**NASA TECHNICAL MEMORANDUM**

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# FEASIBILITY OF SPACE DISPOSAL OF RADIOACTIVE NUCLEAR WASTE

## I - Executive Summary

*Lewis Research Center*
*Cleveland, Ohio 44135*

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16. Abstract

This NASA study, performed at the request of the AEC, concludes that transporting radioactive waste (primarily long-lived isotopes) into space is feasible. Tentative solutions are presented for technical problems involving safe packaging. Launch systems (existing and planned), trajectories, potential hazards, and various destinations were evaluated. Solar system escape is possible and would have the advantage of ultimate removal of the radioactive waste from man's environment. Transportation costs would be low (comparable to less than a 5 percent increase in the cost of electricity) even though more than 100 Space Shuttle launches per year would be required by the year 2000.

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# FOREWORD

An exploratory study to assess the feasibility of sending radioactive waste materials generated by the nuclear power industry into space for disposal was conducted by the National Aeronautics and Space Administration (NASA) and is summarized in two volumes: I - EXECUTIVE SUMMARY and II - TECHNICAL SUMMARY. The study was performed at the request of the Atomic Energy Commission (AEC) as part of a review of various storage and disposal concepts for nuclear waste management.

The study was performed by personnel from various NASA centers, NASA Headquarters, and the AEC. The various sections of the two volumes were written by members of the group and compiled by Robert E. Hyland of the NASA Lewis Research Center. The principal contributors and their respective areas of contribution are as follows:

| | |
|---|---|
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# FEASIBILITY OF SPACE DISPOSAL OF RADIOACTIVE NUCLEAR WASTE

## I - EXECUTIVE SUMMARY

National Aeronautics and Space Administration

Lewis Research Center

## SUMMARY

The concept of disposing of radioactive waste into space was studied and found to be feasible. Tentative solutions are presented for technical problems of safely packaging the separated long-lived actinide wasted. Disposal of these wastes is the primary concern because they will remain radioactive for extremely long times. The package design includes shielding to achieve reasonably low external levels of radiation. The logistics and potential hazards of launching these packages into either high Earth orbits or solar orbits or to escape the solar system have been evaluated. These destinations have been found to be the most promising. Although the solar system escape requires greater energy, it appears to be the most desirable for ultimate disposal.

The total costs of a system for space disposal of radioactive waste are based on the rate of accumulation of fission products and uranium-free actinides in reprocessing plants serving the nuclear power industry and on the launch costs, the destinations, and the launch frequency. The number of waste packages to be launched per year depends on the degree of separation of the long-lived actinides. For example, a package containing about 200 kilograms of separated actinide wastes with about 0.1 percent residual fission products could be ejected out of the solar system for a cost of about $150 000 per kilogram. Fifty to 100 Space Shuttle launches of such packages per year would be required in the 1990-1995 time period to handle the actinide waste. To this cost must be added the estimated cost of separating and encapsulating the actinide waste. Although the space transportation cost would be several billion dollars per year, the cost prorated over the nuclear electrical capacity is less than 0.1 cent per kilowatt-hour.

A packaging design concept has been evolved that appears on a qualitative basis to provide protection against the radioactive waste in accident environments. The concept, however, does need a follow-up experimental program and safety assessment to establish a system design.

## INTRODUCTION

This report (part I) is a condensed summary of an exploratory study (part II) of the feasibility of radioactive waste disposal into space performed by the National Aeronautics and Space Administration (NASA) at the request of the Atomic Energy Commission (AEC). This study was conducted to provide a preliminary assessment of the safety of containment and of launch capability and estimates of transportation costs. It is to be factored in with other studies on potential means for long-term management of high-level radioactive wastes. Battelle Pacific Northwest Laboratories coordinated these studies under contract to the AEC.

## RADIOACTIVE WASTE ACCUMULATION

The electric power industry in the United States is projected to have an installed nuclear capacity that may reach 1000 gigawatts electric by the year 2000. The yearly production rate of nuclear wastes that accompany the increasing nuclear capacity in the U.S. is presented in figure 1. The nuclear wastes consist of fission products and actinides (i.e. radioactive elements above actinium, such as neptunium, plutonium, and curium).

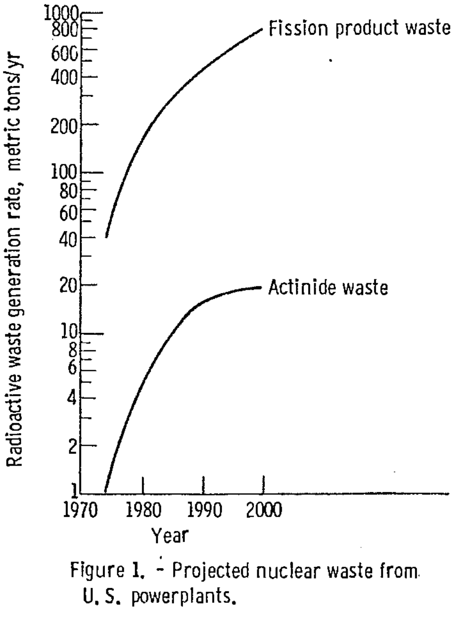


Figure 1. - Projected nuclear waste from U. S. powerplants.

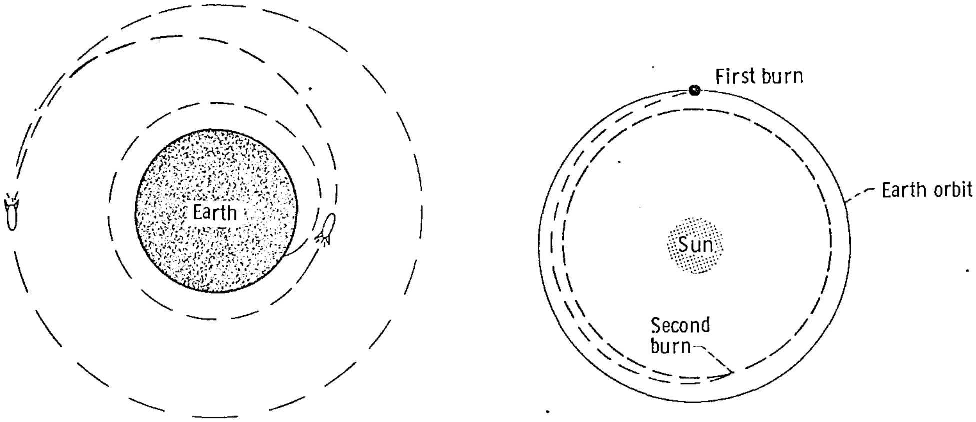
Integration of these rates indicates that by the year 2000 about 9000 metric tons of fission products and 1200 metric tons of actinides will have been accumulated. This assumes that no transmutation of actinides has taken place by further in-pile irradiation. The actinide inventory can be reduced to 300 metric tons by separation of essentially all uranium isotopes. This residual actinide inventory is the waste that is considered in the study. Transmutation of actinides, assuming neutron flux levels in typical pressurized water reactors, could reduce this inventory to about one-third if in-pile transmutation were considered feasible. Many of the actinide isotopes have half-lives measured in tens and hundreds of thousands of years. Representative fission products and actinides are described in table 1. These materials represent a long-term hazard to man and must be either stored or disposed of in an acceptable manner. For some of the isotopes with long half-lives, this could mean several hundred thousand years for storage.

TABLE 1. - SOME RADIOACTIVE ISOTOPES WITH LONG DECAY TIMES

| Waste | Isotope | Half-life, yr | Decay processes |
|---|---|---|---|
| Fission products | Tritium ($^3H$) | 12.3 | Beta (electron) |
| | Strontium-90 | 27.7 | Beta (electron) |
| | Technetium-99 | $2\times10^5$ | Beta (electron) |
| | Iodine-129 | $1.6\times10^7$ | Beta (electron), gamma ray |
| | Cesium-137 | 30 | Beta (electron), gamma ray |
| | Samarium-151 | 87 | Beta (electron), gamma ray |
| Actinides | Plutonium-239 | $2.4\times10^4$ | Alpha (He) particle, gamma ray |
| | Neptunium-237 | $2.1\times10^6$ | ↓ |
| | Americium-241 | 458 | |
| | Americium-243 | $7.6\times10^3$ | |
| | Curium-244 | 18 | |

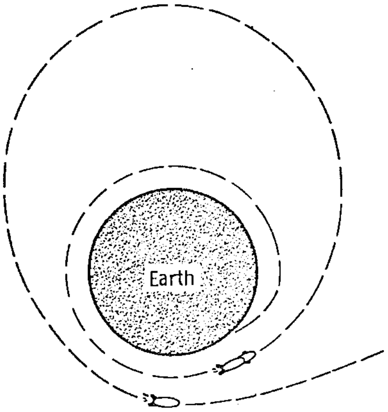
## SPACE DESTINATIONS

The potential space destinations considered were narrowed down to high Earth orbit, solar orbit, and solar system escape. They are illustrated in figure 2.



(a) High Earth orbit. Velocity increment from low earth orbit, ΔV, 4.11 km/sec; single shuttle launch to 370-km orbit; two burns to ~ 90 000-km circular orbit (above synchronous orbit); time between burns, ~ 20 hr.

(b) Solar orbit to 0.9 AU. Velocity increment, ΔV, 4.11 km/sec; single shuttle launch to 370-km orbit; two burns to circular solar orbit (0.9 or 1.1 AU); time between burns, ~ 6 months.



(c) Solar system escape. Velocity increment, ΔV, 8.75 km/sec; two shuttle launches to 370-km orbit (one shuttle carries payload and expendable tug, the other carries reusable tug); two burns at perigee; time between burns, ~ 8 hr.

Figure 2. - Potential space destinations.

## HIGH EARTH ORBIT

Placing waste packages in high Earth orbits (about midway between synchronous orbit and the lunar orbit) requires a relatively low increment in velocity (4.1-km/sec change in velocity from parking orbit). Daily launch opportunities exist for such flights. Retrieval of waste packages from such orbits is reasonable. Until the long-term integrity of the waste package can be guaranteed, such orbits can be considered as interim storage destinations for only hundreds to thousands of years.

## SOLAR ORBIT

Solar orbits (nearly circular at ~0.9 AU) can be achieved with a relatively low increment of velocity (4.1 km/sec) and also can take advantage of daily launch opportunities. Their disadvantage is that the circularization burn occurs approximately 1/2 year after injection into the transfer orbit, therby reducing the reliability of a successful circularization. A malfunction at that time could lead to a possible Earth encounter. Since the long-term stability of such orbits is uncertain, they are not recommended for permanent disposal at this time.

## SOLAR SYSTEM ESCAPE

Although direct escape from the solar system requires a high increment in velocity (8.75 km/sec), such disposal of radioactive waste from man's environment is permanent. Furthermore, the integrity of the package is required for a much shorter time period (years as compared with hundreds of centuries) since it will leave our solar system.

The solar system escape launch appears to be the most desirable and was found to be economically and technically reasonable.

## OTHER DESTINATIONS CONSIDERED

Sending the waste packages directly into the Sun is not possible with present launch vehicles. Indirect flight could be accomplished with present vehicles by using the more advanced planet swing-by trajectories. However, this is not practical because of limited launch opportunities.

Lunar and planetary destinations were not considered because of the possibility of planet contamination and the very high increment in velocity required for soft landings.

## SPACE TRANSPORTATION VEHICLES

The launch vehicles and space tugs considered were those that are available or are being planned and consist of expendable and reusable stages. They are shown in figure 3. The corresponding vehicle launch costs are shown in table 2. The Space Shuttle, in conjunction with either reusable or expendable space tugs, provides the lowest cost per kilogram of payload (total weight of waste package) delivered to the various destinations. Tables 3 and 4 summarize the costs for the various launch vehicles. Because the shuttle is a manned vehicle, its use considerably enhances the

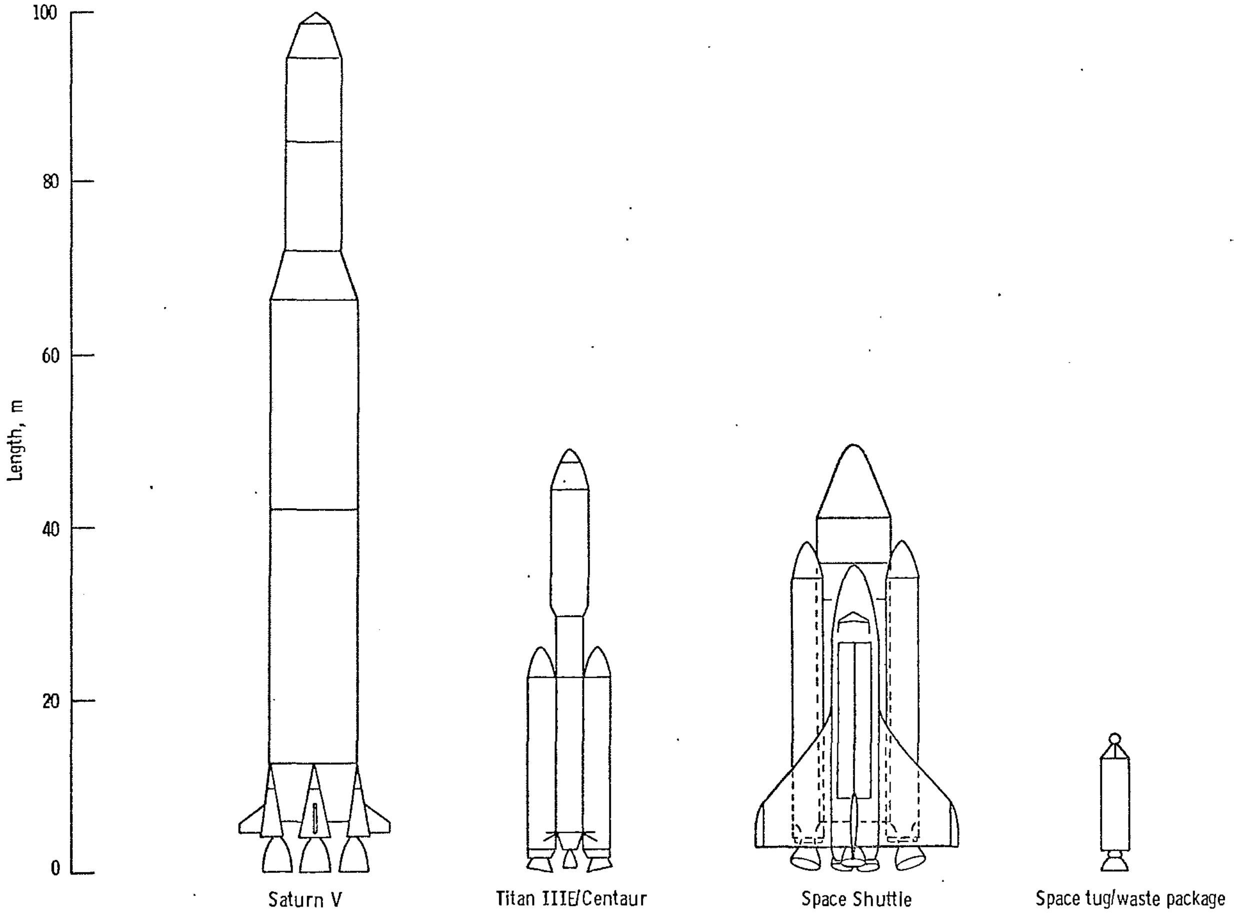


Figure 3. - Space transportation systems.

TABLE 2. - SPACE TRANSPORTATION VEHICLE LAUNCH COST FOR RADIOACTIVE WASTE DISPOSAL MISSION

| Launch vehicle | Launch cost, dollars |
|---|---|
| Titan IIIE/Centaur | $19.00\times10^6$ |
| Saturn V/Centaur | 155.00 |
| Space Shuttle: | 10.50 |
| Reusable tug | 1.75 |
| Expendable tug | 5.80 |

TABLE 3. - LAUNCH VEHICLE PERFORMANCE AND COST SUMMARY FOR HIGH EARTH ORBITS AND SOLAR ORBITS.

[Velocity increment, $\Delta V$, 4.11 km/sec.]

| Launch vehicle | Payload, kg | Launch cost, dollars/kg |
|---|---|---|
| Titan IIIE/Centaur | 3 860 | 4920 |
| Saturn V | 32 660 | 4590 |
| Saturn V/Centaur | 35 290 | 4390 |
| Space Shuttle: | | |
| Reusable tug (current size) | 4 170 | 2940 |
| Reusable tug (optimum size) | 4 670 | 2620 |
| Centaur (current size) | 6 490 | 2460 |
| Centaur (optimum size) | 8 480 | 1920 |

TABLE 4. - LAUNCH VEHICLE PERFORMANCE AND COST

SUMMARY FOR DIRECT SOLAR ESCAPE MISSION.

[Velocity increment, ΔV, 8.75 km/sec.]

| Launch vehicle | Payload, kg | Launch cost, dollars | Cost, dollars/kg |
|---|---|---|---|
| Saturn V/Centaur | 7480 | $155\times10^6$ | 20 720 |
| (2, 1, 1) Shuttle/tug configuration:[a] | | | |
| Without perigee propulsion | 2270 | $28.75\times10^6$ | 12 660 |
| With perigee propulsion | 3270 | 28.75 | 8 790 |
| (3, 1, 2) Shuttle/tug configuration:[b] | | | |
| Without perigee propulsion | 3040 | $41.0\times10^6$ | 13 490 |
| With perigee propulsion | 4400 | 41.0 | 9 320 |

[a] Two shuttle launches, one expendable tug, one reusable tug.

[b] Three shuttle launches, one expendable tug, two reusable tugs.

reliability of the mission from launch to ignition of the tug engine following deployment.

For the waste package mounted on a space tug within the manned shuttle orbiter, a dose level of 1 rem per hour at 1 meter from the surface of the package has been assumed. This value is reasonable and can be further attenuated by distance and by intervening structure in order to reduce the dose to the crew. The waste package will be subcooled prior to launch. Upon reaching orbit its decay heat will raise the package temperature. This heat will be dissipated by radiation to space when the cargo bay doors are opened. Reflectors will be provided in the cargo bay to direct the heat out through the bay door opening.

A typical shuttle launch-to-landing sequence is shown in figure 4. The shuttle launch vehicle is assisted at lift-off by two solid-fueled rocket motors. These are separated and dropped for recovery while the orbiter continues, fueled by the expendable external fuel tank. This external tank is jettisoned and deorbited by a small retrorocket. The orbiter's payload (waste package plus tug) is deployed from the bay of the orbiter. The orbiter later returns and lands at the prescribed landing site. Depending on the destination, the space tug with the waste package either awaits a second tug (solar escape) or initiates its firing sequence to place the package on its desired trajectory.

A method of mounting the space tug with the waste package in, and deploying it from, the orbiter is shown in figure 5. If a malfunction should occur after deployment and before initiation of propulsion by the tug, the orbiter could retrieve either or both. If the malfunction were to occur in later stages of the mission, another tug, capable of retrieving the package, would be dispatched.

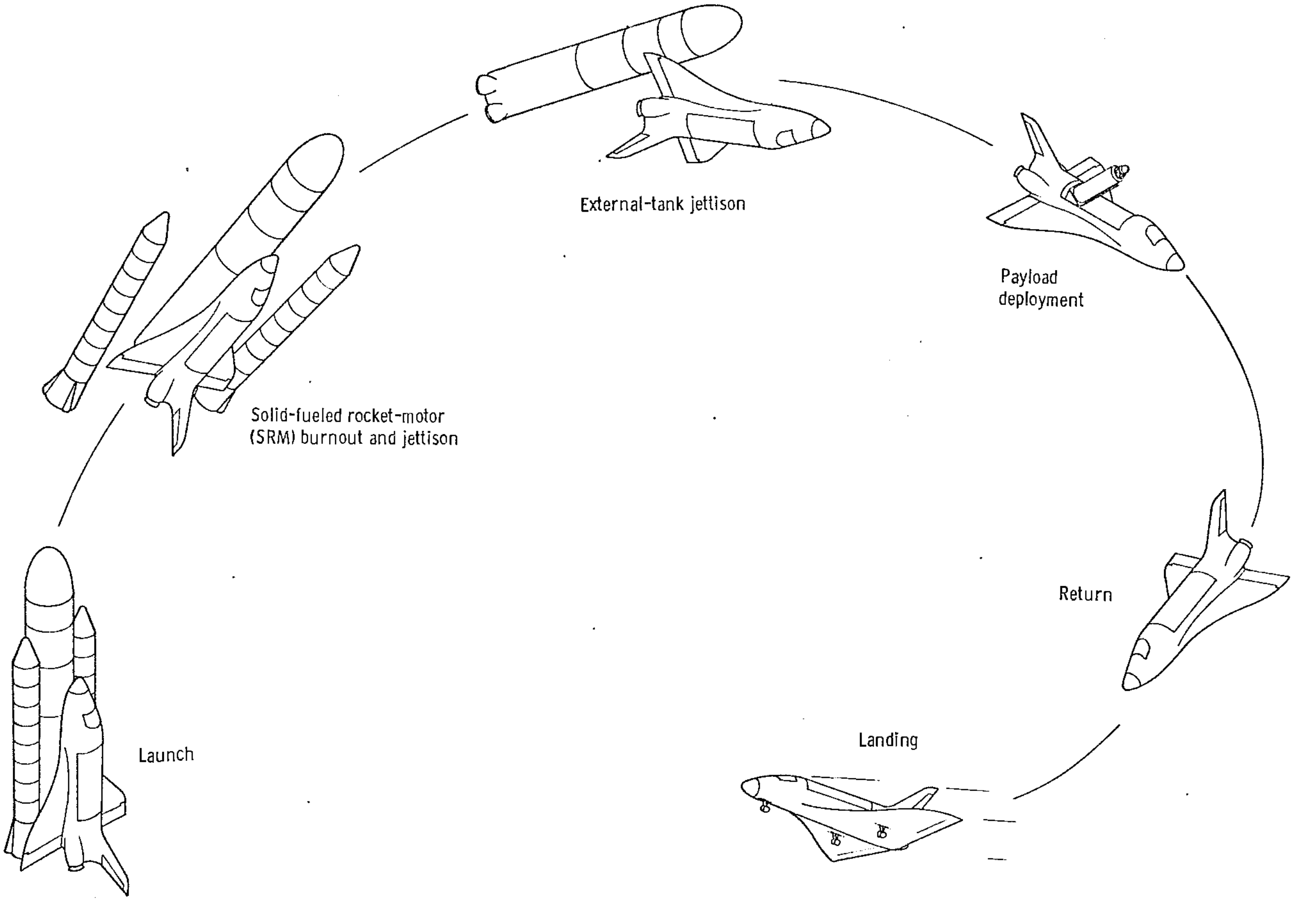


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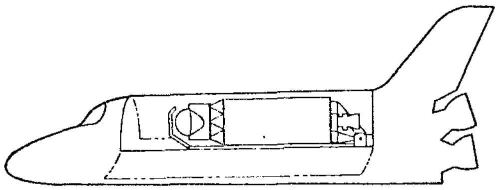
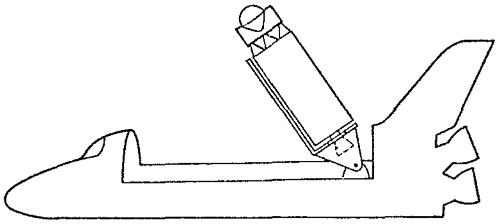
Figure 4. - Space Shuttle launch-to-landing sequence.



(a) Mounted in cargo bay.



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(b) Readied for deployment.

Figure 5. - Space Shuttle orbiter with nuclear waste package and tug.

## NUCLEAR WASTE PACKAGE DESIGN

The radioactive wastes from nuclear powerplants can be processed to separate them into two waste streams: fission products, and actinides with residual amounts of fission products. Fission products in various concentrations were assumed to remain in the actinide waste because the cost of complete separation would be too great.

A representative package design is shown in figure 6. The radioactive wastes are contained within a storage matrix which acts as a partial neutron and gamma shield as well as a heat-conducting medium. The actinide waste is in the form of small spheres approximately 3.5 millimeters in diameter. The spheres are coated with a refractory metal and an oxidation-resistant material for retention of radioactive waste at high temperatures. The matrix, containing approximately 10 percent actinides by volume, is enclosed in a sphere of stainless steel to protect it against impact and fragmentation. This sphere also contains layers of neutron and gamma shielding material. The impact protection sphere is enclosed within an aerodynamically stable reentry body designed to

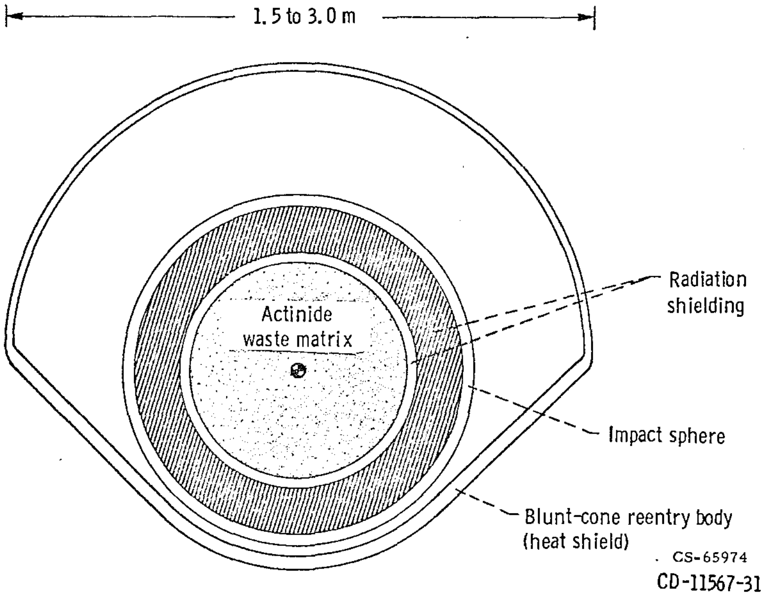


Figure 6. - Representative nuclear waste package.

TABLE 5. - WEIGHT BREAKDOWN OF TYPICAL

NUCLEAR WASTE PACKAGE

[Solar system escape for actinides.]

| Component | Weight, kg |
|---|---|
| Actinide waste | 200 |
| Matrix containing waste | 625 |
| Gamma shield | 1190 |
| Neutron shield | 180 |
| Impact sphere | 640 |
| Reentry body (heat shield) | 410 |
| Total | 3245 |

survive reentry heating. This reentry body consists of two layers. The outer layer is a composite fiber of quartz woven into a mat with a silica binder that acts as a highly reflecting medium for steep-angle reentry protection. The inner layer is composed of 3D graphite to handle the convective heat load from shallow-angle reentries.

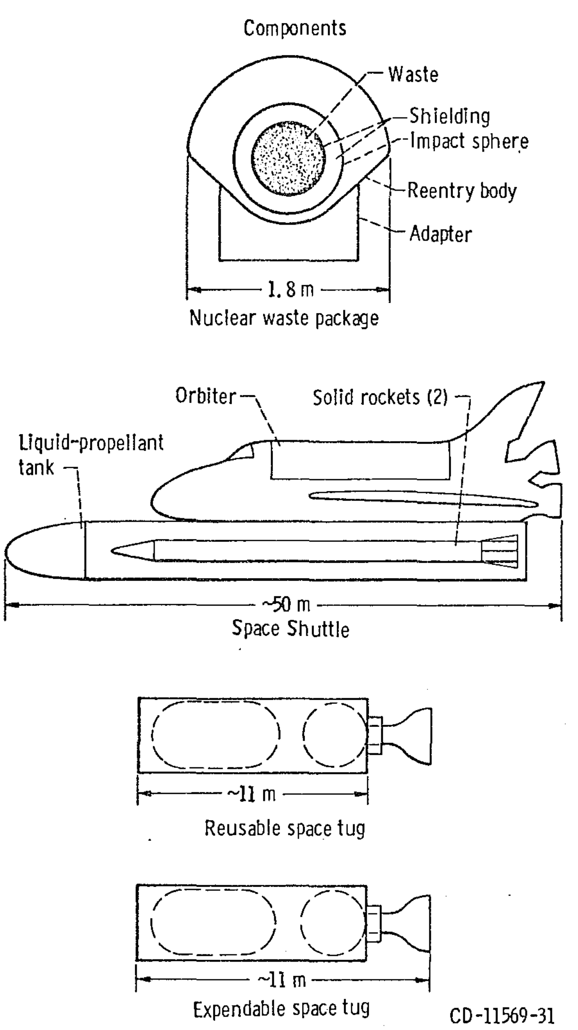
A biological dose constraint of 1 rem at 1 meter from the surface of the waste package was assumed for the configuration that was designed for solar escape. The package is thus weight optimized to contain about 1 kilogram of waste for every 30 kilograms of total package weight when actinide wastes contain 1 percent residual fission products. As the composition of fission products is reduced to 0.001 percent, the weight fraction of actinide waste increases to 1 kilogram in every 10 kilograms of package weight. These optimized weights are essentially independent of space destination. A representative package weight breakdown is presented in table 5. For some of the heavier payloads considered, the heat generated by the radioactive waste was a limiting factor in the design of the waste package. The waste package design concept presented in part II of this report would be applicable for disposal of other compositions of radioactive waste.

## TYPICAL DISPOSAL MISSION

The sequence of events for a typical waste disposal mission to solar system escape is as follows:

(1) Launch shuttle 1 to 370-kilometer parking orbit.
(2) Deploy reusable tug to rendezvous position.
(3) Launch shuttle 2 to 370-kilometer parking orbit.
(4) Deploy expendable tug and waste package to rendezvous with reusable tug.
(5) Maneuver tugs to dock in tandem configuration.
(6) Reusable tug fires to required $\Delta V$, separates, and returns to shuttle 2.
(7) Expendable tug fires and injects waste package into solar system escape trajectory.

The major components involved in such a mission are shown in figure 7.



| Component | Weight, kg |
|---|---|
| Nuclear waste package: | |
| Waste (actinides plus 0.1 percent fission products) | 200 |
| Shielding (LiH, W, matrix) | 1 995 |
| Impact sphere | 640 |
| Reentry body (heat shield) | 410 |
| Adapter | 120 |
| Space Shuttle: | |
| Orbiter (dry weight) | 68 000 |
| Liquid propellant and tank | 737 000 |
| Solid rockets | 1 030 000 |
| Reusable space tug: | |
| Propellant weight | 23 900 |
| Burnout weight | 2 900 |
| Expendable space tug: | |
| Propellant weight | 22 000 |
| Burnout weight | 2 900 |

Figure 7. - Component weights for nuclear waste space disposal mission. Required for mission: one shuttle carrying reusable space tug, and another shuttle carrying expendable space tug and nuclear waste package.

## LAUNCH FREQUENCY

The frequency of Space Shuttle launches required is an important factor in considering the space destinations, the costs, and the launch facility requirements. For each radioactive waste composition and each disposal package design, the number of required annual shuttle launches was determined through the year 2010 for the three space destinations described. The high Earth orbits and the circular solar orbits require approximately the same number of annual flights and are plotted together in figure 8. This figure is for the extreme case of disposing of all fission products that have been ground stored for 10 years.

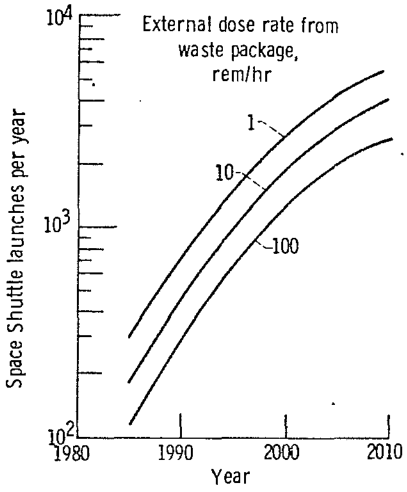


Figure 8. - Number of Space Shuttle launches required per year for disposal of all fission products into solar orbit or high Earth orbit. Prior 10-year Earth storage.

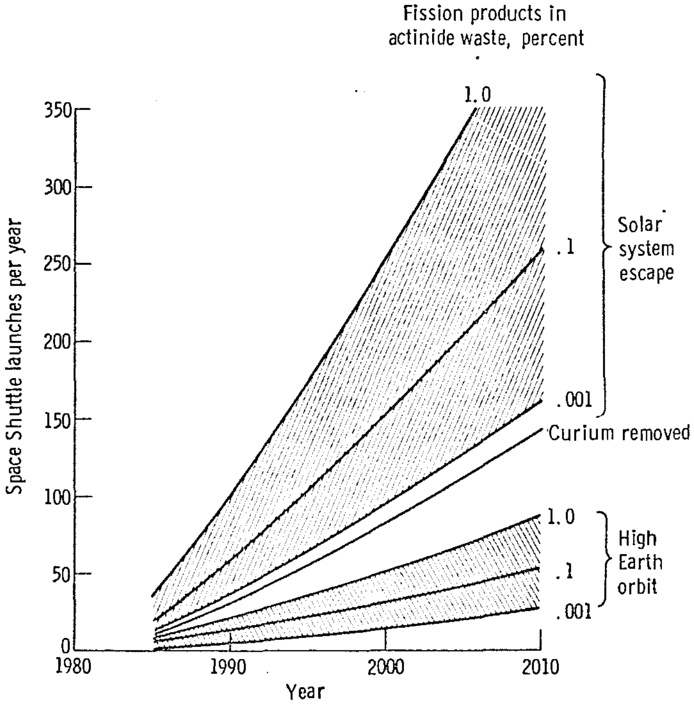


Figure 9. - Number of Space Shuttle launches required per year for disposal of only actinides into high Earth orbit or by solar system escape. Prior 10-year Earth storage.

After 1990, more than one launch per day would be required. This launch frequency is not considered practical at this time.

The launch frequencies required for space disposal of only the separated actinides are more reasonable, as shown in figure 9. Required launch rates vary from less than 10 to 350 per year through the year 2010 depending on the fission product composition of the actinides and the destination.

With the launch facilities that are available and that could be made available, as many as 140 launches per year are possible. The estimated cost for additional equipment and facilities to handle this many launches per year is $230 million. This cost includes two new launch pads.

## SPACE TRANSPORTATION COSTS

The launch costs for the shuttle and tugs, presented in table 2, are the overriding space transportation costs. These costs, coupled with the packaging cost ($650/kg of actinides) and the expense of additional launch facilities (estimated at $70 000/flight for 140 flights/yr), determines the costs for transportation of radioactive waste to the space destinations considered. (The cost of separating the fission products from the actinides is not included here.) The waste disposal per mission and the space transportation costs are presented in table 6. To present these costs in perspective, they may be put in terms of the additional power cost to the consumer (i.e., space transportation costs per kW-hr of electrical power generated in producting the nuclear waste). The space transportation cost for the disposal of all the fission products is 1 to 5 cents per kilowatt-hour. For disposing of only the separated actinides, the cost is 0.01 to 0.1 cent per kilowatt-hour. The cost depends on the space destination and on the composition of residual fission products contained within the actinides.

The results of an optimization study that balanced estimated fission product separation costs against waste package transportation costs are shown in figure 10 and point to a fission product composition of less than 1 percent as desirable. Compared with the present cost of electricity, the space disposal of the separated actinide wastes represents less than a 5 percent increase in power costs to the consumer.

Adding the estimated cost of separating fission products to the cost of transporting the waste to space yields the total cost. The optimum total cost, 0.1 cent per kilowatt-hour, occurs for an actinide waste containing about 0.1 percent fission products and for disposal beyond our solar system.

The total annual costs for transporting actinides containing 0.1 percent fission products after a 10-year temporary storage on Earth, as shown in figure 11, range from $30 million to $5 billion per year.

TABLE 6. - TRANSPORTATION COSTS FOR DISPOSAL OF RADIOACTIVE WASTE

| Type of waste | Destination for disposal | Amount of waste disposed of per mission,[a] kg | Transportation cost,[b] dollars/kg |
|---|---|---|---|
| Fission products | Earth orbit or solar orbit | 189 | 88 000 |
| | Solar system escape | 73 | 394 000 |
| Actinides plus 1 percent fission products | Earth orbit or solar orbit | 288 | 57 000 |
| | Solar system escape | 113 | 255 000 |
| Actinides plus 0.1 percent fission products | Earth orbit or solar orbit | 447 | 37 000 |
| | Solar system escape | 200 | 151 000 |
| Actinides plus 0.001 percent fission products | Earth orbit or solar orbit | 858 | 19 000 |
| | Solar system escape | 308 | 94 000 |

[a] Mission launch system: for high Earth or solar orbit, Space Shuttle with Centaur (optimum size); for solar system escape, two Space Shuttles, one reusable tug, and one expendable tug.

[b] Includes cost of packaging and additional launch facilities but not the separation cost.

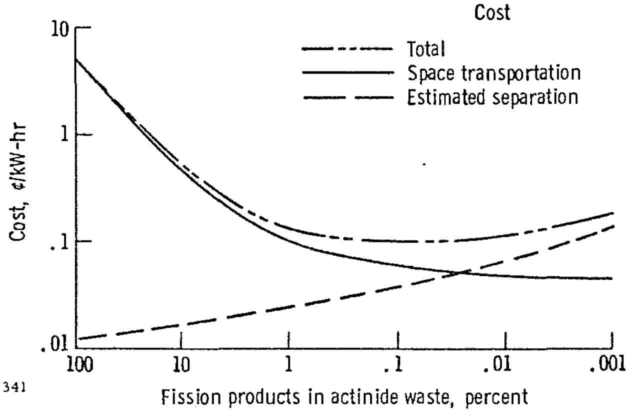


Figure 10. - Optimization of costs for space disposal of actinide waste by solar system escape.

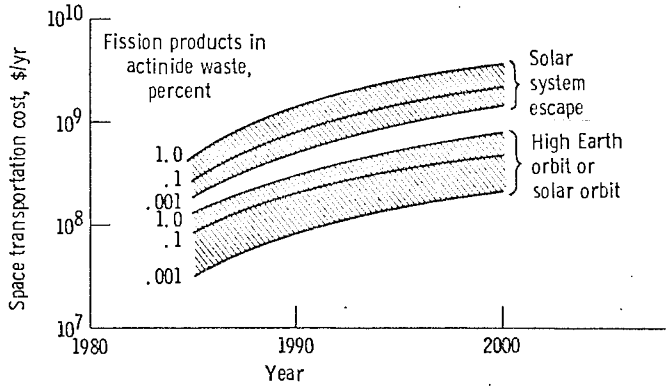


Figure 11. - Annual space transportation cost for space disposal of actinide waste.

## SAFETY

The safety goal for nuclear waste disposal in space is to transport the radioactive waste to an acceptable destination in such a manner that potential radiation exposures and contamination are negligible.

The accident conditions considered and the responses of the design waste package are summarized in table 7. In all cases the response of the waste package to the proposed accidents indicates that the release of radioactive waste would be prevented by the various protection shells designed into the total waste package. The package response analysis was verified, where possible, by simulation experiments. However, much additional development and testing are required to confirm the design concept.

TABLE 7. - POSSIBLE ACCIDENTS AND PACKAGE RESPONSES

| Type of accident | Accident condition | Package response |
|---|---|---|
| Blast overpressure | 150 atm | No yielding to 175 atm |
| Fragmentation | Fragments up to 1070 m/sec | No penetration to 1360 m/sec |
| Fireball | $2750^\circ$ C, 20 sec | No melting |
| Residual fire | $2400^\circ$ C, 5 min | Outer stainless-steel layer near melting |
| Reentry heating | 300 kW/cm$^2$, 3 to 4 sec | Sufficient thickness |
| Impact on earth, water, or concrete | 300 m/sec | Some deformation, no release |
| Postimpact | Deep burial | Outer vessel rupture due to pressure after about 5 days |
| | Deformed - no burial | Integrity maintained |

With an appropriate package design and launch operation, the overall risks are expected to be low. Since the mission hardware and launch parameters were of a preliminary nature only, a risk assessment on a quantitative basis could not be performed.

The key requirement for the overall safety of waste disposal missions is early recovery of the waste package in the event of an accident during any phase of the mission. For most accidents the early recovery could be handled satisfactorily. For some accidents, particularly an uncontrolled abort occurring in the later stages of a mission (i.e., after deployment and prior to the tug achieving the required $\Delta V$), recovery from space may be difficult if not impossible.

# CONCLUSIONS

## GENERAL

The results of this exploratory study indicate that space disposal of the long-lived radioactive actinides from nuclear waste appears feasible from the viewpoint of both economy and safety. The transportation costs for ejecting the actinides out of the solar system, for example, would represent less than 5 percent increase in the consumer bill for electric power generated by nuclear powerplants. Such missions involve certain risks, however small, which would have to be balanced against the benefits to be derived from removing the long-lived radioactive waste from man's environment and thus relieving future generations of the responsibility of protecting themselves against our radioactive waste. Quantitative evaluation of the risks requires more study, development, and testing.

## SPACE DESTINATIONS

Of the destinations considered, three look promising: high Earth orbits (above synchronous orbit altitude), nearly circular solar orbits inside the Earth's orbit, and solar system escape. Only the last destination provides a permanent disposal of the nuclear waste. It is therefore the most promising destination, even though the costliest. Sending the waste directly into the Sun is not within the capabilities of present vehicles. Sending it into the Sun with acceleration assists from planetary swing-by is not practical.

## SPACE TRANSPORTATION VEHICLE

The currently planned Space Shuttle, in conjunction with space tugs, provides a substantially lower cost per kilogram of waste delivered to the space destinations than any of the current expendable launch vehicles. Because the shuttle is manned and has considerable maneuvering capability, the overall safety aspects of such a transportation system could be superior to those of expendable launch vehicle systems.

## WASTE PACKAGE DESIGN CONCEPT

The nuclear waste package design allows sufficient radioactive waste per package for economic disposal and should prevent release of radioactive waste under the accident conditions reviewed. Further study could optimize the design to increase the waste content and to better define its limitations.

## SAFETY

No quantitative risk assessment was possible because the mission hardware and the mission parameters are preliminary. Only a qualitative evaluation was performed. This evaluation indicated the design could prevent release of radioactive waste under conditions imposed in accident environments. With appropriate system design and launch operations, the risks involved are expected to be relatively low.

## COSTS

The transportation costs for space disposal of radioactive actinides would represent an increase in the consumer's electric costs of approximately 5 percent. To this transportation cost must be added the cost for separating the actinide waste and the fission product waste. Preliminary data from a study conducted by Battelle Pacific Northwest Laboratories for the Atomic Energy Commission indicate that the separation costs will be of the same order or less than the costs of transportation out of the solar system. Both the space transportation cost and the launch frequency are feasible and practical for the disposal of separated actinide waste. However, the space disposal of all fission product waste is neither economically nor practically feasible at this time because the large quantities would require an excessive launch rate.

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