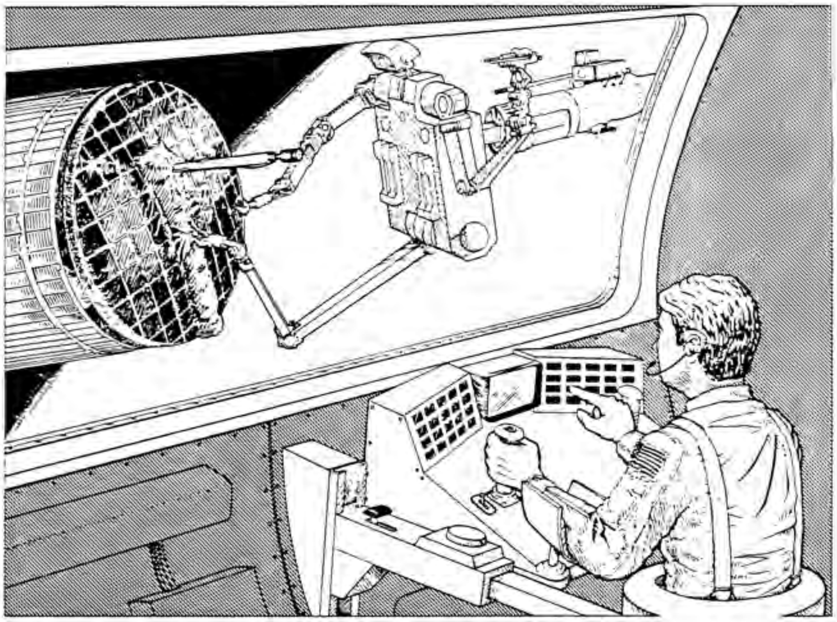


Fig. 4. Telerobotic Systems will Enhance Space Station Capabilities.

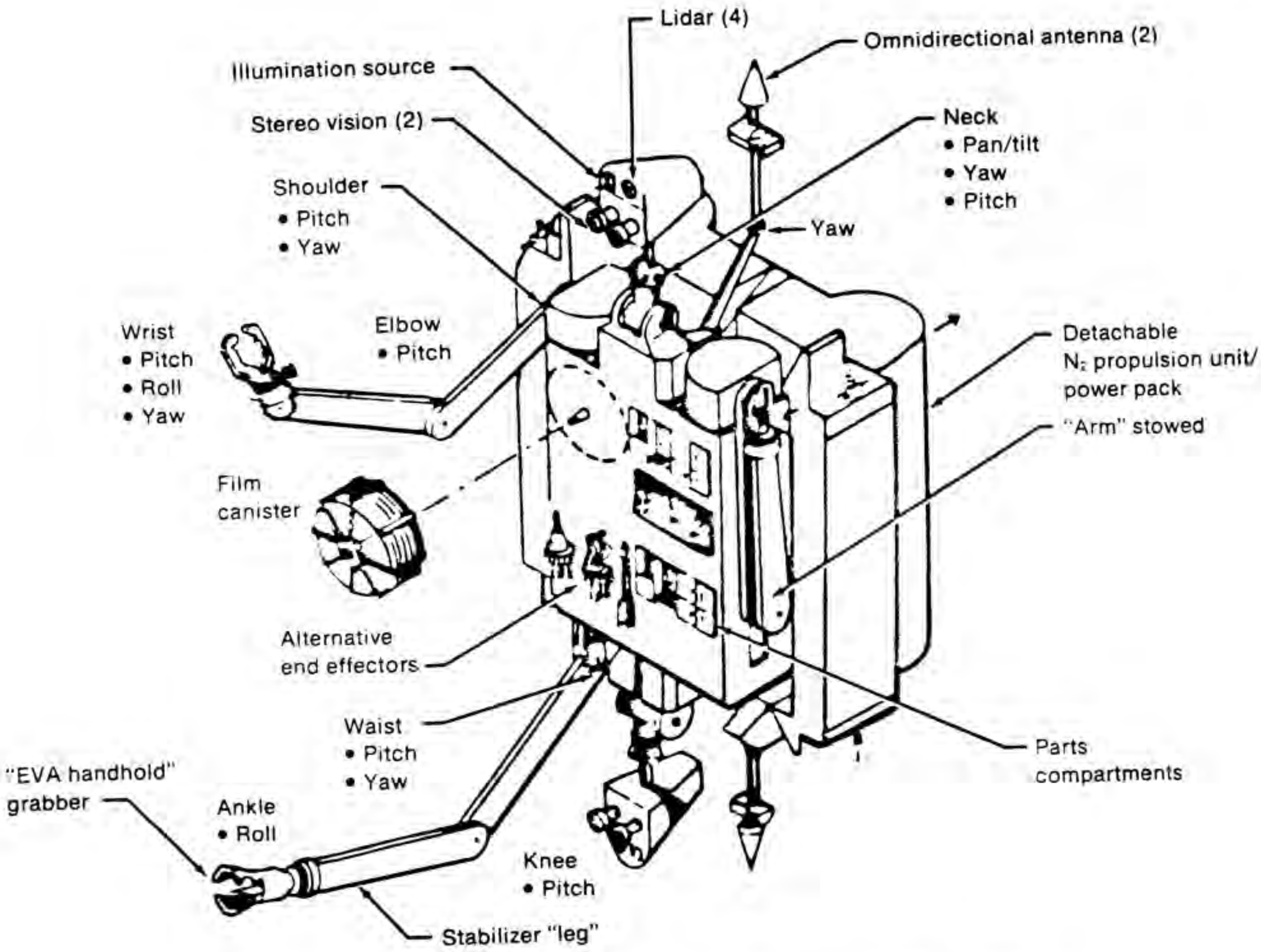


Fig. 5. First Generation Orbital Manuvering Vehicle (OMV).

TABLE III

Potential Space Destinations For Spent

Space Reactors

DESTINATION	VELOCITY INCREMENT* (km/sec)
High Earth Orbit	4.00
Lunar Orbit	4.25
Lunar Surface (Soft Landing)	6.05-6.30
Solar Orbit (E.G. 0.86 Au)	4.45
Solar System Escape	8.75 (Direct) 7.01 (Via Jupiter Swingby)
Solar Impact	24.08 (Direct) 7.62 (Via Jupiter Swingby)

* Required to leave low Earth orbit.

concerns. Reactor mission planners and designers must not only consider the launch and initial operational activities, but also a safe, internationally acceptable means of disposing spent reactor cores. The Space Station, smart space robots, and a lunar base could all support post-operational disposal strategies for spent space reactors, including lunar surface disposal in an internationally designated repository.

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