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16. Abstract

The feasibility of transporting radioactive waste produced in the process of generating electricity in nuclear powerplants into space for ultimate disposal was investigated at the request of the AEC as a NASA in-house effort. The investigation is part of a broad AEC study of methods for long-term storage or disposal of radioactive waste. The results of the study indicate that transporting specific radioactive wastes, particularly the actinides with very long half-lives, into space using the Space Shuttle/tug as the launch system, appears feasible from the engineering and safety viewpoints. The space transportation costs for ejecting the actinides out of the solar system would represent less than a 5-percent increase in the average consumer's electric bill.

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FOREWORD

An exploratory study to assess the feasibility of sending radioactive waste materials generated by the projected 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:

Robert E. Hyland . . . . Coordinator, package concept and reports
NASA Lewis Research Center

Robert Thompson . . . . Destinations, vehicles, and trajectories
NASA Lewis Research Center

Richard L. Puthoff . . . . Impact and postimpact conditions
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Millard L. Wohl . . . . Shielding, impact, and fragmentation
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The Physics International Company studied and performed tests on fragment impact effects on spherical shells that simulated waste impact shells, and the Astronuclear Laboratory of Westinghouse Electric Corporation analyzed postimpact temperatures and pressures within waste packages, both under contract to NASA Lewis Research Center.

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FEASIBILITY OF SPACE DISPOSAL OF RADIOACTIVE NUCLEAR WASTE

II - TECHNICAL SUMMARY

National Aeronautics and Space Administration

Lewis Research Center

SUMMARY

The feasibility of transporting radioactive waste from nuclear powerplants into space for ultimate disposal was investigated at the request of the Atomic Energy Commission (AEC) as a NASA in-house effort. The investigation is part of a broad AEC study of various concepts for long-term storage or disposal of radioactive waste. Both expendable and reusable space vehicles were considered for the space disposal missions. The Space Shuttle in conjunction with either reusable or expendable space tugs provided the lowest cost per payload for delivery to the various destinations investigated.

The choice of space destinations was narrowed to high Earth orbits, solar orbits, and solar system escape. The latter destination appears to be the most desirable and was found to be economically and technically feasible. The nuclear waste packages were designed to prevent loss of radioactive waste in accident environments. Several compositions of radioactive nuclear waste were considered: fission products, and actinides containing various percentages of fission products. The long-lived radioactive isotope group referred to as actinides (heavy isotopes, with atomic numbers above 89), which could be a separate part of the waste, received the greatest attention. The disposal of only this relatively small quantity of the most dangerous components of nuclear waste appears to be cost effective.

The results of this exploratory study indicate that disposal into space of the long-lived actinides of nuclear waste appears feasible, from both the economic and safety viewpoints. (Space disposal of all fission products does not appear practical.) The transportation costs for ejecting the actinides out of the solar system would represent less than a 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 dangerous long-lived radioactive waste from man's environment and relieving future generations from the responsibility of protecting themselves against our radioactive waste. Firm plans for such nuclear disposal missions must be based on more study, development, and testing.

The major components and sequence of events for a typical waste disposal mission to solar escape are presented in figure 1.

INTRODUCTION

The Atomic Energy Commission (AEC) and the National Aeronautics and Space Administration (NASA), and others have suggested that radioactive nuclear wastes could be transported into space for disposal, thereby eliminating the long-term storage of such wastes on Earth. This method potentially resolves the difficulties presented by controlled Earth storage of wastes that have decay half-lives measured in thousands of years.

This preliminary study was performed by NASA at the request of the AEC to explore the feasibility of transporting several compositions of radioactive waste into space for disposal and to assess the safety and economic implications of such an endeavor. The results will be factored in with other studies concerned with disposal and/or storage of radioactive waste to enable the AEC to compare all such methods for future planning.

Specifically, this study focused on the technical feasibility, costs, and safety of space disposal of several representative radioactive wastes from nuclear electric powerplants in the United States.

Launch vehicle performance (Saturn V, Titan IIIE/Centaur, and the reusable Space Shuttle) was compared to determine the possible payload weights to various destinations. The destinations include high Earth orbits, solar orbits, solar impacts, and solar system escape. Preliminary designs of nuclear waste packages were made. These packages must provide radiation shielding and protection during all phases of launch, flight aborts, reentry conditions following aborts, and reencounters and impacting on Earth following uncontrolled reentry. Several representative radioactive waste compositions were screened early in the study so that efforts could concentrate on the waste composition most feasible for space disposal. These screening studies are reported in references 1 and 2. The two basic waste materials considered were fission products, which are wastes created by fissioning the nuclear fuel, and actinides, which are heavy metallic elements generated by neutron absorption in elements above actinium. A preliminary safety analysis of the packages was performed, and a cost estimate of space transportation to selected destinations was made.

The depth of the study varied in different portions of the study. The study of launch vehicle performance was limited to vehicles in operation or in the planning stage. The study does point out where improvement could be made that could result in a more effective delivery system. Comparisons between expendable and reusable vehicles are discussed. The choice of destinations excludes landing on planets and satellites for several reasons including the possibility of contamination and the extra energy required for soft landings. A detailed discussion of vehicle destinations and payloads is given in reference 3.

It was not intended to establish any single launch system, destination, or package design for space disposal of radioactive nuclear waste but merely to determine whether or not such an approach is feasible and to appraise what problems might be encountered.

RADIOACTIVE WASTE PROBLEM

As nuclear powerplants are beginning to be used to generate electrical energy, there has begun a corresponding buildup of radioactive waste. Most of the isotopes in the waste decay or return to a stable energy level in a short time. However, some require years, and there are some which require hundreds of thousands of years. As our nuclear power industry increases, so does the radioactive waste.

According to the AEC (ref. 4), all radioactive waste shall be handled, stored, or disposed of so that it will neither endanger the health and safety of personnel closely involved with it or the public nor have an adverse impact on man's environment or on the ecology.

CATEGORIES OF RADIOACTIVE WASTF

Many different radioactive wastes result from the fissioning process and the handling of radioactive material. This study does not address the feasibility of space disposal for all waste compositions but has selected representative wastes. The term radioactive waste as used in this report is defined basically as those nuclides or isotopes remaining in the waste after the spent fuel elements from nuclear electric powerplants have been processed. These wastes fall into two main categories: (1) fission products, such as those listed in table 1, which are radioactive isotopes created in the fission process; and (2) the actinide isotopes, which result from neutrons being absorbed in the fuel atoms (uranium and plutonium) without fissioning and thus forming heavier isotopes which are radioactive. The actinide waste was assumed to contain small percentages of fission products as a result of incomplete separation processes. No actinides were considered to remain in the fission product waste. These then were the basic categories of radioactive waste that were considered for the study. This does not mean that other categories of isotopes could not be considered. It is merely a representative range both in quantity and in type of radioactive waste.

PROJECTED AMOUNT OF RADIOACTIVE WASTE GENERATION IN THE UNITED STATES

The amount of radioactive waste was based on projections of nuclear electric power generation to the year 2000 (ref. 5). The estimated amounts are shown graphically in figure 2. The amount of actinides (with the uranium removed) was based on an average of 30 kilograms remaining in the waste for every 1000 megawatt-years of electrical power. The figure shows that by 1985 a total of 295 metric tons of fission products and 40 to 45 metric tons of actinides would be generated per year. The projections are based predominantly on the light-water reactors (LWR) and some high-temperature gas-cooled reactors (HTGR) until about 1985. The liquid-metal-cooled fast-breeder reactors (LMFBR) were projected to come into use about this time and generate the bulk of the nuclear power by the year 2000.

Figure 3 shows the accumulation of both the fission products and the actinides. By the year 2000, the nuclear power industry will have generated approximately 9000 metric tons of fission products, from all types of reactors, and 1200 metric tons of actinides.

CHARACTERISTICS OF RADIOACTIVE WASTE

Fission Products

Fission products are radioactive isotopes created by splitting the atoms in the fissioning process. The amounts produced in a representative LWR were obtained from reference 6 and are presented in tables 1 to 3. These tables indicate (1) the amount of each isotope remaining in the waste after a metric ton of fuel from a light-water-moderated reactor is reprocessed, (2) the radioactive decay in curies (a measure of a quantity of radioactive material with 3.7×10^{10} disintegrations per sec), and (3) the thermal power in watts produced by each isotope. The values presented are for various times after removal from the reactor from 90 days to 1000 years. The time period of interest for this study was 10 years (3652 days). That is, it was assumed that the material was allowed to decay for 10 years prior to being transported into space. This selection was strictly arbitrary.

For some isotopes, 10 years would be enough time to reduce their radioactivity to safe levels. For others, such as strontium-90, ruthenium-106, antimony-125, cesium-134, cesium-137, and promethium-147, 10 years is not sufficient, and they still would be large contributors to the radioactivity and heat sources in the waste material packaged for space disposal. All fission products were considered for space disposal regardless of their decaying process or their hazardous effect on man. They were assumed to be prepared in a solidified matrix for packaging and space disposal. The methods of packaging and solidification are discussed in the section NUCLEAR WASTE PACKAGING (p. 21 ff). It was further assumed that the fission product waste could be processed so that it would not contain any measurable amounts (parts per billion) of actinides. This assumption was based on the results presented in reference 7.

Actinides

The second category of radioactive material considered was the actinides. Actinides are not fission products but are formed through neutron absorption in the nucleus of heavy isotopes, such as uranium and plutonium, which does not cause fissioning (splitting) of the nucleus. Instead, a new isotope is formed which can in turn absorb additional neutrons, so a variety of heavy isotopes are formed. These isotopes are referred to as actinides since they are above actinium in the periodic table. For a given type of nuclear fuel and reactor, a distribution of these actinides can be obtained. Examples of these distributions are shown in tables 4 to 6 for the LWR's and in tables 7 to 9 for the LMFBR's. These tables show the masses, radioactivity (in curies), and thermal power (in watts) per metric ton of nuclear fuel after the spent or used fuel elements are processed. There is considerably less material to be disposed of than in the case of the fission products. Again the assumption was that the waste would be held for 10 years prior to space transportation. Since the actinides do not decay as rapidly as many of the fission products, a 10-year period has a much smaller effect on both the radioactivity level and the thermal power.

The actinide waste was considered to be free of all uranium isotopes but to contain small percentages of the fission products. The various waste compositions are shown in table 10, along with the radioactivity and thermal power per gram of mixed waste. The amount of actinides to be disposed of when the uranium has been removed is shown in figures 2 and 3. The method of packaging is discussed in the section NUCLEAR WASTE PACKAGING (p. 21 ff).

Half-Lives

As previously noted, fission products and actinides are formed differently. They also decay radioactively at different rates. A measure of the decay rate is called the half-life, the time in which one-half of the radioactive species will decay to a lower or stable energy state. Several of the isotopes with long half-lives, from both the fission products and the actinide group, are listed in table 11. Basically, the fission products decay by emitting a negative electron (beta) from the nucleus, although a few decay by emitting gamma rays. The actinides generally decay by emitting an alpha particle (helium nucleus) from the nucleus of the isotope, and again some decay by emitting gamma rays. In addition to the alpha decay processes in the actinides, some of the isotopes give off neutrons spontaneously, similar to uranium. All these particles or rays of energy are hazardous to man and must be isolated from him. As a rule of thumb, the activity would be reduced to less than 1 percent in seven half-lives (i.e., $2^{-7} = 0.008$).

Relative Hazards

Each isotope has a different level of radioactivity (curies) and a different quantity. The effects of radioactive isotopes on man have been discussed for some time and, in general, the total effect is not known. In order to obtain a relative hazard factor for some of the isotopes, the maximum permissible body doses presented in reference 8 were used. This does in no way infer that these are the present acceptable levels. For the isotopes with the longer half-lives listed in table 11, the accumulated doses, based on the permissible body dose and the amount of material generated to the year 2000, are presented in table 12. The biggest contributors appear to be strontium in the fission products and americium and curium in the actinides, although all the isotopes represent large doses. More information on relative hazards can be found in reference 9.

POTENTIAL SPACE DESTINATIONS FOR RADIOACTIVE NUCLEAR WASTE DISPOSAL

BASIC CONSIDERATIONS

The space destinations considered in this study include Earth orbits, solar orbits, solar system escape, and solar impact. The mission requirements and the relative advantages and disadvantages for each destination are discussed. The space destinations are discussed in the order of increasing energy requirement. All launches are assumed to occur from the Eastern Test Range (ETR), Kennedy Space Center, in an easterly direction. For comparison purposes, it is assumed that the launch vehicle first enters a low circular Earth parking orbit, although this is not always necessary nor advantageous. After parking in this orbit, the launch vehicle's upper stage or stages inject the waste package towards its final destination. Mission energy is characterized by the mission ΔV requirement, which is defined as the sum of all the velocity increments that the launch vehicle system has to provide after reaching low Earth orbit. In some cases the launch system alone can place, or inject, the waste package towards its final destination. In other cases the waste package, after separation from the launch system, requires subsequent trajectory (midcourse) corrections or propulsion in order to reach its destination. In these cases the waste package becomes an active spacecraft requiring propulsion, guidance, control, and communications systems. These requirements are pointed out where needed. The potential destinations are summarized in table 13, and the more promising ones are depicted in figure 4.

POTENTIAL DESTINATIONS

High Earth Orbits

To achieve high circular final Earth orbits starting from a low circular parking orbit, two propulsion maneuvers are required. The first maneuver is made in the parking orbit and places the payload on an elliptical transfer orbit. After the payload coasts along the transfer orbit to the desired final altitude, the second maneuver is made to circularize the final orbit. Both these maneuvers are expected to be performed by the launch system's upper stage.

In the event of a propulsion failure after reaching low Earth orbit but prior to final placement into high Earth orbit, corrective action can be taken. The resulting orbit would have an adequate lifetime (several months) so that a second launch could be made to rendezvous with the waste package. The waste package would then either be sent into its final orbit or retrieved. This discussion also applies to other destinations if the propulsion failure were to occur before Earth-escape velocity was reached.

It is not yet clear which orbit altitudes would be acceptable for the disposal of nuclear waste. Orbit lifetime is a primary factor. Orbit lifetimes of a million years or longer may be required if extremely long-half-lived wastes are to be disposed of into space. At reasonably high orbit altitudes, above several thousand kilometers, atmospheric drag is negligible; but other perturbations such as solar pressure and solar, lunar, and planetary gravitational perturbations must be considered. Orbits near the Moon must be avoided to minimize lunar perturbations. High-traffic regions or orbits important from a science or applications point of view (such as synchronous orbit altitude and some lower altitudes) should not be chosen. Therefore, probably the best choice for high Earth orbits would be those orbits lying between synchronous orbit altitude and the Moon. However, such orbits have the highest ΔV requirement of the high Earth orbits, of the order of 4.11 kilometers per second.

Advantages. - The advantages of high Earth orbit are as follows:

(1) The ΔV required is relatively low in comparison with some of the other destinations.

(2) The waste package could conceivably be retrieved at a later date either to recover the waste material or to remedy some unforeseen problem.

(3) There is a launch opportunity any day.

(4) The waste package could be passive, requiring no guidance or propulsion capability since the second propulsive burn is performed by the launch system's upper stage.

Disadvantages. - High Earth orbits present the following disadvantages:

(1) The stability of high Earth orbits and hence orbit lifetime over a long period of time (of the order of a million years, which may be required for some of the waste to

decay sufficiently) is not well understood. To date, the complexity of the multiperturbation problem precludes rigorously verifying the stability of these orbits over many thousands of years.

(2) There is no assurance of the integrity of the relatively hot waste package when it is exposed to the space environment over these long periods of time.

(3) Eventually, the waste packages will be randomly located within a belt around the Earth. Gravitational perturbations cause orbits of the waste packages to precess, thus producing variations in orbits in this belt. Future planetary spacecraft would regularly penetrate this belt. However, because of the wide spacing between waste packages at such high placement altitudes, the probability of a collision would be extremely remote.

Since neither orbit stability nor waste package integrity are well understood (for times of the order of a million years), high Earth orbits cannot be considered a permanent disposal site. Unless further studies can resolve these problems, Earth orbits should be considered only as a temporary (hundreds or a few thousand years) storage site requiring further action at a later date.

Solar Orbits

The solar orbits considered in this study are those achievable with relatively low ΔV's (table 13). These orbits include (1) solar orbits achievable by injecting the waste package to Earth-escape velocity or slightly beyond, (2) circular solar orbits slightly inside or outside the Earth's orbit around the Sun achievable by additional propulsion after Earth escape, and (3) solar orbits achievable by swinging by Mars or Venus.

Earth escape. - The simplest method for achieving a solar orbit is to have the launch system inject the waste package to Earth-escape energy. This can be done with a single propulsive burn from Earth orbit with a ΔV of approximately 3.23 kilometers per second. The waste package would then be separated from the launch system and after escaping the Earth's gravitational field would be in an orbit around the Sun. The waste package would be in essentially the Earth's orbit around the Sun but in a different angular position.

With the waste package in this orbit, there is a high probability of the waste package reencountering the Earth at some future time. Because of inherent limitations on injection accuracy and long-term gravitational perturbation effects - principally from the Earth, the waste package could not be maintained at a fixed position from the Earth. As a result of these effects the waste package would tend to drift with respect to the Earth, and preliminary calculations indicate a high probability of reencountering the Earth within a few thousand years or less.

A better approach would be to provide somewhat more ΔV than required for Earth escape (an additional ΔV of approximately 0.42 km/sec), so that the waste package would be in a slightly elliptic solar orbit with a small inclination to the ecliptic plane (plane of the Earth's orbit around the Sun). Initially, the orbit of the waste package would intersect the Earth's orbit at only one point. With time, planetary gravitational effects would tend to precess the orbit of the waste package with respect to the Earth's orbit, making an encounter even less likely. Preliminary calculations indicate that such is the case at least for a few thousand years.

Advantages: The advantages of an Earth-escape solar orbit are as follows:

(1) Of all the mission destinations or orbits considered, except for some Earth orbits, Earth-escape solar orbit requires the lowest ΔV. The ΔV required is approximately 3.65 kilometers per second, which is slightly more than that required to reach Earth-escape velocity.

(2) Only a single propulsive phase from low Earth orbit is needed.

(3) There is a launch opportunity any day.

(4) The waste package could be passive, requiring no active spacecraft systems.

Disadvantages: Earth-escape solar orbit presents the following disadvantages:

(1) There is no assurance that the waste package will not reencounter the Earth after a few thousand years.

(2) There is an abort gap past Earth-escape velocity. If the launch vehicle should fail after reaching Earth-escape velocity, the waste package would be left in an unplanned solar orbit with subsequent Earth reencounter possibilities. With current launch vehicle technology, it would be impractical to recover the waste package from these orbits.

There is no assurance that trajectories can be developed (and demonstrated analytically) which eliminate the possibility of a reencounter with Earth for times of the order of a million years. Because of this uncertainty, Earth-escape solar orbit cannot be established as a proven, acceptable destination at this time.

Circular solar orbits. - In order to provide a positive separation between the orbit of the waste package and the orbit of the Earth, the waste package could be placed in a nearly circular solar orbit, either inside or outside the Earth's orbit about the Sun. These circular orbits should be either inside 0.983 AU (astronomical unit) or outside 1.071 AU (the perihelion and aphelion distances of the Earth's elliptical orbit) to ensure that the waste package does not collide with the Earth. There is an incentive, however, for going no further than necessary since the required ΔV increases with increasing distance from the Earth's orbit. For comparison purposes, a final orbit radius of 0.9 AU, which is inside the Earth's orbit, is used in this study. Starting from Earth orbit, two propulsive burns are required to reach the desired 0.9-AU circular solar orbit. The first burn requires a 3.3-kilometer-per-second ΔV to inject the waste package to slightly past Earth-escape energy. After escaping from the Earth the waste package is in an elliptical solar transfer orbit having the desired perihelion but with an aphelion still at the distance of the Earth's orbit from the Sun. The second burn adds

0.81 kilometer per second and circularizes the orbit. This burn is performed by another propulsion stage upon reaching perihelion after approximately a 6-month coast.

Advantages: The advantages of circular solar orbits are as follows:

(1) The ΔV required is low in comparison with some of the other destinations. For the 0.9-AU circular solar orbit, a total ΔV of 4.11 kilometers per second is required.

(2) There is a launch opportunity any day.

Disadvantages: Circular solar orbits present the following disadvantages:

(1) The problem of guaranteeing the stability of solar orbits for times of the order of a million years is unresolved, generally for the same reasons given for Earth-escape and high Earth orbits. Presumably, the final orbit could be placed sufficiently far from the Earth's orbit to preclude a subsequent collision with the Earth over the times required.

(2) There is an abort gap past Earth-escape velocity. (i.e., The package could be left in an unplanned solar orbit with possible Earth encounter in future and would be unrecoverable with present vehicles.)

(3) In addition to the launch system, another propulsion system, as well as guidance, control, and communications systems, is required to perform the second burn. It is impractical to accomplish this burn with the launch system because of the long coast phase. This disadvantage could be diminished by performing the second burn for circularization with a simple spin-stabilized, solid rocket motor.

(4) If the circularization burn should fail, the waste package would be left in an elliptic solar orbit, intersecting the Earth's orbit near aphelion. For these cases there is a high probability that the payload will eventually reencounter the Earth. This probability can be reduced by using departure trajectories similar to those suggested earlier for the Earth-escape case.

The integrity of the waste package is an important consideration for this mission because its possible disintegration over long periods of time can influence the choice of an interior or exterior orbit. If the waste package should disintegrate, the Poynting-Robertson effect will tend to draw the smaller fragments into the Sun. If part of the waste package should vaporize, the solar wind could tend to move some of the material out from the Sun. If the integrity of the waste package cannot be guaranteed over a long time period, these and other effects will have to be evaluated, not only in making the selection of orbit location, but also to establish the ultimate destinations of the waste material.

If the integrity of the package can be determined and if the stability of the circular solar orbits (near Earth) can be established, circular solar orbits can be considered as a possible disposal destination. In addition, further study is required to evaluate the consequences of possible failure situations.

Solar orbit via Venus and Mars swing-bys. - Another method for achieving solar orbits that do not cross the Earth's orbit is to swing by another planet, using the gravitational attraction of that planet to change the initial swing-by trajectory. The resulting trajectory does not cross the Earth's orbit; however, it will periodically cross the swing-by planet's orbit. Both Mars and Venus swing-bys can be achieved with ΔV's only slightly higher than for Earth escape. The total ΔV is the sum of two ΔV's. The first ΔV is performed by the launch sytem and injects the payload into a planet swing-by trajectory. The second ΔV is performed by another propulsion system after the planet swing-by and places the waste package into the desired solar orbit. This second maneuver is performed to prevent a subsequent encounter with the swing-by planet. The total ΔV for either a Venus or Mars swing-by mission is approximately 4.11 kilometers per second.

Advantages: The advantages of a Venus or Mars swing-by mission are as follows:

(1) The total ΔV required for either mission is relatively low compared with those required for some of the other destinations.

(2) With a properly oriented swing-by the trajectory can be altered so that the resulting orbit will no longer cross the Earth's orbit.

Disadvantages: Venus and Mars swing-by missions present the following disadvantages:

(1) The launch opportunities are limited. A launch opportunity to Venus occurs only once every 19 months and to Mars about once every 26 months. The duration or "width" of each of these launch opportunities, called the launch window, can be about 3 to 4 months without major increases in injection ΔV (the wider the launch opportunity, the higher the required injection ΔV).

(2) The waste package will require a midcourse trajectory correction system (with currently achievable injection accuracies) to ensure achievement of a proper swing-by position at the swing-by planet.

(3) An additional propulsion system is required to prevent a subsequent encounter with the target planet. This propulsion system and associated systems must perform reliably after a long coast phase.

(4) The problems of long-time stability of the solar orbit and containment system integrity are unresolved, although these problems would be less important than for the previously discussed destinations which are closer to Earth.

(5) There is abort gap past Earth-escape velocity. (i.e., The package could be left in unplanned solar orbit with possible Earth encounter in the future and would be unrecoverable with present vehicles.)

Launch opportunities for either a Venus or Mars swing-by appear to be too limited to effectively support the anticipated number of launches required, as discussed in the section NUCLEAR WASTE PACKAGING. Such an operation would be expensive in terms of the required Space Shuttle fleet size, the required number of launch facilities, and use of ground crews. (For example, the reusable Space Shuttle is expected to have a two-week turnaround time between launches.) These swing-by missions offer no outstanding advantages over the 0.9-AU solar orbit mission, which can be launched on any day.

Solar System Escape

Since both Earth orbit and solar orbit destinations involve uncertainties regarding long-time orbit stability and containment system integrity, solar system escape and solar impact should also be considered as possible waste package destinations. Of the two, it takes less energy (table 13) to escape the solar system, and this case is discussed first.

Direct solar system escape. - Solar system escape can be achieved directly with a single propulsion burn from low Earth parking orbit (fig. 4) with all the propulsion and guidance provided by the launch vehicle. There is a small variation in injection ΔV, depending on the launch day. The most efficient trajectories are those in or near the ecliptic plane, and consequently the waste package would traverse the asteroid belt. It would take only about 20 years for the waste package to reach the mean orbital distance of Pluto, but there is no difficulty in targeting the trajectory to miss the outer planets. And it would take over a million years for it to reach the nearest stars. Thus, except for its high ΔV requirement, solar system escape is the most attractive destination discussed thus far.

Advantages: The advantages of direct solar system escape are as follows:

(1) The waste package is removed from the solar system.

(2) The waste package can be passive and requires no additional propulsion or astrionics systems.

(3) There is a launch opportunity any day.

Disadvantages: Direct solar system escape presents the following disadvantages:

(1) An 8.75-kilometer-per-second ΔV is required. This is high in comparison with the ΔV's required for high Earth orbits and solar orbits.

(2) There is an abort gap past Earth-escape velocity.

Solar system escape via Jupiter swing-by. - Solar system escape can be achieved with a properly designed swing-by of Jupiter using a single propulsion phase from low Earth orbit. As a result of using a Jupiter swing-by, the ΔV required to achieve solar escape energy is somewhat less than that required for a direct solar system escape mission.

Advantage: The advantage of the Jupiter swing-by mission, as with direct solar system escape, is that the waste package is removed from the solar system.

Disadvantages: The Jupiter swing-by mission presents the following disadvantages:

(1) The ΔV required is approximately 7.01 kilometers per second, which is still high in comparison with some of the other destinations.

(2) The launch opportunity is limited, occurring only once every 13 months with perhaps a 60- to 90-day launch window.

(3) A midcourse trajectory correction capability is needed, as was the case for the Venus and Mars swing-bys.

(4) There is an abort gap past Earth-escape velocity.

The Jupiter launch opportunity is too limited to support effectively the anticipated number of launches required. In general, the Jupiter swing-by could be more restrictive than the Mars and Venus swing-bys. It would be simpler to use a direct solar system escape, even though the ΔV is some 1.74 kilometers per second higher than for the Jupiter swing-by.

Solar Impact

A solar impact is possible either directly or indirectly via a Jupiter swing-by to turn the trajectory into the Sun. However, direct solar impact cannot be achieved with current launch vehicles. Again the purpose of using a Jupiter swing-by is to reduce the ΔV requirement.

Direct solar impact. - Direct solar impact can be achieved with a single propulsion maneuver out of a low Earth orbit, with all the propulsion and guidance provided by the launch system. The required ΔV must be provided by the launch system to cancel the Earth's orbital speed about the Sun, so that the waste package "falls into" the Sun. For a direct impact, a ΔV of approximately 24.08 kilometers per second is required. For grazing impact into the edge of the Sun the ΔV requirement is reduced to about 21.34 kilometers per second. For this mission the ΔV's required are far beyond the capability of current launch systems, and therefore it is considered impractical.

Advantages: The advantages of solar impact are as follows:

(1) The waste package is destroyed.

(2) The waste package can be passive.

(3) There is a launch opportunity any day.

Disadvantages: Direct solar impact presents the following disadvantages:

(1) The ΔV required is extremely high.

(2) There is an abort gap past Earth-escape velocity.

(3) The waste package would probably burn up prior to reaching the Sun, and its contents could be scattered in space.

Solar impact via Jupiter swing-by. - Using a single propulsive maneuver from a low Earth parking orbit and a Jupiter swing-by to achieve a solar impact requires a ΔV

appreciably less than that for a direct solar impact. For this mission the ΔV required is 7.62 kilometers per second.

Advantage: The advantage of the Jupiter swing-by mission, as with direct solar impact is that the waste package is destroyed.

Disadvantages: Solar impact via Jupiter swing-by presents the following disadvantages

(1) The ΔV is still high in comparison with those required for some of the other destinations.

(2) The launch opportunity is limited, occurring only once every 13 months with perhaps a 30- to 60-day launch window.

(3) A midcourse trajectory correction capability is needed, which increases mission complexity.

(4) There is an abort gap past Earth-escape velocity.

The ΔV required for this case is about 1.13 kilometers per second less than that required for a direct solar system escape mission. Nevertheless, the Jupiter launch opportunity is too limited to support effectively the high launch rates expected for waste disposal missions, and it would appear simpler to use the direct solar escape mission.

Other Destinations

Many other space destinations in addition to the ones discussed have been suggested. Examples include depositing the waste packages on the Moon, on planets, in planetary orbits, on asteroids, and at Lagrangian equilibrium points. These destinations were not considered in this study although in some cases they could warrant further investigation. The general arguments against these destinations include the following:

(1) The regions are unexplored and/or are of scientific interest.

(2) Some of the regions could be of future value from an applications standpoint.

(3) Launch opportunities are limited.

(4) Deep-space propulsion is required and in many cases the retropropulsion ΔV's are high.

COMPARISON OF DESTINATIONS

As a summary of the destinations discussed, table 13 lists the typical ΔV requirements for the various missions and their principal advantages and disadvantages. The ΔV's shown are representative for each destination, although there will be some variation depending on the particular launch opportunity and the details of the mission profile.

The ΔV for high Earth orbits is an upper value for orbits between synchronous and lunar orbit altitudes. The Earth-escape ΔV includes some provision for additional ΔV in an effort to minimize the probability of a subsequent Earth reencounter as was previously discussed. For the other solar orbits an additional ΔV is required to prevent the waste package from encountering any planet. The term "passive waste package" implies that the package will require no special space propulsion or midcourse corrections and thus no associated astrionics systems. The abort possibility past Earth-escape velocity (referred to as the abort gap) is a disadvantage associated with all destinations beyond the Earth.

The conclusions reached thus far indicate the remaining candidate mission destinations are high Earth orbits, solar orbits (near Earth), and direct solar system escape, as shown in figure 4. The payload capabilities of possible launch systems for each candidate mission destination are discussed in the next section.

POTENTIAL SPACE TRANSPORTATION VEHICLE PERFORMANCE AND COST

BASIC CONSIDERATIONS

Only large current and planned launch vehicles have been considered in this study. They are shown in figure 5. The Titan IIIE/Centaur is the expendable booster that will launch the 1975 Viking mission to Mars. The Saturn V is the three-stage expendable Apollo booster. Its two-stage version has been used to launch Skylab. The Space Shuttle is primarily reusable and is to be operational in 1980. It is planned as a replacement for virtually all the nation's space boosters in operation today.

One of the most important factors in assessing the feasibility of space disposal of nuclear wastes is cost. This section considers the space transportation cost, which consists of the vehicle launch and operations costs. These data can be used for comparative purposes for preliminary determination of the best launch vehicles and the most promising mission destinations. However, the total cost of space disposal will have to include the cost of separating and concentrating the waste material, the cost of transporting the nuclear waste and handling it at the launch site, and the cost of the flight containment system and its associated flight systems.

EXPENDABLE LAUNCH VEHICLE PERFORMANCE AND COST

Performance and cost data for the Titan IIIE/Centaur and the Saturn V are listed in table 14 for high Earth and solar orbits and for solar system escape. Performance data are based on a due-East launch from ETR into a 185-kilometer parking orbit. The upper stage of the launch vehicle provides the ΔV needed to accelerate the payload to higher energies from the parking orbit. Typical ΔV requirements for the selected destinations are shown in the table. Actual ΔV's will vary somewhat depending on the specific mission design. The direct solar impact mission (24.08 km/sec) is not shown because it is well beyond the capability of current launch vehicles.

The costs of the expendable launch vehicles depend greatly on the use rate. The Tital IIIE/Centaur cost is about $27 million at a production rate of four per year. At the higher launch rates expected for space disposal of radioactive waste, the costs would be expected to be considerably lower. For this study, it is assumed that the cost of the Titan IIIE/Centaur at high launch rates can be reduced about 30 percent, and thus its cost would be at $19 million as shown in table 14. Similarly, the cost of the Saturn V and Saturn V/Centaur are taken at $150 and $155 million, respectively. The costs used herein include only the costs of the launch vehicles and their operations. They do not include operational costs associated with handling the nuclear waste at the launch site. These are discussed later in the section <u>TOTAL COSTS FOR SPACE DISPOSAL OF NUCLEAR WASTES.</u>

SPACE SHUTTLE/THIRD-STAGE PERFORMANCE AND COST

The Space Shuttle by itself can deliver payloads only to low Earth orbit. Missions beyond low Earth orbit will be accomplished by having the Space Shuttle carry both a propulsion stage and the mission payload to Earth orbit in its cargo bay. The extra propulsion stage is generally referred to as a Space Shuttle third stage. After the third stage and payload are deployed in Earth orbit from the shuttle orbiter, the third stage will inject the payload to its destination. Existing expendable upper stages are currently being evaluated for early use as Space Shuttle third stages. These stages would be expended on each flight. However, it is planned to eventually develop a new space tug explicitly for use as a Space Shuttle third stage which would have the capability of being recovered and reused. The Space Shuttle would launch the tug and payload into low Earth orbit. After the tug and payload are deployed from the shuttle orbiter, the tug will inject the payload to its mission destination. Following the injection burn, the payload is separated from the tug, and the tug performs a series of burns to return to the waiting shuttle orbiter for recovery and reuse.

Several Space Shuttle/third-stage options were considered in this study:

(1) One of the reusable space tug concepts under study by NASA: The tug is designed to have the capability of performing a roundtrip mission to geostationary (synchronous) orbit with a 1360-kilogram payload. It is a hydrogen-oxygen fueled stage with an

engine specific impulse of 470 seconds, and it has a propellant capacity of approximately 24 040 kilograms.

(2) A similar reusable tug but optimally sized for the waste disposal mission

(3) The existing expendable Centaur stage: It also uses hydrogen-oxygen propellants and has an engine specific impulse of 444 seconds and a propellant capacity of about 13 610 kilograms.

(4) A similar expendable Centaur stage but resized for the waste disposal mission

Performance

With these various Space Shuttle/third-stage options, useful payloads are achievable to only high Earth orbit and solar orbit destinations. The performance of these systems, which is based on a mission ΔV of 4.11 kilometers per second, is shown in table 15. The performance data are based on a Space Shuttle delivery capability of 29 484 kilograms into a due-East 185-kilometer orbit. The optimally sized third stages have higher payloads. For the waste disposal mission, higher payloads are achievable to high Earth orbits (higher than the geostationary option) because no payload is returned by the tug. This increase in payload must be offset by decreasing the tug's propellant (off-loaded) to stay within the payload limits of the Space Shuttle. For the high Earth orbits and solar orbits, the reusable tug, at its current size, can deliver a payload of 4170 kilograms. The optimally sized tug (about 20 870 kg propellant) can deliver a payload of 4670 kilograms. In the case of the Centaur, the propellant capacity for the current size is too small to utilize the full orbital capability of the Space Shuttle. The performance of the Centaur stage can be improved if its propellant capacity is increased. For the high Earth orbits and solar orbits, the current Centaur stage can deliver 6490 kilograms. An optimally sized Centaur (about 17 240 kg propellant capacity) can deliver a payload of 8480 kilograms.

It should be recognized that the higher payload capability shown for the Centaur stage is a consequence of its being expended rather than recovered. For the reusable tug, a portion of its propellant is required for its return to the shuttle orbiter waiting in low Earth orbit. For the expendable Centaur stage, all the propellant is used to achieve the desired mission ΔV and its payload capability is accordingly higher. If the tug were expended, its performance would be comparable to that for the optimally sized Centaur stage.

Cost

The cost per Space Shuttle flight is estimated at approximately $10.5 million. In addition, the cost per reusable tug flight is assumed to be $1.75 million. This cost includes operations, refurbishment, and amortization of a unit production cost of $20 million. Totaling the two, the cost per flight of a Space Shuttle/reusable tug is about $12.25 million. The cost of the expendable Centaur stage at the high launch rates required for waste disposal would be about $5.5 million. In total, the cost of a Space Shuttle/expendable Centaur launch is about $16 million. The performance and cost per flight of these configurations are summarized in table 15.

LAUNCH VEHICLE PERFORMANCE/COST COMPARISON

Except for the Saturn V/Centaur, the launch vehicles considered thus far can deliver useful payloads only to high Earth orbit or solar orbit destinations. In order to provide an overall vehicle comparison for these destinations, the payload, cost per flight, and cost per kilogram of payload delivered to a ΔV of 4.11 kilometers per second are summarized in table 16. These data should be used only for making preliminary comparisons since other factors will have to be considered in making a vehicle selection. For example, there are limits on the desired waste package size. Also, the nuclear waste is only a small fraction of the total waste package weight, and this fraction will vary with waste package size. These and other factors will influence the choice of a launch vehicle for a particular destination. Nonetheless, table 16 shows that the Space Shuttle vehicles are more cost effective than the current expendable launch vehicles. The cost per kilogram of total payload delivered by the Space Shuttle vehicles is of the order of one-half of that delivered by expendable launch vehicles.

For the shuttle-launched missions, it appears worthwhile to resize the upper stages for the waste disposal mission. The improved performance and cost effectiveness should readily justify the nonrecurring costs associated with resizing the stages. For the high Earth orbits or solar orbits the cost per kilogram of payload delivered for the resized Centaur stage is about 25 percent lower than for the resized reusable tug. This indicates that an expendable third stage would be more cost effective than a reusable stage. This conclusion is sensitive to the required mission ΔV. If the required mission ΔV were below about 3.3 kilometers per second, a reusable third stage (tug) could be more cost effective than an expendable stage (Centaur).

The Shuttle third-stage options considered in this portion of the study were all single stages. Many additional options become available if multistage configurations (e.g., reusable tug plus expendable kick stage) were to be considered, although it is not clear that they will necessarily be more effective. In addition to performance and cost, safety considerations and specific mission details can influence the final choice of a third stage. It is therefore recommended that both reusable and expendable third stages continue to be considered in further evaluations.

MULTIPLE SPACE TUG CONFIGURATION PERFORMANCE AND COST

The only launch vehicle considered thus far that has a useful payload capability for the direct solar escape mission is the Saturn V/Centaur. As shown in table 14, it can deliver a payload of about 7480 kilograms to this destination. At a launch cost of $155 million, this results in a specific cost of $20 720 per kilogram. This is roughly an order of magnitude higher than for the shuttle launches to high Earth or solar orbits. One possibility for providing a more cost-effective solar escape capability is to use several shuttle/tug launches to assemble a tandem tug in Earth orbit. This approach could also be used to provide higher payloads for the Earth orbit and solar orbit destinations.

The procedure would be to use several shuttle launches to place several tugs along with the payload into low Earth orbit. The tugs, which have the inherent capability of being able to rendezvous and dock with each other, would be assembled in orbit to form a tandem vehicle. In performing the mission, the tug stages burn sequentially. And each stage, if it is to be recovered, returns to its waiting shuttle orbiter.

In this preliminary evaluation of a tandem vehicle, only the fixed-size tug concept is considered. It is assumed to be available in both reusable and expendable configurations. The tug and shuttle performance parameters and costs are the same as discussed previously. The one exception is the cost of an expended tug. The expected unit cost of the reusable tug is of the order of $20 million. If the waste disposal mission required expending a tug, the cost of the expendable tug could be considerably lower. The production rate for an expended tug would be much higher than for a reusable tug since each disposal mission would require a new tug. The high use rate would probably justify development of an expendable tug that incorporated only the features necessary for accomplishment of the waste disposal mission. As an alternate approach, a modified version of the existing Centaur stage could be used as an expendable tug. An accurate cost for the expendable tug cannot be established at this time, but for the purposes of this study it is taken as $6 million per flight.

Each of several tandem tug configurations can accomplish the direct solar escape mission. Two such configurations are considered here for illustrative purposes. The first tandem configuration considered consists of two stages, a reusable tug plus an expendable tug; it requires two shuttle launches. The first shuttle launch carries a fully loaded reusable tug (full propellant tanks) to orbit and a second shuttle carrying an off-loaded expendable tug plus payload. The second tandem configuration considered consists of three stages, two fully loaded reusable tugs plus an off-loaded expendable tug and payload, and requires three shuttle launches. In both configurations the recoverable tugs are the lower stages (burned first) since this is an optimum arrangement. The recoverable tugs are brought back to Earth with the shuttle orbiters used to initially launch the tugs so that there is no additional shuttle cost for returning a tug.

The ideal payload capability to solar escape for the two- and three-stage tandem configurations is 3900 and 6080 kilograms, respectively. However, gravity losses will significantly reduce the actual performance of these multitug configurations. The gravity losses have been determined for these configurations by assuming the tug has a thrust level of 88 940 newtons (20 000 lbf). The actual payload capability of the two- and three-stage configurations for direct solar escape is 2270 and 3040 kilograms, respectively.

A higher tug thrust level could be used to reduce the gravity losses, but it is not expected that the new tug engine will have a thrust level higher than 88 940 newtons. Another approach for reducing the gravity losses is to use a technique referred to as perigee propulsion. This is operationally more complicated and necessitates carrying the waste package once around the Earth in an elliptical orbit between tug burns. However, using perigee propulsion increases the payload capability of the two- and three-stage configurations for direct solar escape to 3270 and 4400 kilograms, respectively.

An overall comparison of launch vehicle performance and cost for the direct solar escape mission is shown in table 17. The expendable Saturn V/Centaur provides the highest payload weight, but at a cost of about $20 700 per kilogram. The multiple shuttle/tug configurations using perigee propulsion achieve lower payloads, at a cost of about $9000 per kilogram. This lower cost, however, is of the order of four times higher than the cost for the high Earth orbit and solar orbit destinations using the Shuttle/third stages considered (table 16).

SPACE TRANSPORTATION SYSTEM CONCLUSIONS

The currently planned Space Shuttle is more cost effective than current expendable launch vehicles by about a factor of 2. The Space Shuttle will require a third stage to perform the disposal missions. Depending on the particular mission, this third stage could be either a reusable stage such as the Space Tug or an expendable stage such as a Centaur. In either case, the third stage should be resized for the selected disposal mission. In fact, the launch rates required for waste disposal are expected to be sufficiently high that it will probably be worthwhile to develop a version of the entire launch vehicle dedicated to providing maximum performance, lowest cost, and higher reliability for the disposal mission.

In this study, only current or planned space transportation systems were considered. However, the waste disposal problem will extend far into the future, and new space technology and systems development can be expected. Consequently, the performance and cost data presented in this section may be conservative as far as future capability is concerned.

NUCLEAR WASTE PACKAGING

GENERAL CONSIDERATIONS

For this study the nuclear waste material was divided into two main categories: fission products, and actinides with various residual amounts of fission products. Preliminary screening studies were first conducted to determine the minimum cost of transporting these wastes into space (refs. 1 and 2). The penalties due to accident and reentry protection systems were not included. Hence, the amount of waste carried per launch was a maximum. If these minimum costs were acceptable, a more detailed design and analysis was conducted. For the fission products the costs were high, and only a preliminary study was made. For the actinide wastes a more thorough study was conducted to determine the technical and economic feasibility. This detailed study included design for protection during reentry and other accident conditions.

In order to transport nuclear waste material in a Space Shuttle, as shown in figure 6, there are certain requirements which the waste package must meet. These requirements pertain to the operation of the shuttle and the general safety at the launch site and of the public. The requirements of the nuclear waste package integrated with the shuttle are discussed in the next main section.

ACCIDENT ENVIRONMENTS

In conceptually designing a package the total environment must be considered. This includes all types of potential accidents and conditions the radioactive waste package could be subjected to. The accident environments were separated into three areas of interest:

(1) Launch pad and launch environment

(2) Reentry in case of an aborted mission

(3) Environment at impact and after impact

How the nuclear waste packages might respond to these environments is discussed in the section NUCLEAR SAFETY CONSIDERATIONS.

Launch Pad and Launch Accident Environment

At the time the shuttle and tug are loaded with fuel and during the initial sequence of lift-off, the possibility of explosion and fire exists. The following are the estimated conditions that may occur during such an explosion or fire:

Blast overpressure. - Assuming a mixing mode yielding not more than 20 percent TNT equivalency for the liquid propellant in the orbiter, an explosion could produce about 150 atmospheres (2200 psi) blast overpressure. For the two solid-propellant boosters, assuming a yield of 5 percent TNT equivalent (difficult to involve more solids in an explosion), a blast overpressure of about 100 atmospheres ($\sim$1500 psi) could occur.

Fragmentation. - During an explosion, many sizes and shapes of particles or fragments (ref. 10) with different velocities move radially outward from the center of the explosion. The effect on the radioactive waste package is a function of the mass of the projectile, its velocity, and the difference in the material properties of the projectile and the protecting surface. Most of the particles involved in the explosion would be soft (such as aluminum) compared to the stainless-steel impact vessel.

The velocity distribution of a typical explosion involving propellant and tanks conducted under Project PYRO (ref. 11) is shown in figure 7. The smaller particles will have the higher velocities, and the larger particles the lower velocities.

Fireball. - A fireball from the liquid propellants could last 20 seconds and would range in temperature from 2750° C to approximately 982° C. The solid propellants would not create such a fireball.

Afterfire. - After the fireball the liquid propellant would burn at around 982° C for approximately 30 minutes. The solid propellant when exposed to air and ignited would burn at approximately 2360° C and could last minutes depending on the thickness of the chunk of propellant. The maximum web thickness of solid propellant considered was 1.22 meters. In all probability, pieces smaller than the web thickness would exist around the nuclear waste package.

All these environments were considered in the design of the protection system for the radioactive waste.

Reentry Environment in Case of an Aborted Mission

During the flight to orbit, in orbit, and during the flight from orbit to the final destination, the mission could accidentally be aborted in such a manner that the waste package would reenter the Earth's atmosphere. For the conceptual design of the package, a perpendicular reentry (90°) from a solar orbit was assumed. This reentry could not be obtained in the Earth orbit destination. The velocity at atmospheric reentry was taken as 11 kilometers per second. During this type of reentry the surface is exposed to a heat flux, such as that shown in figure 8, which has a peak around 300 kilowatts per square centimeter. The duration of this high heat flux is 1 or 2 seconds, as indicated in figure 8. Other reentry angles and possible velocities were considered less severe. The reentry shielding was designed to survive the 90° reentry.

A plot showing the sea-level impact velocity as a function of the hypersonic ballistic coefficient is presented in figure 9 for several reentry angles. (The ballistic coefficient is equal to mass times area times the drag coefficient, mAC_d, when $C_d = 0.98$.) For spherical-shaped reentry packages the diameter of the reentry shell needed to slow the package down can be easily determined for any total weight to impact at a prescribed velocity. All reentry packages were designed to impact at sea level with a velocity of 300 meters per second or less. The effect of impact on the package is discussed in the appendix. The designs of the reentry package are presented in the section Overall Configuration with Reentry Shell (p. 29).

Impact Environment

At the time of impact the package would be thermally heated from the waste and from additional heating during the reentry. Impact could be on land or water. It could be either on soft material in which the package penetrates the surface, such as water or soil, or on hard material which deforms the package.

Soft impact would leave the package intact and buried beneath the surface. The thermal energy would then have to be dissipated to the surrounding material whether it is water, soil, mud, or sand. For any of these conditions the package should contain no more heat-source material (radioactive waste) than could be safely dissipated without melting the containment shell and releasing radioactive waste.

Impact on a sufficiently hard surface, such as granite, concrete, or steel, would cause the containment shell to deform but not to bury itself. The package would be left on the surface in a nonsymmetric shape. The package could transfer its heat by conduction to the surface, convection to the air, or radiation to the surrounding environment. The problem would be less severe from the standpoint of heat removal than for the deep-burial condition, but it would be more severe from the standpoint of impact deformation to the package. This is discussed in more detail in the appendix.

Postimpact Environment

Even though the nuclear waste package is designed to maintain its integrity, it may be possible to breach the containment shell. If this should happen and the package is above ground, some oxidation of the materials inside could take place unless they are protected against oxidation. If the outer shell should be breached in the case of soft impact (burial), which is much less likely than for hard impact, any oxidation would be slowed down by lack of airflow. However, after burial in soil the temperature of the layers would be much higher because of the poor conductivity of soil. The temperature would be less if the package were in water or very moist ground.

The design approach is to keep the package intact and to maintain the radiation shielding around the nuclear waste.

PACKAGE I - ALL FISSION PRODUCTS IN SOLID MATRIX IN CYLINDRICAL CONTAINERS

Space disposal of actinides looks more promising than space disposal of all fission products. Consequently, the actinides were studied in more detail. This section summarizes the results of the preliminary study of fission product disposal.

Description of Contents

The fission products considered for space disposal, listed under package I in table 10, were assumed to be mixed oxides of the isotopes described in table 1 contained in a solid matrix form. Several matrix forms were reviewed. And it was concluded that a solid matrix, such as the spray melt, could be used to maximize the amount of fission products without exceeding stable temperature levels. Some of the characteristics of the spray melt are given in table 18. (Also see ref. 12 for more data on spray melts and other types of solid matrices.) The spray melt was considered over other matrices primarily because its higher stable temperature (1170 K) and its relatively higher thermal conductivity (1.8 W/m-K), which allowed the highest mass of fission products per unit volume.

In the screening analysis it was assumed that the nuclear waste would be stored for a period of 10 years to reduce the activity and the heat loads as shown in tables 2 and 3 under the column for 3652 days. The material would then be processed into a solid matrix and formed into cylinders with a compatible canning material, such as stainless steel as described in reference 13. The cylinders would be surrounded by gamma ray and beta particle radiation shields, and an outer layer would be added for impact protection. A typical cylindrical package is shown in figure 10. This geometry had been previously selected for Earth storage and not for space disposal.

Radiation Shielding

Since the radioactive waste is composed of fission products, the main sources of radiation are beta and gamma rays from the decay processes of the isotopes. The beta particles (electrons) can be stopped by less than a millimeter of material. The gamma rays require a much greater mass to stop them. The shielding material chosen as representative was depleted uranium. Shielding was added to reduce the dose rate at 3 meters from the center of the package. Dose rates between 1 and 500 rem per hour were considered. The required shield thicknesses are shown in figure 11 as they apply to the maximum diameter of 0.71 meter for the fission product matrix obtained in the screening study of reference 1.

Impact Protection

Preliminary tests of the impact strength of spherical shapes approximately 0.6 meter in diameter were made. Based on the results, a 2.54-centimeter-thick stainless-steel impact shell was added to the shielded waste package. Impact tests of this sphere on reinforced concrete at velocities to 320 meters per second exhibited its capability to withstand severe deformation without cracking or splitting open. However, no data on high-velocity impact tests on cylinders were available. The drag coefficient appearing in the ballistic coefficient in figure 9 is higher for cylinders than for spheres, as illustrated in figure 12 and will, for the same total mass, result in a lower impact velocity.

Normal Operating Temperatures

The thermal energy from the decay of the fission products must be dissipated. The screening study sized the diameter of the package so that the accepted maximum stable temperature of the matrix would not be exceeded when the only means for dissipating heat was through radiation to space. For spray-melt matrices the maximum stable temperature is 1170 K. For a shielded fission product waste disposal package with an outer diameter of 0.97 meter (maximum diameter of 0.71 m for matrix without exceeding stable temperature), the surface temperature when radiating to space will be approximately 500 K. The shielding for this case was based on 10 rem per hour at 3 meters from the center.

Packaging Dimensions

The diameter of the cylindrical package for the disposal of all fission products can be set by the limiting matrix temperatures and the desired exterior shielding dose rate.

The remaining dimension to fix is the length. Based on the different payloads for different destinations as presented in the section SPACE SHUTTLE/THIRD STAGE PERFORMANCE AND COST, the length of the waste package can be readily determined. Shielding for the ends was also taken into consideration, and the weight for end pieces was deducted from the payload levels prior to determining the length.

Diameters and corresponding lengths as a function of the exterior dose rate are presented in figures 13 and 14. The lengths are shown for an assumed payload of 7750 kilograms. Allowing for a reentry shield of 730 kilograms results in the payload obtained from table 16 for the Space Shuttle with an optimized Centaur for either a high Earth orbit destination or a solar orbit destination (near 0.9 AU).

Packaging Weight Ratios for Package I

From the preceding dimensions and the characteristics of the matrix material, the amount of fission products within a package can be determined. For a payload of 7750 kilograms, the packaging weight ratio (i.e., total weight to fission product weight) without the reentry shield varies from approximately 45 at a dose constraint of 1 rem per hour to about 13 at 500 rem per hour, as shown in figure 15. These weight ratios are for the high Earth orbit destination. Because the ΔV's are comparable, it also applies to the solar orbit destination or Earth escape.

Space Shuttle Launch Frequency for Disposal of Package I

The number of Space Shuttle flights needed for the high Earth orbit destination was based on the total amount of all fission products (fig. 2) and the use of the Space Shuttle and the optimum-sized tug. It was assumed that the fission products would be stored for 10 years after they were taken from the reactor and prior to launch. Figure 16 shows the rapid increase in shuttle launches required to dispose of all fission products to a high Earth orbit destination. Any other destination would require more shuttle launches.

Before the turn of the century, assuming the program started in 1985, the number of shuttle launches would exceed three per day even for packages with shielding to a dose rate of 500 rem per hour, which in itself would be unacceptable. More separation to concentrate the more hazardous fission products is recommended to reduce the launch rate and possibly to improve the economics, see the section ECONOMICS (p. 58).

PACKAGE II - ACTINIDES WITH 0.1 AND 1 PERCENT OF FISSION PRODUCTS

The second type of radioactive nuclear waste reviewed was the actinide elements containing a percentage by weight (0.1 and 1 percent) of the fission products discussed in the previous section. The ratio of actinide weight to fission product weight for actinides containing 1 percent of the fission products is about 3 to 1. After the screening study (ref. 2) the actinides were studied in more detail to provide a conceptual design for determining the feasibility of the total approach. This design, presented in the following subsections, is the design on which the safety considerations are based. The packaging concept is shown schematically in figure 17.

Description of Contents

The actinides and the fission products, as listed in tables 1 to 6 for the LWR's, were assumed to be in an oxide form. The personnel at Battelle Pacific Northwest Laboratories, who were preparing the comparison study for the AEC, suggested the following form for encapsulating the actinide and fission product oxides:

(1) Speroidizing them to approximately 3.16 millimeters in diameter

(2) Coating them with a refractory metal such as 0.127-millimeter-thick tungsten, leaving a void on the inside for helium (alpha) decay

(3) Coating them with an oxidation-resistant alloy such as 0.025-millimeter-thick molybdenum disulfide or aluminum oxide (Al_2O_3)

(4) Mixing the resulting spherical particle in a matrix material combined with a highly thermal conducting material: This study used a matrix of 50 volume percent lithium hydride (LiH) with equal parts copper and aluminum

A model of the matrix with spheres of nuclear waste is shown in figure 18. The amount of actinide waste relative to the matrix was varied to obtain the maximum amount of actinide waste with fission products in a payload without exceeding a limiting temperature in the matrix. (See ref. 2 for details.) It was found that approximately 8 to 10 percent by volume of actinides can be contained in the matrix without exceeding the prescribed temperature limit of 860 K imposed on the matrix. Lithium hydride dissociation was the primary factor limiting actinide content. The activity and the thermal power for the actinides with fission products are presented in table 10. The values used in the study are for the LWR waste. The density assumed for the actinide oxides was 10 grams per cubic centimeter. The thermal conductivity of the matrix was calculated as 29.44 W/m-K by using methods from reference 14.

Radiation Shielding

Shielding for the actinide waste containing fission products is required to reduce the external dose rate to acceptable levels. These levels must be acceptable for handling, transporting in a manned Space Shuttle, or possible accidental exposure to the general public. The value of 1 rem per hour at 1 meter from the external surface of the package was chosen as the base point ("Standards for Protection Against Radiation," IOCFR-20, Code of Federal Regulations, Titles 10-11, 1968) for accidental exposure to the general public. However, the study also considered dose rates as high as 100 rem per hour.

Since the shielding was for neutrons, alpha and beta particles, and gamma rays, a weight optimization study as discussed in reference 2 was used. This resulted in a single layer of tungsten (W) followed by a layer of lithium hydride. The calculations showed that the main source to be shielded was the gamma rays from the fission products and not the neutrons or the alpha particles from the actinides. Shielding thickness as a function of fission product contamination and mass of actinide for a range of dose rates are shown in figures 19 and 20. As shown in figure 20 the actinides within the matrix become self-shielding, that is the shielding thickness approaches a constant value for increased amounts of actinides.

In order to minimize the shield weight, which is a major portion of the total payload weight, a spherical geometry was chosen. The layer adjacent to the matrix material containing the actinides is composed of the high-density gamma shielding material, in this case tungsten. For safety purposes a layer of stainless steel was added on the outside of the tungsten to prevent oxidation of the tungsten in the event of a break in the outer vessels. The next layer is the neutron shielding; lithium hydride was selected for this study. These layers complete the shielding for the actinides and fission products contained in the matrix. The layers of material external to these were not considered as part of the shielding analysis.

Impact Protection

The primary impact protection for the actinide waste package is a spherical shell on the outside of the lithium hydride. The spherical shell selected, based on experiments and analysis, was 1.58-centimeter-thick 304 stainless steel. This was backed up by an additional shell of 0.95-centimeter-thick 304 stainless steel between the lithium hydride and the tungsten shields. More discussion on impact can be found in the appendix.

Overall Configuration with Reentry Shell

For reentry protection, a reentry shell must be added to the exterior of the impact-protected nuclear waste. An aerodynamically stable configuration was considered necessary to minimize the weight penalty. Based on previous studies for stable reentry configurations for planetary exploration (ref. 15), the Planetary Atmospheric Experiment Tests (PAET) shape (fig. 21) was selected for the reentry shell.

In order to ensure stability, the nuclear waste and matrix with shielding are offset forward approximately 5 percent of the radius. The outer diameter of the reentry body can be determined for any total weight with the assumptions used previously in the section Reentry Environment in Case of an Aborted Mission. For the suggested missions (i.e., high Earth orbits, solar orbits, and solar system escape), payload capabilities are discussed in the section POTENTIAL SPACE TRANSPORTATION VEHICLE PERFORMANCE AND COST. The destination payload capabilities, for a Space Shuttle as the basic launch vehicle, were 8480 kilograms for high Earth orbit or solar orbit missions and 3270 kilograms for the solar system escape missions. These payloads may be designed as single waste packages or as multiple waste packages each with its own reentry shell.

Single and multiple reentry packages. - The screening study noted that the temperature limit on the matrix would prevent the choice of a single sphere for the high Earth orbit package with 0.1 percent of the fission products. Therefore, the weight for this type would have to be divided into two or more packages. For the package II actinide waste with 1 percent of the fission products, the design can be single packages. However, future safety analyses may indicate that multiple packaging would be more advantageous.

Reentry shell material. - In reentry, the heating rates on the package vary depending on velocity, angle, and atmospheric density. At low heating rates the convective heat transfer is most important, and materials such as graphite function well. Apollo reentries are an example of convective heating rates. For high velocities, such as can be encountered in planetary entry following Earth-escape velocities at steep angles, the radiative heating rate dominates and a reflective type of material is required. One such material that has high reflective capability with multiple reflective sites for scattering and reflecting is a composite made of quartz fibers woven into a mat, similar to fiberglass, with a silica binder added. This material, proposed by the NASA Ames Research Center, results in a very good reflective barrier for the reentry shell. Some of its thermophysical properties are

Density, g/cm^3	2.5
Specific heat, J/g-K	1.15
Thermal conductivity, J/sec-cm-K	2.5×10^{-2}
Thermal expansion coefficient, per K	5.6×10^{-7}

This layer of composite silica fibers must be backed with a thin silver film followed by graphite (3D) to act as the reentry heat shield in the slower reentry mode. These layers and the thicknesses required based on analytical studies are presented in figure 22. Insulation is added primarily to protect the stainless-steel containment vessel from excessive heating during the reentry or during a launch pad fire (see the section ACCIDENT ENVIRONMENTS). On the back of the reentry shield, the thicknesses are reduced and the insulation has been removed to allow for the waste heat from the actinides and fission products to be conducted and radiated away. These thicknesses are shown in figure 22(b). The reentry shell weights represent approximately 13 percent of the package weight.

This discussion on reentry shells could apply to package I for all fission products. They could be designed to be within the weight allowance of 730 kilograms for the size required.

Overall package configuration. - The representative configurations based on the reentry shells discussed in the preceding section for impact protection and shielding against radioactivity are presented in figures 23 to 25. Payloads containing actinides with 0.1 percent of the fission products destined for high Earth orbits were divided into three equal packages, each with its own impact and reentry protection (fig. 24). The largest single package (fig. 23) has a diameter of 2.80 meters, with a 1.37-meter-diameter stainless-steel sphere surrounding the nuclear shielding and the matrix containing the actinide waste with 1 percent of the fission products. This package weighs 8400 kilograms, including 384 kilograms of actinides and 134 kilograms of fission products. Other data for all the actinide packages considered are given in table 19.

In order to prevent any free hydrogen that could be present in the lithium hydride from reaching the outer stainless-steel impact shell, a 0.127-millimeter-thick layer of tungsten can be deposited on the inside of the stainless-steel shell. This layer should prevent hydrogen from diffusing into the stainless-steel shell. However, there are no data available for the period of time involved in this application.

Package Equilibrium Temperature

While the nuclear waste package is in the Space Shuttle bay, the total package, after having been precooled, slowly increases in temperature. After separation from the orbiter, the waste package will come to an equilibrium temperature. Based on the thermal heat source (table 19) and the dimensions of the package, steady-state temperature calculations were made. Using the limiting temperature criterion for the matrix material as a guide to limit the amount of actinides determined the minimum number of packages per total payload. The steady-state temperature distribution through the package is shown in figure 26 for the single-package design for high Earth orbit with actinides and 1 percent of the fission products. The peak temperature at the center is 860 K, the limiting temperature. The other waste packages described in table 19 were below the maximum operating temperature, with the exception of the single package for high Earth orbit with 0.1 percent of the fission products in the actinide waste.

Total Packaging Weight Ratio for Package II Based on External Dose Rate

The preceding discussion and design has been primarily for an external dose rate of 1 rem per hour at 1 meter from the surface of the impact shell. If this dose rate could be increased (subject to safety assessment and acceptance), the amount of radioactive actinide with fission products disposed of per launch could be increased. The effect of dose rate on the packaging weight ratio is shown in figure 27 for two destinations.

The choice of destination does not substantially change the packaging weight ratio. The greatest effect on the weight ratio is the reduced shielding for the higher dose rates. The predominant gain is by raising the allowable dose rate to 10 rem per hour. Beyond that, the gains are small and in view of the safety considerations discussed in the section NUCLEAR SAFETY CONSIDERATIONS are probably not worth the increased risks. The packaging weight ratios shown in figure 27 are economically feasible ratios, as discussed in the section ECONOMICS.

Space Shuttle Launch Frequency for Disposal of Package II

The number of Space Shuttle launches per year that would be needed is a function of the amount of actinide waste available (assuming a 10-yr Earth storage), the amount of actinide waste contained in the payload, and the destination.

For analysis, two representative destinations were selected, the high Earth orbit and the solar system escape. For the high Earth orbit destination the total destination payload from table 16 is 8480 kilograms. One percent of this payload was deducted for extraneous structure used to mount the package or packages. Any additional weight penalties should be relatively small and will not greatly alter the results. For the second destination, solar system escape, the payload selected was 3270 kilograms from table 17. This destination requires a double shuttle launch. One launch carries a reusable tug, while the other launch carries the waste package mounted on an expendable tug. The two tugs then rendezvous in orbit. This payload was achieved by applying thrust at the perigee to obtain the required ΔV (8.75 km/sec). Therefore, for each nuclear waste package delivered to solar system escape, two shuttles must be launched.

The amount of actinides per waste package or per payload, depending on the number of packages, can be obtained from table 19 for a dose rate of 1 rem per hour at 1 meter from the surface of the package. For the amount of actinides available, data from figures 2 and 3 were used, with the assumption that no launches would take place before 1985 and that the waste would be stored for a minimum of 10 years prior to transporting it to space for disposal. For the high Earth orbit destinations, it was assumed that the nuclear waste payload would be contained in three separate packages for each disposal mission.

With the preceding assumptions the number of shuttle launches required per year to transport the actinide waste containing either 0.1 or 1 percent of the fission products are presented in figure 28. As indicated in the curves, the number of shuttle launches remains under 100 per year for the high Earth orbit destinations through the year 2010 (waste material produced in the year 2000). For the solar system escape destination, more than 250 launches per year (only 125 carry waste) are required in the year 2000 for actinides with 1 percent of the fission products remaining. If more fission products are removed (i.e., only 0.1 percent remaining), the number of launches required is reduced to approximately 150 (75 with nuclear waste) by the year 2000. Extrapolations beyond the year 2010 were not considered in this study. The economic feasibility of disposal of actinide nuclear waste into either of the aforementioned representative destinations is discussed in the sections TOTAL COSTS FOR SPACE DISPOSAL OF NUCLEAR WASTES and ECONOMICS.

PACKAGE III - PURE ACTINIDES WITH AND WITHOUT CURIUM

The third type of package considered in the study was one in which essentially all fission products were separated out, leaving an actinide purity of 0.99999. A variation of this case was to remove 99 percent of the curium isotopes (the main heat source in the actinides). Table 6, which lists the thermal power for each isotope in the actinide waste, shows that the isotope curium-244 contains most of the thermal power in the waste. Therefore, removal of this isotope alone would help in those cases where the thermal heat restricted the size of the waste package.

Description of Contents

The waste content for package III was considered to be identical to that for package II, except it was assumed that for shielding purposes and for weight estimates there were no fission products. The matrix material and the spheroidizing of the actinide oxides were the same as for package II.

For the variation of removing 99 percent of the curium isotopes, the basic changes occur in the thermal power, which is greatly reduced (from 0.071 to 0.011 W/g) for the water-moderated reactors (LWR), and in the radioactivity (table 10). With these changes the amount of actinides in a single package can be increased without exceeding the temperature limit.

Overall Configuration for Package III

Pure actinides with curium. - The thermal power of essentially pure actinides (0.99999) is slightly more per gram than for package II (table 10). Thus, the amount of matrix material cannot be decreased because it is needed to conduct heat out of the waste package. The shielding required for pure actindes with curium when the steel impact shells (total thickness, 2.54 cm) are included will be less than 0.8 centimeter of tungsten plus the same thickness of LiH as used in package II for 1 rem per hour for actinides with 0.1 percent of the fission products. This is because the tungsten is for gamma rays (associated with fission products) and the lithium hydride is primarily for the neutrons (associated with the actinides). The impact shell arrangement used in package II remains. The reentry shell, which is a function of the total package weight only, remains the same as for package II. Table 20 lists the characteristics for this case.

Pure actinides with curium removed. - With the removal of the curium isotopes, for LWR waste only, the thermal problem is considerably reduced. Not only can we assume that a single package is acceptable (unless safety analyses require multiple packaging), but also the amount of matrix material can probably be reduced. Therefore, several times more pure actinides could be disposed of per package when the curium has been removed. The limit would be to replace all matrix material with actinides (which is probably not possible). For this study the matrix ratio was not changed, and there was a 12-percent increase in the actinide waste payload.

Packaging Weight Ratios for Package III - Pure Actinides

Based on the preceding discussion, overall package weights were determined for the pure actinide in a matrix for dose rates between 1 and 100 rem per hour at 1 meter from the outer stainless-steel containment (impact) shell. This was done for multiple packages for the representative destinations (high Earth orbit and solar system escape) assuming curium remained in the waste. The resultant overall packaging weight ratios, including the reentry body, are plotted in figure 27 (0.001 percent of the fission products). For a dose rate of 1 rem per hour the packaging weight ratio for both destinations is approximately 10:1. For high Earth orbit, three packages per payload were required; for solar system escape, two packages per payload were required.

Space Shuttle Launch Frequency for Disposal of Package III

Based on the packaging weight ratio, the number of Space Shuttle launches required per year was obtained similarly to those for package II, as shown in figure 29. Fewer launches are required for package III. However, the cost of separation to obtain the 0.99999 purity will probably exceed the gains made in the increase per payload, so that the overall disposal costs may be more than those for package II. Removing 99 percent of the curium reduced the number of launches by about 10 percent.

REQUIREMENTS FOR WASTE PACKAGE INTEGRATION WITH SPACE VEHICLE SYSTEM

GENERAL CONDITIONS

The Space Shuttle, selected for its cost effectiveness, is a manned vehicle. The presence of men onboard the orbiter will considerably reduce the probability of severe accidents following an aborted mission. However, there are some additional safety requirements for a shuttle payload (i.e., nuclear waste package and tug) because the shuttle is manned. Furthermore, some of the requirements to integrate the nuclear waste package with the shuttle and with a tug are also different from those for non-radioactive payloads. Some of the normal requirements are covered in reference 16 on Space Shuttle system payload accommodations.

NUCLEAR WASTE PACKAGE AND TUG OR TUG ALONE WITH SPACE SHUTTLE

Mounting in Bay Compartment

For the suggested destinations the shuttle will carry either a tug with the nuclear waste payload or a tug which will be mated in a parking orbit with another tug containing the waste package. There are several methods for mounting the tug either alone or with the waste package in the bay. Some of these are illustrated in figures 30 and 31. The requirements for mounting include

(1) Sufficient distance or material between the nuclear waste package and the crew area to provide necessary shielding for the crew
(2) A means for securely fastening the nuclear waste package and tug or the tug alone within the bay to prevent their accidental release in the event the orbiter must land with its payload
(3) Selective surface arrangement (shape and thermal radiation absorption and emission characteristics) to maintain interior bay surface wall temperatures at or below maximum
(4) An active cooling system that can be integrated on the launch pad with exterior cooling and also supply emergency cooling during flight
(5) A support to ensure that the payload stays in place

Monitoring Requirements

Since the bay will contain either a tug with propellants or a tug with a nuclear waste package and propellants, several types of monitoring are required:

(1) Monitoring the position of the tug or the package and tug within the bay
(2) Monitoring the waste package for external radiation
(3) Monitoring the waste package and the tug for temperature and boiloff of propellant
(4) Monitoring the position of the waste package and tug or tugs during deploying and propulsion phases

Deployment

After the orbiter has reached its parking orbit, the payload (tug or waste package and tug) will be deployed. Several schemes for deployment of packages and tugs have been considered in a variety of shuttle studies. A few representative ones are illustrated in figure 31. The basic requirement is that the deployment places the tug and package combination at a safe distance from the orbiter before the propulsive phase of the tug is initiated.

Retrieval

Retrieval by the orbiter in a parking orbit of reusable tugs returning from providing the waste package with the required velocity is a scheduled operation. An unscheduled retrieval of a tug with its waste package may occur if a malfunction of the tug or package should become evident while it is in orbit. Regardless of whether the retrieved payload is repaired in orbit or returned to Earth the aforementioned monitoring and cooling equipment is required.

NUCLEAR WASTE PACKAGE WITH TUG

The nuclear waste package as envisioned will be mounted to a tug. This arrangement will require an adapter, the design of which was not a part of this study. Sample sketches of a waste package mounted to a tug are shown in figure 32. The adapter must be sufficient to support the nuclear waste package during all shuttle and tug maneuvers and to prevent heat transfer from the package to the tug as well as be capable of docking a tug to a package.

An adapter will also be required between two tugs if the destination is beyond the solar system. Both of these adapters must be capable of decoupling.

THERMAL REQUIREMENTS

On Ground

On the ground, prior to launch, the nuclear waste package must be cooled to an acceptable temperature. That temperature depends on the thermal load of the package, the interior shuttle bay temperature requirements, and the time from launching to opening of bay doors in orbit. For this study a temperature range from 0^{o} to 10^{o} C was selected.

In Flight

The thermal requirements during flight depend on the thermal power of the package (in kW) and the length of time between launching and the time when the bay doors of the orbiter can be opened in orbit to allow radiation of the heat to space. The temperatures of the package and the shuttle bay surfaces as a function of time after launch are shown in figure 33. The thermal power for these examples was 25 kilowatts. As shown by the data, the bay doors must be opened as soon as possible, within 9 hours after launch, to maintain interior temperatures at or below the limiting values. In the event the bay doors cannot be opened, an active emergency cooling system is required with sufficient cooling ability to maintain temperature until the doors can be opened or the package can be returned to Earth and connected to a ground cooling system.

GROUND SUPPORT REQUIREMENTS

GENERAL CONSIDERATIONS

The ground support requirements are the facilities and hardware used during the prelaunch, landing, and vehicle refurbishing phases of operation at the launch facility. The prelaunch phase consists of the period from the arrival of the radioactive waste package at the launch facility through completion of the countdown with terminates in ignition of the first-stage booster. The Kennedy Space Center is the reference launch facility.

General considerations used in the analysis of payload prelaunch activities are

(1) Launch rate, 20 to 100 payloads per year

(2) Payload weight, 8000 kilograms

(3) Dose rate, 1 rem per hour at 1 meter from the surface of the waste package container

(4) Surface temperature[1] of the waste package, cooled to 0° C (273 K)

(5) Launch system, Space Shuttle with reusable tug

FACILITIES

Extensive use can be made of existing facilities at the Kennedy Space Center. The only new facility required to support an initial 20 launches per year for a nuclear waste program is a controlled-area nuclear waste package handling facility. This facility would accommodate special receiving-and-inspection confidence checks of the waste package and would provide environmentally controlled storage sufficient for 100 launches per year. All special and existing facilities designated to support the waste package must provide nuclear radiation protection and monitoring, security, and environmental control capability.

Maximum utilization of manipulators and other remotely operated devices is anticipated to limit the radiation dose to ground support personnel. Dose limits will be based upon recommendations by the Federal Radiation Council and the National Committee for Radiation Protection. Facility construction and modifications and shielding

[1]Surface temperature in space under normal conditions for the 1-percent-fission-product case is 576 K with a center temperature of 865 K at 31.6 kW in the waste.

requirements will be based on the "Standards for Protection Against Radiation," IOCFR-20, Code of Federal Regulations, Titles 10-11, January 1968, and "Basic Radiation Protection and Measurements," January 1971. As a reference, the normal sea-level yearly radiation background in the vicinity of the Kennedy Space Center is 0.15 rem.

Nuclear Waste Package Handling Facility

The nuclear waste package handling facility is designated for receiving and inspection, checkout, security, and affixing of handling and attachment mechanisms to the waste package for transportation to the launch pad and integration to pad lifting devices. The building is anticipated to be approximately 45 meters by 36 meters with a usable area of 1400 square meters because of walls or shielded partitions in the interior. It will accommodate as many as 10 waste packages in various stages of launch preparation, including one hot cell for retention and evaluation of a damaged waste package recovered after a pad abort or landing accident.

The estimated cost of the handling facility is $4 million (FY 1971) based upon prior Space Station/Space Base Nuclear Assembly Building (NAB) cost estimates. Facility costs are included in the section <u>TOTAL COSTS FOR SPACE DISPOSAL OF NUCLEAR WASTES</u>.

Nuclear Waste Package Transporter

Transport and handling of the waste package is somewhat complicated by the large size and mass of the payload and the necessity of continuous environmental control. The transporter must provide common attachment mechanisms for interface equipment and special ground support equipment to the waste package and tug. The transporter must also serve as a storage trailer for contingencies, providing environmental protection and status monitoring during transport, storage, checkout, and integration operations. It must be designed to minimize handling functions and potentially hazardous situations.

One waste package transporter will be required at inception of disposal operations. For the 100-waste-package-per-year operation, two would be required in operation, with a third necessary as backup. Cost of the three waste package transporters should not exceed $500 000.

Modification and Construction of Space Shuttle Base Requirements

Figure 34 parametrically identifies the additional facilities and modifications to facilities other than the nuclear waste package handling facility and the waste package transporter that will be needed. The data were developed as follows:

(1) Where available, Space Shuttle trade-off studies, as well as Space Shuttle preliminary engineering reports were used. Their subjects included

(a) Modified mobile launchers (3)

(b) Maintenance and checkout facility adjacent to the Vehicle Assembly Building

(c) Solid rocket booster disassembly facility

(d) Storage area for external tanks and solid rocket boosters

(e) Hypergolic facility

(2) Other items not anticipated for current Space Shuttle schedule include

(a) New mobile launchers

(b) New crawler

(c) New launch pad

The cost of these items was estimated by using original value, Space Shuttle modifications, and an escalation rate of 5 percent.

Factors that will be affected but are not identified in figure 34 because of insufficient data for estimating are

(1) Tug facilities and equipment

(2) Liquid propellant storage

(3) Shops and laboratories

(4) Office space

(5) Backup pad(s) (not considered)

OPERATIONS

GENERAL CONSIDERATIONS

The prelaunch phase starts with the arrival of the waste product at the Kennedy Space Center and terminates with lift-off of the booster from the launch pad. Following this are the ascent and the orbital phases of the mission. In the orbital phase the waste package and tugs are deployed for launching and expended reusable tugs are retrieved.

All operations associated with radioactive flight hardware will be safely implemented to minimize the risk to personnel and the ecology and to provide assurance of mission success. Nuclear safety at the Kennedy Space Center will be provided through safety-oriented planning, analysis of mission operations, and implementation of procedural safeguards. Further, radiological control will be administered (1) by establishing and rigidly controlling radiation-designated work and exclusion areas, and (2) through the use of impact/recovery teams and locating devices.

LAUNCH AND GROUND OPERATIONS ASSUMPTIONS

Ground operations are predicated on the availability of the facilities and equipment previously described. These include the following dedicated facilities and equipment:

(1) Two Vehicle Assembly Building type bays

(2) Two crawler-transporters

(3) Pad 39C, new construction and prime

(4) A payload servicing tower at both pads

(5) A payload mobile retriever

Other assumptions include

(1) An orbiter recycle time of 240 hours (three 8-hr shifts for 10 days)

(2) A tug recycle time of 290 hours

(3) No emergency on-pad ejection of the waste package will be used

  (a) Because Space Shuttle/orbiter reliability after checkout approaches 100 percent

  (b) Because the waste package will be designed to withstand on-pad conflagration

(4) A nuclear fleet of six orbiters

(5) One orbiter on call from NASA fleet

(6) Eight tugs

GROUND OPERATIONS

Ground Operations for Launch Vehicle

Based on the data available at this time, we do not believe that ground operations would be materially different for the orbiter and tug than they are currently planned for other Space Shuttle missions. However, for the nuclear waste disposal missions, the payload would be inserted on the launch pad, which would require a new payload servicing tower. Orbiter servicing is assumed to take 240 hours on a three-shift, 8-hour, year-round basis. An equivalent tug recycle system will exist and will take 290 hours on a three-shift, 8-hour, year-round basis. Some modification of the present orbiter schedule will be required, probably lengthening it by several hours to the 240-hour recycle time. This time is intended to ensure airline reliability after checkout and to give extra inspection time during the recycle period. A major consideration will be the waste package insertion on the pad, which is not contemplated in today's Space Shuttle model.

Ground Operations for Nuclear Payload

A flow diagram of anticipated ground operations for nuclear waste packages is shown in figure 35. A special receiving and inspection station would allow launch site personnel to provide a confidence check of the waste package upon its receipt at the launch site. The unit is then transported to storage. Storage in an air-conditioned (new) facility is required until the schedule allows the package to be launched. An inspection of the package is required after storage removal and prior to affixing the handling mechanisms and other hardware for flight. A nuclear waste package transporter would transport the waste package to the pad lifting device. Man-tended attachments could be accomplished in the payload servicing tower. Once the waste package was aloft, transfer to the insertion arm and insertion into the orbiter cargo bay would be accomplished.

A remotely operated mechanical docking adapter to connect the waste package to the tug is envisioned that will allow waste package installation and integration to the tug as late in the countdown as possible. This will permit final preparation of the shuttle with manned attendance until the waste package arrives. A short launch sequence follows during which the orbiter payload bay is closed, the insertion arm is retracted, and the terminal countdown is culminated in launch.

Should a launch-pad abort be required, the insertion arm can undock the waste package and return it to a remotely controlled transfer vehicle for return to the waste package storage facility.

Recovery From Abort Near Launch Site

Although not addressed at this time, some thought has been given to the abort mode and recovery. A concept under consideration is a large armored vehicle with 4-meter pneumatic wheels which can traverse dense underbrush. A dry-ice bath container would be carried piggyback for emergency waste package cooling. An alternate scheme suggested is the use of a hovercraft or helicoper for prompt (river) recovery.

ASCENT OPERATIONS

During the ascent the solid rocket motors (SRM) and the main engine will provide thrust. The two SRM's will be dropped into the Atlantic Ocean following a prescribed sequence. The main engine will continue to boost the Space Shuttle to an elliptical orbit.

ORBITAL OPERATIONS

The following important operations take place during the orbital phase of a mission. Although they are not part of this study, reference 17 presents detailed examples of operations involving Space Shuttle, payloads, and tugs (both single and multiple).

Parking Orbit

After the shuttle-orbiter reaches the initial orbit (assumed to be 100 km by 370 km), transfer maneuvers by an orbital maneuvering system will inject the orbiter into a circular parking orbit at 370 kilometers. The altitude for this parking orbit is based on overall safety for both the orbiter and the waste package. This parking orbit altitude provides a long-term (months) decay orbit to ensure retrieval for a waste package in case of a failure at that point in the mission.

As soon as possible the orbiter bay doors are to be opened to allow the heat from the nuclear waste package to radiate out to space (blackbody radiation).

Deployment of Nuclear Waste Package with Tug

All physical interfaces with the orbiter are disconnected. The nuclear waste package and tug or the tug alone is deployed from the bay. A separation maneuver is performed by the orbiter to ensure its safe distance from the tug prior to further operations.

Orientation and Firing of Tug

The orbital position of the tug relative to the required destination is determined. Then the tug performs an orientation maneuver and initiates the firing sequence. In case of a malfunction of a tug, the orbiter may be required to retrieve it (either the tug with the waste package or the tug or the waste package alone) for return to base.

Following any abort after the package has been deployed from the Space Shuttle, it will be desirable to retrieve the waste package for either mounting it to another space vehicle (tug) or returning it to base. If the abort occurs after Earth-escape velocity is achieved, the package could not be recovered with any presently envisioned vehicle. This condition may require selecting trajectories that would limit the possibility of encountering the Earth if an abort occurred past Earth-escape velocity.

TRAJECTORY CONSIDERATIONS

This section discusses primarily Space Shuttle trajectories and some abort modes of the shuttle and the tug which are of concern for nuclear waste disposal missions. Shuttle performance data and other shuttle information are based on the shuttle baseline configuration (ref. 16).

The Space Shuttle, as shown in figure 5, is a launch vehicle composed of the recoverable manned orbiter containing the main engines, an external drop tank containing the orbiter's propellants (liquid hydrogen and liquid oxygen), and two solid rocket motors. The space tug, presently under study by NASA, is an upper stage which would be designed to inject a payload into orbits beyond the capability of the shuttle. Both expendable and reusable configurations are under study as discussed in the section POTENTIAL SPACE TRANSPORTATION VEHICLE PERFORMANCE AND COST.

SHUTTLE ASCENT

For the type of mission discussed herein, the Space Shuttle, carrying a nuclear waste package and a space tug within its cargo bay, would be launched from the Kennedy Space Center into an elliptical orbit of approximately 100 kilometers by 370 kilometers. Figure 36 shows the sequence of events for such an ascent trajectory and return.

At lift-off, the SRM's and the orbiter's main engines fire in parallel. When the SRM's have used their propellants, their cases are separated from the orbiter, drop into the ocean downrange, and are recovered. The orbiter's main engines continue burning to orbit insertion, at which time the expendable external propellant tank is separated from the orbiter and then deorbited by a small retrorocket. Subsequently, the orbiter circularizes its orbit at apogee by using its orbital maneuvering system. It then deploys the tug with its nuclear waste package. After performing its on-orbit mission operations, the orbiter and its crew return to Earth.

SELECTION OF PARKING (DEPLOYMENT) ORBIT ALTITUDE

For this mission a parking altitude of 370 kilometers, which has an orbital decay time of several months, has been assumed. This time period would be sufficient for remedial action if any problem should occur after deployment of the nuclear waste package and tug and shortly after tug ignition. A second tug would either be stationed in orbit or could be brought up to retrieve the waste package or to properly inject it to its destination. Such a contingency mission would require rendezvous and docking with the waste package after it was undocked from a disabled tug.

INTACT SPACE SHUTTLE ABORT

In the event of a premature mission termination prior to the deployment of the tug and the waste package, the orbiter would return them to Earth, as it has the capability for intact abort throughout its mission. The ascent to the initial orbit takes approximately 8 minutes. If an abort were initiated during approximately the first 5 minutes after lift-off, the orbiter could fly back to the launch site. This return flight, depending on the time of abort decision, could be on a glidepath or it could be a powered maneuver using the main engines.

If the abort were initiated between approximately 5 and 6 minutes after lift-off, the orbiter could perform a so-called once-around abort during which it would land at the launch site after circling the Earth. Figure 37 shows several ground tracks for such aborts for launch azimuths from 90° to 130° E. The figure indicates the entry points for a landing at Kennedy and the approximate maximum capability landing envelope for the 90° azimuth trajectory based on an orbiter cross-range capability of 2590 kilometers. An orbiter on any of the trajectories shown could land at either Kennedy or another preselected base.

For aborts after more than 6 minutes of flight along the ascent trajectory, the orbiter would have the capability to achieve a parking orbit from which it would deorbit later and land in its normal manner.

UNCONTROLLED ABORT DURING ASCENT PHASE

There is the possibility - although it is of a very low probability - that a malfunction could occur during the Space Shuttle ascent phase which would result in an uncontrolled impact on Earth by the shuttle. In such a case the potential points of impact, which are called the instantaneous impact points (IIP), would lie on one of the curves shown in figure 38 for different launch azimuths (not considering dispersions and atmospheric effects). The instantaneous impact curves are over water with the exception of a very short dwell time over the southern part of Africa, of the order of 1 second for the 90° launch azimuth. Such an impact would occur if the malfunction were to occur during the period of approximately 2 to 3 seconds prior to orbiter main engine cutoff.

If necessary, the short dwell time over Africa can be further reduced by increasing the launch azimuth above 90° at the expense of a reduced payload capability (ref. 3). There are, however, limits to this because of the Caribbean Islands. In order to provide an adequate miss distance for those islands, the highest launch azimuth generally used for current expendable launch vehicles is 108°. However, by using a special type of ascent trajectory, the vehicle could avoid passing over land entirely on ascent. With such a trajectory, commonly called a dogleg, the shuttle would initially fly an easterly heading, thereby avoiding IIP overpasses over the Caribbean area and would then yaw right to swing the IIP trace around the southern tip of Africa (fig. 39). Preliminary studies have shown that a dogleg trajectory with a launch azimuth of 97.5° maximizes shuttle payload to approximately 17 700 kilograms, as compared with the due-East trajectory shuttle payload capability of 29 500 kilograms. The IIP trace of this dogleg trajectory provides an adequate miss distance for the Caribbean Islands, South America, and Africa. Such dogleg trajectories are presently not considered because of the high inherent safety of the manned Space Shuttle and because the trajectory reduces the payload-carrying capability of the shuttle to such an extent that a waste package and a fully fueled tug could not be carried to a parking orbit. This problem could be handled by carrying only nuclear waste packages in the shuttle ascending on a dogleg trajectory and carrying the tug in another shuttle on a conventional trajectory. The package and the tug would then be mated in orbit. This concept, however, adds further complexity to the mission and greatly increases the number of launches.

We have been discussing a failure aboard an ascending shuttle which could precipitate an uncontrolled abort leading to a potential land impact. An uncontrolled abort could also occur during an orbiter return to Earth with a waste package onboard.

UNCONTROLLED ABORT DURING ORBITAL MISSION PHASE

A malfunction, such as that of a navigation, guidance, and/or control system, during a tug burn could possibly change the tug trajectory into an inadvertent uncontrolled reentry trajectory leading to an Earth impact. Such undesirable trajectories can, however, be avoided by an error-sensing device which cuts off engine thrust in the event of a malfunction of those systems. In such a case, the tug with its waste package would remain in an elliptic orbit, and another tug would be dispatched to either retrieve the package or send it to its mission destination.

NUCLEAR SAFETY CONSIDERATIONS

The fundamental philosophy of nuclear safety for radioactive waste disposal missions in space can be stated as follows: Potential radiation exposure and harmful contamination of individuals, the population at large, and the ecology shall be negligible. This statement also applies to celestial bodies, as required by the treaty to promote peaceful exploration and use of outer space, which was signed by 60 nations including the United States. For operations during all phases of a nuclear waste disposal mission, exposure and contamination should be negligible for the population at large and should be within the permissible standards for the personnel involved in the mission.

The nuclear waste disposal missions discussed herein are basically like other shuttle/tug missions that will carry radioactive materials to synchronous Earth orbit or to planetary orbits. However, much larger amounts of radioactive material would be flown on the space disposal missions.

This section presents the results from an evaluation of the response of the nuclear waste package design to potential accidents during the various phases of waste disposal missions. Because the mission hardware and systems and the mission parameters are in a preliminary definition phase, only a qualitative evaluation could be performed.

NUCLEAR SAFETY REQUIREMENTS

The nuclear waste imposes certain requirements on the package design, its supporting equipment, and mission operations. Some of these requirements are as follows:

(1) Waste package requirements:
  - (a) Subcritical design under all conditions
  - (b) Waste material encapsulation
  - (c) External radiation shielding
  - (d) Reentry protection
  - (e) Impact protection
  - (f) Fire and explosion protection
  - (g) Transponders

(2) Shuttle orbiter supporting equipment:
  - (a) Temperature control
  - (b) Monitoring equipment

(3) Operational requirements:
  - (a) Parking orbit altitude with long decay time
  - (b) Recovery preparedness
  - (c) Future encounter avoidance
  - (d) Means of orbital retrieval

ACCIDENT MODEL[2]

Potential accidents are discussed qualitatively in this section, indicating the environments which could be present at various times during the accidents. No probability numbers are used because of insufficient definition of the hardware and the mission.

[2]See also the section ACCIDENT ENVIRONMENT for data used in the preliminary design.

Ground Handling

Provided that proper procedures are established, the probability of an accident while handling the nuclear waste package, including installation within the Space Shuttle cargo bay, will be extremely small.

Launch Pad Abort

A potential accident at or immediately after launch, causing the Space Shuttle to explode and burn, would expose the waste package to an adverse environment. The environment created by such an accident would be blast overpressures, impact of fragments, fireball, impact on the ground, and residual liquid- and solid-propellant fires. The residual fire of the solid propellant could last about 5 minutes at a temperature of approximately 2400 K.

High-Velocity Impact

If a malfunction should cause the Space Shuttle to make a 180° change in direction soon after launch, a powered impact could occur. The resulting environment would be similar to that encountered during launch-pad abort, except that the impact would be at high velocity. However, a portion of the propellants would have been consumed, the residual fires would be of shorter duration, and the fireball would be smaller. The presence of a crew onboard which could take action to prevent the occurrence of such an accident would reduce it to a very low probability.

The actual impact response for the waste package itself would be lower than that of the shuttle because of the cushioning effects of the orbiter structure.

Failure During Ascent

Many ascent failures and malfunctions which would lead to a catastrophic failure in an unmanned space vehicle would cause mission changes or aborts, but not an accident, in the manned Space Shuttle (see section INTACT SPACE SHUTTLE ABORT). However, there remains a possibility, although small, that a catastrophic accident could occur onboard the Space Shuttle. In such an accident, if the shuttle remained intact, the result would likely be impact at relatively low velocity.

If an explosion of the main propellant tanks of the shuttle should occur during ascent, the blast overpressure could damage the reentry shield and change the reentry characteristics of the package. In the worst case, the reentry shield could be stripped off, leaving the smaller impact shell as the outer shield. The package would continue to ascent until its vertical velocity component had been attenuated by air resistance or by gravity forces. The spherical package would then fall back toward the Earth and the velocity would increase either to terminal velocity if in the atmosphere or to a higher velocity if considerably above the effective atmosphere. In the former case the terminal velocity would be within the impact capability of the waste package, especially for water impacts. Impacts on water would be much less severe than on land or hard surfaces. For the cases where the waste package ascends above the atmosphere the package would accelerate in its gravity fall and might exceed terminal velocity prior to entering the atmosphere. After entering the atmosphere the waste package should slow down until it either reaches terminal velocity or impacts the Earth.

The impact velocity for the waste package was determined by assuming the accident occurred at various times throughout the boast phase (~500 sec). For those cases where sufficient fuel and air density could cause extensive damage to the reentry shield the impact velocity did not exceed 360 meters per second. Although this value is above design, the impacts should occur on water, and the spherical waste package is not expected to be damaged for water impacts at that impact velocity. Spheres impact tested at velocities in the range of 300 meters per second show little damage when they impacted on soil as compared to impacting on reinforced concrete, which implies that impacts on water would also be less severe than on reinforced concrete.

If after an explosion the waste package remained attached to the tug, any explosion on impact (with blase overpressure, fragments, a fireball, and a liquid-propellant fire) would be of considerably lower magnitude than during a launch-pad abort because of the relatively small quantity of tug propellants. If after an explosion the waste package was detached from the tug, the impact velocity would be less than design since the package would not be slowing down from a high reentry velocity, but would be merely in a free fall or at terminal velocity. If the reentry shell was damaged, this terminal velocity would be approximately the same as the impact design velocity.

Crash Landing

There is a possibility that the Space Shuttle orbiter will make a crash landing. If there was insufficient time to dump the tug propellants prior to the landing, overpressures, impacts of fragments, a fireball, and propellant fires could occur.

Uncontrolled Reentry and Impact

Uncontrolled reentry and impact accidents could occur after the waste package has been deployed from the orbiter. There are two resulting possibilities: the waste package could reenter by itself or still attached to the tug. The environment encountered by the waste package, the tug/waste package, or the tug/tug/waste package depends on the atmospheric entry velocity and the entry angle. (In this exploratory study, only the vertical reentry of the waste package was analyzed.) The waste package would be exposed to reentry heating and thermal stress. If the heat shield of the waste package were to fail, the waste material encapsulation could fail also and expose the radioactive waste to the reentry and impact conditions. The impact velocity of an intact waste package as designed is 300 meters per second. It is virtually impossible because of design of the tug for it to remain attached to the waste package throughout the atmospheric reentry.

Postimpact Conditions

After impact the waste package may be exposed to environments which could cause melting, oxidation, and/or corrosion and might eventually cause some release of the radioactive material and/or an increase in the external radiation dose. For any postimpact condition the external radiation dose represents a potential hazard. The intact package was designed to have an external dose of 1 rem per hour at 1 meter from the surface of the package. If breaching or deformation of the package should occur, the external radiation could increase, whether or not radioactive material was released.

ANALYTICAL RESULTS

Only a qualitative evaluation was made of the possible release of radioactive materials and the potential hazards resulting from external radiation. A quantitative evaluation of such a release and the determination of probabilities of events can only be made once a more detailed hardware, system, and mission definition has been made. Some of the analytical methods have been confirmed with experiments, such as large-sphere impact tests at velocities greater than 300 meters per second and fragmentation tests at velocities to 1500 meters per second.

Nuclear Waste Package Response

The basic nuclear waste package design used in the analysis was the single-package design for disposal of actinide waste containing 1 percent of the fission products shown in figure 23. Where possible, the analytical methods were checked against experiments that were related to the accident conditions. As a conservative approach the analysis for launch-connected accidents was performed on the waste package without the reentry shell. This approach was selected to allow for the possibility of removal of the outer shell during an explosion.

Overpressure. - An accident at the launch pad which results in an explosion of the main liquid propellants could produce a blast overpressure of approximately 150 atmospheres (assuming a mixing mode yielding not more than 20 percent TNT equivalent).

The stainless-steel impact shell with a radius of 0.68 meter and a 2.54-centimeter-thick wall can withstand an external pressure of 175 atmospheres without yielding. Since this limit is greater than the overpressure, the nuclear waste package will not be breached by the blast overpressure.

Fragments. - During explosion-type accidents, fragments of varying sizes and of various materials (predominantly aluminum) could impact the nuclear waste package at varying impact velocities. The code (PISCES 2DL) used in the impact study (appendix) was applied to analyze the fragment impact on the stainless-steel vessel. The analysis assumed aluminum fragments (sharp and blunt) impacting at 1520 meters per second, which exceeds previous velocities considered (fig. 7). The results indicated the impact shell would not be penetrated from fragments from a launch explosion.

In addition to the analytical study, an experimental test was set up in which aluminum pellets were fired at a stainless-steel sphere with a wall thickness of 1.58 centimeters. The results presented in reference 18 indicated no penetration at velocities to 1360 meters per second for aluminum pellets of 6.6 grams and no penetration at velocities to 1280 meters per second for aluminum pellets of 13.3 grams. These conditions are comparable to the particle masses achieving high velocity in explosions of liquid propellants in thin-wall aluminum tanks.

Fireball. - Comparison with other capsules involved in fireball tests indicated that because of the short duration (seconds) of the fireball and the large mass of the nuclear waste package, no serious damage should result to the nuclear waste package from the fireball.

Residual propellant fires. - Of the two types of fires, the solid propellant produces the higher temperature (2360 K). In order to evaluate the response of the nuclear waste package to the solid propellant, a heat-transfer model was established which consisted of 72 nodes for the various layers of material. The heat-transfer calculations (convection, radiation, and conduction) were performed using code CINDA (ref. 19).

The results of these calculations are shown in figure 40. Both the surface temperature and the surface heat flux are plotted. Initially the surface heat flux is high since the temperature of the impact shell is low. As the surface temperature increases, the radiation effect from the propellant fire diminishes and the heat flux drops. Selecting an emissivity of 0.3 resulted in a close match to experimental results for heat flux to the surface. The temperature of the impact shell approaches the melting point in about 5 minutes. Because of the high temperature, a breach of the outer impact shell is possible if the solid-propellant fire were to last for more than 5 minutes adjacent to the package. It is estimated that the fire could last for 5 minutes. Although in this situation, melting of the outer shell is possible, other layers would prevent release of the radioactive nuclear waste. However, the shielding (LiH) could be lost, and thus the external dose rate would increase. Recovery therefore would require a shielded or remotely operated vehicle (see the section GROUND SUPPORT REQUIREMENTS).

Atmospheric reentry. - In the event of an aborted mission where the nuclear waste package returns to Earth in an uncontrolled manner (i.e., not carried by the orbiter), there will be many possible combinations of velocity and angle of reentry. The case which was analyzed and which resulted in establishing the required thickness of the reentry shell (fig. 21) was vertical reentry at 11 kilometers per second. This type of reentry would expose the reentry shell surface to a peak heat flux of 300 kilowatts per square centimeter. This high heat flux would last from 1 to 2 seconds (fig. 8).

For vertical reentry the reentry shell has sufficient thickness to prevent melting through to the impact shell. The calculations indicate that the impact shell temperature does not increase under this condition, nor does it increase for orbital decay reentry (fig. 41).

Although it was assumed the vertical reentry might be the most severe condition on the reentry shell, it must be checked for other reentry conditions.

Impact. - Following an uncontrolled abort (i.e., the nuclear package not brought back by a controlled shuttle), the package will impact the Earth. Based on the design of the reentry shell, the impact velocity should be 300 meters per second or less. This velocity would only be exceeded if there was an abort with a tug attached and thrusting in. Because of the design, there would be a very low probability of this occurring.

Based on the experiments and analyses discussed in the appendix, it appears that in most impacts on Earth the package would be buried in the soil or at the bottom of bodies of water with relatively little damage to the outer shell. However, if the package lands on a surface that does not absorb any of the energy, such as a solid noncrushable surface, the waste package would probably be breached. This might or might not result in release of radioactive waste, since the waste is a small percentage of the matrix and is encapsulated with the molybdenum and tungsten protection layers. It can be assumed that during impact on hard surfaces the waste package would be deformed and possibly breached. There would be some increase in the external dose if some of the outer lithium hydride were lost. However, most of the shielding is supplied by the tungsten and the matrix.

After impact. - After an impact the waste package will be either buried beneath the surface, partially buried, or on the surface in either an intact or breached condition. A series of calculations were performed for various degrees of burial and are reported in reference 20. The results (table 21) indicated that for no burial or partial burial the vessel would not rupture within 23 days (approaching equilibrium condition). For deep burial, all calculations except those in which the waste produced less than 2 kilowatts of thermal power resulted in rupture of the impact vessel. This rupture was caused by the increased temperature and pressure from helium released in the decay process and from dissociating LiH. The rupture would in all probability be a minor crack to relieve the pressure. The use of pressure-relief valves or filters, a means used on nuclear packages already launched, could solve this problem.

There were no experimental data to determine whether or not the surfaces would melt. The calculations did not account for any material changes in the soil; however, its conductivity was varied with temperature. There have been tests conducted which indicate that the surrounding soil properties can change and provide a better heat sink.

If the impact vessel remains intact, there will be no oxidation and no corrosion for extended periods of time. If the outer vessel is breached, there would be some loss in the effectiveness of the shielding. The waste material which is already in the oxide form should not react with the surrounding environment. The radiation level in the immediate area would increase somewhat because of the loss or degradation of the shielding. Therefore, it would be desirable to locate and recover the waste package as soon as possible.

RECOVERY OF NUCLEAR WASTE PACKAGE

For aborts near the launch pad and during early ascent the vehicle will be tracked. Under these conditions the waste package can be recovered without undue hazards to people in the vicinity. For aborts which could occur in later phases of the mission the waste package would be tracked but the determination of the impact location would generally take considerable time and recovery would be delayed. If the waste package were to impact in deep ocean, it probably could not be recovered.

If an abort were to occur when the tug with the waste package attained or exceeded the ΔV for Earth escape, the waste package could be inadvertently put into an orbit which could result in an Earth encounter at some future date. Depending on the orbit, the encounter could be hundreds to thousands of years later. During this time, the radiation level from the actinides and fission products will diminish as indicated in figure 42. Although this would reduce the potential hazard, a considerable radiation level still remains. Locating the impact point under such conditions would be extremely difficult and the inclusion of a long-lived transmitter for locating the waste package prior to Earth encounter would be desirable.

NUCLEAR SAFETY CONCLUSIONS

Within the framework of this exploratory study, nuclear waste disposal missions, as described in this report, appear feasible. The nuclear waste package design concept with its various protection shells and the reentry system will prevent release of radioactive waste under most accident conditions. However, much study, development, and testing effort will be required to confirm the concept and to have the confidence to firmly plan such missions. It must be realized, however, that there are certain risks involved, however small, which would have to be balanced against the benefits to be derived from removing the dangerous long-lived radioactive waste from man's present environment and relieving future generations from the responsibility of protecting themselves from our radioactive waste.

The safety study of accident models and package responses points out certain key issues regarding the attainment of overall nuclear safety for space disposal of nuclear waste packages:

(1) The waste package should be designed to maintain integrity without releasing any of its radioactive contents throughout all potential hazardous events during all mission phases.

(2) Radiation emanating from the package, whether it is intact or damaged, has to be held to a minimum, so that recovery can be accomplished without undue exposure to the population. (This might require development of locating and recovery means for Earth-impacted waste packages.)

(3) Potential accident conditions that could lead to uncontrolled reentry of the waste package have to be minimized. This would be accomplished by careful selection of trajectories and the use of highly reliable vehicles.

It would be desirable to develop vehicles for retrieving waste packages from accident orbits beyond Earth escape.

COSTS FOR SPACE TRANSPORTATION SYSTEM

The total cost for disposal of radioactive nuclear waste in space must include the cost for separation, encapsulation, storage as assumed herein, packaging, transportation to the launch site, launch site, launch vehicle, and operations. This report was primarily concerned with the costs involving the launch and operations. The other costs are discussed to give a relative comparison with the space transportation costs. The vehicle costs, launch costs, and operations costs are essentially a function of the number of vehicles and the launch rate. These costs are also a function of the destination and are discussed on that basis as well. Two representative destinations are used: high Earth orbit and solar system escape.

The Kennedy Space Center was used as the reference launch facility as discussed in the section GROUND SUPPORT REQUIREMENTS, and the facility costs are based on the general considerations presented in that section.

SPACE TRANSPORTATION COSTS

The space transportation costs presented in this report include costs of technical support and operations.

Launch Costs

For the two representative destinations the most cost-effective vehicles were selected for determining the space transportation costs. The vehicles and their payloads are obtained from tables 16 and 17.

High Earth orbit. - From table 16 the most cost-effective vehicle was the Space Shuttle with a Centaur of optimum size (approx. 17 240 kg of propellant). The launch cost for this vehicle is estimated at $16.3 million ($10.5 million for the reusable shuttle launch and $5.8 million for the optimum expendable Centaur). These costs are based on 1972 dollars, 100 total flights per vehicle, and not more than 40 flights per year. The shuttle launch cost of $10.5 million includes propellant costs and operational costs based on the given flight rate. If the flight rate is increased to 140 per year, the operational cost per flight would be reduced by as much as 75 percent of the operational cost for 40 flights per year. The estimated reduction in operational cost per flight, which is a small portion of the launch cost, was based on the following guidelines and assumptions:

(1) Guidelines:

(a) All payloads are launched in an easterly direction from the Kennedy Space Center.

(b) The current Space Shuttle development program and an operating model of 40 flights per year are used as the baseline.

(c) Payload handling and checkout are not included in the cost.

(d) Estimates are in fiscal year 1972 dollars.

(e) An orbiter (4.5-m by 18-m compartment; 29 484-kg capacity) and twin solid rocket boosters are used for estimating propellant cost (as included in the total cost).

(2) Assumptions:

(a) The cost-per-flight estimate is only a rough order of magnitude.

(b) Additional facilities and equipment to handle more than 40 flights per year are discussed elsewhere (fig. 34).

(c) The overhaul of the orbiter main engines and the operations and refurbishment of solid rocket booster casings are not included.

(d) Vehicle and support manpower are considered for the additional vehicles, facilities, and equipment needed for more than 40 flights per year.

Solar system escape. - This mission requires more than one Space Shuttle per nuclear waste payload (single or multiple packages). As noted in the section POTENTIAL SPACE TRANSPORTATION VEHICLE PERFORMANCE AND COST, at least two tugs are necessary to supply to a sufficiently large payload the ΔV required to escape the attracting forces of our solar system. Thus, two shuttles must be used to launch these tugs. The results presented in table 17 indicate the most cost-effective method for the solar system escape destination involves perigee propulsion. In this method, two shuttles, a reusable tug, and an expendable tug are used, for a total cost of $28. 75 million per mission. The effect of launch rate on cost is the same as for the high Earth orbit destination.

Ground Facilities Costs

The the section GROUND SUPPORT REQUIREMENTS, it was noted that many of the existing facilities could be used on the basis of 20 flights per year. Beyond that rate, additional facilities would be required. In addition to launch and operations facilities, a new facility for receipt and inspection of nuclear waste packages and for storing the packages in a controlled environment would be required. Cost of this facility would be approximately $4 million.

As the number of launches exceeds 20 per year, additional facilities are needed, as presented in figure 34. It we project to 100 launches per year, an additional $136 million (±20 percent) would be needed for mobile launchers, a new maintenance and checkout facility, a new crawler and maintenance facility, a new launch pad, and a new solid rocket booster disassembly facility.

From the results presented in the section NUCLEAR WASTE PACKAGING, the number of shuttle launches for package II (actinide with 1 or 0. 1 percent of the fission products) would not exceed the 100-launches-per-year rate for 30 years after the start if the high-Earth-orbit destination were selected. For the destinations of the solar-system-escape type, after the year 2000 some other arrangement for launch facilities would be required since it would be difficult to handle more than 120 to 140 launches per year at Kennedy. For package III (pure actinides), this launch rate would not be exceeded.

Other Support Costs

After the launch, other facilities come into use, such as tracking and monitoring stations, recovery teams, and possibly facilities for handling the Space Shuttle at other locations. Most of these facilities will already be in existence and would probably only need modifying. These modifications should be an order of magnitude less than the costs for the ground facilities.

Total Space Transportation Costs

The total transportation costs for both representative destinations are presented in table 22 for a launch rate of 40 per year. The facility cost per launch, which is based on a 30-year period, increases from \$0.01 million to \$0.07 million if the launch rate increases by 100. In going from 40 to 140 flights per year it is expected that the operational costs per flight, which are small, will be reduced by as much as 75 percent. If more than 140 flights per year are required, a different approach to launching would be necessary.

For the disposal of all fission products (package I), 140 shuttle flights per year would be required at the very beginning of any space disposal program based on present and expected amounts of fission products. For disposal of only the actinides (package II or III), the launch rate of 140 per year would not be reached for a high Earth orbit or a solar orbit during the time period considered. For solar system escape, this launch rate would be reached by 1993, 1999, and 2010 for actinides containing 1, 0.1, and 0.001 percent of the fission products, respectively. All package designs were shielded to reduce the external dose rate to 1 rem per hour.

By redesigning the launch vehicles and/or tugs to accommodate more payload, the number of launches would be reduced. If improved packaging designs decrease the ratio of total package weight to radioactive waste weight, the number of launches would also be reduced.

ESTIMATES OF SEPARATION, ENCAPSULATION, AND PACKAGING COSTS

It was not the intent of this study to determine the cost of preparing the waste and packaging it for space disposal. However, some indication of the relative costs is needed to put the costs for space disposal in the proper perspective. The cost for processing spent fuel is estimated at \$30 000 per metric ton of fuel containing radioactive waste. Assuming 33 000 megawatt days of operation per metric ton, each metric ton would contain about 1 kilogram of actinides, excluding uranium, and 35 kilograms of fission products. Additional cost is required to remove the fission products from the actinide waste. Rough estimates by Battelle Pacific Northwest Laboratories indicates this additional cost may be $30 per gram of actinides to remove all but 1 percent of the fission products and $60 per gram to remove all but 0.1 percent of the fission products. This would bring the estimated cost of processing and separation for space disposal to $60 000 to $90 000 per kilogram of actinides with 1 and 0.1 of the percent fission products, respectively. For 0.001 percent of the fission products remaining in the waste, the cost was extrapolated to $150 000 per kilogram of actinides. For fission products only, the processing and separation cost is only $860 per kilogram. The encapsulating and packaging cost for actinides is estimated at $650 per kilogram. This cost is small relative to the space transportation cost and the processing and separation costs.

ESTIMATED TOTAL COSTS FOR PREPARING WASTE, PACKAGING, AND TRANSPORTATION

The estimated total costs for space disposal to the two representative destinations are presented in table 23 for a launch rate of 40 missions per year.

Based on the assumptions in this report, the vehicles selected, and the package designs, the estimated space transportation cost per kilogram of actinide waste decreases as the percent of fission products remaining in the actinide waste decreases. However, obtaining the more pure actinide waste is more costly. Thus, there should be a minimum cost as a function of fission products remaining in the long-lived actinide waste. In any case, the costs must be related to the cost for producing electrical power. This is discussed in the next section, ECONOMICS.

For package I, in which only fission products are being disposed of, the total cost for space disposal per kilogram of waste is $88 060 for high Earth orbit and $395 000 for solar system escape. For package II (actinide waste with 1 and 0.1 percent of the fission products) and package III (actinide waste with 0.001 percent of the fission products), the total cost for space disposal per kilogram of actinide waste is $116 700, $126 500, and $169 000, respectively, for high Earth orbit. Of this $56 700, $36 500, and $19 000, respectively, represent the transportation costs. For space disposal of the purer actinide waste the predominant cost is that of processing and separation. The space transportation cost for actinides decreases with increased separation of fission products from the actinides.

For actinide waste escaping the solar system, the estimated cost per kilogram for space transportation, processing, separation, and packaging is $314 500 for 1 percent of the fission products remaining in the actinides, $240 500 for 0.1 percent of the fission products, and $243 400 for 0.001 percent of the fission products. The transportation cost per kilogram is $254 500, $150 500, and $93 400, respectively. These costs may appear high, but it should be remembered that every kilogram of actinides in the waste represents approximately 245 million kilowatt-hours of electricity. And at 2.4 cents per kilowatt-hour, that amount of power would cost $5 880 000. This subject is discussed in more detail in the following section, ECONOMICS. The yearly estimate for total space transportation costs, excluding separation costs, is presented in figure 43.

ECONOMICS

ECONOMIC ASSUMPTIONS

In order to place the large total cost for disposal of radioactive nuclear waste into space in its proper perspective, it is compared with the cost to the consumer of nuclear electric power. This comparison is based on the following assumptions:

(1) The cost to the consumer of nuclear electric power is 2.5 cents per kilowatt-hour (of which 0.8 ¢/kW-hr is the cost to produce the electricity).

(2) The amount of actinides (less the uranium isotopes) produced in generating 1 kilowatt-hour in a nuclear powerplant is 0.409×10^{-8} kilogram.

(3) The amount of fission products produced in generating 1 kilowatt-hour in a nuclear powerplant is 0.135×10^{-6} kilogram.

(4) The cost for processing the fuel is not included since it would be the same for most disposal methods.

(5) The cost for separation, to be determined by the AEC, was not included. (Estimates are shown in the preceding section.)

(6) Cost of 10-year storage prior to encapsulation for transporting into space is 0.0001 cent per kilowatt-hour.

EFFECT OF SPACE DISPOSAL OF RADIOACTIVE NUCLEAR WASTE ON COST TO THE CONSUMER OF ELECTRIC POWER

These assumptions and the cost for space transportation per kilogram of waste for the different package designs for each type of waste considered (packages I, II, and III) were used to determine the cost of space disposal in terms of the cost of electricity. This is presented in tables 24 and 25 for package I (fission products only), package II (actinides with 1 and 0.1 percent of the fission products), and package III (pure actinides with and without curium, respectively). All packages assumed an external dose rate of

1 rem per hour measured at 3 meters from the center for package I and at 1 meter from the surface for packages II and III.

The design data for the packages to be launched by the shuttle/tug system were also applied to the expendable launch vehicles. This approach is conservative because the package design is based on the radiation shielding criteria for the general public. If these criteria were neglected, a higher dose constraint could be used since there would be no crew onboard the expendable vehicle. For the large payloads to high Earth orbits obtainable with the Saturn V, a weight penalty for cooling the higher heat load during launching and staging would have to be subtracted prior to determining the package weight.

From tables 24 and 25 it is apparent

(1) That the Space Shuttle provides the lowest launch cost for space disposal of radioactive waste

(2) That the space transportation cost to the consumer is low, less than 5 percent of the cost of electricity, for disposal of the actinide waste to any of the representative destinations, but high for disposal of all the fission products

PERTURBATIONS ON COST TO THE CONSUMER

Effect of Discount Rate and Time on Cost to Consumer

In the space disposal of radioactive waste, the actual disposal of the material occurs many years after the production of the electrical energy. This time period can be used to reduce the cost to the consumer who uses that energy. If a charge is made at the time the electrical energy is used and the money placed in a fund with an annual interest, the fund would then increase at some rate until the designated time for launching. The storage period used in this study was 10 years. In reality, storage could be extended to any time period and would depend on the conditions imposed on ground storage, industrial accumulations, acceptable launch frequency, and the desirability of disposing of the waste.

The data in figure 44 show the fractional amount of the actual space transportation cost from tables 24 and 25 that would be charged at the time the consumer used the electrical energy. The data are based only on the time between initial charge and actual launch preparation. The interest rate would be compounded on an annual basis. However, the costs are based on 1972 dollars and do not take into account possible increased costs.

Example 1. - Assume that it is desirable to transport actinides with 0.1 percent of the fission products to solar system escape. The cost (table 25(b)) would be 0.061 cent per kilowatt-hour. If it were decided to transport to space after 30 years, the cost to the consumer, charged at the time of electrical production, would be only 0.015 cent per kilowatt-hour (assuming a 5-percent interest rate). This charge is less than 1 percent of the present (1972-73) cost to the consumer for electrical energy.

Example 2. - Assume that after 50 years the fissioning process for obtaining electrical energy is replaced by another means and the decision is made to take all fission products to solar system escape. The cost (table 24) would be 5.2 cents per kilowatt-hour. However, if the charge were made at the time of electrical production, it would be only 0.45 cent per kilowatt-hour (assuming a 5-percent interest rate), or less than 20 percent of the present (1972-73) cost of electricity. These examples illustrate the strong effect of an early charge for handling radioactive waste disposal on the program economics.

Effect of Separation of Waste Material for Space Disposal

The space transportation cost per unit mass of waste decreases as the degree of separation of the specific isotopes increases. However, the separation cost increases as the degree of separation increases, that is, as the wastes contain less residual specific isotopes.

The rough cost estimates for separation to 1 and 0.1 percent of the fission products, as discussed in the preceding section, were used to obtain the curves in figures 45 and 46 for the representative destinations. These costs do not reflect the reductions possible by establishing a charge to the consumer prior to storage or disposal.

Figure 45 shows that the minimum cost of disposal of actinides in high Earth or solar orbits occurs with actinides containing approximately 0.4 percent of the fission products. The curve, however, is relatively flat between 1 and 0.1 percent of the fission products so that other reasons could determine which direction to take on separation. The cost for disposal of actinides to escape the solar system minimizes at around 0.1 percent of the fission products (fig. 46). The minima of figures 45 and 46 can vary since the separation costs were estimated. However, the total cost of about 0.1 cent per kilowatt-hour is unlikely to be greatly altered. Even this cost, which is 4 percent of today's price of electricity to the average consumer, is not excessive. Furthermore, the cost can be reduced by prepayment into a fund for future separation and disposal.

CONCLUSIONS

The results of this exploratory study indicate that disposal into space of the long-lived actinides of nuclear waste (the most hazardous waste because of their long half-lives) appears feasible from the viewpoint of safety and reasonable from that of economics. The transportation costs for ejecting the actinides out of the solar system would represent less than a 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 dangerous long-lived radioactive waste from man's environment and relieving future generations from the responsibility of protecting themselves against our radioactive waste. Firm plans for such nuclear disposal missions must be based on more study, development, and testing.

SPACE DESTINATIONS

Of all the destinations considered, only three look promising: high Earth orbits (above synchronous orbit altitude), nearly circular solar orbits inside the Earth's orbit, and escape from our solar system. Only the latter destination provides a permanent means of disposal of the waste. Sending the waste into the Sun is not possible with presently conceived vehicles on a direct mission and not practical with indirect (planet swing-by) missions.

TRANSPORTATION VEHICLE

The currently planned Space Shuttle, supplemented by space tugs, will provide a substantially lower cost per deliverable kilogram of waste to the promising space destinations than any of the current expendable launch vehicles. Because the shuttle is a manned vehicle and has considerable maneuvering capability, the overall safety aspects of such a transportation system would be superior to those of expendable launch vehicle systems. With either expendable or reusable tugs, or a combination, the three promising destinations can be attained with a sufficiently sized radioactive waste payload, ranging from approximately 200 to 500 kilograms of actinides per mission, depending on the destination.

WASTE PACKAGE DESIGN CONCEPT

The nuclear waste package design developed during this exploratory study allows sufficient payload (radioactive waste) per package from an economic viewpoint and provides adequate protection under the accident conditions reviewed. Further effort could optimize the design to increase its payload and to improve its safety features.

NUCLEAR SAFETY

No quantitative risk assessment was possible because the mission hardware and the mission parameters are in a preliminary definition phase. Only a qualitative evaluation could be performed. With appropriate system design and operations, the risks are expected to be relatively low.

ECONOMICS

The transportation costs for space disposal of nuclear waste represent an increase in the consumer's electric bill of approximately 1 to 5 percent. To this transportation cost must be added the cost for separating the fission products from the actinide 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 as the cost of transportation out of the solar system. Both the cost and the launch frequency are feasible and practical for the disposal of the actinide waste. However, the space disposal of all fission product waste was found to be neither economically nor practically feasible because of the large bulk rate, which would require a very high launch rate.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 12, 1973,
770-18.

APPENDIX - ACCIDENTAL EARTH IMPACT AND POSTIMPACT

ANALYSES AND EXPERIMENTAL RESULTS

In the event of an abort during ascent, in orbit, or during the propulsion phase to destination, the possibility of an impact on Earth exists. These impacts can be at various velocities and can occur in various areas of the Earth, which means impacting on different surfaces (water, soil, sand, rock, etc.). For this reason, analyses of the nuclear waste package during and after impact were conducted. Some of the analyses were backed up with experimental results from other unrelated programs having similar accident conditions.

TYPES OF SURFACES FOR IMPACT

There are many different types of surfaces that a package can encounter when impacting the Earth's surface. In general, the surfaces can be divided into two categories: a hard surface, and a soft surface. Hard surfaces include concrete, granite, and steel. Water and the various types of soil are soft surfaces.

Seventy-one percent of the Earth's surface is water. Therefore, it can be assumed that a high probability exists that the package will impact upon a soft surface. Most of the remaining surface of the Earth consists of soil. There are many different types of soil which in themselves have varying degrees of hardness, but no soil is as hard as granite, concrete, or steel. Sandia Laboratories has conducted a number of tests on impacting soil of varying consistency. Their work is reported in reference 21.

After water and soil the remainder of the Earth's surface consists of many types of structures and surfaces with degrees of hardness. Examples can be urban communities containing steel, brick, and wood buildings; airport runways and roads; and timbered forests. In all, these impact surfaces represent a very small percentage of the Earth's surface, and essentially either fall into the hard or soft surface categories.

DEFORMATION OF WASTE PACKAGE ON IMPACT

The largest deformations occur when the sphere impacts against a hard surface. Impacts against concrete result both in deformation of the package and in spalling and/or total fracture of the concrete. Figures 47(a) and (b) show a reinforced concrete block, approximately 1.5 meters on a side weighing 8200 kilograms, before and after impact. It was impacted by a 0.61-meter-diameter sphere with a 1.59-centimeter-thick 304-stainless-steel shell containing a mockup of shielding materials. The sphere weighed 450 kilograms and impacted at about 300 meters per second. The concrete contained reinforced steel. The impacted package, although severely deformed, did not lose the integrity of its outer shell. The reinforced concrete block was totally destroyed. A more detailed discussion is given in reference 22. Package impact on a steel surface backed by concrete is another example of a hard-surface impact. Upon impact, the package must absorb all the kinetic energy since the steel surface is essentially nonyielding. Thus, the package deformation is more severe than for impact on concrete since the total fracture of the concrete block is a form of energy absorption.

The impact of a hollow steel sphere on reinforced concrete at 120 meters per second is described in reference 23. The sphere deformed and dimpled severely but did not rupture. The PISCES 2DL computer code was used to analyze the deformation of the sphere on impact and predicted it quite accurately (ref. 24).

The PISCES 2DL code was then used to simulate the impact of a contained waste disposal package with dimensions similar to those of a single package for high Earth orbit shown in table 19 (1) on a flat reinforced concrete surface (fig. 48) and (2) on a sharply stepped reinforced concrete surface (fig. 49). It appears that at 322 meters per second the package will survive impact on the flat concrete surface but that the impact shell might be breached on an unyielding stepped surface.

To compare these simulations with experiment, figure 50 shows the impact of a 2.61-meter-diameter package against a rock mounted upon a concrete block. Localized deformation occurred at the rock with overall deformation as a result of the concrete block backing the rock. Most impacts with sharp objects, however, are not as severe as first thought since the sharp object is generally not supported and therefore cannot cause a great deal of penetration before it begins to deform and loose its effectiveness.

One advantage of a hard-surface impact is that after the impact the package remains on the Earth's surface. Figure 50 shows a package that impacted into a concrete block and finally rested on the ground. In a soft surface the same impact would result in less deformation but complete penetration into the surface.

DEPTH OF PENETRATION FOR SOFT SURFACE

Figure 51 shows the impact of a 0.61-meter-diameter model weighing 364 kilograms on soil. The impact was at over 244 meters per second vertically downward into the soil (ref. 25). In this case the package buried itself almost 4.6 meters into the soil. This depth will vary for different soils. The soil in this case had a consistency of dense clay. The depth of penetration can be calculated for various sized packages impacting at different velocities. The empirical equation for predicting depth of penetration is presented in reference 21. Soil constants are given to various soils. For a spherical configuration the depth of the penetration is essentially proportional to its impact velocity and the square root of its weight per unit area.

No tests of impact on water have been conducted. This type of impact is considered a soft impact with the package sinking to the bottom of the ocean, lake, or river.

CONDITION OF WASTE PACKAGE FOLLOWING IMPACT AND PENETRATION

The amount of deformation of the package depends on the type of surface it impacts against and the package design itself. For instance, a hollow containment vessel will deform more than one that has been designed with material inside the package that is capable of absorbing some or all of the impact energy. Also, the hardness or yielding characteristics of the surface the package impacts against have a great deal to do with the amount of deformation. A steel surface backed by concrete is essentially unyielding. Therefore, all the energy of impact must be absorbed by the package.

Shape

The final shape of the package may be measured by δ/R (where δ is defined as the diameter of the vessel before impact minus the height of the vessel after impact and R is the vessel radius before impact). Typical values of δ/R of 0.90 have been measured for 0.6-meter-diameter spherical packages weighing 455 kilograms after impact at 300 meters per second against concrete. These packages contained energy-absorging material such as metal saddles and granular salt between the central payload and the containment vessel. For the package considered in this report the impact at 300 meters per second against a concrete block would result in a final shape similar to that shown in figure 52.

For a soil impact the amount of deformation will be less, as shown in figure 53. Its condition is characterized by minor overall deformation but with localized indentations. These indentations are a result of rocks in the soil that impact the package as it buries itself.

Temperature and Pressure

Impacted packages must dissipate the heat of the decaying fission products after the impact event. In a hard impact, the package remains on top of the surface of the Earth, and the heat can be dissipated through natural convection and radiation. Radiation becomes the major mode of heat removal when surface temperatures exceed 700 K. In a soft impact, the heat is removed by conduction from the package to the surrounding soil. Many soils are very poor conductors of heat, and the surface temperature of the package will become quite high - approaching the melting point of the soil. At this point, the conductivity of the soil will increase.

Typically, as the packages considered in this report reenter the Earth's atmosphere, their surface temperatures will be higher than the environment at point of impact. After impact these high surface temperatures result in heat transferred to the surrounding environment, and a surface cooling trend results. Later as the internal regions heat up, the surface temperature increases. Figure 54 is a plot of the surface temperature from reference 22 of a package after impact and burial into the Earth. The surface temperature initially shows a decrease since the heat is actually flowing into the surrounding soil. After 2 hours the internal generated heat begins to reach the surface, the amount of heat generated internally exceeds the amount being dissipated to the soil, and the surface temperature begins to increase.

During the entire period the pressure due to alpha emissions (helium) from actinide decay in and hydrogen release from hydride dissociation will increase with temperature. Eventually, if the soil cannot conduct the heat away to balance that being generated, the pressure-temperature relation will cause the vessel to fail. The waste products may or may not escape. This area needs further calculation and confirming experimentation.

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TABLE 1. - TOTAL MASSES OF SIGNIFICANT FISSION PRODUCT ELEMENTS CALCULATED TO BE PRESENT IN SPENT FUEL FROM DIABLO CANYON REFERENCE LIGHT-WATER REACTOR AND IN WASTES GENERATED BY REPROCESSING OF THIS FUEL[a]

[Power, 30 MW/metric ton; burnup, 33 000 MW-days/metric ton; flux, 2.91×10^{13} neutrons/cm^2-sec; charge, 0.]

Element	Waste decay times (processed after 90 days), days					
	90	150	365	3652	36 525	365 250
	Element concentration, g/metric ton of fuel					
H	7.20×10^{-2}	7.14×10^{-2}	6.90×10^{-2}	4.16×10^{-2}	2.61×10^{-4}	0
Ga	1.04×10^{-19}	0	0	0	0	0
Ge	3.79×10^{-1}	3.79×10^{-1}	3.79×10^{-1}	3.79×10^{-1}	3.79×10^{-1}	3.79×10^{-1}
As	8.78×10^{-2}	8.78×10^{-2}	8.78×10^{-2}	8.78×10^{-2}	8.78×10^{-2}	8.78×10^{-2}
Se	5.2×10^{1}	5.20×10^{1}	5.20×10^{1}	5.20×10^{1}	5.20×10^{1}	5.19×10^{1}
Br	1.5×10^{1}	1.51×10^{1}	1.51×10^{1}	1.51×10^{1}	1.51×10^{1}	1.51×10^{1}
Kr	3.74×10^{2}	3.73×10^{2}	3.72×10^{2}	3.60×10^{2}	3.45×10^{2}	3.45×10^{2}
Rb	3.33×10^{2}	3.33×10^{2}	3.34×10^{2}	3.46×10^{2}	3.62×10^{2}	3.62×10^{2}
Sr	9.02×10^{2}	8.96×10^{2}	8.85×10^{2}	7.78×10^{2}	3.97×10^{2}	3.51×10^{2}
Y	4.71×10^{2}	4.68×10^{2}	4.65×10^{2}	4.65×10^{2}	4.65×10^{2}	4.65×10^{2}
Zr	3.66×10^{3}	3.66×10^{3}	3.66×10^{3}	3.77×10^{3}	4.15×10^{3}	4.20×10^{3}
Nb	2.22×10^{1}	1.32×10^{1}	1.51	3.93×10^{-3}	3.45×10^{-2}	3.40×10^{-1}
Mo	3.42×10^{3}	3.44×10^{3}	3.46×10^{3}	3.47×10^{3}	3.47×10^{3}	3.47×10^{3}
Tc	8.35×10^{2}	8.35×10^{2}	8.35×10^{2}	8.35×10^{2}	8.35×10^{2}	8.32×10^{2}
Ru	2.28×10^{3}	2.26×10^{3}	2.22×10^{3}	2.14×10^{3}	2.14×10^{3}	2.14×10^{3}
Rh	3.84×10^{2}	3.89×10^{2}	3.92×10^{2}	3.92×10^{2}	3.92×10^{2}	3.92×10^{2}
Pd	1.28×10^{3}	1.29×10^{3}	1.33×10^{3}	1.41×10^{3}	1.41×10^{3}	1.41×10^{3}
Ag	6.01×10^{1}	6.01×10^{1}	6.01×10^{1}	6.00×10^{1}	6.00×10^{1}	6.00×10^{1}
Cd	8.35×10^{1}	8.35×10^{1}	8.36×10^{1}	8.36×10^{1}	8.36×10^{1}	8.36×10^{1}
In	1.20	1.20	1.20	1.20	1.20	1.20
Sn	5.16×10^{1}	5.15×10^{1}	5.15×10^{1}	5.15×10^{1}	5.15×10^{1}	5.14×10^{1}
Sb	1.80×10^{1}	1.77×10^{1}	1.66×10^{1}	1.07×10^{1}	1.00×10^{1}	1.00×10^{1}
Te	5.66×10^{2}	5.65×10^{2}	5.66×10^{2}	5.72×10^{2}	5.72×10^{2}	5.72×10^{2}
I	2.71×10^{2}	2.72×10^{2}	2.73×10^{2}	2.73×10^{2}	2.73×10^{2}	2.73×10^{2}
Xe	5.42×10^{3}	5.42×10^{3}	5.42×10^{3}	5.42×10^{3}	5.42×10^{3}	5.42×10^{3}
Cs	2.74×10^{3}	2.72×10^{3}	2.68×10^{3}	2.32×10^{3}	1.46×10^{3}	1.34×10^{3}
Ba	1.37×10^{3}	1.39×10^{3}	1.42×10^{3}	1.79×10^{3}	2.65×10^{3}	2.77×10^{3}
La	1.27×10^{3}	1.27×10^{3}	1.27×10^{3}	1.27×10^{3}	1.27×10^{3}	1.27×10^{3}
Ce	2.92×10^{3}	2.88×10^{3}	2.79×10^{3}	2.64×10^{3}	2.64×10^{3}	2.64×10^{3}
Pr	1.19×10^{3}	1.20×10^{3}	1.20×10^{3}	1.20×10^{3}	1.20×10^{3}	1.20×10^{3}
Nd	3.87×10^{3}	3.91×10^{3}	4.00×10^{3}	4.15×10^{3}	4.15×10^{3}	4.15×10^{3}
Pm	1.21×10^{2}	1.07×10^{2}	9.16×10^{1}	8.47	3.86×10^{-10}	0
Sm	8.03×10^{2}	8.08×10^{2}	8.23×10^{2}	9.04×10^{2}	8.92×10^{2}	8.73×10^{2}
Eu	1.82×10^{2}	1.82×10^{2}	1.80×10^{2}	1.64×10^{2}	1.54×10^{2}	1.72×10^{2}
Gd	1.02×10^{2}	1.03×10^{2}	1.05×10^{2}	1.23×10^{2}	1.54×10^{2}	1.54×10^{2}
Tb	1.82	1.80	1.78	1.77	1.77	1.77
Dy	9.93×10^{-1}	1.02	1.07	1.12	1.12	1.12
Ho	8.49×10^{-2}	8.49×10^{-2}	8.49×10^{-2}	8.49×10^{-2}	8.49×10^{-2}	8.49×10^{-2}
Er	2.79×10^{-2}	2.79×10^{-2}	2.79×10^{-2}	2.79×10^{-2}	2.79×10^{-2}	2.80×10^{-2}
Total	3.51×10^{4}	3.51×10^{4}	3.51×10^{4}	3.51×10^{4}	3.51×10^{4}	3.51×10^{4}

[a]Data from ref. 6.

TABLE 2. - CALCULATED RADIOACTIVITY LEVELS OF SIGNIFICANT FISSION PRODUCT NUCLIDES PRESENT IN SPENT FUEL FROM DIABLO CANYON REFERENCE LIGHT-WATER REACTOR AND IN WASTES GENERATED BY REPROCESSING OF THIS FUEL[a]

[Power, 30 MW/metric ton; burnup, 33 000 MW-days/metric ton; flux, 2.91×10^{13} neutrons/cm^2-sec; charge, 0.]

Nuclide	Waste decay times (processed after 90 days), days					
	90	150	365	3652	36 525	365 250
	Radioactivity, Ci/metric ton of fuel					
H^3	6.98×10^2	6.92×10^2	6.69×10^2	4.03×10^2	2.53	0
Kr^{85}	1.13×10^4	1.12×10^4	1.08×10^4	6.05×10^3	1.83×10^1	↓
Rb^{86}	1.72×10^1	1.85	6.49×10^{-4}	0	0	↓
Sr^{89}	2.14×10^5	9.60×10^5	5.47×10^3	5.12×10^{-16}	0	↓
Sr^{90}	7.69×10^4	7.66×10^4	7.55×10^4	6.04×10^4	6.56×10^3	1.50×10^{-6}
Y^{90}	7.69×10^4	7.66×10^4	7.55×10^4	6.05×10^4	6.57×10^3	1.50×10^{-6}
Y^{91}	3.22×10^5	1.59×10^5	1.26×10^4	1.88×10^{-13}	0	0
Zr^{93}	1.88	1.88	1.88	1.88	1.88	1.88
Zr^{95}	5.24×10^5	2.76×10^5	2.79×10^4	1.68×10^{-11}	0	0
Nb^{95M}	1.11×10^4	5.86×10^3	5.92×10^2	3.56×10^{-13}	0	0
Nb^{95}	8.69×10^5	5.18×10^5	5.93×10^4	1.89×10^{-5}	0	0
Tc^{99}	1.42×10^1	1.42×10^1	1.42×10^1	1.42×10^1	1.42×10^1	1.42×10^1
Ru^{103}	2.55×10^5	8.91×10^4	2.07×10^3	0	0	0
Rh^{103M}	2.55×10^5	8.91×10^4	2.07×10^3	0	↓	↓
Ru^{106}	4.59×10^5	4.10×10^5	2.73×10^5	5.50×10^2	↓	↓
Rh^{106}	4.59×10^5	4.10×10^5	2.73×10^5	5.50×10^2	↓	↓
Ag^{110M}	3.08×10^2	2.61×10^2	1.45×10^2	1.78×10^{-2}	↓	↓
Ag^{110}	4.01×10^1	3.40×10^1	1.89×10^1	2.31×10^{-3}	↓	↓
Cd^{115M}	1.17×10^2	4.43×10^1	1.39	0	↓	↓
Sn^{119M}	1.29×10^1	1.09×10^1	6.02	6.62×10^{-4}	↓	↓
Sn^{123M}	5.11×10^2	3.66×10^2	1.11×10^2	1.35×10^{-6}	↓	↓
Sb^{124}	1.73×10^2	8.63×10^1	7.20	2.33×10^{-16}	↓	↓
Sn^{125}	1.67×10^1	2.00×10^{-1}	2.61×10^{-8}	0	↓	↓
Sb^{125}	8.48×10^3	8.13×10^3	6.99×10^3	6.93×10^2	6.39×10^{-8}	↓
Te^{125M}	3.32×10^3	3.28×10^3	2.89×10^3	2.87×10^2	2.65×10^{-8}	↓
Te^{127M}	9.04×10^3	6.18×10^3	1.57×10^3	1.32×10^{-6}	0	↓
Te^{127}	8.94×10^3	6.11×10^3	1.56×10^3	1.30×10^{-6}	↓	↓
Te^{129M}	2.27×10^4	6.69×10^3	8.36×10^1	0	↓	↓
Te^{129}	1.46×10^4	4.29×10^3	5.36×10^1	↓	↓	↓
I^{131}	3.81×10^2	2.17	1.98×10^{-8}	↓	↓	↓

Nuclide	Waste decay times (processed after 90 days), days					
	90	150	365	3652	36 525	365 250
	Radioactivity, Ci/metric ton of fuel					
Xe^{131M}	1.06×10^2	3.27	1.08×10^{-5}			0
Cs^{134}	2.25×10^5	2.13×10^5	1.75×10^5	8.33×10^3	5.18×10^{-10}	0
Cs^{136}	5.10×10^2	2.08×10^1	2.18×10^{-4}	0	0	0
Cs^{137}	1.07×10^5	1.06×10^5	1.05×10^5	8.53×10^4	1.07×10^4	9.93×10^{-6}
Ba^{137M}	9.99×10^4	9.96×10^4	9.82×10^4	7.98×10^4	9.97×10^3	9.29×10^{-6}
Ba^{140}	1.11×10^4	4.30×10^2	3.78×10^{-3}	0	0	0
La^{140}	1.28×10^4	4.95×10^2	9.75×10^1	↓	↓	↓
Ce^{141}	2.05×10^5	5.67×10^4	5.70×10^2	↓	↓	↓
Pr^{143}	1.44×10^4	6.94×10^2	1.31×10^{-2}	↓	↓	↓
Ce^{144}	8.92×10^5	7.70×10^5	4.56×10^5	1.50×10^2	↓	↓
Pr^{144}	8.92×10^5	7.70×10^5	4.56×10^5	1.50×10^2	↓	↓
Nd^{147}	2.16×10^3	5.10×10^1	7.54×10^{-5}	0	↓	↓
Pm^{147}	1.04×10^5	9.94×10^4	8.51×10^4	7.87×10^3	3.59×10^{-7}	↓
Pm^{148M}	1.06×10^3	3.92×10^2	1.13×10^1	0	0	↓
Pm^{148}	8.82×10^1	3.15×10^1	9.07×10^{-1}	0	0	↓
Sm^{151}	1.15×10^3	1.15×10^3	1.15×10^3	1.07×10^3	5.21×10^2	4.00×10^{-1}
Eu^{152}	1.16×10^1	1.15×10^1	1.11×10^1	6.59	3.64×10^{-2}	0
Gd^{153}	2.66×10^1	2.24×10^1	1.21×10^1	9.85×10^{-4}	0	0
Eu^{154}	6.87×10^3	6.82×10^3	6.65×10^3	4.50×10^3	9.13×10^1	1.06×10^{-15}
Eu^{155}	6.79×10^3	6.37×10^3	5.09×10^3	1.62×10^2	1.75×10^{-13}	0
Eu^{156}	3.51×10^3	2.19×10^2	1.06×10^{-2}	0	0	↓
Tb^{160}	5.34×10^2	3.00×10^2	3.80×10^1	7.59×10^{-13}	↓	↓
Gd^{162}	1.86×10^2	1.66×10^2	1.11×10^2	2.16×10^{-1}	↓	↓
Tb^{162M}	1.86×10^2	1.66×10^2	1.11×10^2	2.16×10^{-1}	↓	↓
Subtotal	6.19×10^6	4.39×10^6	2.22×10^6	3.17×10^5	3.44×10^4	1.65×10^1
Total	6.19×10^6	4.39×10^6	2.22×10^6	3.17×10^5	3.44×10^4	2.07×10^1

[a]Data from ref. 6.

TABLE 3. - CALCULATED THERMAL POWER OF SIGNIFICANT FISSION PRODUCT NUCLIDES PRESENT IN SPENT FUEL FROM DIABLO CANYON REFERFNCE LIGHT-WATER REACTOR AND IN WASTES GENFRATED BY REPROCESSING OF THIS FUEL[a]

[Power, 30 MW/metric ton; burnup, 33 000 MW-days/metric ton; flux, 2.91×10^{13} neutrons/cm^2-sec; charge, 0.]

Nuclide	Waste decay times (processed after 90 days), days					
	90	150	365	3652	36 525	365 250
	Thermal power, W/metric ton of fuel					
H^{3}	2.48×10^{-2}	2.46×10^{-2}	2.38×10^{-2}	1.43×10^{-2}	8.99×10^{-5}	0
Kr^{85}	1.82×10^{1}	1.89×10^{1}	1.73×10^{1}	9.71	2.95×10^{-2}	
Rb^{86}	8.08×10^{-2}	8.69×10^{-3}	3.05×10^{-6}	0	0	
Sr^{89}	7.69×10^{2}	3.45×10^{2}	1.97×10^{1}	1.84×10^{-18}	0	
Sr^{90}	1.00×10^{2}	9.98×10^{1}	9.84×10^{1}	7.58×10^{1}	8.56	1.95×10^{-9}
Y^{90}	4.40×10^{2}	4.38×10^{2}	4.32×10^{2}	3.46×10^{2}	3.76×10^{1}	8.57×10^{-9}
Y^{91}	1.23×10^{3}	6.04×10^{2}	4.79×10^{1}	7.15×10^{-16}	0	0
Zr^{95}	2.74×10^{4}	1.45×10^{3}	1.46×10^{2}	8.79×10^{-14}		
Nb^{95M}	1.55×10^{1}	8.17	8.25×10^{-1}	4.96×10^{-16}		
Nb^{95}	4.17×10^{3}	2.48×10^{3}	2.85×10^{2}	9.05×10^{-8}		
Tc^{99}	9.62×10^{-3}	9.62×10^{-3}	9.62×10^{-3}	9.62×10^{-3}	9.61×10^{-3}	9.58×10^{-3}
Ru^{103}	8.31×10^{2}	2.91×10^{2}	6.75	0	0	0
Rh^{103M}	6.04×10^{1}	2.11×10^{1}	4.90×10^{-1}	0		
Ru^{106}	2.72×10^{1}	2.43×10^{1}	1.62×10^{1}	3.26×10^{-2}		
Rh^{106}	4.44×10^{3}	3.96×10^{3}	2.64×10^{3}	5.31		
Ag^{110M}	4.97	4.22	2.34	2.87×10^{-4}		
Ag^{110}	2.91×10^{-1}	2.47×10^{-1}	1.37×10^{-1}	1.68×10^{-5}		
Ag^{111}	2.32×10^{-2}	9.07×10^{-5}	2.13×10^{-13}	0		
Cd^{115M}	4.75×10^{-1}	1.80×10^{-1}	5.64×10^{-3}	0		
Sn^{119M}	6.81×10^{-3}	5.77×10^{-3}	3.18×10^{-3}	3.49×10^{-7}		
Sn^{123M}	1.74	1.25	3.79×10^{-1}	4.80×10^{-9}		
Sb^{124}	2.33	1.17	9.73×10^{-2}	3.15×10^{-18}		
Sn^{125}	1.01×10^{-1}	1.21×10^{-3}	1.58×10^{-10}	0		
Sb^{125}	2.84×10^{1}	2.73×10^{1}	2.34×10^{1}	2.33	2.14×10^{-10}	
Te^{125M}	2.85	2.82	2.48	2.47×10^{-1}	2.28×10^{-11}	
Sb^{126}	9.25×10^{-3}	6.11×10^{-3}	5.99×10^{-3}	5.99×10^{-3}	5.99×10^{-3}	5.95×10^{-3}
Te^{127M}	4.99	3.40	8.68×10^{-1}	7.25×10^{-10}	0	0
Te^{127}	1.46×10^{1}	9.95	2.54	2.12×10^{-9}		
Te^{129M}	4.50×10^{1}	1.33×10^{1}	1.65×10^{1}	0		
Te^{129}	5.29×10^{1}	1.56×10^{1}	1.94×10^{-1}	0		

Nuclide	Waste decay times (processed after 90 days), days					
	90	150	365	3652	36 525	365 250
	Thermal power, W/metric ton of fuel					
I^{131}	1.57	8.94×10^{-3}	8.15×10^{-11}	0	0	0
Xe^{131M}	1.03×10^{-1}	3.18×10^{-3}	1.05×10^{-3}	0	0	
Cs^{134}	2.36×10^{3}	2.24×10^{3}	1.83×10^{3}	8.74×10^{1}	5.43×10^{-12}	
Cs^{136}	7.89	3.22×10^{-1}	3.38×10^{-6}	0	0	
Cs^{137}	1.73×10^{2}	1.72×10^{2}	1.70×10^{2}	1.38×10^{2}	1.73×10^{1}	1.61×10^{-8}
Ba^{137M}	3.92×10^{2}	3.91×10^{2}	3.85×10^{2}	3.13×10^{2}	3.91×10^{1}	3.64×10^{-8}
Ba^{140}	3.74×10^{1}	1.45	1.27×10^{-5}	0	0	0
La^{140}	2.12×10^{2}	8.21	1.62			
Ce^{141}	4.02×10^{2}	1.12×10^{2}	1.12			
Pr^{143}	3.13×10^{1}	1.51	2.84×10^{-5}			
Ce^{144}	7.82×10^{2}	6.76×10^{2}	4.00×10^{2}	1.31×10^{-1}		
Pr^{144}	6.63×10^{3}	5.73×10^{3}	3.39×10^{3}	1.11		
Nd^{147}	6.05	1.43×10^{-1}	2.11×10^{-7}	0		
Pm^{147}	5.35×10^{1}	5.13×10^{1}	4.39×10^{1}	4.06	1.85×10^{-10}	
Pm^{148M}	1.34×10^{1}	4.98	1.43×10^{-1}	0	0	
Pm^{148}	7.21×10^{-1}	2.58×10^{-1}	7.42×10^{-3}	0	0	
Sm^{151}	2.01	2.01	2.00	1.86	9.07×10^{-1}	6.97×10^{4}
Eu^{152}	1.41×10^{-1}	1.40×10^{-1}	1.35×10^{-1}	8.05×10^{-2}	4.45×10^{-4}	0
Gd^{153}	3.93×10^{-2}	3.22×10^{-2}	1.74×10^{-2}	1.42×10^{-6}	0	0
Eu^{154}	$6.44\times10^{-}$	6.39×10^{1}	6.23×10^{1}	4.22×10^{1}	8.55×10^{-1}	9.90×10^{-18}
Eu^{155}	5.71	5.36	4.28	1.36×10^{-1}	1.47×10^{-16}	0
Eu^{156}	3.70×10^{1}	2.31	1.12×10^{-4}	0	0	
Tb^{160}	4.50	2.53	3.20×10^{-1}	6.39×10^{-15}		
Gd^{162}	6.34×10^{-1}	5.66×10^{-1}	3.76×10^{-1}	7.36×10^{-4}		
Tb^{162M}	1.25	1.11	7.41×10^{-1}	1.45×10^{-3}		
Subtotal	2.62×10^{4}	1.93×10^{4}	1.00×10^{4}	1.03×10^{3}	1.04×10^{2}	1.62×10^{-2}
Total	2.62×10^{4}	1.93×10^{4}	1.00×10^{4}	1.03×10^{3}	1.04×10^{2}	1.77×10^{-2}

[a]Data from ref. 6.

TABLE 4. - CALCULATED MASSES OF ACTINIDE ISOTOPES PRESENT IN WASTES

GENERATED BY REPROCESSING OF SPENT FUEL FROM DIABLO CANYON

REFERENCE LIGHT-WATER REACTOR[a]

[Power, 30 MW/metric ton; burnup, 33 000 MW-days/metric ton; flux, 2.91×10^{13} neutrons/cm^2-sec.]

Nuclide	Charge	Waste decays times (processed after 90 days), days					
		90	150	365	3652	36 525	365 250
		Nuclide concentration, g/metric ton of fuel					
Th^{228}	0	1.27×10^{-6}	1.20×10^{-6}	9.80×10^{-7}	1.58×10^{-7}	6.35×10^{-8}	1.10×10^{-11}
Th^{229}		6.06×10^{-8}	6.06×10^{-8}	6.06×10^{-8}	6.09×10^{-8}	6.37×10^{-8}	9.00×10^{-8}
Th^{230}		6.80×10^{-6}	6.80×10^{-6}	6.84×10^{-6}	1.28×10^{-5}	5.43×10^{-4}	1.59×10^{-2}
Th^{231}		3.22×10^{-10}	1.61×10^{-12}	1.61×10^{-12}	1.61×10^{-12}	1.61×10^{-12}	1.64×10^{-12}
Th^{232}		2.48×10^{-4}	2.48×10^{-4}	2.48×10^{-4}	2.54×10^{-4}	3.06×10^{-4}	8.85×10^{-4}
Th^{233}		0	0	0	0	0	0
Pa^{231}		2.03×10^{-6}	2.03×10^{-6}	2.03×10^{-6}	2.04×10^{-6}	2.07×10^{-6}	2.37×10^{-6}
Pa^{232}		0	0	0	0	0	0
Pa^{233}		7.78×10^{-8}	1.71×10^{-8}	7.41×10^{-11}			
Pa^{234M}		0	0	0			
Pa^{234}		0	0	0			
U^{232}		1.17×10^{-6}	1.35×10^{-6}	1.96×10^{-6}	5.17×10^{-6}	2.37×10^{-6}	4.12×10^{-10}
U^{233}		8.64×10^{-6}	8.70×10^{-6}	8.72×10^{-6}	8.72×10^{-6}	8.71×10^{-6}	8.68×10^{-6}
U^{234}		1.10×10^{-2}	1.29×10^{-2}	2.93×10^{-2}	4.53×10^{-1}	3.48	6.68
U^{235}	3.30×10^{4}	3.98×10^{1}	3.98×10^{1}	3.98×10^{1}	3.98×10^{1}	3.98×10^{1}	4.06×10^{1}
U^{236}	0	2.04×10^{1}	2.04×10^{1}	2.04×10^{1}	2.04×10^{1}	2.07×10^{1}	2.43×10^{1}
U^{237}	0	8.22×10^{-6}	1.73×10^{-8}	4.47×10^{-18}	0	0	0
U^{238}	9.67×10^{5}	4.72×10^{3}	4.72×10^{3}	4.72×10^{3}	4.72×10^{3}	4.72×10^{3}	4.72×10^{3}
U^{239}	0	0	0	0	0	0	0
Np^{236}		0	0	0	0	0	0
Np^{237}		7.62×10^{2}	7.62×10^{2}	7.62×10^{2}	7.62×10^{2}	7.70×10^{2}	8.06×10^{2}
Np^{238}		3.52×10^{-13}	8.81×10^{-22}	0	0	0	0
Np^{239}		7.48×10^{-5}	7.48×10^{-5}	7.48×10^{-5}	7.47×10^{-5}	7.41×10^{-5}	6.83×10^{-5}
Pu^{236}		4.91×10^{-6}	4.72×10^{-6}	4.09×10^{-6}	4.58×10^{-7}	1.43×10^{-16}	0
Pu^{238}		8.26×10^{-1}	2.12	4.76	6.04	3.07	7.44×10^{-3}
Pu^{239}		2.69×10^{1}	2.69×10^{1}	2.69×10^{1}	2.70×10^{1}	2.77×10^{1}	3.38×10^{1}
Pu^{240}		1.08×10^{1}	1.10×10^{1}	1.17×10^{1}	2.03×10^{1}	4.02×10^{1}	3.73×10^{1}
Pu^{241}		5.07	5.03	4.87	3.02	2.48×10^{-2}	3.58×10^{-23}
Pu^{242}		1.75	1.75	1.75	1.75	1.77	1.82
Pu^{243}		0	0	0	0	0	0
Am^{241}		5.30×10^{1}	5.30×10^{1}	5.31×10^{1}	5.43×10^{1}	5.00×10^{1}	1.28×10^{1}
Am^{242M}		4.14×10^{-1}	4.14×10^{-1}	4.13×10^{-1}	3.96×10^{-1}	2.63×10^{-1}	4.33×10^{-3}
Am^{242}		4.97×10^{-6}	4.97×10^{-6}	4.95×10^{-6}	4.75×10^{-6}	3.15×10^{-6}	5.20×10^{-8}
Am^{243}		9.04×10^{1}	9.04×10^{1}	9.05×10^{1}	9.03×10^{1}	8.96×10^{1}	8.26×10^{1}
Am^{244}		0	0	0	0	0	0
Cm^{242}		5.83	4.52	1.81	9.62×10^{-4}	6.32×10^{-4}	1.04×10^{-5}
Cm^{243}		8.76×10^{-2}	8.72×10^{-2}	8.61×10^{-2}	7.09×10^{-2}	1.01×10^{-2}	3.45×10^{-11}
Cm^{244}		3.09×10^{1}	3.07×10^{1}	3.00×10^{1}	2.13×10^{1}	6.77×10^{-1}	7.32×10^{-16}
Subtotal	1.00×10^{6}	5.76×10^{3}	5.76×10^{3}	5.76×10^{3}	5.76×10^{3}	5.76×10^{3}	5.76×10^{3}
Total	1.00×10^{6}	5.76×10^{3}	5.76×10^{3}	5.76×10^{3}	5.76×10^{3}	5.76×10^{3}	5.76×10^{3}

[a]Data from ref. 6.

TABLE 5. - CALCULATED RADIOACTIVITY OF ACTINIDE ISOTOPES PRESENT IN WASTES GENERATED BY REPROCESSING OF SPENT FUEL FROM DIABLO CANYON REFERENCE LIGHT-WATER REACTOR[a]

[Power, 30 MW/metric ton; burnup, 33 000 MW-days/metric ton; flux, 2.91×10^{-3} neutrons/cm^2-sec.]

Nuclide	Charge	Waste decay times (processed after 90 days), days					
		90	150	365	3652	36 525	365 250
		Radioactivity, Ci/metric ton of fuel					
Th^{228}	0	1.05×10^{-3}	9.88×10^{-4}	8.05×10^{-4}	1.29×10^{-4}	5.21×10^{-5}	9.07×10^{-9}
Th^{229}		1.30×10^{-8}	1.30×10^{-8}	1.30×10^{-8}	1.30×10^{-8}	1.36×10^{-8}	1.93×10^{-8}
Th^{230}		1.32×10^{-7}	1.32×10^{-7}	1.33×10^{-7}	2.49×10^{-7}	1.05×10^{-5}	3.08×10^{-4}
Th^{231}		1.70×10^{-4}	8.52×10^{-7}	8.52×10^{-7}	8.53×10^{-7}	8.54×10^{-7}	8.71×10^{-7}
Th^{232}		2.71×10^{-11}	2.71×10^{-11}	2.72×10^{-11}	2.77×10^{-11}	3.35×10^{-11}	9.68×10^{-11}
Th^{233}		0	0	0	0	0	0
Pa^{231}		9.69×10^{-8}	9.69×10^{-8}	9.69×10^{-8}	9.71×10^{-8}	9.85×10^{-8}	1.13×10^{-7}
Pa^{232}		0	0	0	0	0	0
Pa^{233}		1.59×10^{-3}	3.49×10^{-4}	1.52×10^{-6}			
Pa^{234M}		0	0	0			
Pa^{234}		0	0	0			
U^{232}		2.50×10^{-5}	2.90×10^{-5}	4.20×10^{-5}	1.11×10^{-4}	5.08×10^{-5}	8.83×10^{-9}
U^{233}		8.19×10^{-8}	8.24×10^{-8}	8.26×10^{-8}	8.26×10^{-8}	8.26×10^{-8}	8.23×10^{-8}
U^{234}		6.83×10^{-5}	7.99×10^{-5}	1.81×10^{-4}	2.80×10^{-3}	3.15×10^{-2}	4.14×10^{-2}
U^{235}	7.07×10^{-4}	8.52×10^{-7}	8.52×10^{-7}	8.52×10^{-7}	8.53×10^{-7}	8.54×10^{-7}	8.71×10^{-7}
U^{236}	0	1.29×10^{-3}	1.29×10^{-3}	1.29×10^{-3}	1.29×10^{-3}	1.32×10^{-3}	1.54×10^{-3}
U^{237}	0	6.71×10^{-1}	1.42×10^{-3}	3.65×10^{-13}	0	0	0
U^{238}	3.22×10^{-1}	1.57×10^{-3}	1.57×10^{-3}	1.57×10^{-3}	1.57×10^{-3}	1.57×10^{-3}	1.57×10^{-3}
U^{239}	0	0	0	0	0	0	0
Np^{236}		0	0	0	0	0	0
Np^{237}		5.37×10^{-1}	5.37×10^{-1}	5.37×10^{-1}	5.38×10^{-1}	5.43×10^{-1}	5.68×10^{-1}
Np^{238}		9.19×10^{-8}	2.30×10^{-16}	0	0	0	0
Np^{239}		1.74×10^{1}	1.74×10^{1}	1.74×10^{1}	1.74×10^{1}	1.72×10^{1}	1.59×10^{1}
Pu^{236}		2.61×10^{-3}	2.51×10^{-3}	2.18×10^{-3}	2.44×10^{-4}	7.60×10^{-14}	0
Pu^{238}		1.39×10^{1}	3.57×10^{1}	8.04×10^{1}	1.02×10^{2}	5.19×10^{1}	1.26×10^{-1}
Pu^{239}		1.65	1.65	1.65	1.66	1.70	2.08
Pu^{240}		2.39	2.43	2.58	4.48	8.87	8.22
Pu^{241}		5.79×10^{2}	5.74×10^{2}	5.65×10^{2}	3.44×10^{2}	2.84	4.09×10^{-21}
Pu^{242}		6.81×10^{-3}	6.81×10^{-3}	6.81×10^{-3}	6.82×10^{-3}	6.92×10^{-3}	7.09×10^{-3}
Pu^{243}		0	0	0	0	0	0
Am^{241}		1.72×10^{2}	1.72×10^{2}	1.72×10^{2}	1.76×10^{2}	1.62×10^{2}	4.15×10^{1}
Am^{242M}		4.02	4.02	4.01	3.85	2.55	4.21×10^{-2}
Am^{242}		4.02	4.02	4.01	3.85	2.55	4.21×10^{-2}
Am^{243}		1.74×10^{1}	1.74×10^{1}	1.74×10^{1}	1.74×10^{1}	1.72×10^{1}	1.59×10^{1}
Am^{244}		0	0	0	0	0	0
Cm^{242}		1.93×10^{4}	1.50×10^{4}	6.00×10^{3}	3.18	2.09	3.46×10^{-2}
Cm^{243}		4.03	4.01	3.96	3.26	4.64×10^{-1}	1.58×10^{-9}
Cm^{244}		2.50×10^{3}	2.49×10^{3}	2.43×10^{3}	1.72×10^{3}	5.49×10^{1}	5.92×10^{-14}
Subtotal	3.23×10^{-1}	2.26×10^{4}	1.83×10^{4}	9.29×10^{3}	2.40×10^{3}	3.25×10^{2}	8.45×10^{1}
Total	3.23×10^{-1}	2.26×10^{4}	1.83×10^{4}	9.29×10^{3}	2.40×10^{3}	3.25×10^{2}	8.45×10^{1}

[a]Data from ref. 6.

TABLE 6. - CALCULATED THERMAL POWER OF ACTINIDE ISOTOPES PRESENT IN WASTES GENERATED BY REPROCESSING OF SPEND FUEL FROM DIABLO CANYON REFERENCE LIGHT-WATER REACTOR[a]

[Power, 30 MW/metric ton; burnup, 33 000 MW-days/metric ton; flux, 2.91×10^{13} neutrons/cm^2-sec.]

Nuclide	Charge	Waste decay times (processed after 90 days), days					
		90	150	365	3652	36 525	365 250
		Thermal power, W/metric ton of fuel					
Th^{228}	0	3.43×10^{-5}	3.24×10^{-5}	2.64×10^{-5}	4.24×10^{-6}	1.71×10^{-6}	2.97×10^{-10}
Th^{229}	↓	3.92×10^{-10}	3.92×10^{-10}	2.92×10^{-10}	3.94×10^{-10}	4.12×10^{-10}	5.82×10^{-10}
Th^{230}	↓	3.73×10^{-9}	3.74×10^{-9}	3.75×10^{-9}	7.03×10^{-9}	2.98×10^{-7}	8.71×10^{-6}
Th^{231}	↓	2.35×10^{-7}	1.18×10^{-9}	1.18×10^{-9}	1.18×10^{-9}	1.18×10^{-9}	1.20×10^{-9}
Th^{232}	↓	6.56×10^{-13}	6.56×10^{-13}	6.57×10^{-13}	6.71×10^{-13}	8.10×10^{-13}	2.34×10^{-12}
Th^{233}	↓	0	0	0	0	0	0
Pa^{231}	↓	2.96×10^{-9}	2.96×10^{-9}	2.96×10^{-9}	2.96×10^{-9}	3.01×10^{-9}	3.45×10^{-9}
Pa^{232}	↓	0	0	0	0	0	0
Pa^{233}	↓	4.04×10^{-6}	8.85×10^{-7}	3.84×10^{-9}	↓	↓	↓
Pa^{234M}	↓	0	0	0	↓	↓	↓
Pa^{234}	↓	0	0	0	↓	↓	↓
U^{232}	↓	8.01×10^{-7}	9.29×10^{-7}	1.35×10^{-6}	3.55×10^{-6}	1.63×10^{-6}	2.83×10^{-10}
U^{233}	↓	2.38×10^{-9}	2.40×10^{-9}	2.40×10^{-9}	2.40×10^{-9}	2.40×10^{-9}	2.39×10^{-9}
U^{234}	↓	1.97×10^{-6}	2.30×10^{-6}	5.22×10^{-6}	8.07×10^{-5}	6.19×10^{-4}	1.13×10^{-3}
U^{235}	1.96×10^{-5}	2.37×10^{-8}	2.37×10^{-8}	2.37×10^{-8}	2.37×10^{-8}	2.37×10^{-8}	2.42×10^{-8}
U^{236}	0	3.51×10^{-5}	3.51×10^{-5}	3.51×10^{-5}	3.51×10^{-5}	3.57×10^{-5}	4.18×10^{-5}
U^{237}	0	1.44×10^{-3}	3.04×10^{-6}	7.83×10^{-16}	0	0	0
U^{238}	8.15×10^{-3}	3.98×10^{-5}	3.98×10^{-5}	3.98×10^{-5}	3.98×10^{-5}	3.98×10^{-5}	3.98×10^{-5}
U^{239}	0	0	0	0	0	0	0
Np^{236}	↓	0	0	↓	↓	↓	↓
Np^{237}	↓	0	0	↓	↓	↓	↓
Np^{238}	↓	4.72×10^{-10}	1.18×10^{-18}	↓	↓	↓	↓
Np^{239}	↓	5.16×10^{-2}	5.16×10^{-2}	5.16×10^{-2}	5.16×10^{-2}	5.11×10^{-2}	4.71×10^{-2}
Pu^{236}	↓	9.09×10^{-5}	8.73×10^{-5}	7.57×10^{-5}	8.48×10^{-6}	2.64×10^{-15}	0
Pu^{238}	↓	4.62×10^{-1}	1.18	2.66	3.38	1.72	4.16×10^{-3}
Pu^{239}	↓	5.13×10^{-2}	5.13×10^{-2}	5.13×10^{-2}	5.15×10^{-2}	5.28×10^{-2}	6.45×10^{-2}
Pu^{240}	↓	7.45×10^{-2}	7.58×10^{-2}	8.04×10^{-2}	1.39×10^{-1}	2.76×10^{-1}	2.56×10^{-1}
Pu^{241}	↓	2.40×10^{-2}	2.38×10^{-2}	2.31×10^{-2}	1.43×10^{-2}	1.18×10^{-4}	1.70×10^{-25}
Pu^{242}	↓	2.01×10^{-4}	2.01×10^{-4}	2.01×10^{-4}	2.01×10^{-4}	2.04×10^{-4}	2.09×10^{-4}
Pu^{243}	↓	0	0	0	0	0	0
Am^{241}	↓	5.73	5.73	5.75	5.87	5.41	1.39
Am^{242M}	↓	1.15×10^{-3}	1.14×10^{-3}	1.14×10^{-3}	1.10×10^{-3}	7.27×10^{-4}	1.20×10^{-5}
Am^{242}	↓	5.37×10^{-3}	5.36×10^{-3}	5.35×10^{-3}	5.13×10^{-3}	3.41×10^{-3}	5.63×10^{-5}
Am^{243}	↓	5.61×10^{-1}	5.61×10^{-1}	5.61×10^{-1}	5.60×10^{-1}	5.56×10^{-1}	5.12×10^{-1}
Am^{244}	↓	0	0	0	0	0	0
Cm^{242}	↓	7.11×10^{2}	5.15×10^{2}	2.21×10^{2}	1.17×10^{-1}	7.72×10^{-2}	1.27×10^{-3}
Cm^{243}	↓	1.47×10^{-1}	1.47×10^{-1}	1.45×10^{-1}	1.19×10^{-1}	1.69×10^{-2}	5.79×10^{-11}
Cm^{244}	↓	8.75×10^{1}	8.79×10^{1}	8.50×10^{1}	6.03×10^{1}	1.92	2.07×10^{-15}
Subtotal	8.17×10^{-3}	8.06×10^{2}	6.46×10^{2}	3.15×10^{2}	7.06×10^{1}	1.01×10^{1}	2.27
Total	8.17×10^{-3}	8.06×10^{2}	6.46×10^{2}	3.15×10^{2}	7.06×10^{1}	1.01×10^{1}	2.27

[a]Data from ref. 6.

TABLE 7. - CALCULATED MASSES OF ACTINIDE ISOTOPES PRESENT IN WASTES GENERATED BY REPROCESSING OF SPENT FUEL FROM ATOMICS INTERNATIONAL REFERENCE OXIDE LIQUID-METAL-COOLED FAST-BREEDER REACTOR[a]

[Power, 58.23 MW/metric ton; burnup, 32 977 MW-days/metric ton; flux, 2.65×10^{15} neutrons/cm^2-sec.]

Nuclide	Charge	Waste decay times (processed after 30 days), days					
		30	365	1096	3652	36 525	365 250
		Nuclide concentration, g/metric ton of fuel					
Th^{228}	0	5.78×10^{-7}	4.22×10^{-7}	2.33×10^{-7}	1.06×10^{-7}	4.76×10^{-8}	8.27×10^{-12}
Th^{229}		1.20×10^{-8}	1.20×10^{-8}	1.20×10^{-8}	1.21×10^{-8}	1.35×10^{-8}	2.70
Th^{230}		1.89×10^{-5}	1.91×10^{-5}	2.07×10^{-5}	4.09×10^{-5}	1.98×10^{-3}	6.64×10^{-2}
Th^{231}		5.74×10^{-11}	2.87×10^{-13}	2.88×10^{-13}	2.90×10^{-13}	3.20×10^{-13}	6.21×10^{-13}
Th^{232}		1.16×10^{-6}	1.17×10^{-6}	1.18×10^{-6}	1.23×10^{-6}	3.21×10^{-6}	1.61×10^{-4}
Th^{233}		0	0	0	0	0	0
Pa^{231}		5.94×10^{-7}	5.95×10^{-7}	5.05×10^{-7}	5.95×10^{-7}	6.01×10^{-7}	6.89×10^{-7}
Pa^{232}		5.92×10^{-17}	0	0	0	0	0
Pa^{233}		1.32×10^{-9}	2.75×10^{-13}	2.56×10^{-21}			
Pa^{234M}		0	0	0			
Pa^{234}		0	0	0			
U^{232}		6.98×10^{-7}	1.45×10^{-6}	2.58×10^{-6}	3.87×10^{-6}	1.78×10^{-6}	3.09×10^{-10}
U^{233}		4.02×10^{-6}	4.02×10^{-6}	4.02×10^{-6}	4.02×10^{-6}	4.02×10^{-6}	4.00×10^{-6}
U^{234}		4.23×10^{-2}	1.29×10^{-1}	4.53×10^{-1}	1.63	1.29×10^{1}	2.92×10^{1}
U^{235}	1.46×10^{3}	7.10	7.11	7.13	7.18	7.91	1.54×10^{1}
U^{236}	0	1.88×10^{-1}	1.97×10^{-1}	2.17×10^{-1}	2.87×10^{-1}	1.27	1.09×10^{1}
U^{237}	0	5.23×10^{-4}	6.00×10^{-19}	0	0	0	0
U^{238}	9.20×10^{5}	4.39×10^{3}	4.39×10^{3}	4.39×10^{3}	4.39×10^{3}	4.39×10^{3}	4.39×10^{3}
U^{239}	0	0	0	0	0	0	0
Np^{236}		7.05×10^{-16}	0	0	0	0	0
Np^{237}		1.26×10^{2}	1.27×10^{2}	1.28×10^{2}	1.34×10^{2}	1.96×10^{2}	5.17×10^{2}
Np^{238}		4.54×10^{-6}	0	0	0	0	0
Np^{239}		3.10×10^{-2}	2.13×10^{-4}	2.13×10^{-4}	2.13×10^{-4}	2.11×10^{-4}	1.95×10^{-4}
Pu^{236}		3.86×10^{-6}	3.09×10^{-6}	1.90×10^{-6}	3.46×10^{-7}	1.08×10^{-16}	0
Pu^{238}	9.40×10^{2}	3.32	1.80×10^{1}	2.22×10^{1}	2.15×10^{1}	1.23×10^{1}	1.11×10^{-1}
Pu^{239}	4.69×10^{4}	2.88×10^{2}	2.88×10^{2}	2.88×10^{2}	2.88×10^{2}	2.90×10^{2}	3.02×10^{2}
Pu^{240}	1.88×10^{4}	9.65×10^{1}	9.70×10^{1}	9.81×10^{1}	1.01×10^{2}	1.10×10^{2}	1.01×10^{2}
Pu^{241}	9.43×10^{3}	2.63×10^{1}	2.50×10^{1}	2.25×10^{1}	1.55×10^{1}	1.28×10^{-1}	1.84×10^{-22}
Pu^{242}	3.17×10^{3}	1.63×10^{1}	1.63×10^{1}	1.63×10^{1}	1.64×10^{1}	1.69×10^{1}	1.79×10^{1}
Pu^{243}	0	0	0	0	0	0	0
Am^{241}		4.84×10^{2}	4.84×10^{2}	4.85×10^{2}	4.87×10^{2}	4.39×10^{2}	1.12×10^{2}
Am^{242M}		8.91	8.88	8.80	8.52	5.65	9.33×10^{-2}
Am^{242}		1.07×10^{-4}	1.07×10^{-4}	1.06×10^{-4}	1.02×10^{-4}	6.79×10^{-5}	1.12×10^{-6}
Am^{243}		2.58×10^{2}	2.59×10^{2}	2.58×10^{2}	2.57×10^{2}	2.55×10^{2}	2.35×10^{2}
Am^{244}		0	0	0	0	0	0
Cm^{242}		1.98×10^{1}	4.78	2.34×10^{-1}	2.06×10^{-2}	1.36×10^{-2}	2.25×10^{-4}
Cm^{243}		8.40×10^{-1}	8.24×10^{-1}	7.89×10^{-1}	6.78×10^{-1}	9.65×10^{-2}	3.29×10^{-10}
Cm^{244}		1.53×10^{1}	1.48×10^{1}	1.37×10^{1}	1.05×10^{1}	3.33×10^{-1}	3.60×10^{-16}
Subtotal	1.00×10^{6}	5.74×10^{3}	5.74×10^{3}	5.74×10^{3}	5.74×10^{3}	5.74×10^{3}	5.74×10^{3}
Total	1.00×10^{6}	5.74×10^{3}	5.74×10^{3}	5.74×10^{3}	5.74×10^{3}	5.74×10^{3}	5.74×10^{3}

[a]Data from ref. 6.

TABLE 8. - CALCULATED RADIOACTIVITY OF ACTINIDE ISOTOPES PRESENT IN WASTES GENERATED BY REPROCESSING OF SPENT FUEL FROM ATOMS INTERNATIONAL REFERENCE OXIDE LIQUID-METAL-COOLED FAST-BREEDER REACTOR[a]

[Power, 58.23 MW/metric ton; burnup, 32 977 MW-days/metric ton; flux, 2.65×10^{15} neutrons/cm^2-sec.]

Nuclide	Charge	Waste decay times (processed after 30 days), days					
		30	365	1096	3652	36 525	365 250
		Radioactivity, Ci/metric ton of fuel					
Th^{228}	0	4.74×10^{-4}	3.47×10^{-4}	1.91×10^{-4}	8.71×10^{-5}	3.91×10^{-5}	6.80×10^{-9}
Th^{229}		2.56×10^{-9}	2.56×10^{-9}	2.57×10^{-9}	2.59×10^{-9}	2.00×10^{-9}	5.77×10^{-9}
Th^{230}		3.68×10^{-7}	3.71×10^{-7}	4.02×10^{-7}	7.94×10^{-7}	3.85×10^{-5}	1.29×10^{-3}
Th^{231}		3.04×10^{-5}	1.52×10^{-7}	1.53×10^{-7}	1.54×10^{-7}	1.70×10^{-7}	3.29×10^{-7}
Th^{232}		1.27×10^{-13}	1.28×10^{-13}	1.29×10^{-13}	1.35×10^{-13}	3.51×10^{-13}	1.76×10^{-11}
Th^{233}		0	0	0	0	0	0
Pa^{231}		2.83×10^{-8}	2.83×10^{-8}	2.83×10^{-8}	2.84×10^{-8}	2.86×10^{-8}	3.28×10^{-8}
Pa^{232}		2.52×10^{-11}	0	0	0	0	0
Pa^{233}		2.69×10^{-5}	5.62×10^{-9}	5.23×10^{-17}			
Pa^{234M}		0	0	0			
Pa^{234}		0	0	0			
U^{232}		1.50×10^{-5}	3.10×10^{-5}	5.52×10^{-5}	8.29×10^{-5}	3.80×10^{-5}	6.62×10^{-9}
U^{233}		3.81×10^{-8}	3.81×10^{-8}	3.81×10^{-8}	3.81×10^{-8}	3.81×10^{-8}	3.79×10^{-8}
U^{234}		2.62×10^{-4}	8.00×10^{-4}	2.80×10^{-3}	1.01×10^{-2}	8.01×10^{-2}	1.81×10^{-1}
U^{235}	3.12×10^{-5}	1.52×10^{-7}	1.52×10^{-7}	1.53×10^{-7}	1.54×10^{-7}	1.79×10^{-7}	3.29×10^{-7}
U^{236}	0	1.20×10^{-5}	1.25×10^{-5}	1.38×10^{-5}	1.82×10^{-5}	8.04×10^{-5}	6.89×10^{-4}
U^{237}	0	4.27×10^{1}	4.90×10^{-14}	0	0	0	0
U^{238}	3.06×10^{-1}	1.46×10^{-3}	1.46×10^{-3}	1.46×10^{-3}	1.46×10^{-3}	1.46×10^{-3}	1.46×10^{-3}
U^{239}	0	0	0	0	0	0	0
Np^{236}		4.26×10^{-10}	0	0	0	0	0
Np^{237}		8.91×10^{-2}	8.96×10^{-2}	9.06×10^{-2}	9.42×10^{-2}	1.38×10^{-1}	3.65×10^{-1}
Np^{238}		1.19	0	0	0	0	0
Np^{239}		7.22×10^{3}	4.96×10^{1}	4.95×10^{1}	4.95×10^{1}	4.91×10^{1}	4.53×10^{1}
Pu^{236}		2.85×10^{-3}	1.66×10^{-3}	1.01×10^{-3}	1.84×10^{-4}	5.73×10^{-14}	0
Pu^{238}	1.59×10^{4}	5.61×10^{1}	3.06×10^{2}	3.75×10^{2}	3.62×10^{2}	2.87×10^{2}	1.88
Pu^{239}	2.88×10^{3}	1.76×10^{1}	1.77×10^{1}	1.77×10^{1}	1.77×10^{1}	1.78×10^{1}	1.85×10^{1}
Pu^{240}	4.14×10^{3}	2.13×10^{1}	2.14×10^{1}	2.16×10^{1}	2.23×10^{1}	2.43×10^{1}	2.22×10^{1}
Pu^{241}	1.03×10^{6}	3.00×10^{3}	2.86×10^{3}	2.57×10^{3}	1.77×10^{3}	1.46×10^{1}	2.10×10^{-20}
Pu^{242}	1.24×10^{1}	6.36×10^{-2}	6.36×10^{-2}	6.37×10^{-2}	6.39×10^{-2}	6.59×10^{-2}	6.97×10^{-2}
Pu^{243}	0	0	0	0	0	0	0
Am^{241}		1.57×10^{3}	1.57×10^{3}	1.57×10^{3}	1.58×10^{3}	1.42×10^{3}	3.64×10^{2}
Am^{242M}		8.67×10^{1}	8.63×10^{1}	8.55×10^{1}	8.28×10^{1}	5.50×10^{1}	9.07×10^{-1}
Am^{242}		8.67×10^{1}	8.68×10^{1}	8.55×10^{1}	8.28×10^{1}	5.50×10^{1}	9.07×10^{-1}
Am^{243}		4.96×10^{1}	4.96×10^{1}	4.95×10^{1}	4.95×10^{1}	4.91×10^{1}	4.53×10^{1}
Am^{244}		0	0	0	0	0	0
Cm^{242}		6.55×10^{4}	1.58×10^{4}	7.74×10^{2}	6.82×10^{1}	4.51×10^{1}	7.44×10^{-1}
Cm^{243}		3.86×10^{1}	3.79×10^{1}	3.63×10^{1}	3.12×10^{1}	4.44	1.52×10^{-8}
Cm^{244}		1.24×10^{3}	1.20×10^{3}	1.11×10^{3}	8.48×10^{2}	2.70×10^{1}	2.91×10^{-14}
Subtotal	1.10×10^{6}	7.90×10^{4}	2.21×10^{4}	6.74×10^{3}	4.96×10^{3}	1.97×10^{3}	5.01×10^{2}
Total	1.10×10^{6}	7.90×10^{4}	2.21×10^{4}	6.74×10^{3}	4.96×10^{3}	1.97×10^{3}	5.01×10^{2}

[a]Data from ref. 6.

TABLE 9. - CALCULATED THERMAL POWER OF ACTINIDE ISOTOPES PRESENT IN WASTES GENERATED BY REPROCESSING OF SPENT FUEL FROM ATOMICS INTERNATIONAL REFERENCE OXIDE LIQUID-METAL-COOLED FAST-BREEDER REACTOR[a]

[Power, 58.23 MW/metric ton; burnup, 32 977 MW-days/metric ton; flux, 2.65×10^{15} neutrons/cm^2-sec.]

Nuclide	Charge	Waste decay times (processed after 30 days), days					
		30	365	1096	3652	36 525	365 250
		Thermal power, W/metric ton of fuel					
Th^{228}	0	1.55×10^{-5}	1.14×10^{-5}	6.27×10^{-6}	2.85×10^{-6}	1.28×10^{-6}	2.23×10^{-10}
Th^{229}		7.74×10^{-11}	7.75×10^{-11}	7.77×10^{-11}	7.84×10^{-11}	8.75×10^{-11}	1.74×10^{-10}
Th^{230}		1.04×10^{-8}	1.05×10^{-8}	1.14×10^{-8}	2.25×10^{-8}	1.09×10^{-6}	3.65×10^{-5}
Th^{231}		4.20×10^{-8}	2.10×10^{-10}	2.11×10^{-10}	2.13×10^{-10}	2.34×10^{-10}	4.55×10^{-10}
Th^{232}		3.08×10^{-15}	3.09×10^{-15}	3.12×10^{-15}	3.26×10^{-15}	8.50×10^{-15}	4.25×10^{-13}
Th^{233}		0	0	0	0	0	0
Pa^{231}		8.64×10^{-10}	8.65×10^{-10}	8.65×10^{-10}	8.65×10^{-10}	8.73×10^{-10}	1.00×10^{-9}
Pa^{232}		8.38×10^{-14}	0	0	0	0	0
Pa^{233}		6.84×10^{-8}	1.43×10^{-11}	1.33×10^{-19}			
Pa^{234M}		0	0	0			
Pa^{234}		0	0	0			
U^{232}		4.80×10^{-7}	9.94×10^{-7}	1.77×10^{-6}	2.66×10^{-6}	1.22×10^{-6}	2.12×10^{-10}
U^{233}		1.11×10^{-9}	1.11×10^{-9}	1.11×10^{-9}	1.11×10^{-9}	1.11×10^{-9}	1.10×10^{-9}
U^{234}		7.53×10^{-6}	2.30×10^{-5}	8.07×10^{-5}	2.90×10^{-4}	2.30×10^{-3}	5.21×10^{-3}
U^{235}	8.67×10^{-7}	4.22×10^{-9}	4.23×10^{-9}	4.24×10^{-9}	4.27×10^{-9}	4.70×10^{-9}	9.13×10^{-9}
U^{236}	0	3.24×10^{-7}	3.39×10^{-7}	3.73×10^{-7}	4.94×10^{-7}	2.18×10^{-6}	1.87×10^{-5}
U^{237}	0	9.17×10^{-2}	1.05×10^{-16}	0	0	0	0
U^{238}	7.75×10^{-3}	3.70×10^{-5}	3.70×10^{-5}	3.70×10^{-5}	3.70×10^{-5}	3.70×10^{-5}	3.70×10^{-5}
U^{239}	0	0	0	0	0	0	0
Np^{236}		1.20×10^{-12}					
Np^{237}		0					
Np^{238}		6.13×10^{-3}					
Np^{239}		2.14×10^{1}	1.47×10^{-1}	1.47×10^{-1}	1.47×10^{-1}	1.46×10^{-1}	1.34×10^{-1}
Pu^{236}		7.14×10^{-5}	5.71×10^{-5}	3.51×10^{-5}	6.40×10^{-6}	1.99×10^{-15}	0
Pu^{238}	5.26×10^{2}	1.86	1.01×10^{1}	1.24×10^{1}	1.20×10^{1}	6.86	6.23×10^{-2}
Pu^{239}	8.95×10^{1}	5.48×10^{-1}	5.48×10^{-1}	5.49×10^{-1}	5.49×10^{-1}	5.53×10^{-1}	5.76×10^{-1}
Pu^{240}	1.29×10^{2}	6.63×10^{-1}	6.67×10^{-1}	6.74×10^{-1}	5.95×10^{-1}	7.57×10^{-1}	6.92×10^{-1}
Pu^{241}	4.47×10^{1}	1.24×10^{-1}	1.18×10^{-1}	1.06×10^{-1}	7.33×10^{-2}	6.04×10^{-4}	8.71×10^{-25}
Pu^{242}	3.65×10^{-1}	1.88×10^{-3}	1.88×10^{-3}	1.88×10^{-3}	1.89×10^{-3}	1.95×10^{-3}	2.06×10^{-3}
Pu^{243}	0	0	0	0	0	0	0
Am^{241}		5.23×10^{1}	5.24×10^{1}	5.25×10^{1}	5.27×10^{1}	4.74×10^{1}	1.22×10^{1}
Am^{242M}		2.47×10^{-2}	2.46×10^{-2}	2.43×10^{-2}	2.36×10^{-2}	1.56×10^{-2}	2.58×10^{-4}
Am^{242}		1.16×10^{-1}	1.15×10^{-1}	1.14×10^{-1}	1.10×10^{-1}	7.33×10^{-2}	1.21×10^{-3}
Am^{243}		1.60	1.60	1.60	1.60	1.58	1.46
Am^{244}		0	0	0	0	0	0
Cm^{242}		2.42×10^{3}	5.83×10^{2}	2.85×10^{1}	2.51	1.69	2.74×10^{-2}
Cm^{243}		1.41	1.38	1.32	1.14	1.62×10^{-1}	5.53×10^{-10}
Cm^{244}		4.34×10^{1}	4.19×10^{1}	3.88×10^{1}	2.97×10^{1}	9.45×10^{-1}	1.02×10^{-15}
Subtotal	7.89×10^{2}	2.54×10^{3}	6.92×10^{2}	1.37×10^{2}	1.01×10^{2}	6.02×10^{1}	1.51×10^{1}
Total	7.89×10^{2}	2.54×10^{3}	6.92×10^{2}	1.37×10^{2}	1.01×10^{2}	6.02×10^{1}	1.51×10^{1}

[a]Data from ref. 6.

TABLE 10. - COMPOSITIONS OF RADIOACTIVE NUCLEAR WASTE CONSIDERED FOR SPACE DISPOSAL FEASIBILITY STUDY

[All waste assumed to be stored for 10 years prior to space disposal.]

Package type	Radioactive waste	LWR	LMFBR	LWR	LMFBR
		Activity, Ci/g		Thermal power, W/g	
I	Fission products only, in solid form	9.06	8.03	0.029	0.023
IIa	Actinides (uranium removed) with 1 percent of fission products remaining	4.10	5.95	.058	.065
IIb	Actinides (uranium removed) with 0.1 percent of fission products remaining	2.62	3.96	.067	.074
IIIa	Actinides (uranium removed) with 0.001 percent of fission products remaining	2.40	3.73	.071	.076
IIIb	IIIa with 99 percent of curium removed	.67	3.02	.011	.051

TABLE 11. - RADIOACTIVE WASTE WITH LONG DECAY TIMES

Isotope	Half-life, yr	Decay processes
H^3	12.3	Beta (electron)
Sr^{90}	27.7	Beta (electron)
Tc^{90}	2×10^5	Beta (electron)
I^{129}	1.6×10^7	Beta (electron), gamma ray
Cs^{137}	30	Beta (electron), gamma ray
Sm^{151}	87	Beta (electron), gamma ray
Pu^{239}	2.4×10^4	Alpha (He) particle, gamma ray
Np^{237}	2.1×10^6	
Am^{241}	458	
Am^{243}	7.6×10^3	
Cm^{244}	18	

TABLE 12. - ACCUMULATED RADIOACTIVE DOSES FROM LONG-LIVED ISOTOPES IN NUCLEAR WASTE

Isotope	Maximum permissible total body dose		Accumulated number of body doses to the year 2000
	μCi	g/body	
H^3	2×10^3	2×10^{-7}	9×10^{14}
Sr^{90}	1	$.7\times10^{-8}$	5×10^{15}
Tc^{99}	5	2.5×10^{-4}	1×10^{11}
I^{129}	3	0.033	2×10^{14}
Cs^{137}	30	3.4×10^{-7}	5×10^{14}
Sm^{151}	100	3.7×10^{-6}	5×10^{13}
Pu^{239}	0.04	1.3×10^{-7}	3×10^{13}
Am^{241}	.05	3×10^{-8}	1×10^{15}
Am^{243}	.10	5.2×10^{-7}	1×10^{14}
Cm^{244}	.10	1.25×10^{-9}	2×10^{15}

TABLE 13. - SUMMARY OF DESTINATIONS

Destination	Type of mission	Velocity increment, ΔV, km sec	Advantages	Disadvantages
High Earth orbit	Direct - second burn to circular orbit	4.11	Low ΔV Launch any day Passive waste package Can be retrieved	Long-term container integrity required Orbit lifetime not proven
Solar orbit	Single burn beyond Earth escape	3.65	Low ΔV Launch any day Passive waste package	Earth reencounter possible (may not be able to prove otherwise) Abort gap past Earth-escape velocity
	Hohmann transfer to circular solar orbit (0.9 AU)	4.11	Low ΔV Launch any day	Orbit stability not proven Requires space propulsion system Abort gap past Earth-escape velocity
	Venus or Mars swing-by	4.11	Low ΔV	Limited launch opportunity Requires midcourse systems Need space propulsion or have possibility of planet encounter
Solar system escape	Direct	8.75	Launch any day Passive waste package Removed from solar system	High ΔV Abort gap past Earth-escape velocity
	Jupiter swing-by	7.01	Removed from solar system	High ΔV Limited launch opportunity Requires midcourse systems Abort gap past Earth-escape velocity
Solar impact	Direct	24.08	Package destroyed Launch any day Passive waste package	Extremely high ΔV Abort gap past Earth-escape velocity
	Jupiter swing-by	7.62	Package destroyed	High ΔV Limited launch opportunity Requires midcourse systems Abort gap past Earth-escape velocity

TABLE 14. - EXPENDABLE LAUNCH VEHICLE PERFORMANCE AND COST SUMMARY FOR CANDIDATE MISSION DESTINATIONS

Launch vehicle	High Earth orbits and solar orbits (ΔV^a = 4.11 km/sec)	Direct solar system escape (ΔV^a = 8.75 km/sec)	Launch cost, dollars
	Payload, kg		
Titan IIIE/Centaur	3 860	0	19×10^6
Saturn V	32 660	0	150
Saturn V/Centaur	35 290	7480	155

[a]Above 300-km parking orbit.

TABLE 15. - SPACE SHUTTLE/THIRD STAGE LAUNCH VEHICLE PAYLOAD AND COST SUMMARY FOR HIGH EARTH ORBITS AND SOLAR ORBITS

[Velocity increment, ΔV, 4.11 km/sec.]

Launch vehicle, Space Shuttle plus-	Payload, kg	Launch cost, dollars
Reusable tug:		
Current size	4170	12.25×10^6
Optimum size	4670	12.25
Centaur:		
Current size	6490	16
Optimum size	8480	16.3

TABLE 16. - LAUNCH VEHICLE PAYLOAD AND COST SUMMARY FOR HIGH EARTH ORBITS AND SOLAR ORBITS

[Velocity increments, ΔV, 4.11 km/sec.]

Launch vehicle	Payload, kg	Launch cost per kilogram, dollars
Tital IIIE/Centaur	3 860	4920
Saturn V	32 660	4590
Saturn V/Centaur	35 290	4390
Space Shuttle plus-		
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 17. - LAUNCH VEHICLE PAYLOAD AND COST SUMMARY FOR DIRECT SOLAR ESCAPE MISSION

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

Launch vehicle	Payload, kg	Launch cost, dollars	Launch cost per kilogram, dollars
Saturn V/Centaur	7480	155.00×10^{6}	20 720
(2, 1, 1) Space Shuttle/tug configuration[a]:			
Without perigee propulsion	2270	28.75	12 660
With perigee propulsion	3270	28.75	8 790
(3, 1, 2) Space Shuttle/tug configuration[b]:			
Without perigee propulsion	3040	41.0	13 490
With perigee propulsion	4400	41.0	9 320

[a]Two shuttle flights, one expendable tug, and one reusable tug.
[b]Three shuttle flights, one expendable tug, and two reusable tugs.

TABLE 18. - CHARACTERISTICS OF SPRAY MELT DESIGNED FOR STORAGE OF FISSION PRODUCT WASTE ON EARTH

Form	Single, tough mold
Hardness	Hard
Leachability in water, g/cm^2-day	10^{-3} to 10^{-6}
Fission product oxides in mixture, mole percent	Up to 30
Thermal conductivity, W/m-K	0.8 to 1.8
Density, g/cm^3	2.7 to 3.5
Maximum stable temperature, K	~1170
Container material	Mild or stainless steel
Maximum dose rate, Ci/cm^3	~9

TABLE 19. - CHARACTERISTICS OF NUCLEAR WASTE PACKAGE FOR SPACE DISPOSAL OF ACTINIDE WASTE

Characteristic	Destination					
	High Earth orbit		Solar orbit		Solar system escape	
Percent of fission products remaining in actinides	0.1	1.0	0.1	1.0	0.1	1.0
Number of packages per launch	1	1	3	3	1	1
Dimensions of package:						
Outside diameter, m	2.896	2.896	1.761	1.761	1.81	1.81
Thickness of stainless-steel shell, cm	0.1	0.1	0.1	0.1	0.1	0.1
Thickness of silica (front), cm	4.0	4.0	4.0	4.0	4.0	4.0
Thickness of silica (rear), cm	1.0	1.0	1.0	1.0	1.0	1.0
Thickness of silver reflector, cm	0.01	0.01	0.01	0.01	0.01	0.01
Thickness of graphite (front), cm	1.0	1.0	1.0	1.0	1.0	1.0
Thickness of graphite (rear), cm	0.5	0.5	0.5	0.5	0.5	0.5
Thickness of insulation (front), cm	2.0	2.0	2.0	2.0	2.0	2.0
Outside diameter of impact sphere, m	1.43	1.37	0.973	0.923	1.036	0.98
Thickness of stainless-steel impact shell, cm	2.54	2.54	2.54	2.54	2.54	2.54
Thickness of LiH shield, cm	12.65	11.74	9.83	8.28	10.51	8.75
Thickness of W shield, cm	3.83	5.54	3.61	4.84	3.60	4.92
Offset of internal sphere forward of PAET shape center, cm	6.7	6.3	3.7	3.5	3.9	3.7
Weight of package, kg	8400	8400	[a]2800/8400	[a]2800/8400	3270	3270
Weight of actinides per package, kg	634	384	149	96	191	113
Weight of fission products per package, kg	22	134	5.2	34	6.7	40
Weight of reentry shield per package, kg	1038	1038	370	370	415	415
Weight of impact vessel per package, kg	1295	1122	565	504	640	567
Weight of LiH shield per package, kg	455	429	168	113	178	135
Weight of W shield per package, kg	2780	3580	1032	1249	1190	1480
Weight of matrix per package, kg	2080	1655	498	415	625	505
Dose rate at 1 meter from surface, rem/hr	1	1	1	1	1	1
Radioactivity from actinides per package[b], Ci	1.52×10^6	0.92×10^6	0.356×10^6	0.23×10^6	0.46×10^6	0.26×10^6
Radioactivity from fission products per package, Ci	0.20×10^6	1.20×10^6	0.045×10^6	0.30×10^6	0.06×10^6	0.37×10^6
Thermal power per package, kW	44.0	30.12	10.36	7.59	13.25	9.26

[a]Ratio of package weight to total payload, kg.
[b]Based on actinides from LWR's, from LMFBR's the radioactivity would be 1.5 times higher.

TABLE 20. - CHARACTERISTICS OF NUCLEAR WASTE PACKAGE III

(FOR DISPOSAL OF PURE ACTINIDES)

[Shielded for external dose rate of 1 rem/hr at 1 m from surface.]

Characteristic	Destination	
	High Earth orbit	Solar system escape
Number of packages per payload	3	2
Dimensions of package:		
Outside diameter, m	1.761	1.308
Thickness of stainless-steel shell, cm	0.1	0.1
Thickness of silica (front), cm	4.0	4.0
Thickness of silica (rear), cm	1.0	1.0
Thickness of silver reflector, cm	0.01	0.01
Thickness of graphite (front), cm	1.0	1.0
Thickness of graphite (rear), cm	0.5	0.5
Thickness of insulation, cm	2.0	2.0
Outside diameter, of impact sphere, m	1.09	0.915
Thickness of stainless-steel impact shell, cm	2.54 (Split)	2.54
Thickness of LiH shield, cm	11.43	9.97
Thickness of W shield, cm	0.82	0.67
Weight of package, kg	[a]2800/8400	[a]1640/3280
Weight of actinide per package, kg	286	154
Weight of reentry shell per package, kg	370	241
Weight of impact shell per package, kg	591	423
Weight of LiH shield per package, kg	248	148
Weight of W shield per package, kg	316	174
Weight of matrix per package, kg	900	495

[a]Ratio of package weight to total payload.

TABLE 21. - CALCULATED POSTIMPACT CONDITION OF NUCLEAR WASTE PACKAGE AFTER IMPACT ON EARTH FOLLOWING UNCONTROLLED REENTRY

<table>
<tr><th rowspan="6"></th><th colspan="8">Type of soil</th></tr>
<tr><th colspan="5">Coastal plain</th><th colspan="3">Podzol</th></tr>
<tr><th colspan="8">Condition of package</th></tr>
<tr><th>Undeformed</th><th>Deformed</th><th colspan="2">Undeformed</th><th>Deformed</th><th colspan="3">Undeformed</th></tr>
<tr><th colspan="8">Depth of burial</th></tr>
<tr><th>37 Percent</th><th>None</th><th>5.8 m</th><th>9.1 m</th><th>None</th><th>10 m</th><th>9.1 m</th><th>9.1 m</th></tr>
<tr><td>Thermal power, kW</td><td>24</td><td>24</td><td>24</td><td>10</td><td>7</td><td>24</td><td>10</td><td>7</td></tr>
<tr><td>Diameter of impact vessel, m</td><td>1.3</td><td>1.3</td><td>1.3</td><td>0.9</td><td>0.9</td><td>1.3</td><td>0.9</td><td>0.9</td></tr>
<tr><td>Maximum temperature of waste, K</td><td>820</td><td>722</td><td>1523</td><td>1543</td><td>563</td><td>1553</td><td>1583</td><td>1501</td></tr>
<tr><td>Maximum temperature of impact vessel, K</td><td>786</td><td>686</td><td>1418</td><td>1433</td><td>548</td><td>1420</td><td>1420</td><td>1401</td></tr>
<tr><td>Internal pressure, atm</td><td>1.43</td><td>1.22</td><td>8.17</td><td>8.5</td><td>1.1</td><td>9.0</td><td>9.5</td><td>8.9</td></tr>
<tr><td>Failure of vessel</td><td>No</td><td>No</td><td>Yes</td><td>Yes</td><td>No</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Time to failure, days</td><td>----</td><td>----</td><td>4.5</td><td>4.3</td><td>---</td><td>5.4</td><td>5.4</td><td>10</td></tr>
</table>

TABLE 22. - SPACE TRANSPORTATION COST FOR DISPOSAL OF RADIOACTIVE WASTE

[Basic launch vehicle, Space Shuttle; number of missions per year, 40; cost basis, FY 1972 dollars.]

	Space transportation cost per payload, dollars
Ground facilities for each flight	0.01×10^6
High Earth orbit:	
Shuttle (1)	10.5×10^6
Optimum Centaur (1)	5.8×10^6
Total per mission	16.31×10^6
Solar system escape:	
Shuttle (2)	21.0×10^6
Expendable tug (1)	6.0×10^6
Reusable tug (1)	1.75×10^6
Total per mission	28.77×10^6

TABLE 23. - ESTIMATED COST FOR SPACE DISPOSAL OF NUCLEAR WASTE USING THE SPACE SHUTTLE

(a) Fission products, based on package I design shielded for 1 rem/hr at 3 meters from center

	Destination	
	High Earth orbit	Solar system escape
Ratio of waste weight to total package weight, kg	187/8400	73/3270
Transportation cost, dollars	16.31×10^6	28.77×10^6
Processing cost, dollars	0.16×10^6	0.06×10^6
Estimated packaging cost, dollars	0.12×10^6	0.05×10^6
Total cost, dollars	16.59×10^6	28.88×10^6
Transportation cost per kilogram of waste, dollars	87.2×10^3	394×10^3
Processing cost per kilogram of waste, dollars	0.86×10^3	0.86×10^3
Total cost per kilogram of waste, dollars	88.06×10^3	395×10^3

(b) Actinides containing small amounts of fission products and shielded for 1 rem/hr at 1 meter from surface of package

	Destination					
	High Earth orbit[a]			Solar system escape		
	Amount of fission products in waste, percent					
	1.0	0.1	0.001	1.0	0.1	0.001
Ratio of actinide waste weight to total package weight, kg	288/8400	447/8400	858/8400	113/3270	191/3270	308/3270
Mission launch cost, dollars	16.31×10^6	16.31×10^6	16.31×10^6	28.77×10^6	28.77×10^6	28.77×10^6
Processing and separation cost[b], dollars	17.27×10^6	40.25×10^6	129×10^6	6.78×10^6	17.2×10^6	46.2×10^6
Estimated packaging cost, dollars	0.187×10^6	0.291×10^6	0.447×10^6	0.073×10^6	0.124×10^6	0.200×10^6
Total cost, dollars	33.77×10^6	56.85×10^6	145.87×10^6	35.62×10^6	46.09×10^6	75.17×10^6
Transportation cost per kilogram of actinide waste, dollars	56.7×10^3	36.5×10^3	19.0×10^3	254.5×10^3	150.5×10^3	93.4×10^3
Processing and separation cost per kilogram of actinide waste, dollars	60×10^3	90×10^3	150×10^3	60×10^3	90×10^3	150×10^3
Total cost per kilogram of actinide waste, dollars	116.7×10^3	126.5×10^3	169×10^3	314.5×10^3	240.5×10^3	243.4×10^3

[a]Radioactive waste divided into three equal packages.

[b]Separation costs are extrapolated from estimates on 1 and 0.1 percent fission products.

TABLE 24. - COST SUMMARY FOR FISSION PRODUCT DISPOSAL (PACKAGE I) AS FUNCTION OF LAUNCH VEHICLE AND MISSION

Representative destination	Vehicle	Waste payload,[a] kg	Radioactivity, Ci	Additional cost of electricity	
				cents/kW-hr	Percent of increase
High Earth or solar orbit	Saturn V	727	6.40×10^{6}	2.8	116
	Space Shuttle and optimum Centaur	189	1.66	1.1	46
Solar system escape	Saturn V and Centaur	161	1.43×10^{6}	13	540
	Space Shuttle (2) and tugs (2)	73	.64	5.2	217

[a]Screening studies did not account for reentry shells.

TABLE 25. - COST SUMMARY FOR ACTINIDE DISPOSAL AS FUNCTION OF LAUNCH VEHICLE AND MISSION

(a) Actinides with 1 percent residual fission products

Representative destination	Launch system	Actinide waste payload, kg	Radioactivity, Ci	Additional cost of electricity	
				cents/kW-hr	Percent of increase
High Earth or solar orbit	Saturn V	[a]1365	7.46×10^{6}	0.045	2
	Space Shuttle and	[b]384	2.12	.017	<1
	optimum Centaur	288	1.59	.023	1
Direct solar system escape	Saturn V and Centaur	[b]341	1.86×10^{6}	0.186	8
	Space Shuttle (2) and tugs (2)	113	.62	.104	4

(b) Actinides with 0.1 percent residual fission products

High Earth or solar orbit	Saturn V	[a]2000	5.43×10^{6}	0.03	1
	Space Shuttle and optimum Centaur	447	1.2	.015	<1
Direct solar system escape	Saturn V and Centaur	498	1.35×10^{6}	0.127	5
	Space Shuttle (2) and tugs (2)	191	.52	.061	3

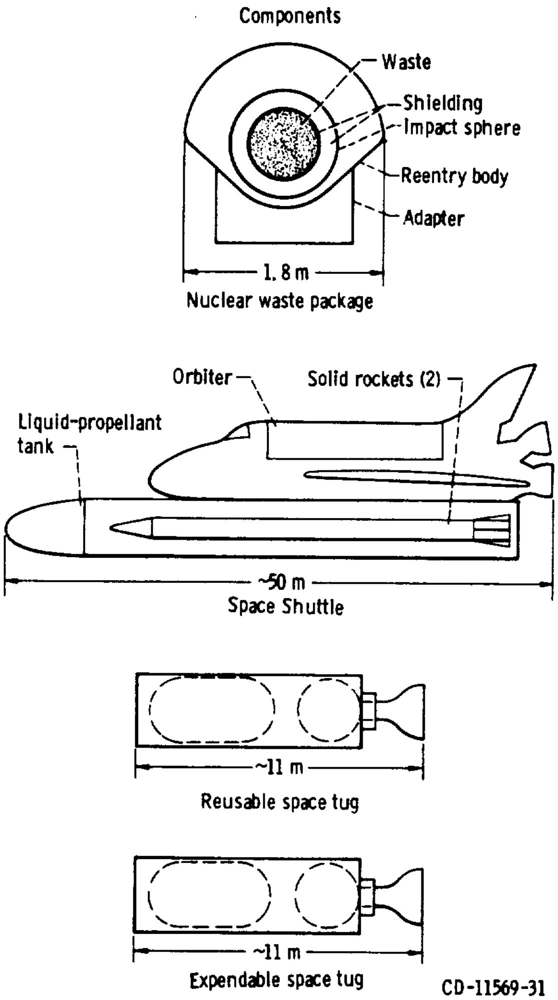
(c) Actinides with 0.001 percent of residual fission products

High Earth or solar orbit	Saturn V	[a]~3000	7.20×10^{6}	0.020	<1
	Space Shuttle and optimum Centaur	858	2.06	.008	<1
Direct solar system escape	Saturn V and Centaur	740	1.77×10^{6}	0.086	3
	Space Shuttle (2) and tugs (2)	308	.74	.038	1.5

(d) Actinides with 0.001 percent of residual fission products, curium removed

High Earth or solar orbit	Saturn V	3335	2.23×10^{6}	0.018	<1
	Space Shuttle and optimum Centaur	920	.62	.007	<1
Direct solar system escape	Saturn V and Centaur	810	0.54×10^{6}	0.079	3
	Space Shuttle (2) and tugs (2)	348	.23	.034	1

[a]Four packages - matrix temperature exceeded.
[b]One package - matrix temperature limit met or exceeded.



Component	Weight, kg
Nuclear waste package:	
Waste (actinides plus 0.1 percent of the 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 1. - Representative components for nuclear waste disposal mission to escape the solar system. Required for such a mission: one Space Shuttle and a reusable tug; a second Space Shuttle and an expendable tug carrying the waste package. Sequence of events:

(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 ΔV, separates, and returns to shuttle 2.
(7) Expendable tug fires and injects waste package into solar system escape trajectory.

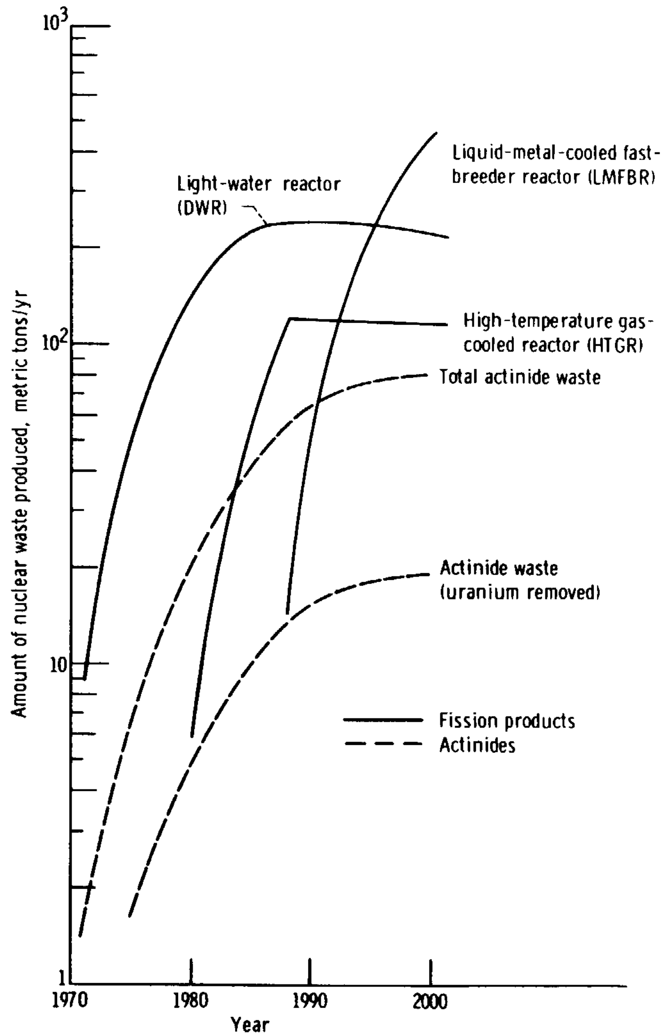


Figure 2. - Estimated production of nuclear waste per year. (Data from case 36 of ref. 5.)

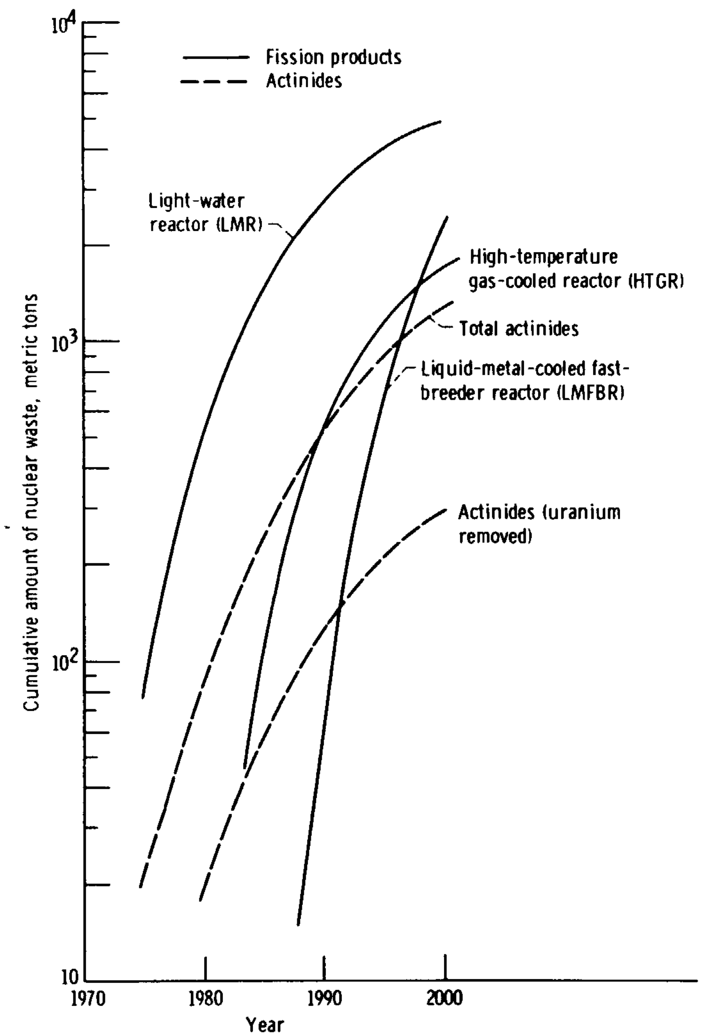
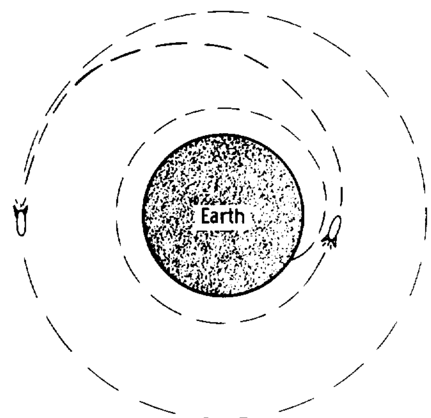
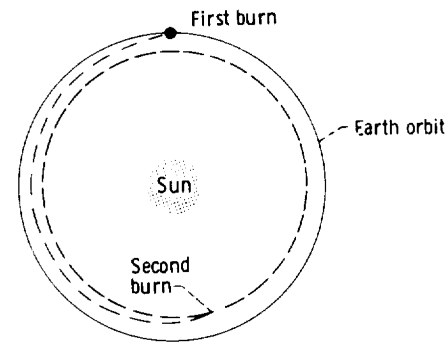


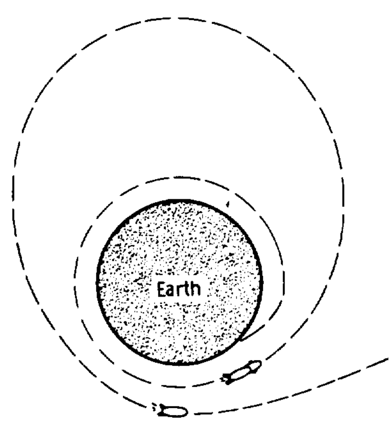
Figure 3. - Estimated cumulative production of nuclear waste by the year 2000. (Data from case 36 of ref. 5.)



(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 4. - Potential space destinations.

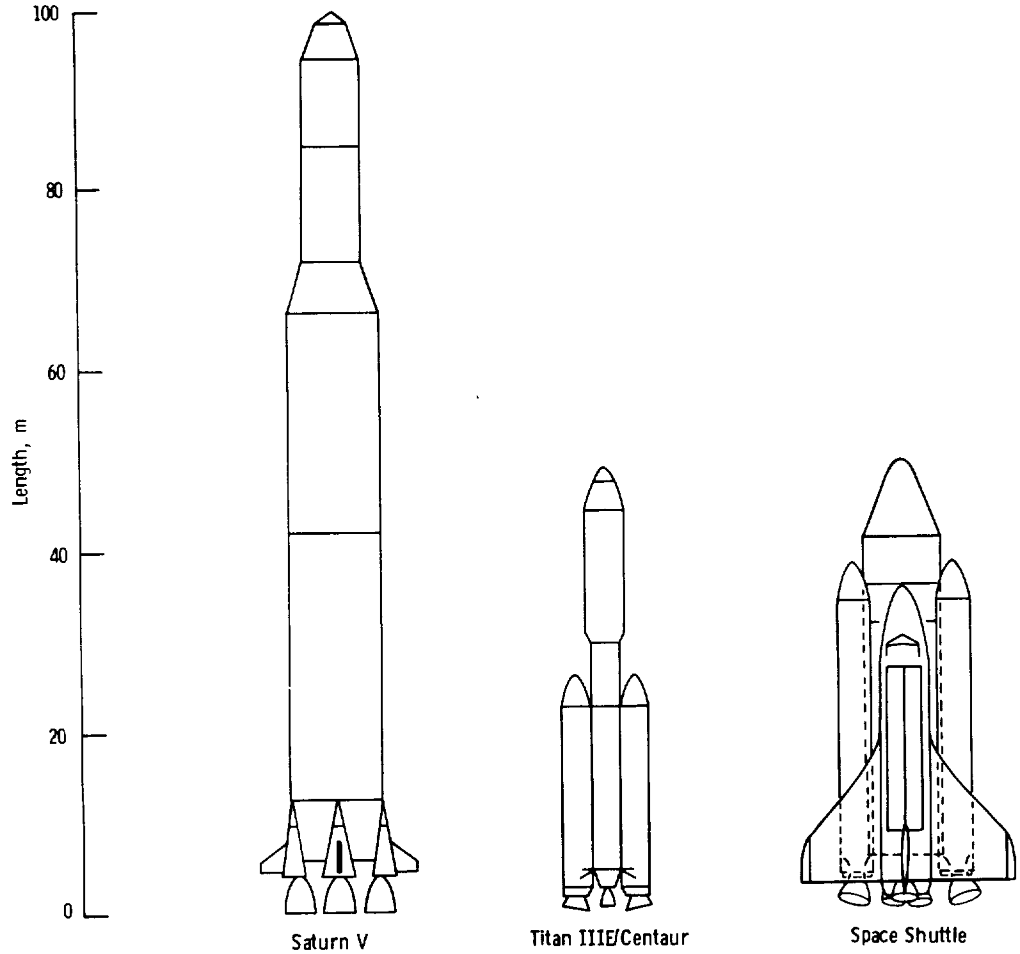


Figure 5. - Launch vehicles considered for space nuclear waste disposal missions.

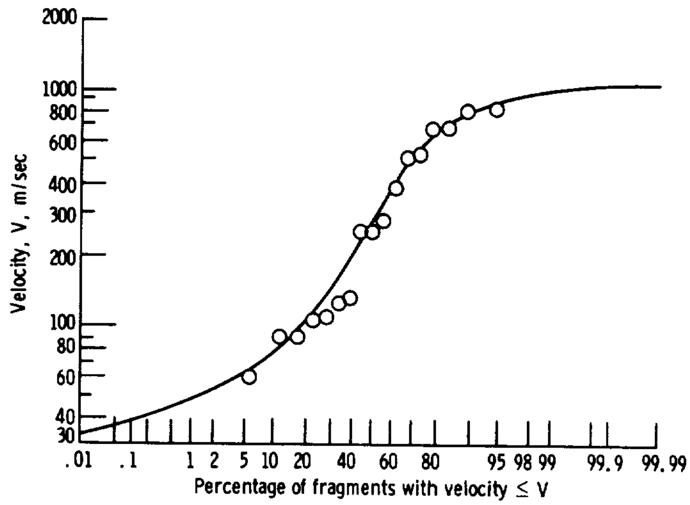


Figure 7. - Upward fragment velocities from typical explosion involving 11 250-kilogram propellant tank. Velocities measured 3 meters from top of dome. (Data from ref. 12.)

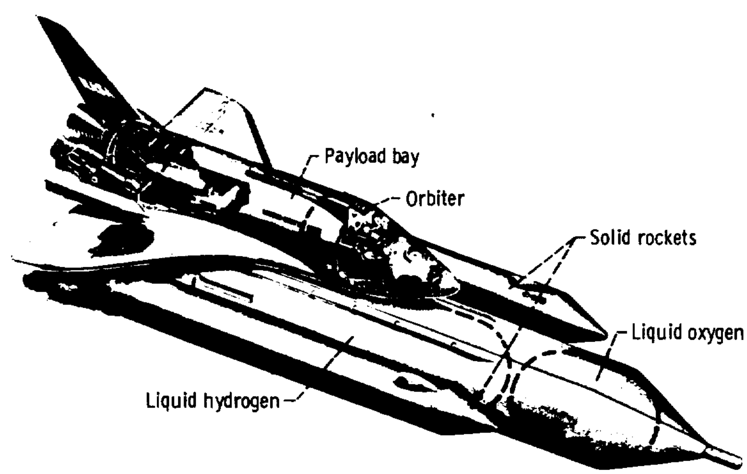


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Figure 6. - Space Shuttle launch vehicle.

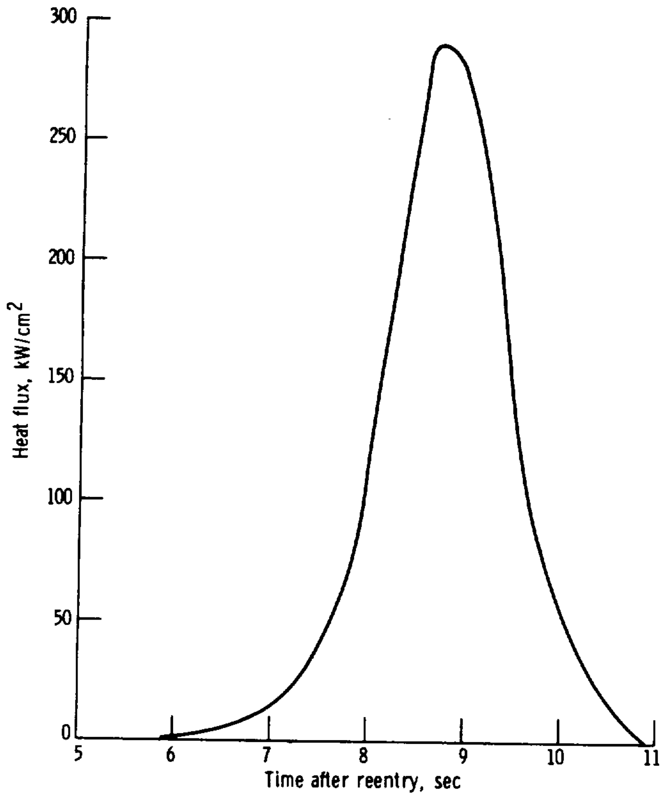


Figure 8. - Heat flux caused by atmospheric heating of reentry vehicle. Initial velocity, 11 kilometers per second; reentry angle, 90°.

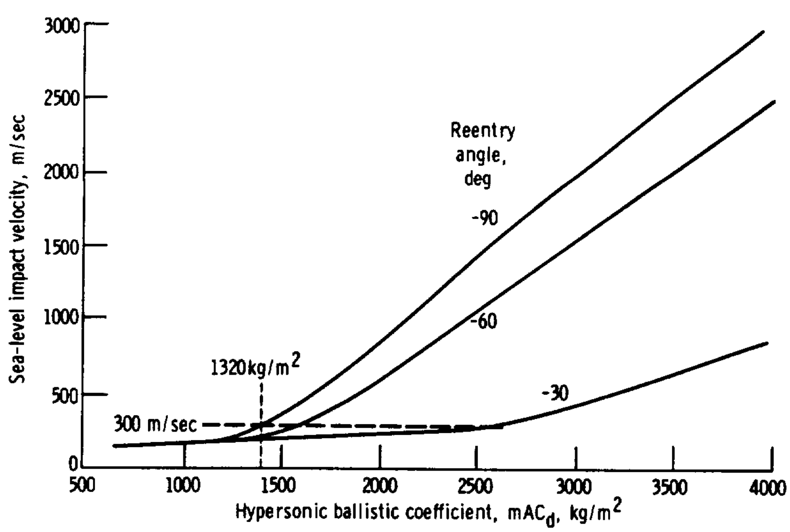


Figure 9. - Impact velocity of spherical nuclear waste package as function of its ballistic coefficient.

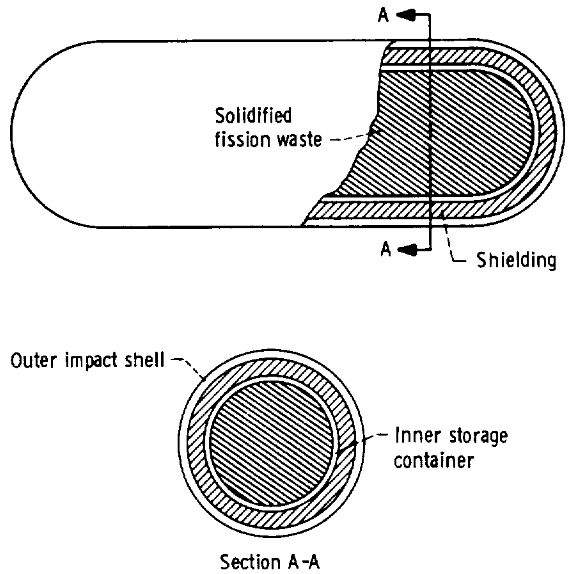


Figure 10. - Typical container and shielding for space disposal of radioactive fission products.

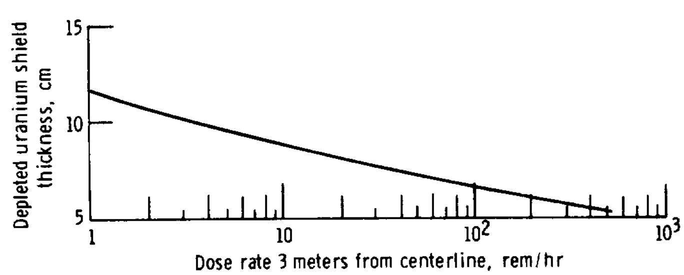


Figure 11. - Thickness of depleted uranium required to decrease external dose rate from fission products mixed in solid spray-melt matrix 0.71 meter in diameter. Radioactivity, 10 curies per cubic centimeter.

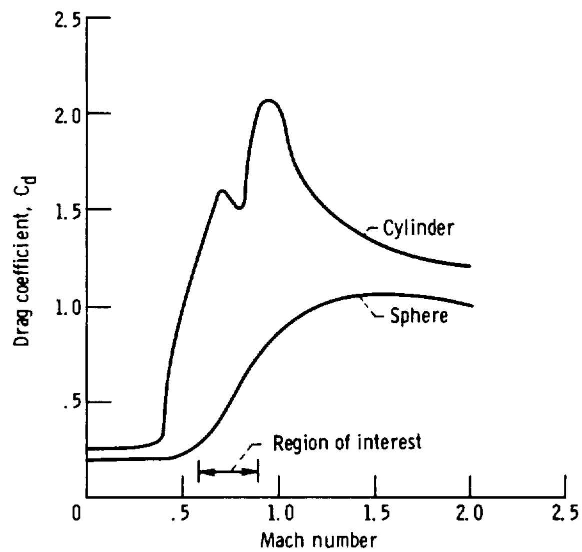


Figure 12. - Drag coefficients of candidate reentry shapes for nuclear waste packages.

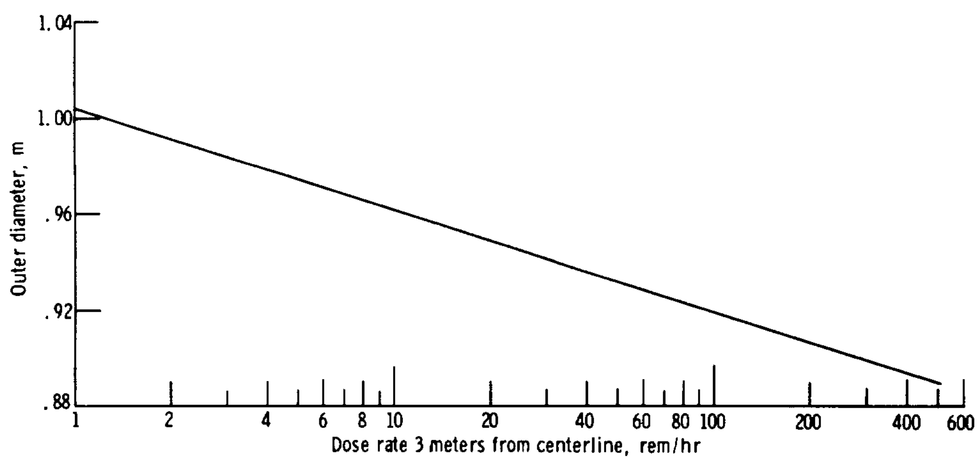


Figure 13. - Package outer diameter as function of dose rate for package I (fission products).

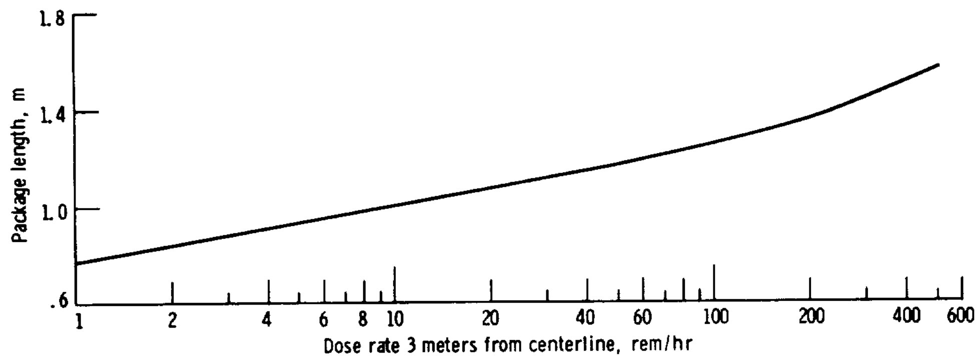


Figure 14. - Package length as function of dose rate for package I (fission products).

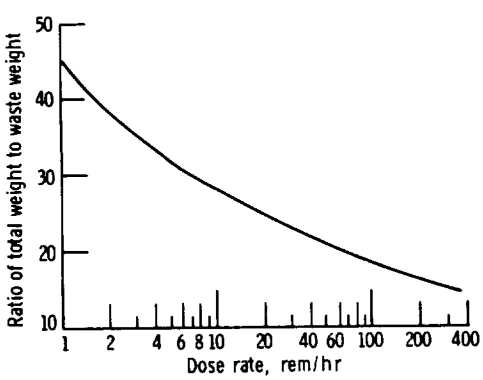


Figure 15. - Packaging ratio for package I (fission products). High Earth orbit; 10-year Earth storage assumed.

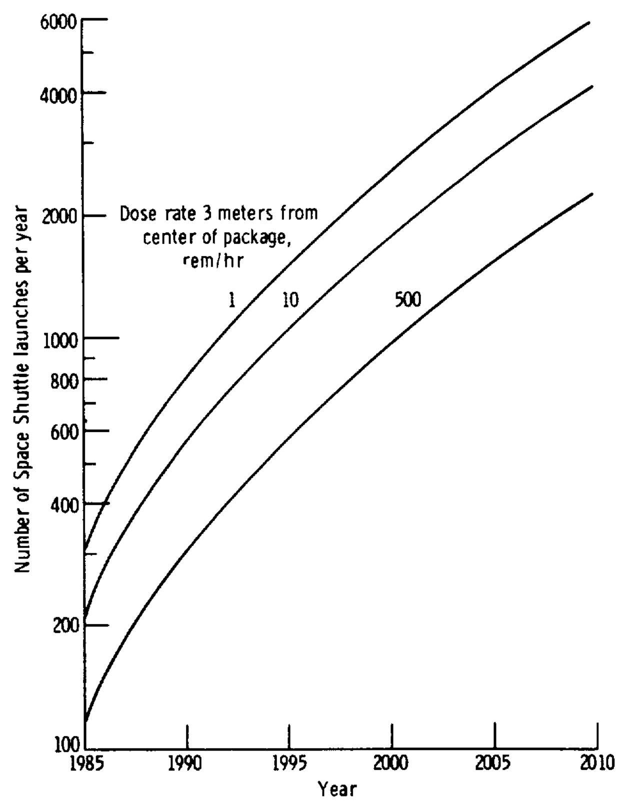


Figure 16. - Number of Space Shuttle launches required per year to dispose of solidified radioactive fission products generated in nuclear powerplants. Material stored for 10 years and packaged in a spray-melt matrix; high Earth orbit.

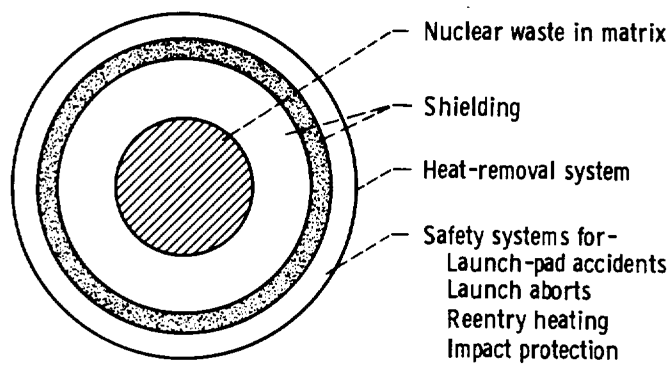


Figure 17. - Schematic of nuclear waste package.

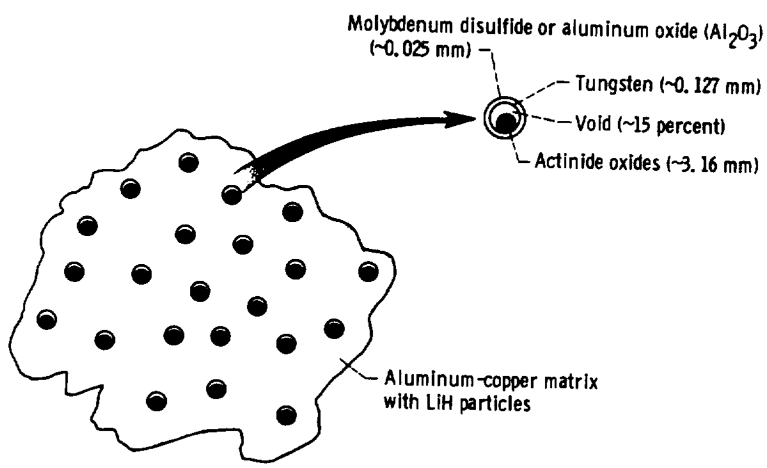


Figure 18. - Model of actinide waste and matrix.

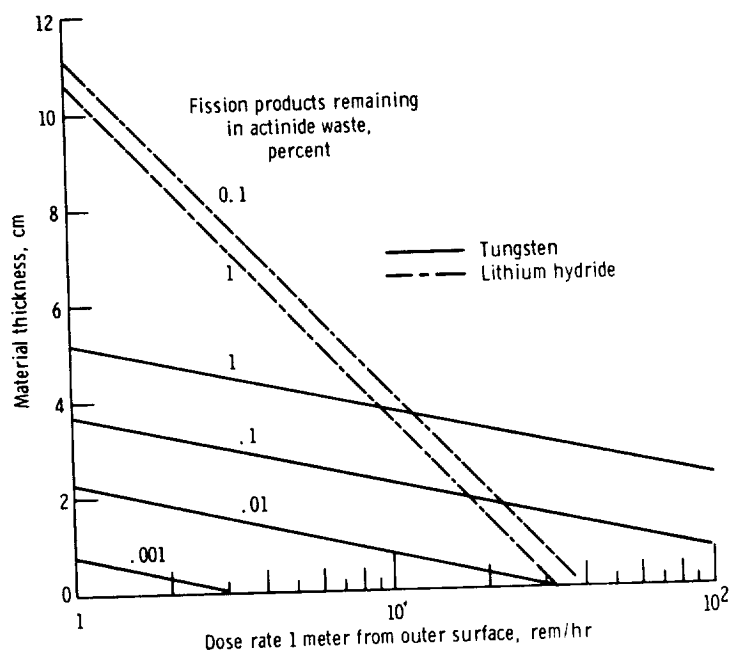
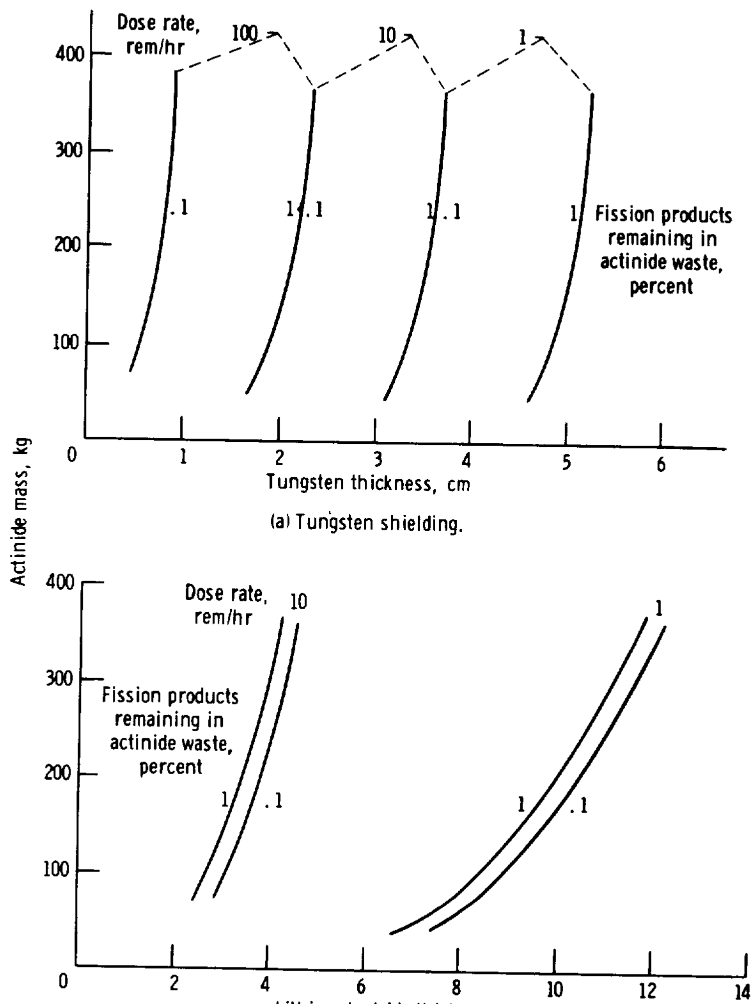


Figure 19. - Thickness of tungsten and lithium hydride shielding material required to reduce dose rate 1 meter from outer surface of package for matrix containing 250 kilograms of actinide waste. Matrix/actinide ratio, 85/9.



(a) Tungsten shielding.

(b) Lithium hydride shielding.

Figure 20. - Working curves for shielding thicknesses.

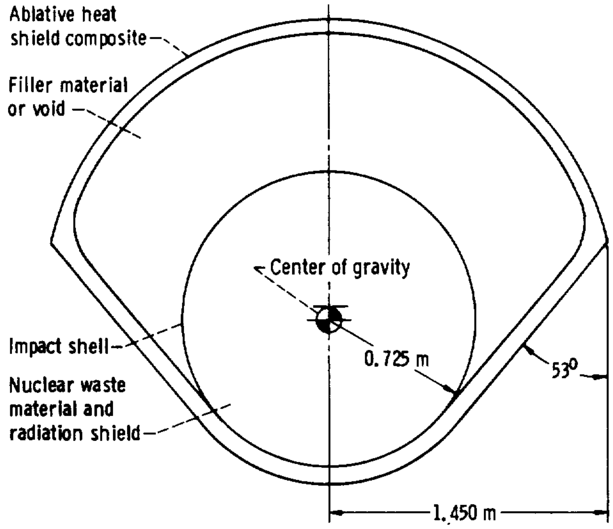
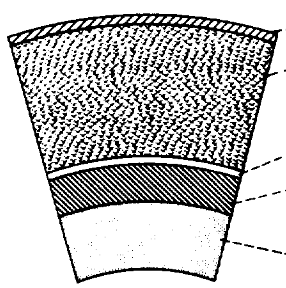
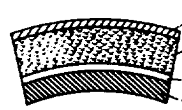


Figure 21. - Nuclear waste reentry package.



Material	Thickness, cm	Function
Steel	0.1	Attachment
Silica fiber composite	4.0	Reflection of radiative heat during reentry
Silver	.01	Mirror reflection
Graphite fiber composite	1.0	Absorbtion of convective heat during reentry
Insulation	2.0	Prevention of heat penetration inwards

(a) Front (blunt cone) reentry shield.



Steel	.1
Silica fiber composite	1.0
Silver	.01
Graphite fiber (3D) composite	.5

(b) Rear (hemispherical) reentry shield.

Figure 22. - Layers of reentry shield for radioactive nuclear waste package.

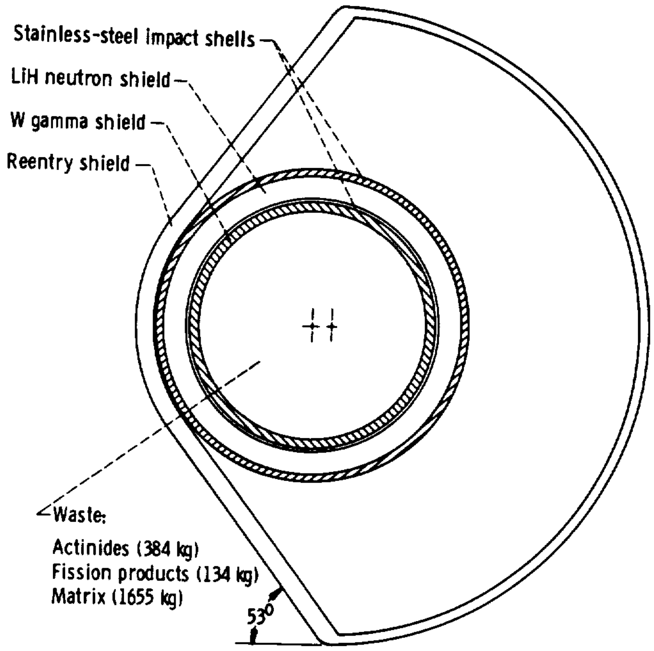


Figure 23. - Configuration of package II (actinide waste with 1 percent of the fission products) for disposal of single package to high Earth orbit. Total weight, 8400 kilograms.

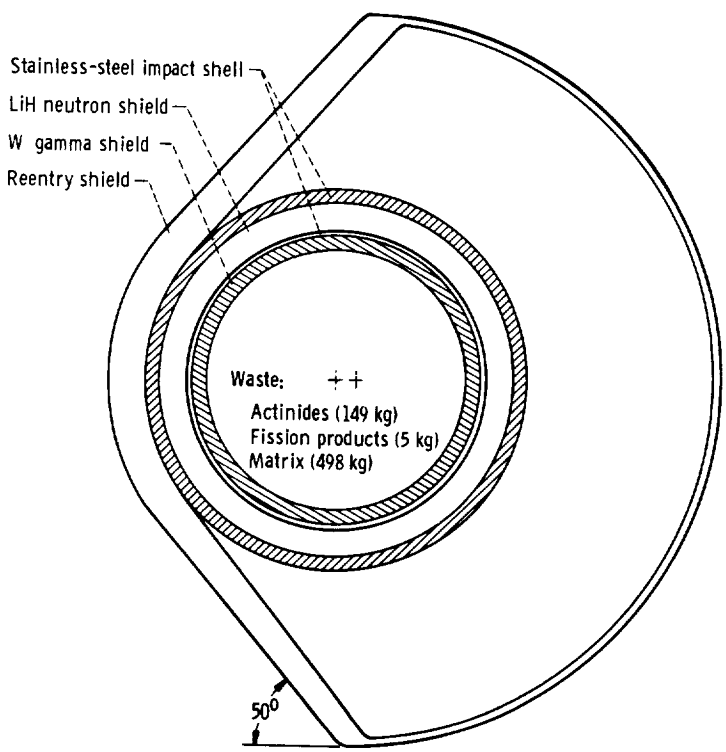


Figure 24. - Configuration of package II (actinide waste with 0.1 percent of the fission products) for disposal of three packages to high Earth orbit or 0.9-AU solar orbit. Weight per package, 2800 kilograms.

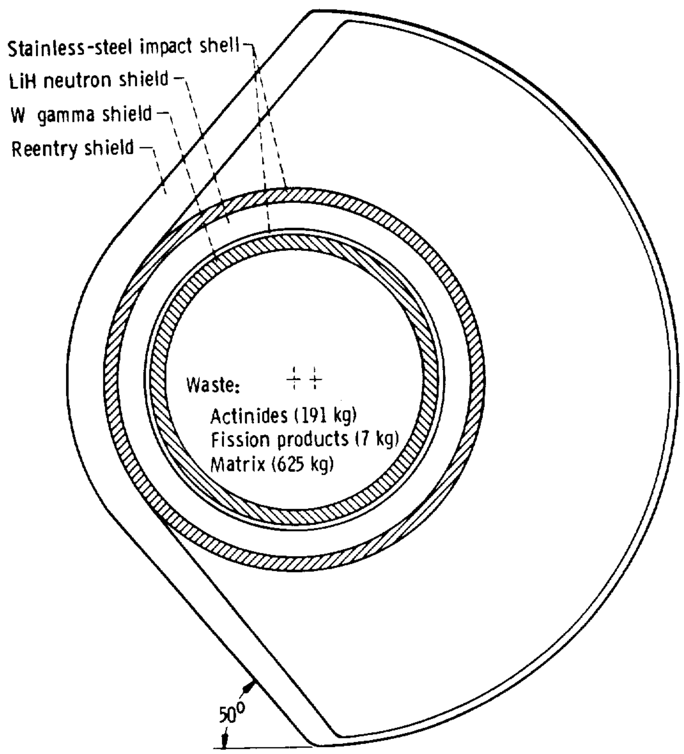


Figure 25. - Configuration of package II (actinide waste with 0.1 percent of the fission products) for disposal of single package to solar system escape. Total weight, 3270 kilograms.

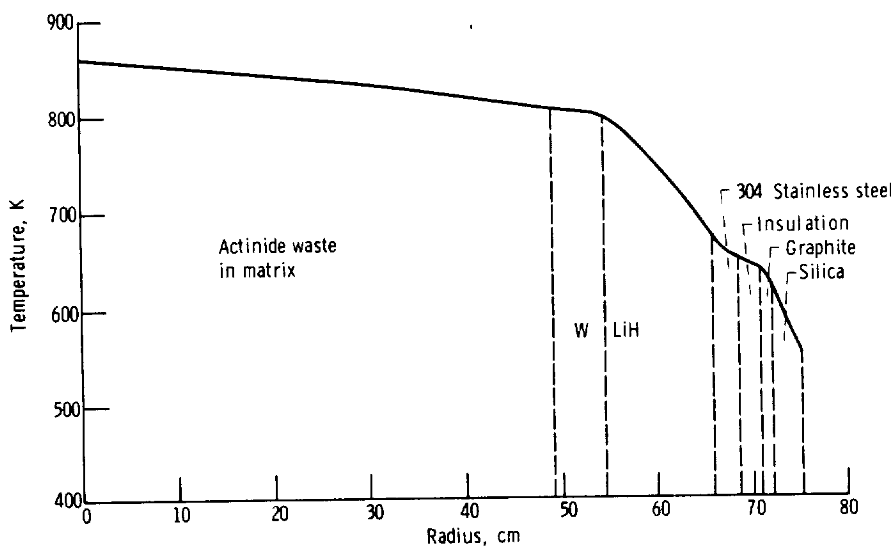
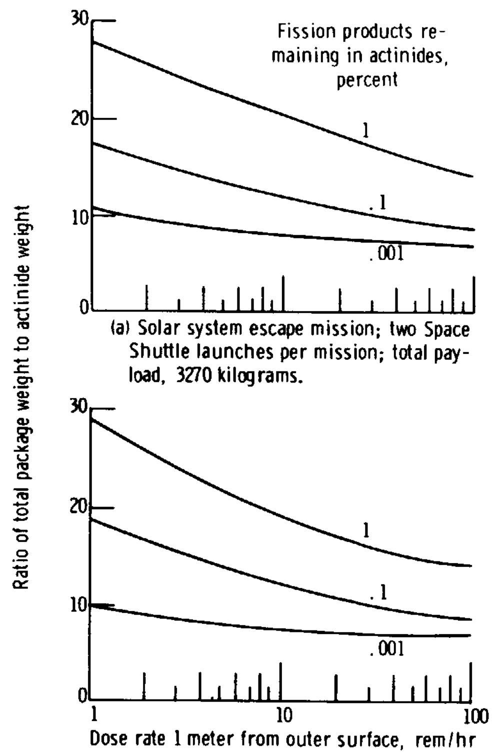


Figure 26. - Steady-state temperature distribution for disposal of single nuclear waste package (package II, actinides with 1 percent of the fission products) to high Earth orbit.



(a) Solar system escape mission; two Space Shuttle launches per mission; total payload, 3270 kilograms.

(b) High Earth orbit mission; single Space Shuttle launch per mission; total payload, 8400 kilograms.

Figure 27. - Total packaging weight ratio for different exterior dose rates, based on minimum number of packages.

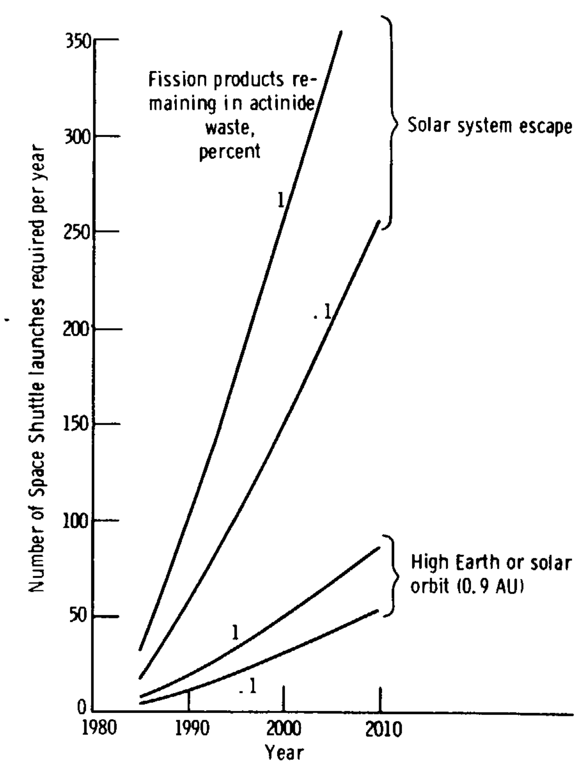


Figure 28. - Space Shuttle launch frequency required for space disposal of radioactive actinides containing 1 and 0.1 percent of the fission products. Shielded for 1 rem/hr at 1 meter from surface; 10-year Earth storage assumed.

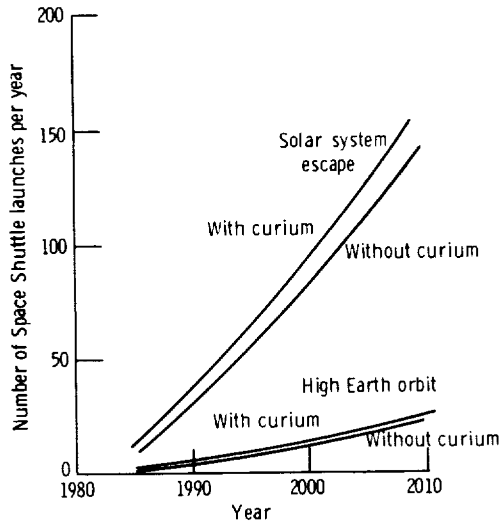


Figure 29. - Space Shuttle launch frequency required for space disposal of radioactive actinides containing 0.001 percent of the fission products with and without curium isotopes. Shielded for 1 rem/hr at 1 meter from surface; 10-year Earth storage assumed.

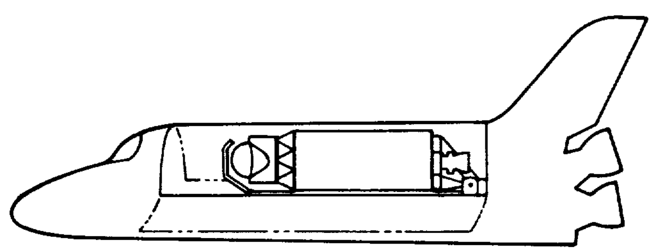
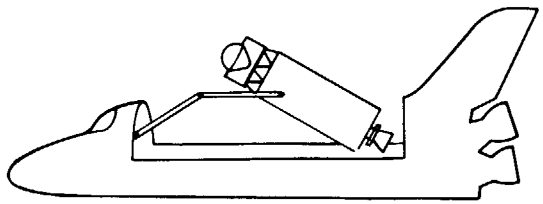
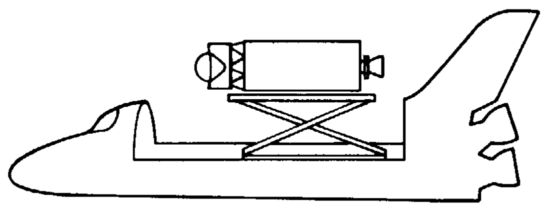


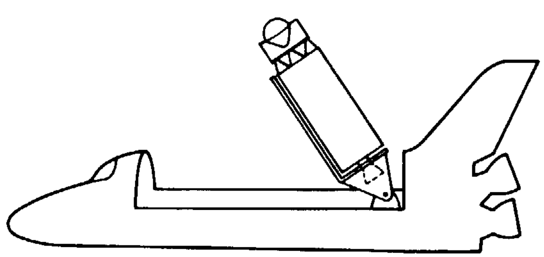
Figure 30. - Space Shuttle orbiter with nuclear waste package and tug.



(a) General manipulator.

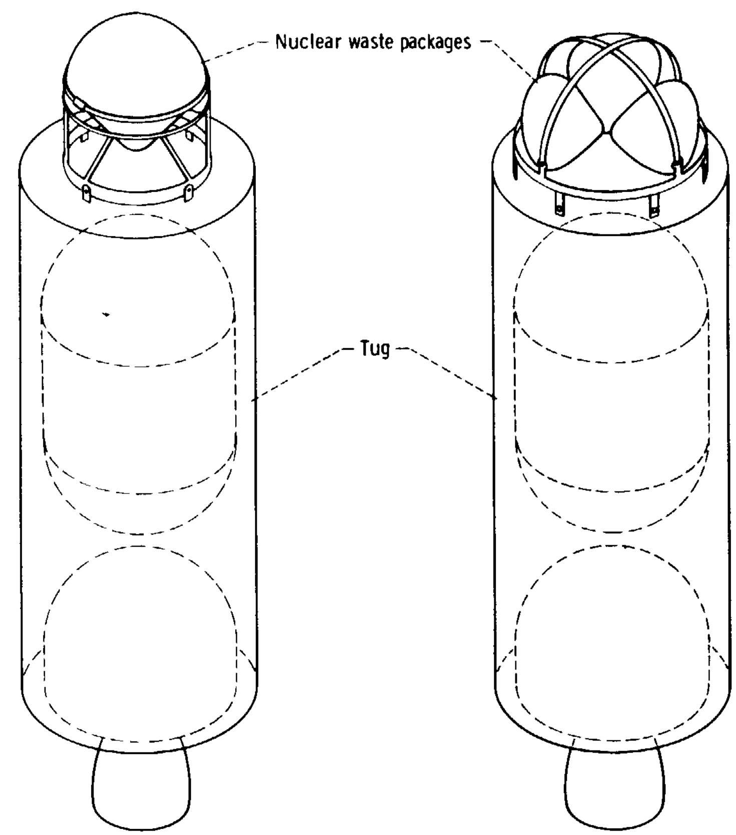


(b) Platform extension.



(c) Rotational pad.

Figure 31. - Schemes for deployment of tug with nuclear waste package.



(a) Single package.

(b) Multiple packages.

Figure 32. - Possible schemes for mounting nuclear waste packages to tug.

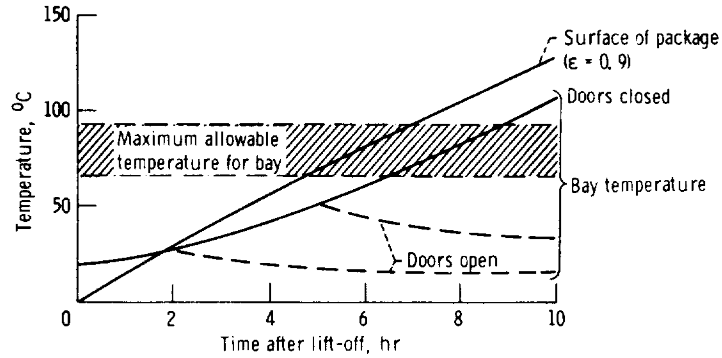


Figure 33. - Temperatures inside bay after cooldown to 0° C and lift-off. Thermal power of nuclear package, ~25 kilowatts.

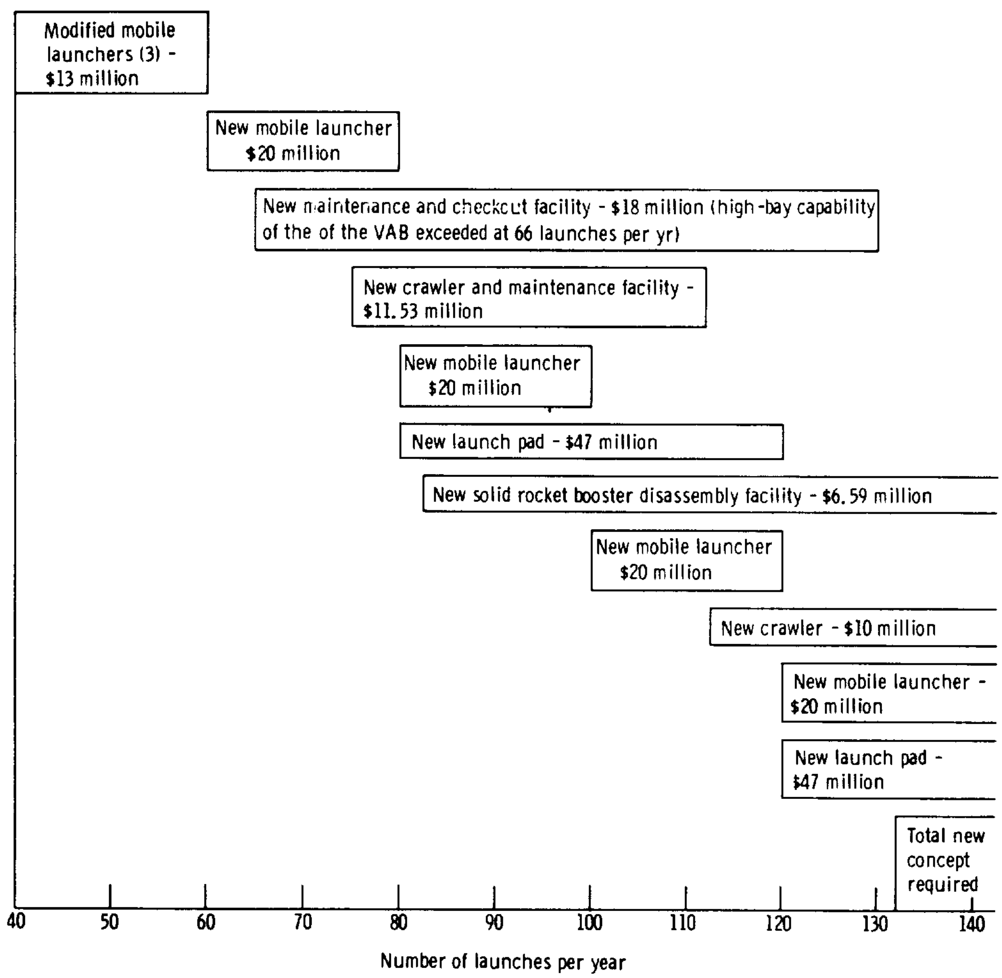


Figure 34. - Additional facilities and modifications to facilities required for space disposal of nuclear waste as function of launch frequency. All costs are in 1971 dollars and are ±20 percent.

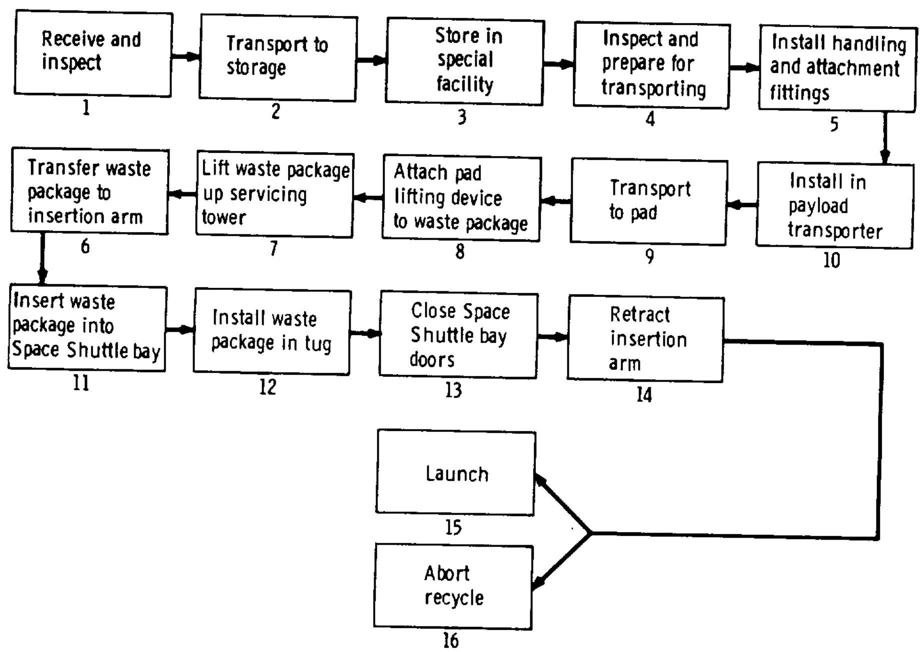


Figure 35. - Anticipated ground operations for space disposal of nuclear waste.

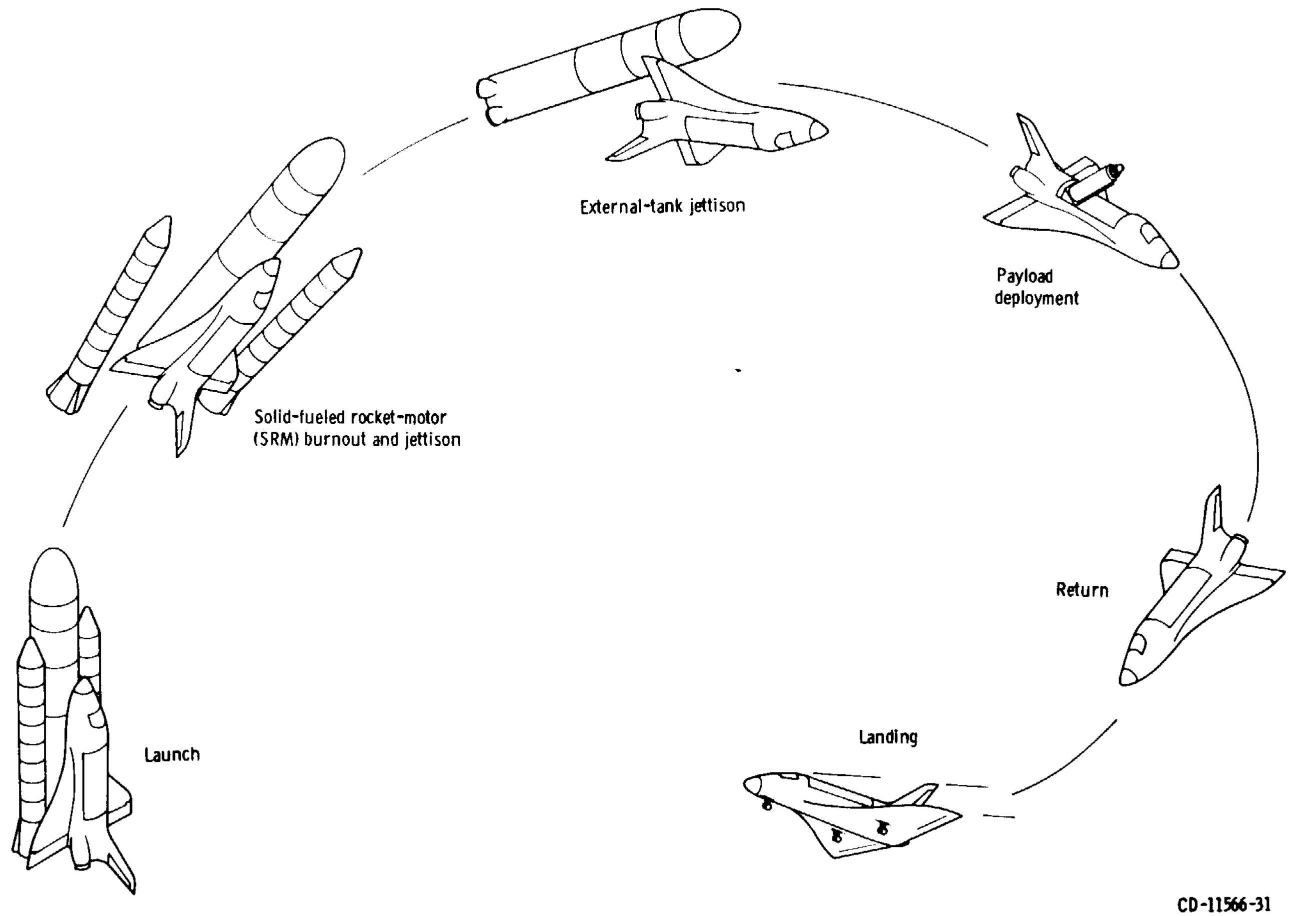


Figure 36. - Space Shuttle launch-to-landing sequence.

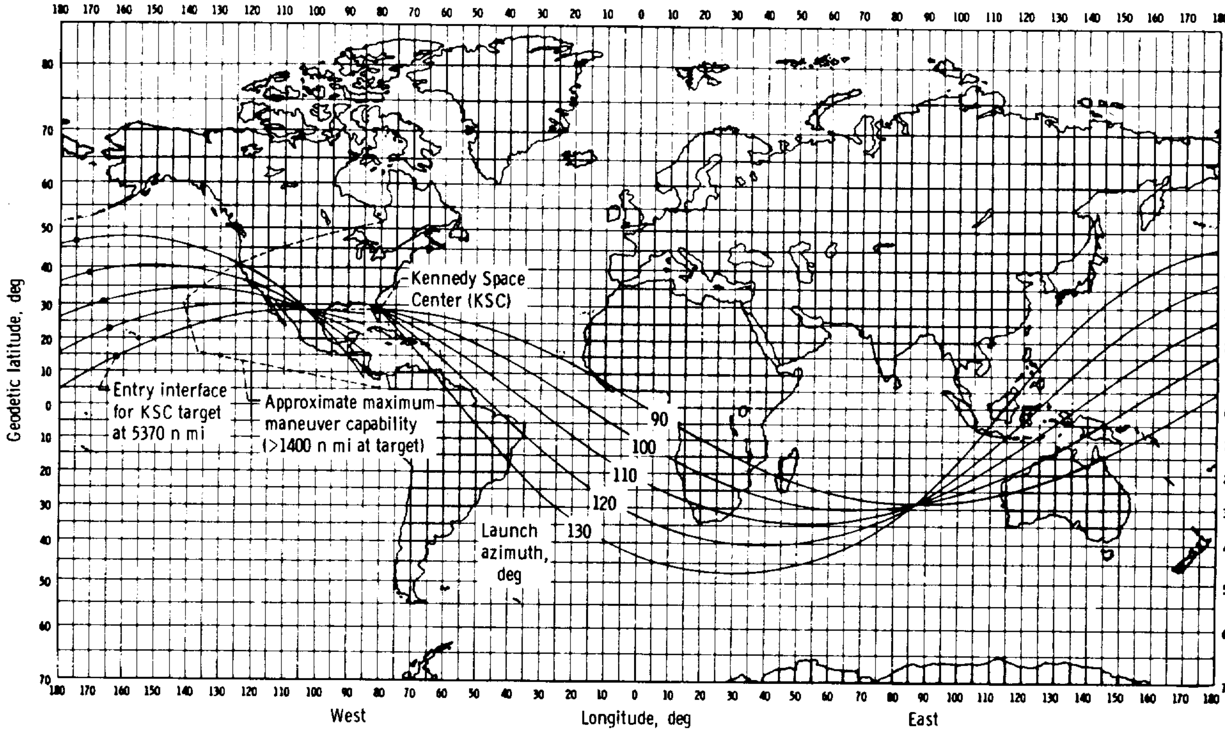


Figure 37. - Once-around abort groundtracks for five launch azimuths from 90° to 130°.

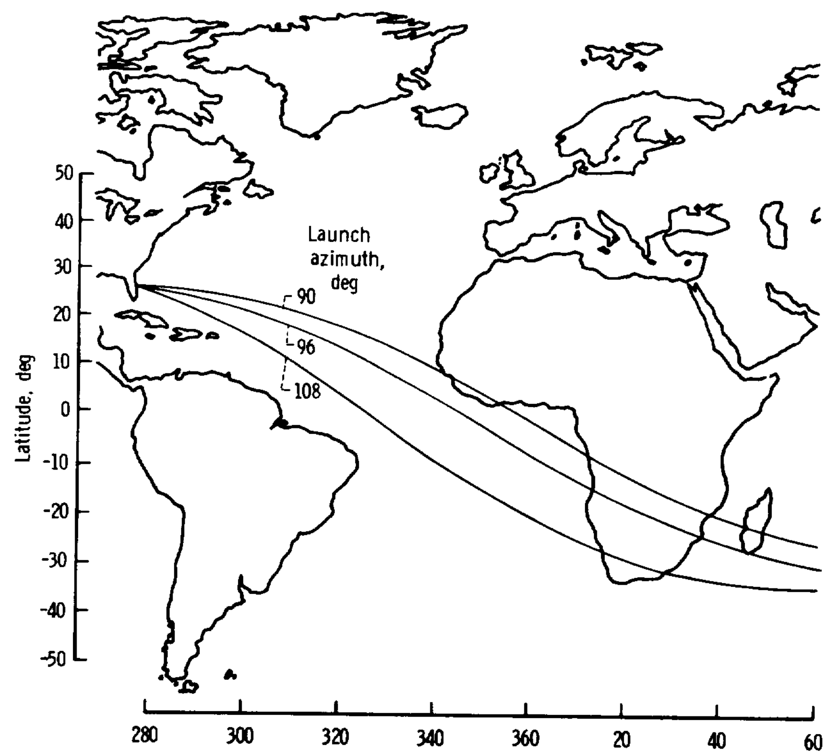


Figure 38. - Space Shuttle instantaneous impact traces for typical easterly launch azimuths.

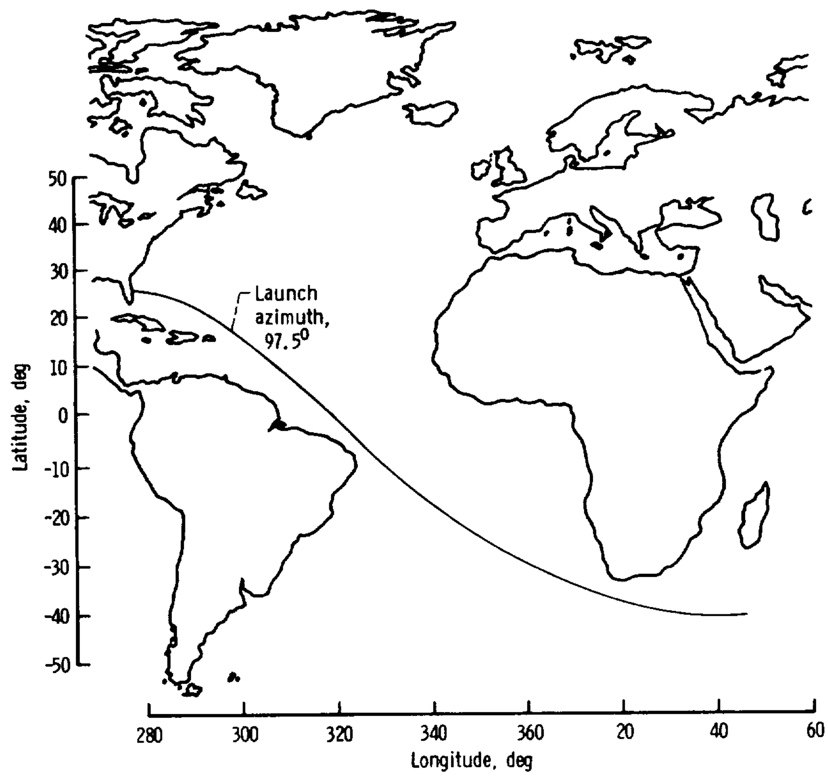


Figure 39. - Space Shuttle instantaneous impact traces for dogleg trajectory. Launch azimuth, 97.5°; final orbit inclination, 40°.

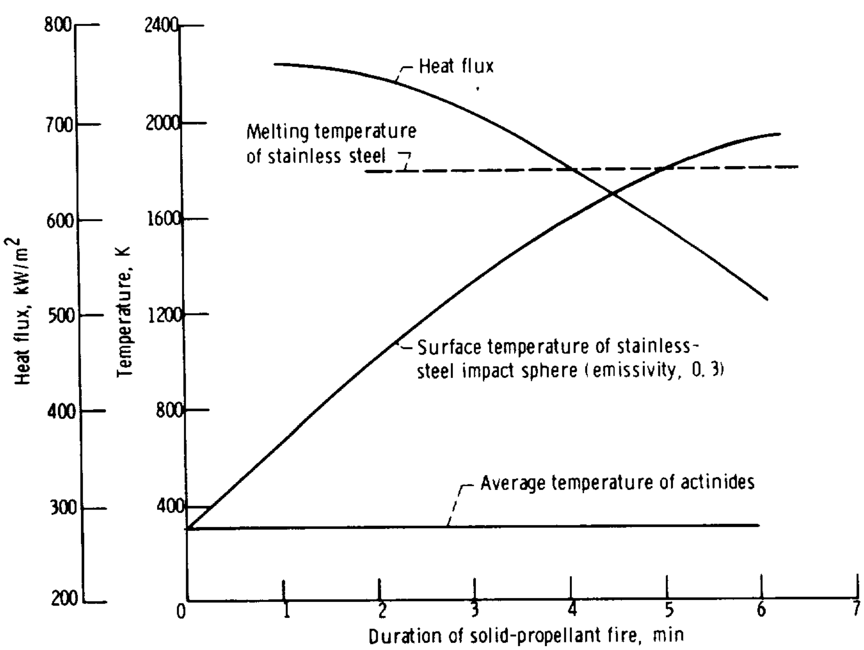


Figure 40. - Temperature of waste package during solid-propellant fire.

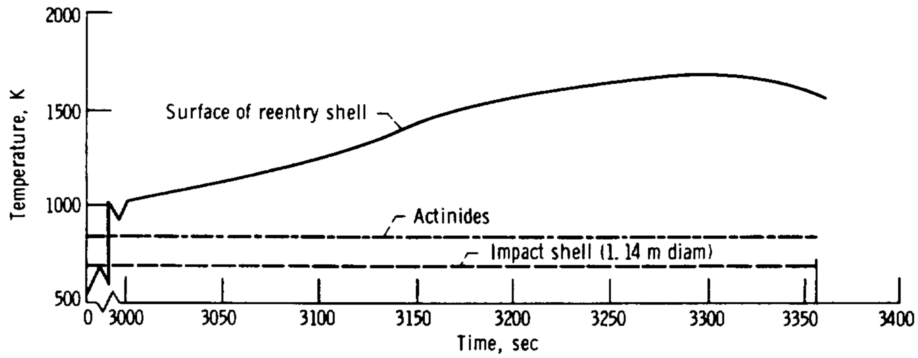


Figure 41. - Temperature of waste package during reentry (orbital decay from 120-km altitude).

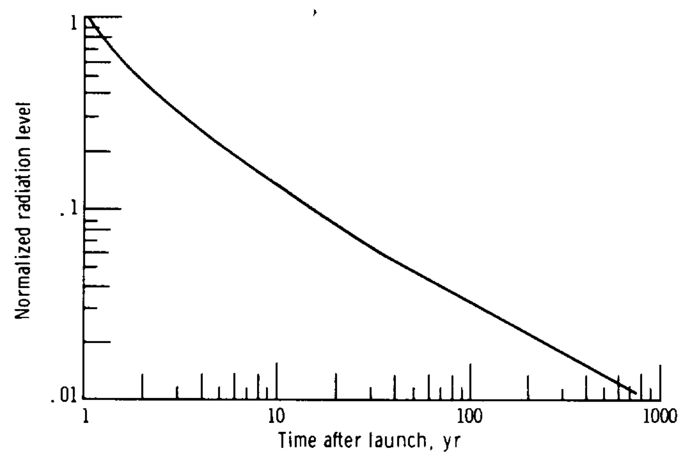


Figure 42. - Radiation level of actinides after space launch normalized to value at launch (10 yr after generation).

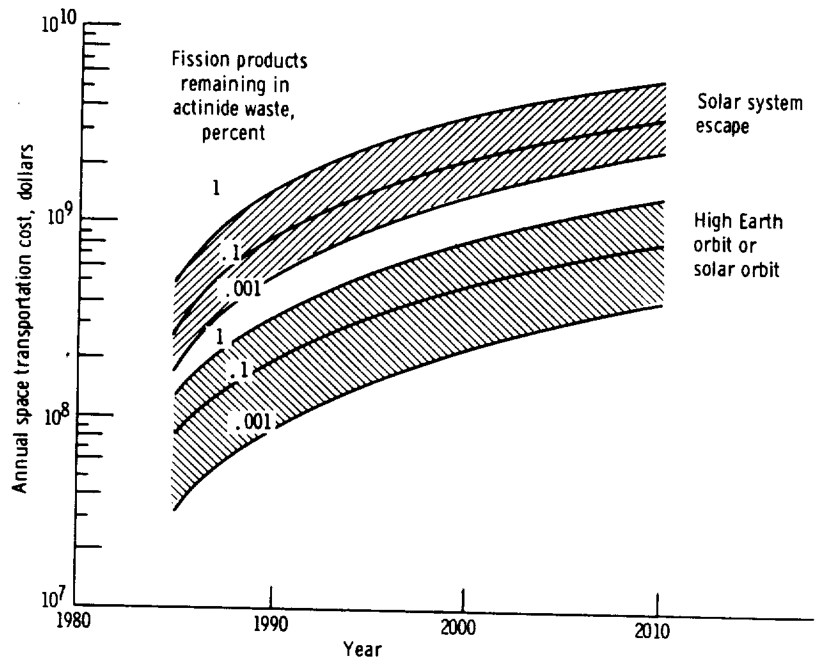


Figure 43. - Annual cost for space disposal of radioactive actinide waste using Space Shuttle/tug launch system.

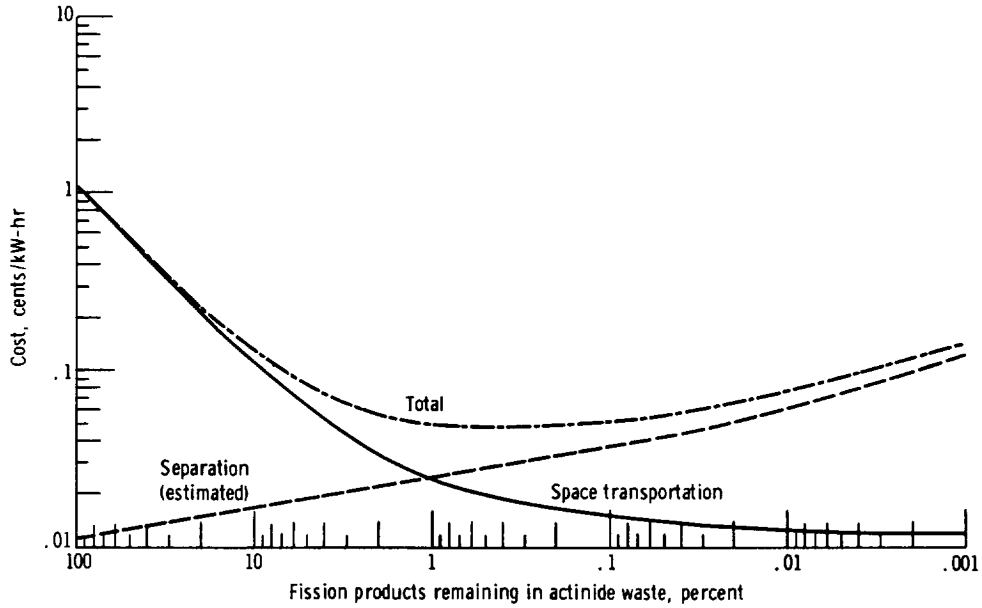


Figure 45. - Optimization of space disposal costs to high Earth or solar orbits. Space Shuttle/Centaur launch system.

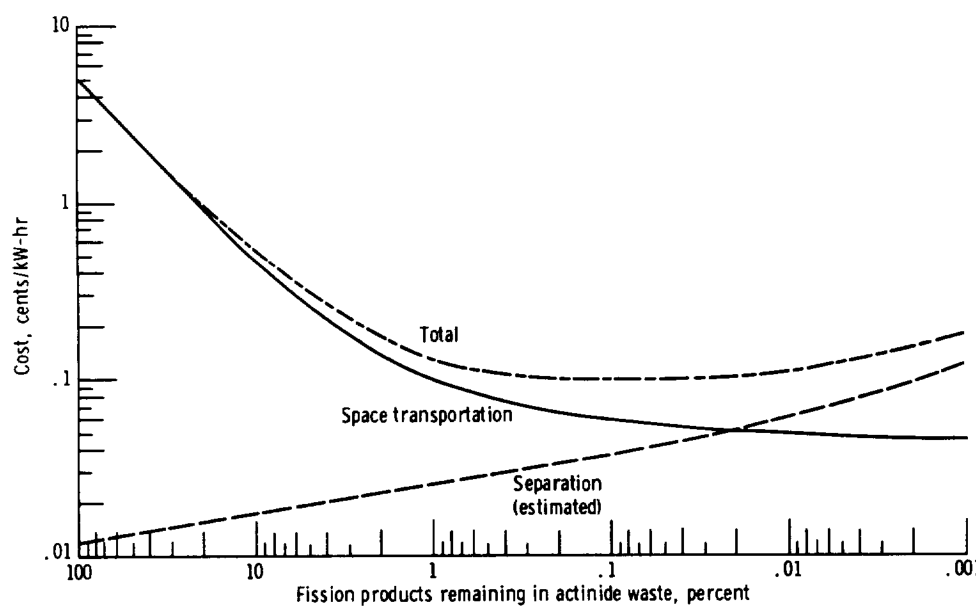
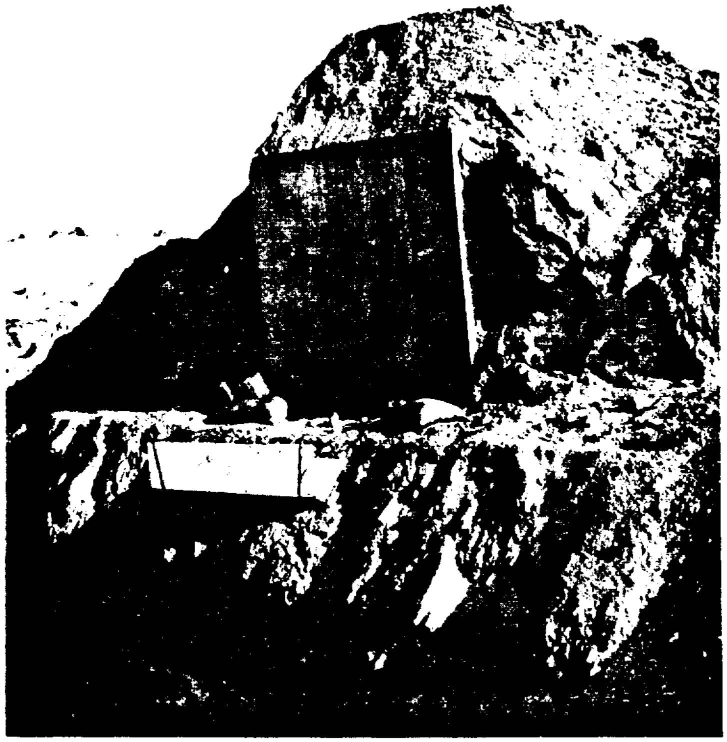
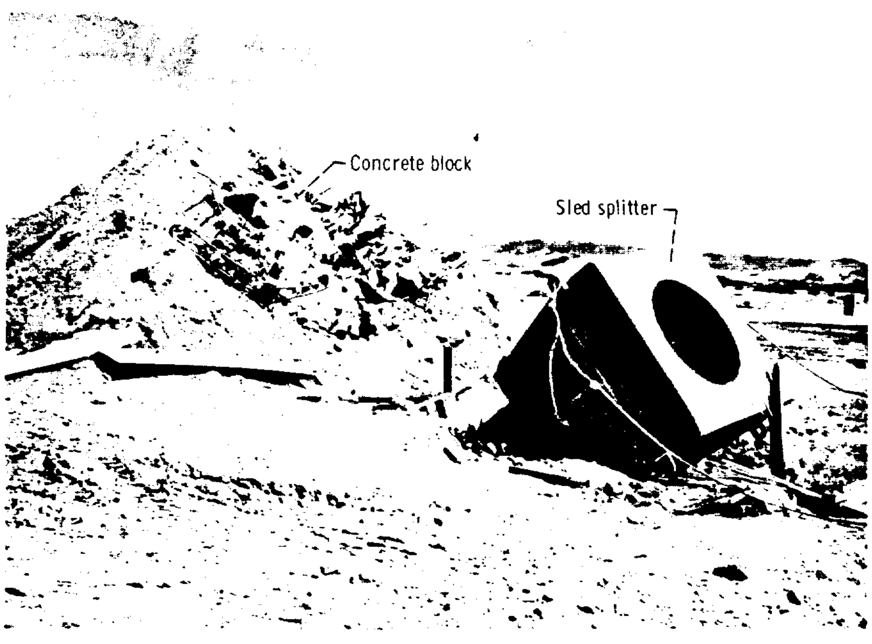


Figure 46. - Optimization of space disposal costs to solar system escape. Space Shuttles (2)/tugs (2) launch system.



(a) Before impact.



(b) After impact.

Figure 47. - Concrete block before and after impact by stainless-steel sphere.

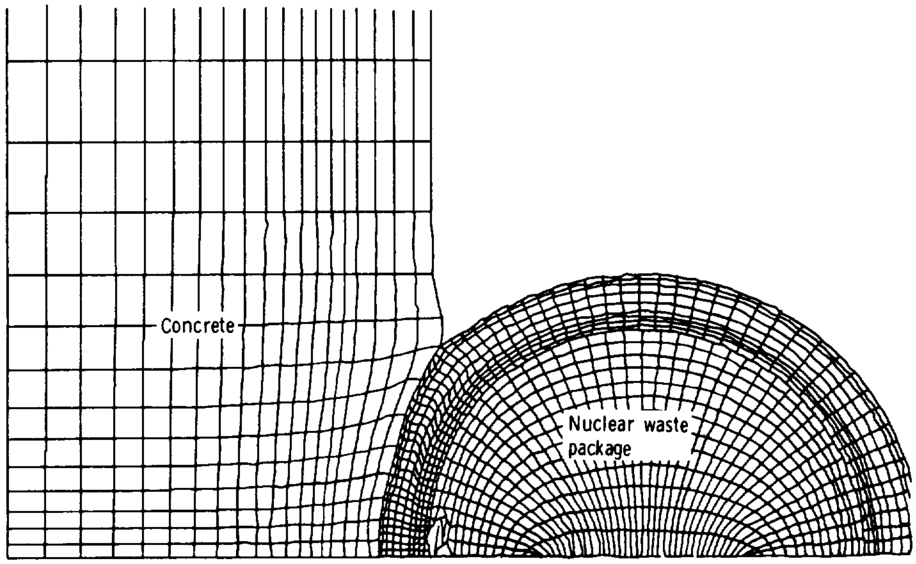


Figure 48. - Computer simulation of nuclear impact on reinforced concrete (smooth surface). Impact velocity, 322 meters per second.

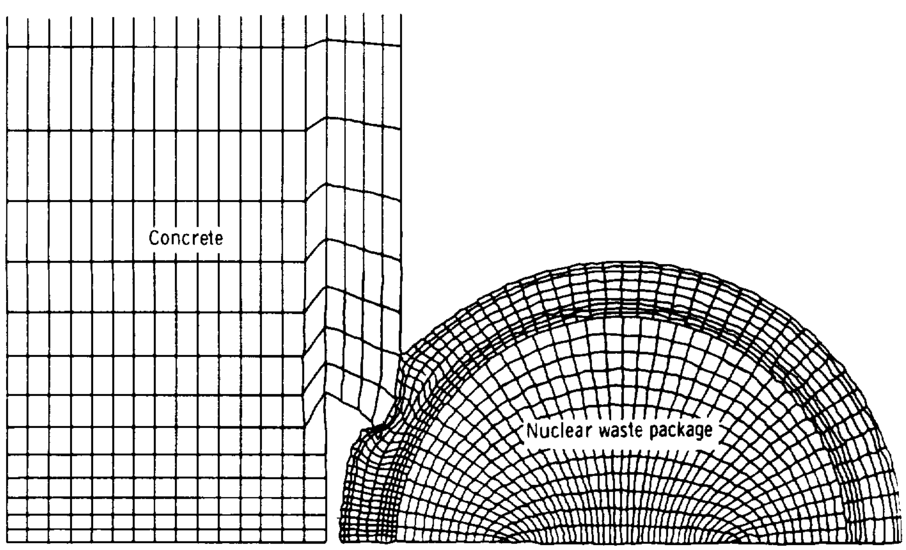


Figure 49. - Computer simulation of nuclear impact on reinforced concrete (stepped surface). Impact velocity, 322 meters per second.

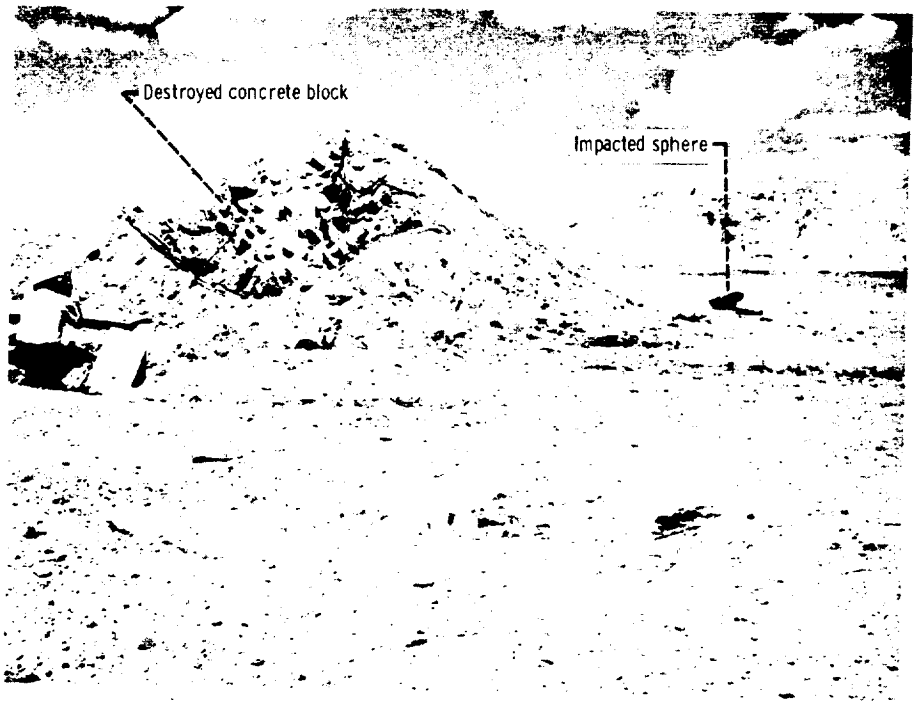


Figure 50. - Model of nuclear waste package remaining on Earth's surface after hard-surface impact.

Figure 51. - Penetration of Earth's surface by model of nuclear waste package after soft-surface impact.

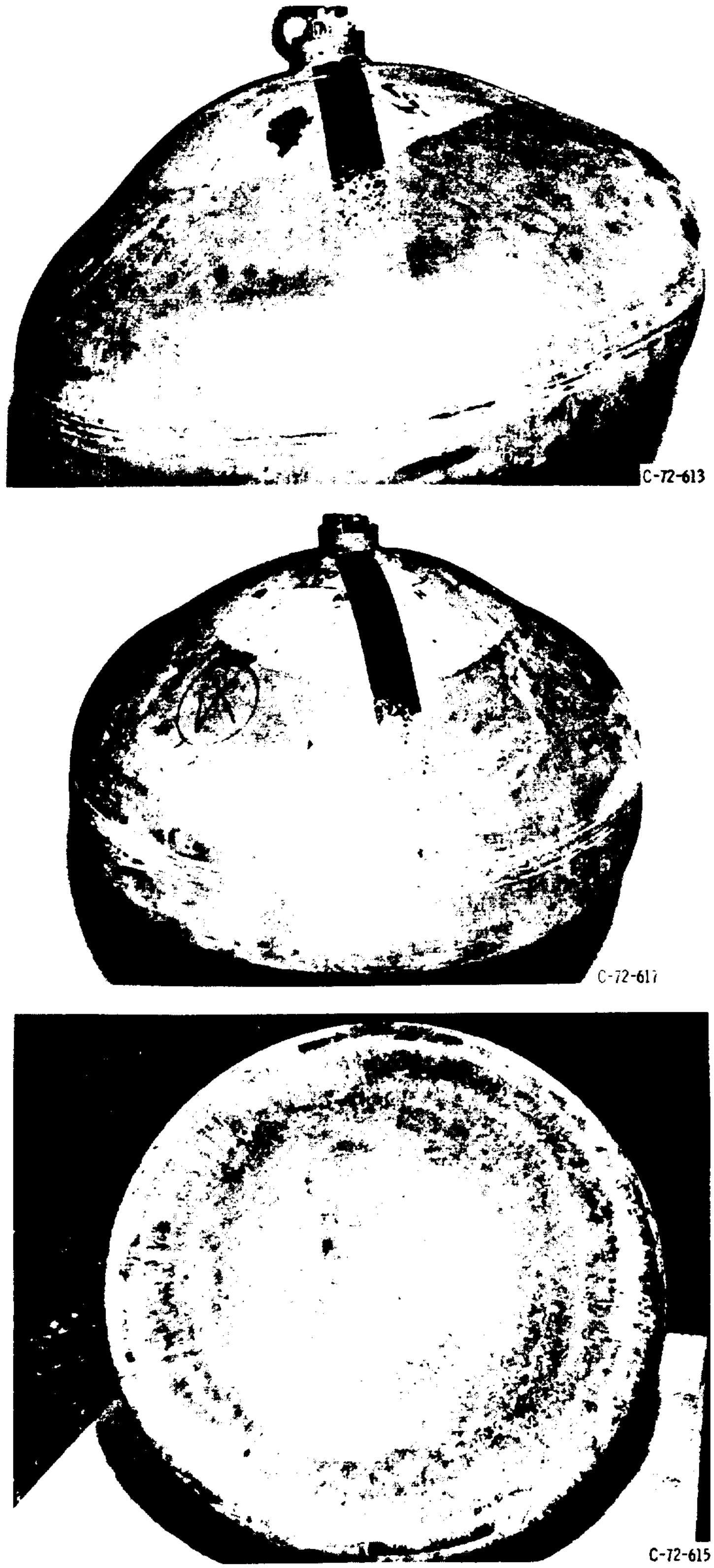


Figure 52. - Model of once-spherical nuclear waste package after impact on hard surface (concrete).

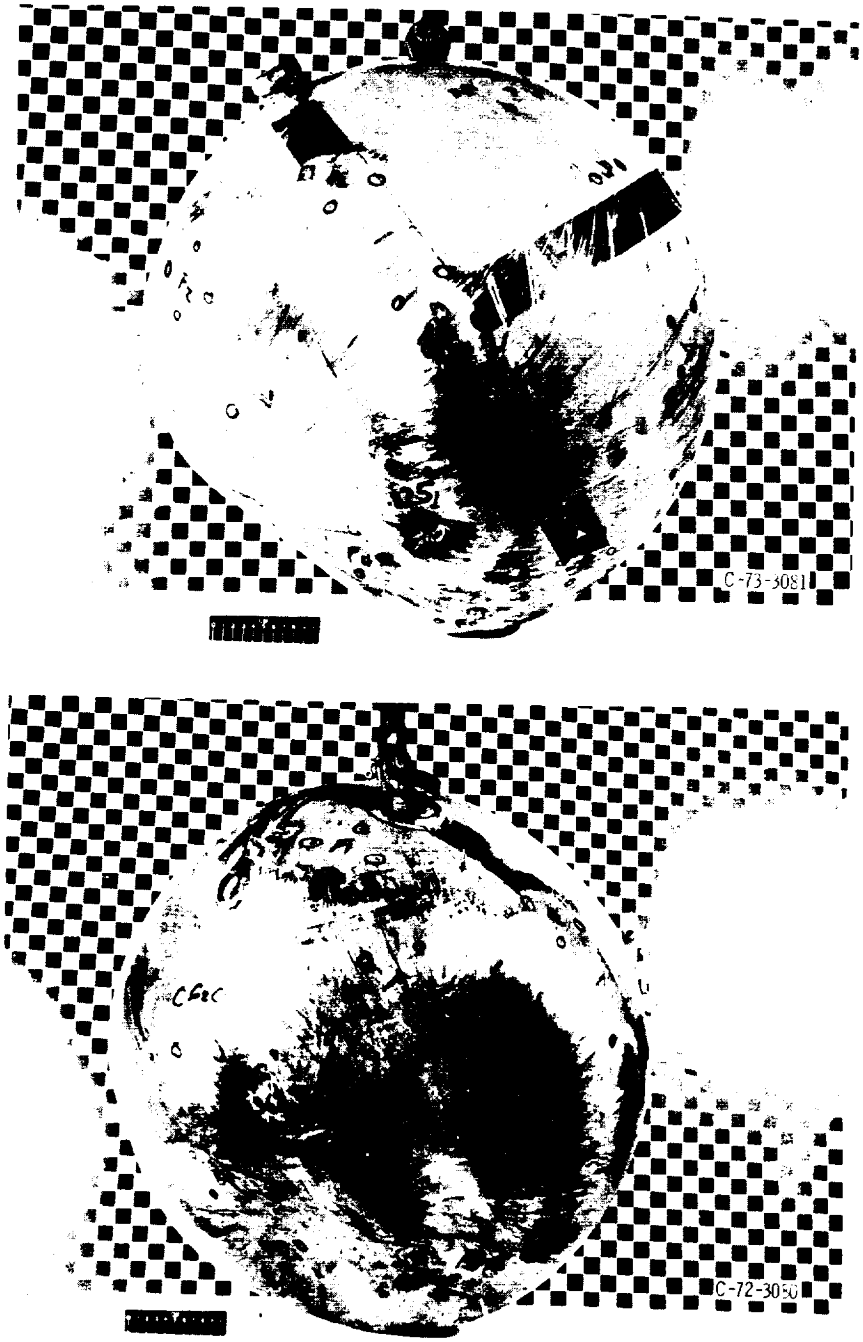


Figure 53. - Model of spherical nuclear waste package after impact on soft surface (soil).

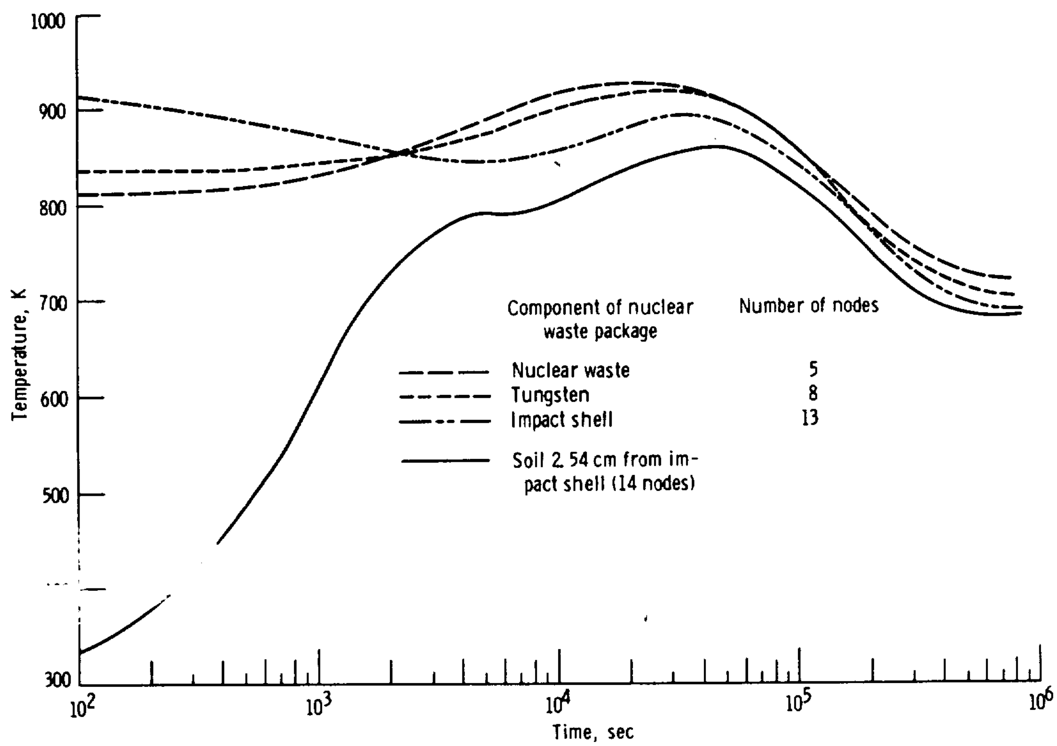


Figure 54. - Surface and internal temperatures of nuclear waste package as function of time after impact and burial in soil.

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