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SUMMARY REPORT OF SPACE TRANSPORTATION AND DESTINATION CONSIDERATIONS FOR EXTRATERRESTRIAL DISPOSAL OF RADIOACTIVE WASTE

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SUMMARY

NASA has been requested by the AEC to conduct a feasibility study of extraterrestrial (space) disposal of radioactive waste. This report summarizes the initial work done on only one part of the NASA study, the evaluation and comparison of possible space destinations and launch vehicles. Only current or planned space transportation systems have been considered thus far. The currently planned Space Shuttle was found to be more cost effective than current expendable launch vehicles, by about a factor of two. The Space Shuttle will require a third stage to perform the disposal missions. Depending on the particular mission this could be either a reusable Space Tug or an expendable stage such as a Centaur.

Of the destinations considered, high Earth orbits (between geostationary and lunar orbit altitudes), solar orbits (such as a 0.90 AU circular solar orbit) or a direct injection to solar system escape appear to be the best candidates. Both Earth orbits and solar orbits have uncertainties regarding orbit stability and waste package integrity for times on the order of a million years, as may be required. These problems can be avoided by injecting the waste package to solar system escape or impacting it into the Sun. The solar system escape mission requires a high Earth departure velocity but the mission

can be accomplished using two or three Space Tugs in tandem, each launched to Earth orbit by the Space Shuttle. However, the resulting space transportation cost is about four times higher than for the high Earth orbit or solar orbit destinations. A direct solar impact mission requires a very high Earth departure velocity and cannot be accomplished with the current or planned launch systems considered in this study. As an alternate, the solar impact mission can be accomplished using a Jupiter swingby trajectory which reduces the Earth departure velocity to values comparable to the solar system escape mission. However, the launch opportunity is limited to perhaps 40 days once every 13 months. The limited launch opportunity would make it difficult to achieve the high launch rates anticipated for disposing of significant amounts of radioactive waste.

Since the waste disposal problem extends far into the future, new space technology and future development of advanced space transportation systems applicable to the waste disposal mission can be expected. This could provide a capability superior to that considered in this report.

INTRODUCTION

The Atomic Energy Commission Division of Waste Management and Transportation has initiated a study to assess the feasibility of various long-term storage or disposal options for radioactive waste. Under this study several concepts are being investigated. NASA has been requested by the AEC to conduct a feasibility study of one of the concepts: extraterrestrial (space) disposal of radioactive wastes.

The NASA study will be used by Battelle Northwest Laboratories who have the responsibility of preparing a comprehensive report summarizing the feasibility, development requirements, and possible schedule and cost of development for each of the alternates.

This report summarizes the initial work done on only one part of the NASA study, the evaluation and comparison of the various space destinations and launch vehicles considered thus far. Other portions of the NASA study (description of nuclear waste, design of containment vessels, shielding considerations, etc.) are reported in reference 1 and in subsequent reports of that series. This will include a more detailed report on transportation and destination considerations.

The space destinations considered in this study include Earth orbits, solar orbits, solar system escape and solar impact. The mission requirements for each destination are presented, and the relative advantages and disadvantages for each destination are discussed. In this report the destinations are referred to as disposal missions although, strictly speaking, some of the destinations could permit future retrieval of the nuclear waste, especially the Earth orbit destination.

The launch systems considered in this study include the larger expendable launch vehicles in current operation as well as the reusable Space Shuttle (with a third stage such as the Space Tug) which is planned to be operational in 1980. Because the radioactive waste disposal problem extends far into the future, new space transportation technology can be expected. Use of this new technology could result in more effective, lower cost transportation systems than those considered in this study. Similarly, the high launch rates anticipated for waste disposal (eventually one launch a week or more) could justify the development of a special launch vehicle dedicated to the disposal mission. However, this initial study is limited to current and planned capability where the basic development costs for the launch vehicle will have already been borne by other programs.

The two most important factors in assessing the feasibility of space disposal are safety and cost. In this report, safety has been considered only qualitatively in the comparisons of destinations, launch vehicles and their associated trajectories. The costs presented include the launch vehicles and their operations. These data can be used for comparative purposes for preliminary determination of the best launch vehicles and the most promising mission destinations. However, total cost of space disposal will have to include other elements such as the cost of separating and concentrating the waste material, transporting the nuclear waste and handling it at the launch site, and the cost of the flight containment system and its associated flight systems. These costs are not considered in this report.

DESTINATIONS AND MISSION REQUIREMENTS

The space destinations considered in this study will be discussed in the order of increasing mission energy requirement. All launches are assumed to occur from the Eastern Test Range (ETR) in an easterly direction. For comparison purposes it is assumed that the launch vehicle will first launch into a low circular Earth parking orbit, although this isn't always necessary or advantageous. After parking in this orbit, the launch vehicle upper stage or stages will inject the waste package to its final destination. In general, for launch vehicles, best mission performance is achieved by using low parking orbit altitudes.

For the mission and vehicle comparisons in this report a parking orbit altitude of 100 N.MI., which is typical of current practice, will be used. However, for the waste disposal mission a higher parking orbit altitude may be preferred from a safety standpoint, as will be discussed later.

Mission energy will be characterized by the mission Delta-V which is the sum of all the velocity increments that the launch vehicle has to provide after reaching low Earth orbit. In many cases the launch vehicle can place or inject the waste package to its final destination. In other cases the waste package, after separation from the launch vehicle, will require subsequent trajectory (midcourse) corrections, or propulsion upon reaching its destination. In these cases the waste package becomes an active spacecraft requiring the addition of guidance, control, communications and propulsion systems. These requirements will be pointed out where needed.

High Earth Orbits

A principal advantage of the Earth orbit destination is the relatively low Delta-V required in comparison to some of the other destinations. Another advantage is that the waste packages could conceivably be retrieved at a later date either to recover the waste material or remedy some unforeseen problem.

Figure 1 depicts the Delta-V required to achieve high circular final orbits starting from a 100 N.MI. circular parking orbit. This mission requires two propulsion maneuvers after reaching the parking orbit. The first is made in the parking orbit and places the payload on an elliptical transfer orbit. After coasting along the transfer orbit to the desired final altitude, the second maneuver is made to circularize the final orbit. It would be expected that both of these maneuvers would be performed by the launch vehicle upper stage and that the waste package itself would require no additional guidance or propulsion capability.

The orbital maneuvers from the initial parking orbit can be arranged so that in the event of a propulsion failure, the resulting orbit would have a lifetime of at least several months. This would allow time for making a second launch which would rendezvous with the waste package and take corrective action.

For the disposal of nuclear waste it is not clear what final orbit altitudes are acceptable. Orbit lifetime is a primary factor. If long half-lived wastes are to be disposed of in space, orbit lifetimes of a million years or longer may be required. At reasonably high orbit altitudes, above several thousand miles, 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 should be avoided to minimize lunar perturbations. Furthermore, orbits beyond the Moon are subject to large solar perturbations and their stability is questionable. High traffic regions or orbits important from a science or applications point of view (such as synchronous orbit altitude) should not be chosen. Orbits lying between synchronous orbit altitude and the Moon are probably the best choice. Unfortunately these orbit altitudes have the highest Delta-V requirement for Earth orbits as can be seen from figure 1. The high altitude of these orbits will, however, minimize the probability of a collision with a future space launch through this region. If the payloads are launched due East from ETR, their orbits will have an inclination of about 28° to the Earth's equator. Gravitational perturbations will precess the orbits. Due to inherent limitations on placement accuracy, there will be slight differences in the orbits and they will precess at different rates. Eventually, the orbits of the waste packages will be randomly located in a belt around the Earth. This region would be regularly penetrated by future lunar or planetary spacecraft. However, because of large spacing of the waste packages at these great distances from the Earth, the probability of a collision would be extremely remote and could probably be ignored.

A more serious problem is that long time stability of the orbit elements (eccentricity, semimajor axis, etc.) and hence orbit lifetime cannot be guaranteed. Intuitively, it might be expected that these high orbits will have satisfactory lifetimes. However, the complexity of the multi-body perturbation problem precludes rigorously verifying the stability of these orbits for times on the order of a million years. Even so, this problem may be academic. There is no assurance of the integrity of the relatively hot waste package when exposed to the space environment over such long periods of time. Since neither orbit stability or waste package integrity problems are well understood (for times on the order of a million years), high Earth orbits cannot now be considered a permanent disposal site. Unless further studies can resolve these problems, Earth orbits should only be considered a temporary (hundreds or a few thousand years) storage site requiring further action at a later date.

Solar Orbits

If Earth orbit destinations for radioactive wastes are unacceptable, solar orbits are the next alternative from a Delta-V standpoint. The solar orbits considered in this study are those achievable with relatively low Delta-V's including (1) solar orbits achievable by injecting the payload to Earth escape energy or slightly beyond, (2) circular solar orbits slightly inside or outside the Earth's orbit about the Sun achieved by additional propulsion after escaping the Earth 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 Delta-V of approximately 10,600 feet per second. (This is actually somewhat less than the Delta-V required for high Earth orbits as shown in figure 1.) The waste package would then be separated from the launch vehicle and after escaping the Earth's gravitational field would be in an orbit about the Sun. The waste package would be in essentially the Earth's orbit about the Sun but at a different angular position.

The advantage of this approach is that the waste package (as in the Earth orbit case) could be passive, requiring no active spacecraft systems. The disadvantage is that there is a high probability of a re-encounter with the Earth at some future time. Due to inherent limitations on injection accuracy and long term gravitational perturbation effects (principally from the Earth itself) the waste package cannot be maintained at a fixed position from the Earth. As a result of these effects it will tend to drift with respect to the Earth, and preliminary calculations indicate a high probability of re-encountering the Earth within a few thousand years or less.

A better approach would be to provide somewhat more Delta-V than required for Earth escape (on the order of a 1000 feet per second), so that after escaping the Earth 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 about the Sun). Initially, the orbit of the waste package would intersect the Earth's orbit at only one point.

Furthermore, planetary gravitational effects could 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 perhaps such is the case at least for a few thousand years, and it is recommended that this approach receive more study. However, there is no assurance that demonstratable techniques can be developed which eliminate the possibility of re-encounter with the Earth for times on the order of a million years. Because of this uncertainty, Earth escape 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 packages can be placed in circular solar orbits either inside or outside the Earth's orbit about the Sun. The selection of the final orbit radius is somewhat arbitrary. However, the further the orbit is from the Earth's orbit, the higher is the required Delta-V. Consequently, there is an incentive to go no further than necessary. The Earth itself is in an elliptic orbit about the Sun at a distance ranging from 0.983 AU (astronomical units) at perihelion to 1.017 AU at aphelion. The final orbit should be at least outside this range to minimize the probability of a subsequent re-encounter with the Earth.

Again, as for orbits about the Earth, the problem of demonstrating the stability of solar orbits for times on the order of a million years is unresolved. 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. The magnitude of the required separation is not known. For comparison purposes, a final orbit radius of 0.90 AU is used in this study. It should be noted that the possible disintegration of the waste package 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 package should vaporize, the solar wind could tend to blow some of the material out from the Sun. If the integrity of the waste package cannot be guaranteed, these and other effects will have to be evaluated, not only in making the selection of orbit location, but also to establish the ultimate destination of the waste material.

The mission profile for a 0.90 AU solar orbit is shown in figure 2. The payload is injected to slightly past Earth escape energy at point 1. It is given sufficient velocity in the proper direction so that after escaping from the Earth it is in an elliptical solar orbit with a perihelion of 0.90 AU. The aphelion of this orbit is still at the Earth's distance from the Sun. After coasting approximately six months the payload reaches perihelion (point 2) and a second Delta-V maneuver is required to circularize the orbit at 0.90 AU. The first Delta-V (10,690 feet per second) is only slightly above Earth escape Delta-V and is performed by the launch vehicle upper stage in departing from the Earth parking orbit. The second Delta-V is 2660 feet per second, and because of the long coast time involved it is impractical to accomplish it with the launch vehicle. A propulsion system along with guidance, control and communications systems will have to be added to the waste package. This introduces two disadvantages to this destination. The cost of the waste package will increase and the propulsion and associated systems added to the waste package must perform reliably over a six month time period. These disadvantages could be diminished by performing the circularization maneuver with a relatively simple spin stabilized solid rocket motor.

If the first burn out of Earth parking orbit should fail prior to reaching Earth escape velocity, the payload will be left in an elliptic Earth orbit. The departure trajectory can be designed so that if this should happen there would be sufficient orbit decay time (months) to permit a second launch for taking corrective action. If the first burn should fail after reaching Earth escape velocity, or if the final circularization burn should fail, the resulting solar orbit would intersect the Earth's orbit near aphelion. For these cases there is a possibility that the waste package would eventually re-encounter the Earth. This is a disadvantage shared by all destinations beyond Earth. The re-encounter probability due to a failure can be reduced by using departure trajectories similar to those suggested earlier for the Earth escape case.

In summary, if the stability of the circular solar orbits can be established, they can be considered as a possible disposal destination. In addition, further study is required to evaluate the possible failure situations that might lead to an Earth re-encounter.

Solar Orbits via Venus and Mars Swingbys[1] - Another method for achieving solar orbits that do not cross the Earth's orbit is to swingby another planet, using the gravitational attraction of that planet to change the initial swingby trajectory. Both Mars and Venus swingbys can be achieved with Delta-V's only slightly higher than for Earth escape. An example of a Venus swingby mission is shown in figure 3. (The Mars case is similar.) The payload would be injected onto a Venus swingby trajectory at point 1. The injection Delta-V is approximately 12,000

1 Data for these destinations were obtained from Victor Bond of the NASA Manned Spacecraft Center

feet per second. After coasting for typically 150 days the waste package will swing by Venus at point 2. With a properly oriented swingby, the aphelion of the solar orbit can be lowered from approximately 1 AU to .75 AU so that it will no longer cross the Earth's orbit. This is the principal advantage of the swingby missions. However, the post swingby orbit will, periodically, cross the orbit of Venus. The waste package could collide with Venus, or its orbit could be significantly perturbed on a subsequent close encounter, although this probability is small. To preclude a subsequent encounter with Venus, the post swingby trajectory can be altered by a propulsion maneuver upon reaching perihelion at point 3 of figure 3. A Delta-V of 1000 to 2000 feet per second could lower the aphelion to slightly inside the orbit of Venus. Even if this maneuver is considered unnecessary, the waste package will require a midcourse trajectory correction system (with currently achievable injection accuracies) to achieve a proper swingby position at Venus. The midcourse correction requirement will increase mission complexity and waste package cost.

A basic disadvantage of all swingby missions is that they cannot be launched everyday as could the previous destinations discussed. 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 can be about three to four months long without major increases in injection Delta-V (wider launch opportunities require higher injection Delta V's). These launch opportunities may be too limited to effectively support the anticipated number of launches required. Even if only the long half-lived material were placed in space, it is anticipated that eventually one launch a week or more on a continuing basis will be required. For a Venus swingby mission, this means that there would have to be almost daily launches over perhaps a 90 day period, once every 19 months. Such an operation would be expensive in terms of required Shuttle fleet size, number of launch facilities and utilization of ground crews. (For example, the reusable Space Shuttle is expected to have a two week turn-around-time between launches.) This problem could be alleviated somewhat by using both the Mars and Venus swingby opportunities. However, since the swingby missions offer no outstanding advantages over the 0.90 AU solar orbit case (which can be launched any day) the latter case seems the better choice.

Solar System Escape

Since both the Earth orbit and solar orbit destinations have uncertainties regarding long time orbit stability and waste package integrity, solar impact and solar system escape should also be considered as possible waste package destinations. Of the two, it takes less Delta-V to escape the solar system, and this case will be discussed first.

Solar system escape can be achieved with a single propulsion burn out of low Earth parking orbit with all the propulsion and guidance provided by the launch vehicle. The waste package can be passive and requires no additional propulsion or astrionics systems. The Delta-V required is 28,700 feet per second from a 100 N.MI. Earth parking orbit. As a point of interest it takes over 20 years before the waste package reaches the mean orbital distance of Pluto. It will take over a million years to reach the distances of the nearest stars. The launch can be made on any day although there is a small variation in injection

Delta-V required throughout the year. There is no difficulty in selecting a trajectory that will miss the outer planets. However, the most efficient trajectories will be in or near the ecliptic plane and consequently will fly through the asteroid belt. Except for its high Delta-V requirement, solar escape is the most attractive destination discussed thus far. It shares one problem with all the destinations beyond Earth. That is, in the event of a propulsion or guidance system failure after reaching earth escape velocity, the waste package will be left in an unplanned orbit about the Sun.

As will be discussed in a later section on launch vehicles, it is difficult to provide the high Delta-V required for the solar escape mission with current launch vehicles. One means for reducing this Delta-V requirement is to utilize a Jupiter swingby trajectory. With a properly designed swingby at Jupiter, the Delta-V required to escape the solar system can be reduced to approximately 23,000 feet per second.

However, the Jupiter swingby mission suffers the same disadvantages that were discussed earlier for the Mars and Venus swingby missions. The waste package can no longer be passive since it will require a trajectory midcourse correction capability. The capability of launching every day is lost since the Jupiter launch opportunity only occurs every 13 months. It would be simpler to use a direct solar escape mission although the Delta-V for this mission is about 5000 to 6000 feet per second higher than for the Jupiter swingby mission to solar escape. The effect of the higher Delta-V on launch vehicle payload capability will be shown later.

Solar Impact

A solar impact trajectory can also be achieved with a single propulsion burn from Earth parking orbit. The mission takes only a little over two months. Otherwise, it shares many of the advantages and disadvantages of the solar system escape mission. The waste package can be passive and can be launched any day. Except for failures, there are no problems of orbit stability or encounters with the Earth or other planets. The problem of a failure at or beyond earth escape velocity is similar to that for the solar system escape mission.

The main disadvantage of the direct solar system impact mission is that it requires an extremely high Delta-V, approximately 79,000 feet per second. A grazing impact into the outer edge of the Sun could reduce the Delta-V requirement to about 70,000 feet per second. In either case, the Delta-V's are far beyond the capability of current launch vehicles and are considered impractical.

A solar impact mission can also be achieved using a Jupiter swingby to turn the trajectory back into the Sun. In this case the mission will take more than three years to reach the Sun, but the Delta-V can be reduced appreciably, down to about 25,000 feet per second. However, all the disadvantages of a planetary swingby trajectory are present. The Jupiter opportunity occurs only every 13 months. Even if the Delta-V were increased to the same value as for the solar escape mission (28,700 feet per second), the width of each opportunity would be only on the order of 40 days. With the high launch rates expected for the waste disposal missions, it would appear simpler to use the solar escape mission which could be launched on any day.

Other Destinations

It should be mentioned that 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, at Lagrangian equilibrium points and so forth. These destinations were not considered in this study although in some cases they could warrant further investigation. The general arguments against these destinations include (1) a landing failure could result in widespread contamination, (2) the regions are unexplored and/or are of scientific interest, (3) some of the regions could be of future value from an applications standpoint, (4) launch opportunities are limited and (5) deep space propulsion is required and in many cases the retro Delta-V's are high.

Comparison of Destinations

To summarize the discussion of the different destinations, Table I lists typical Delta-V requirements for the various missions and their principal advantages and disadvantages. The Delta-V's shown are representative for each destination, although there will be some variation depending on the particular launch opportunity and details of the mission design. The Delta-V for high Earth orbits is an upper value for orbits between synchronous and lunar orbit altitudes. The Earth escape mission includes some additional Delta-V (beyond Earth escape Delta-V) in an effort to minimize the probability of a subsequent Earth re-encounter as was discussed earlier. The Delta-V's for the other solar orbits include the Delta-V's required by the waste package after departing from Earth. Passive waste package implies it will require no special space propulsion, midcourse or 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. As discussed earlier, 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 or planetary encounter possibilities. With the current state of the art it would be impractical to recover the waste package from these orbits.

LAUNCH VEHICLE PERFORMANCE AND COST

Before drawing further conclusions on the various destinations, the capability of possible launch vehicles will be discussed. As was discussed in the INTRODUCTION, only the larger current and planned launch vehicles were considered in this study. The vehicles considered are shown in figure 4. The Titan IIIE/Centaur is the expendable booster that will launch the 1975 Viking mission to Mars. The three stage Saturn V is the expendable Apollo booster. Its two-stage version will be 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. As will be discussed later, the Space Shuttle will require an additional stage for the disposal mission.

Expendable Launch Vehicles

Performance - Data for the Titan IIIE/Centaur and the Saturn V are shown in figure 5. The data are based on a due East launch from ETR into a 100 N.MI. parking orbit. The upper stage of the launch vehicle provides the Delta-V needed to accelerate the payload to higher velocities from the parking orbit. Typical Delta-V requirements for the various destinations discussed previously are shown on the figure. A Delta-V of 13,500 feet per second is used to characterize the Earth orbit and solar orbit destinations. Actual Delta-V's will vary somewhat depending on the details of the specific mission design. The direct solar impact mission (79,000 feet per second) is well beyond the capability of current vehicles. The Titan IIIE/Centaur can deliver 8500 pounds to high Earth and solar orbits. It has no payload capability for a solar escape mission. The Saturn V can deliver 72,000 pounds to high Earth and solar orbits, but it also has no payload capability for a direct solar escape mission. The use of the Centaur as an upper stage on the Saturn V provides a direct solar escape mission payload capability of about 16,000 pounds.

Cost - The costs of the expendable launch vehicles are highly use-rate dependent. The Titan IIIE/Centaur cost is about $27 million at a production rate of four per year. At the higher launch rates required 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 its cost is taken at $19 million. Similarly, the cost of the Saturn V is taken at $150 million. As mentioned in the INTRODUCTION the costs used in this study 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 or the integration of the waste package with the launch vehicle.

Space Shuttle

The Space Shuttle by itself can only deliver payloads 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 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 reusable Space Tug explicitly for use as a Space Shuttle third stage and having 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 does 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. These include (1) the reusable Space Tug under study by NASA, (2) a similar reusable Tug but optimally sized for the waste disposal mission (3) the current expendable Centaur stage and (4) an expendable Centaur stage resized for the waste disposal mission. The high launch rates envisioned for the waste disposal mission could justify resizing the Tug or Centaur stage if the performance gains are worthwhile.

Performance - The performance of the various Space Shuttle/third stage combinations is shown in figure 6. The performance data are based on a Space Shuttle with a payload delivery capability of 65,000 pounds into a due East 100 N.MI. orbit which is a Space Shuttle specification. The reusable Space Tug performance is based on one of the higher performing configurations studied to date. For example, it could perform a round trip mission to geostationary (synchronous) orbit with a 3000 pound payload. It is a hydrogen-oxygen fueled stage with an engine specific impulse of 470 seconds and has a propellant capacity of approximately 53,000 pounds. This propellant capacity is too high for most of the waste disposal missions, and the Tug propellant must be off-loaded. The dashed curve presents the performance achievable when the Space Tug is optimally sized for the waste disposal missions. As can be seen from figure 6, the only destinations which result in useful payloads are high Earth orbits and solar orbits (which for convenience are all characterized by a Delta-V of 13,500 feet per second). At its current size, the reusable Tug can deliver a payload of 9,200 pounds to this destination whereas the optimally sized Tug (about 46,000 pounds propellant) can deliver a payload of 10,300 pounds.

The current Centaur stage also uses hydrogen-oxygen propellants. It has an engine specific impulse of 444 seconds and a propellant capacity of about 30,000 pounds. For the waste disposal missions, this is too small to utilize the full 65,000 pounds orbital capability of the Space Shuttle. Consequently, the performance of the Centaur stage can be improved by increasing its propellant capacity as shown by the dashed curve of figure 6. For the high Earth orbit and solar orbit destinations, the current Centaur stage can deliver a payload of 14,300 pounds. An optimally sized Centaur (about 38,000 pounds propellant capacity) can deliver a payload of 18,700 pounds.

It should be recognized that the higher payload capability shown for the Centaur stage is a consequence of its being an expendable stage. For the reusable Tug, a portion of its on board propellant is required to 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 Delta-V, and its payload 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 currently estimated at approximately $10.5 million. In addition, the cost per reusable Tug flight is assumed to be $1.75 million, which 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 $12.25 million. The cost of the expendable Centaur stage, at high launch rates would be about $5.5 million dollars. In total, the cost of a Space Shuttle/expendable Centaur launch is about $16 million.

Launch Vehicle Performance and Cost Comparisons

Except for the Saturn V/Centaur, the launch vehicles considered thus far can only deliver useful payloads to high Earth orbit or the solar orbit destinations. In order to provide an overall vehicle comparison for these destinations the payload, cost, and cost per pound of payload delivered to a Delta-V of 13,500 feet per second are summarized in Table II. These data should only be used 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 may vary with waste package size. These and other factors will influence the choice of a launch vehicle for a particular destination. Nonetheless, Table II shows that the Space Shuttle vehicles are more cost effective than the current expendable launch vehicles. The cost per pound of total payload delivered using the Space Shuttle is on the order of one half of that when using 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 could readily justify the non-recurring costs associated with resizing the stages. The cost per pound of payload delivered with the resized Centaur stage is about 25 percent lower than for the resized reusable Tug. This indicates that an expendable Shuttle third stage could be more cost effective than a reusable stage. However, it is recommended that both reusable and expendable Shuttle third stages continue to be considered in further evaluations. Safety considerations and specific mission details can influence the final choice. For example, the reusable Tug performance is very sensitive to mission Delta-V. If the selected mission requires a Delta-V somewhat lower than 13,500 feet per second, the reusable Tug performance will improve significantly.

If an expendable stage such as a Centaur is used for the disposal mission it will still be necessary to provide a reusable Tug to recover from possible mission failures. If the Centaur stage should fail before reaching Earth escape velocity the waste package would be left in an unplanned Earth orbit. In this case, a Shuttle/reusable Tug launch could be made to either retrieve or properly inject the waste package. Such a retrieval mission will involve rendezvous and docking with the payload, and only the reusable Tug will have this capability. In this regard, the 100 N.MI. parking orbit which has been used throughout the study for comparison purposes is not a good choice. The orbital decay time of a package left in a 100 N.MI parking orbit would be on the order of a few days. If the injection stage should fail at or shortly after ignition there would be insufficient time for taking corrective action. A parking orbit for deployment of the payload from the Shuttle Orbiter on the order of 200 N.MI. would be a better choice. At 200 N.MI. initial altitude it would take several hundred days for the orbit to decay allowing adequate time for recovering the package or using a second Tug to inject it to its planned destination. The Space Shuttle can also deliver 65,000 pounds to a 200 N.MI. orbit and the performance data presented for the missions utilizing the Space Shuttle are essentially unaffected.

Multiple Space Tug Configurations

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 figure 5, it can deliver a payload of about 16,000 pounds to this destination. At a launch cost of $155 million, this results in a specific cost of 9700 dollars per pound. This is roughly an order of magnitude higher than for the Shuttle launched cases to high Earth or solar orbits. One possibility for providing a more effective solar escape capability is to use several Shuttle/Tug launches to assemble a larger vehicle (consisting of several Space Tugs) in Earth orbit. This same approach could also be used to provide higher payloads for the Earth orbit and solar orbit destinations.

A preliminary study of the use of multiple Shuttle/Tug launches has previously been done for NASA missions (reference 2). The groundrules and assumptions of that study are not all specifically applicable to the waste disposal mission. However, the results will be discussed since they serve to show the potential for achieving the more difficult waste disposal missions.

The procedure would be to use several Shuttle launches to place several Space Tugs in low Earth orbit along with the payload. The Tugs would rendezvous in orbit and be assembled into a tandem configuration. Since the planned reusable Tug is to have the capability of rendezvous, docking and retrieving payloads, the reusable Tugs will have the inherent capability of being able to rendezvous and dock with each other to form the tandem vehicle. In performing the mission, the Tug stages will burn sequentially, and each stage, if it is to be recovered, will return to its waiting Shuttle orbiter.

In the following discussion only a fixed size Tug is used, and 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 earlier. Each Shuttle flight is assumed to cost \$10.5 million and each reusable Tug flight, \$1.75 million. The expendable version of the Tug is assumed to cost \$6.0 million per flight. (The expendable Tug is roughly comparable to the growth version of the Centaur stage used earlier.) The cost should be considerably less than the expected unit cost of the reusable Tug since the expendable Tug configuration can be simpler and will have a much higher production rate. For example, the expendable Tug does not require a rendezvous and docking capability and can use less sophisticated astrionics.

An overall performance map of the various multiple Shuttle/Tug combinations is presented in figure 7. The performance shown is optimistic since gravity losses during Space Tug burns were not included. Gravity losses can be quite high for the tandem Tug configurations as will be discussed later. The most cost effective vehicle for each region on the map is indicated by the coding shown. The first digit indicates the number of Shuttle flights required to launch the Tugs and payload. The second digit indicates the number of expendable Tugs in the assembled vehicle and the third digit the number of reusable Tugs. When a mix of recoverable and expendable Tugs is used, the recoverable Tugs are the lower stages (burned first) since this is the optimum arrangement. When the number of Shuttle launches exceeds the number of Tugs, for example (2,0,1), it implies that the payload is brought up in a separate Shuttle launch.

The number following the three digit coding is the transportation cost per launch. In all cases it is assumed that the recoverable Tugs are brought back to Earth with the Shuttle Orbiters used to initially launch the Tugs and payload. That is, no additional Shuttle cost is charged for returning a Tug.

As can be seen from figure 7, the direct solar impact mission (Delta-V of 79,000 feet per second) still cannot be achieved. However, several of the configurations can accomplish the direct solar escape mission (Delta-V of 28,700 feet per second). The payload for the (1,1,0) configuration is too low to be useful. The (2,2,0) configuration cannot be used since it requires a rendezvous of two expendable Tugs in orbit, neither of which have a rendezvous capability. (A similar argument precludes the use of the (2,1,0) configuration.) This leaves the

(2,1,1) (3,1,1) and (3,1,2) configurations which have a direct solar escape capability of 8600, 9700, and 13,400 pounds respectively. As mentioned earlier, gravity losses will significantly reduce the actual performance of these multi-tug configurations. The gravity losses have been determined for the (2,1,1) and (3,1,2) configurations assuming the Tug has a thrust level of 20,000 pounds. The actual capability of the (2,1,1) and (3,1,2) configurations for direct solar escape is 5000 and 6700 pounds, 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 20,000 pounds. Another approach to 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 (2,1,1) and (3,1,2) configurations for direct solar escape to 7,200 and 9,700 pounds respectively.

An overall comparison of launch vehicle performance and cost for the direct Solar Escape mission is shown in Table III. The expendable Saturn V/Centaur provides the highest payload weight, but at a cost of almost $10,000 per pound. The multiple Shuttle/Tug configurations, using perigee propulsion, achieve lower payloads but at a cost of about $4000 per pound. This lower cost, however, is on the order of four times higher than the cost for the high Earth orbit and solar orbit destinations (Table II).

The multiple Shuttle/Tug vehicles can also provide more capability for the high Earth orbit and solar orbit missions. The (1,0,1) configuration of figure 7 is identical to the current size reusable Tug of Table II, and the (1,1,0) configuration, as would be expected, has essentially the same performance as the optimum size Centaur. However, the multiple launch Shuttle configurations of figure 7, can provide payload weights up to 60,000 pounds, if needed. Although these configurations have not been studied in detail for the high Earth and solar orbit missions, they can provide a higher payload capability at slightly lower costs per pound than the single Shuttle launch configurations.

CONCLUDING REMARKS

Of the destinations considered, high Earth orbits, solar orbits and direct solar system escape remain as candidate destinations and all three should continue to be studied. The final selection will depend on cost and safety considerations beyond those considered in this report.

For high Earth orbits, circular orbits between geostationary (synchronous) and lunar orbit altitudes appear to be the best choice. However, since neither orbit stability nor waste package integrity can be guaranteed for times on the order of a million years, high Earth orbits cannot now be considered a permanent disposal site. Unless further studies can resolve these uncertainties, Earth orbits should only be considered a temporary storage site, since package retrieval or placement to more remote destinations may eventually be required.

Among the possible solar orbit destinations, circular solar orbits suitably displaced from the Earth's orbit about the Sun (for example, at 0.90 AU) currently appear to be the best choice. This destination will require a propulsion maneuver about six months after departing from Earth. The guidance and control requirements associated with this maneuver can be minimized by performing it with a relatively simple spin-stabilized solid rocket motor. However, all the destinations beyond the Earth have an "abort gap" during the Earth departure burn. If the departure propulsion or guidance system should fail at or beyond Earth escape velocity the waste package will be left in an unplanned solar orbit. In this case, there could be a high probability of eventually re-encountering the Earth. This abort problem, as well as the long term stability of solar orbits, needs more investigation. The possibility of achieving acceptable solar orbits using only a single departure burn should also be studied further since this would eliminate the need for a waste package propulsion system.

The problems of long term orbit stability and waste package integrity can be avoided by injecting the waste package to solar system escape or impacting it into the Sun. The solar escape mission can be accomplished by using two or three Space Tugs in tandem. The resulting space transportation cost is about four times higher than for the high Earth orbit and solar orbit destinations. If this is acceptable, solar system escape can eliminate potential orbit stability, long term package integrity and future encounter problems. A direct solar impact mission cannot be achieved with the current or planned launch systems considered in this study. It can be accomplished using a Jupiter swingby for roughly the same Delta-V as for the direct solar system escape mission.

However, the launch opportunity when using a Jupiter swingby will be quite limited.

Regarding the launch system, the currently planned Space Shuttle is more cost effective (by about a factor of two) than current expendable launch vehicles. The Space Shuttle will require a third stage to perform the disposal missions. Depending on the particular mission, this 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 could be worthwhile to develop a version of the entire launch system dedicated to providing maximum performance for the disposal mission.

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

REFERENCES

1. Hyland, R. E.; Wohl, M. L.; Thompson, R. L.; and Finnegan, P. M.: Study of Extraterrestrial Disposal of Radioactive Wastes. Part II: Preliminary Feasibility Screening Study of Extraterrestrial Disposal of Radioactive Wastes in Concentrations, Matrix Materials, and Containers Designed for Storage on Earth. NASA TM X-68147, 1972.
2. Zimmerman, Arthur V.: Performance of Recoverable Single and Multiple Space Tugs for Missions Beyond Earth Escape. NASA TM X-68136, 1972.

TABLE I. - SUMMARY OF DESTINATIONS

Destination	Delta-V ft/sec.	Advantages	Disadvantages
High Earth orbit	13,500	.low Delta-V .launch any day .passive waste package .can be retrieved	.long term container integrity required .orbit lifetime not proven
Solar orbits via: Single burn beyond Earth escape	12,000	.low Delta-V .launch any day .passive waste package	.Earth re-encounter possible (may not be able to prove otherwise) .abort gap past Earth escape velocity
Hohmann transfer to circular solar orbit (0.90 AU)	13,500	.low Delta-V .launch any day	.orbit stability not proven .requires space propulsion system .abort gap past Earth escape velocity
Venus or Mars swingby	13,500	.low Delta-V	.limited launch opportunity .requires midcourse systems .need space propulsion or have possibility of planet encounter .abort gap past Earth escape velocity
Solar system escape Direct	28,700	.launch any day .passive waste package .removed from solar system	.high Delta-V .abort gap past Earth escape velocity
Via Jupiter swingby	23,000	.removed from solar system	.high Delta-V .limited launch opportunity .requires midcourse systems .abort gap past Earth escape velocity
Solar impact Direct	79,000	.package destroyed .launch any day .passive waste package	.extremely high Delta-V .abort gap past Earth escape velocity
Via Jupiter swingby	25,000	.package destroyed	.high Delta-V .limited launch opportunity .requires midcourse systems .abort gap past Earth escape velocity

TABLE II

LAUNCH VEHICLE COST AND PERFORMANCE SUMMARY FOR
HIGH EARTH ORBITS AND SOLAR ORBITS. Delta-V, 13,500 ft/sec.

Launch Vehicle	Payload lb	Cost 10^6 dollars	Cost Per Pound dollars/lb
Saturn V	72,000	150	2,080
Titan IIIE/Centaur	8,500	19	2,240
Space Shuttle			
Reusable Tug Current Size	9,200	12.25	1,330
Reusable Tug Optimum Size	10,300	12.25	1,190
Centaur Current Size	14,300	16	1,120
Centaur Optimum Size	18,700	16.3	870

TABLE III

LAUNCH VEHICLE COST AND PERFORMANCE SUMMARY FOR THE DIRECT SOLAR ESCAPE MISSION

Launch Vehicle	Payload lb	Cost 10^6 dollars	Cost Per Pound dollars/lb
Saturn V/Centaur	16,000	155	9,700
(2,1,1)* Shuttle/Tug Configuration			
without perigee propulsion	5,000	28.75	5,750
with perigee propulsion	7,200	28.75	4,000
(3,1,2)* Shuttle/Tug Configuration			
without perigee propulsion	6,700	41.0	6,120
with perigee propulsion	9,700	41.0	4,230

* (2,1,1) = 2 Shuttle flights, 1 expendable Tug, 1 reusable Tug
(3,1,2) = 3 Shuttle flights, 1 expendable Tug, 2 reusable Tugs

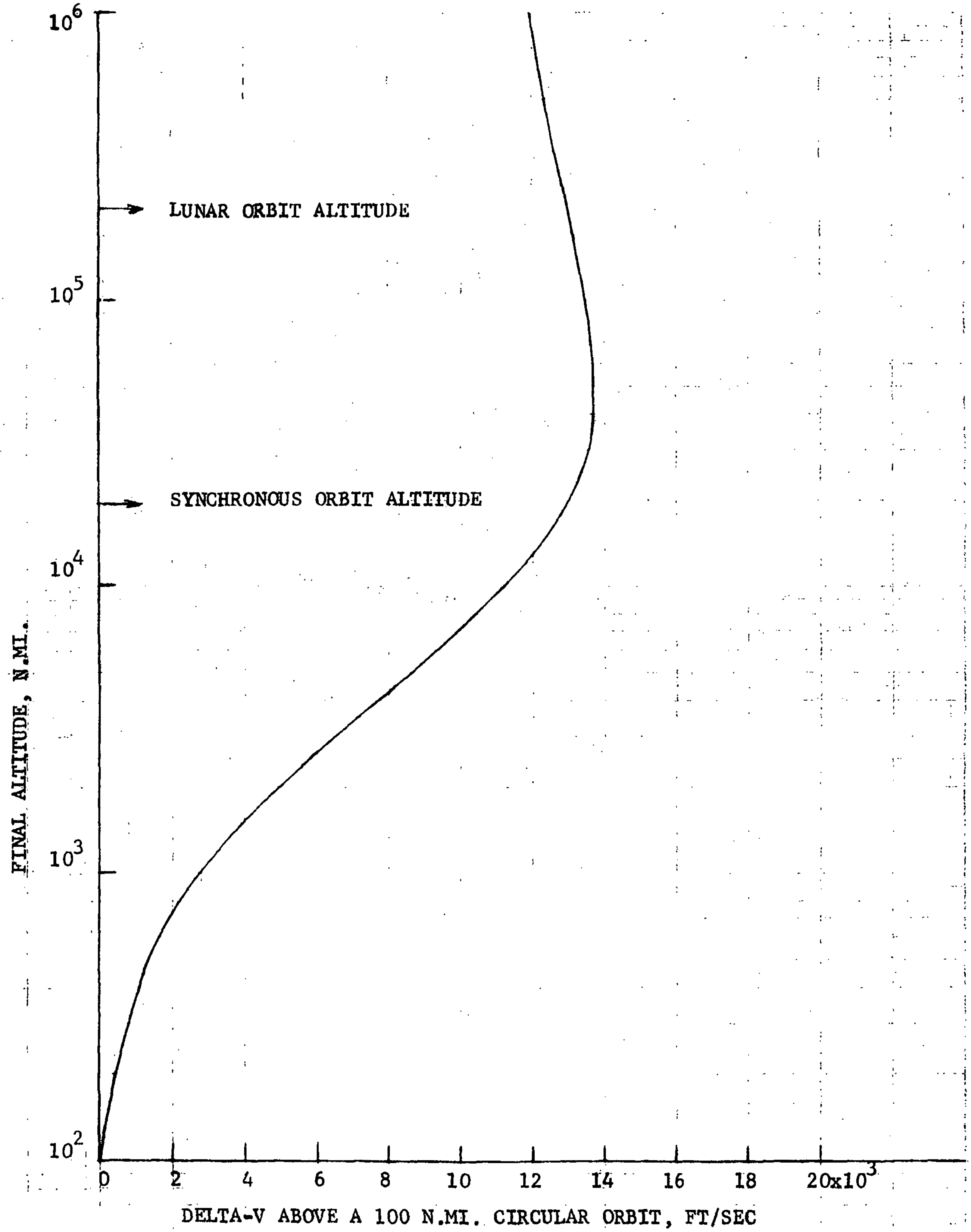
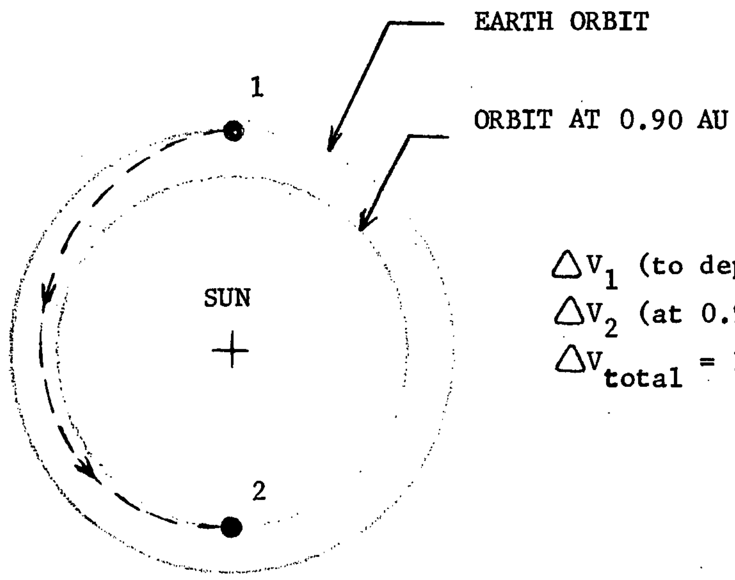


FIGURE 1. – TOTAL DELTA-V REQUIRED FOR CIRCULAR EARTH ORBITS STARTING FROM A 100 N.MI. INITIAL PARKING ORBIT. HOHMANN TRANSFER.



ΔV_1 (to depart Earth) = 10690 FT/SEC
ΔV_2 (at 0.90 AU) = 2660 FT/SEC
ΔV_{total} = 13350 FT/SEC

1 - DEPART EARTH
2 - ARRIVE AT 0.90 AU

FIGURE 2.—MISSION PROFILE FOR 0.90 AU CIRCULAR SOLAR ORBIT

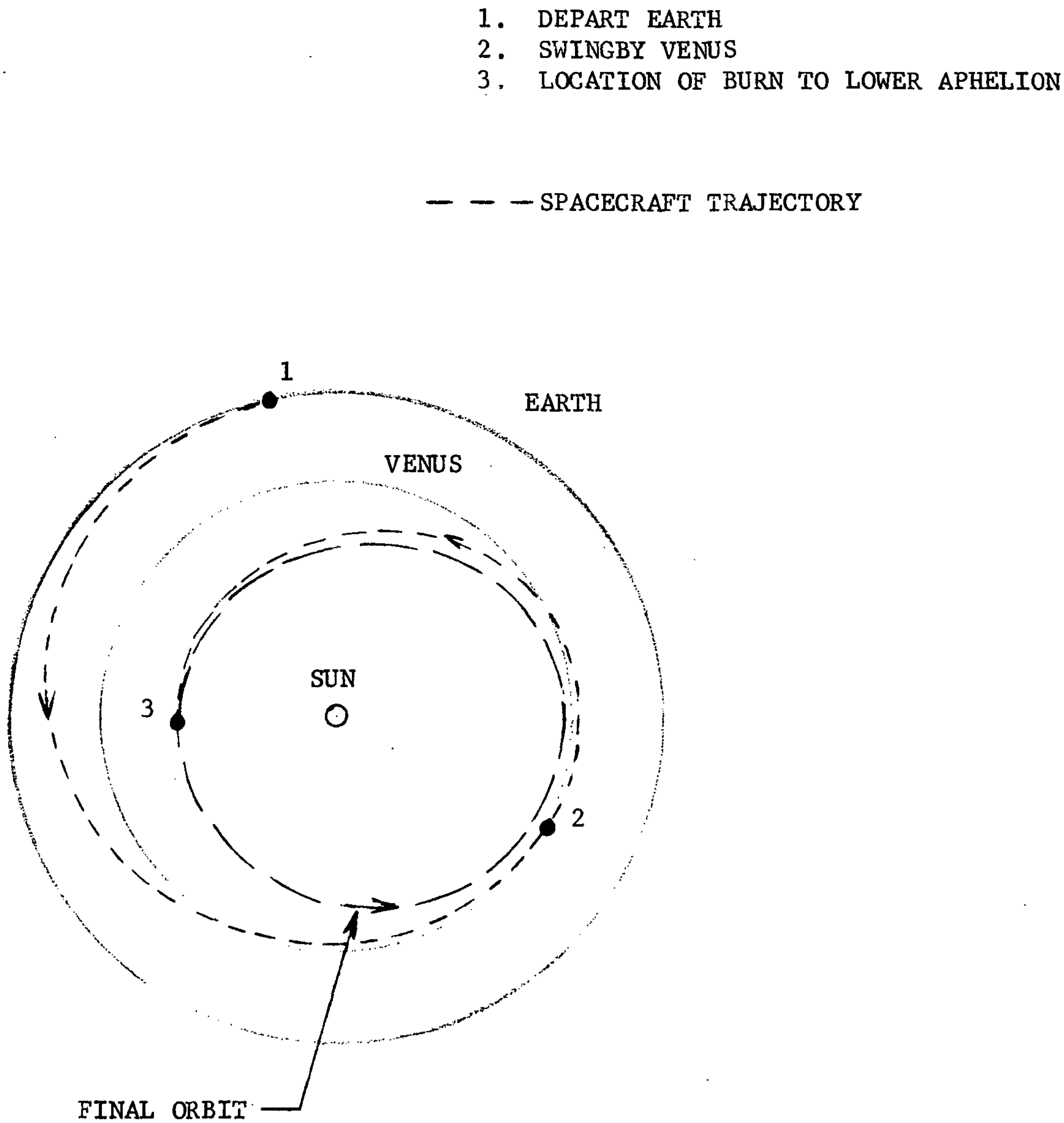


FIGURE 3.—EARTH-VENUS SWINGBY INTO A LOW SOLAR ORBIT

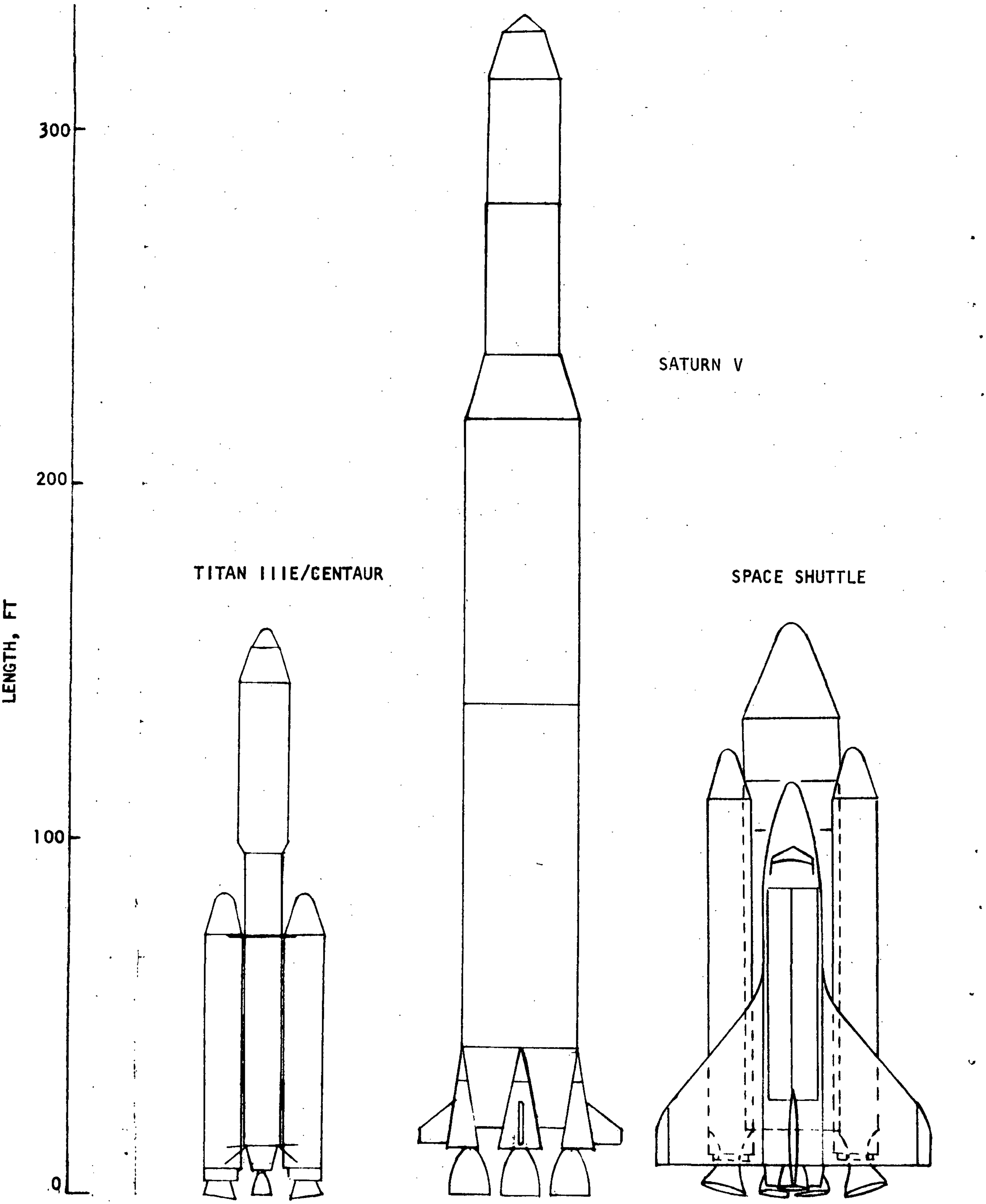


FIGURE 4.— LAUNCH VEHICLES

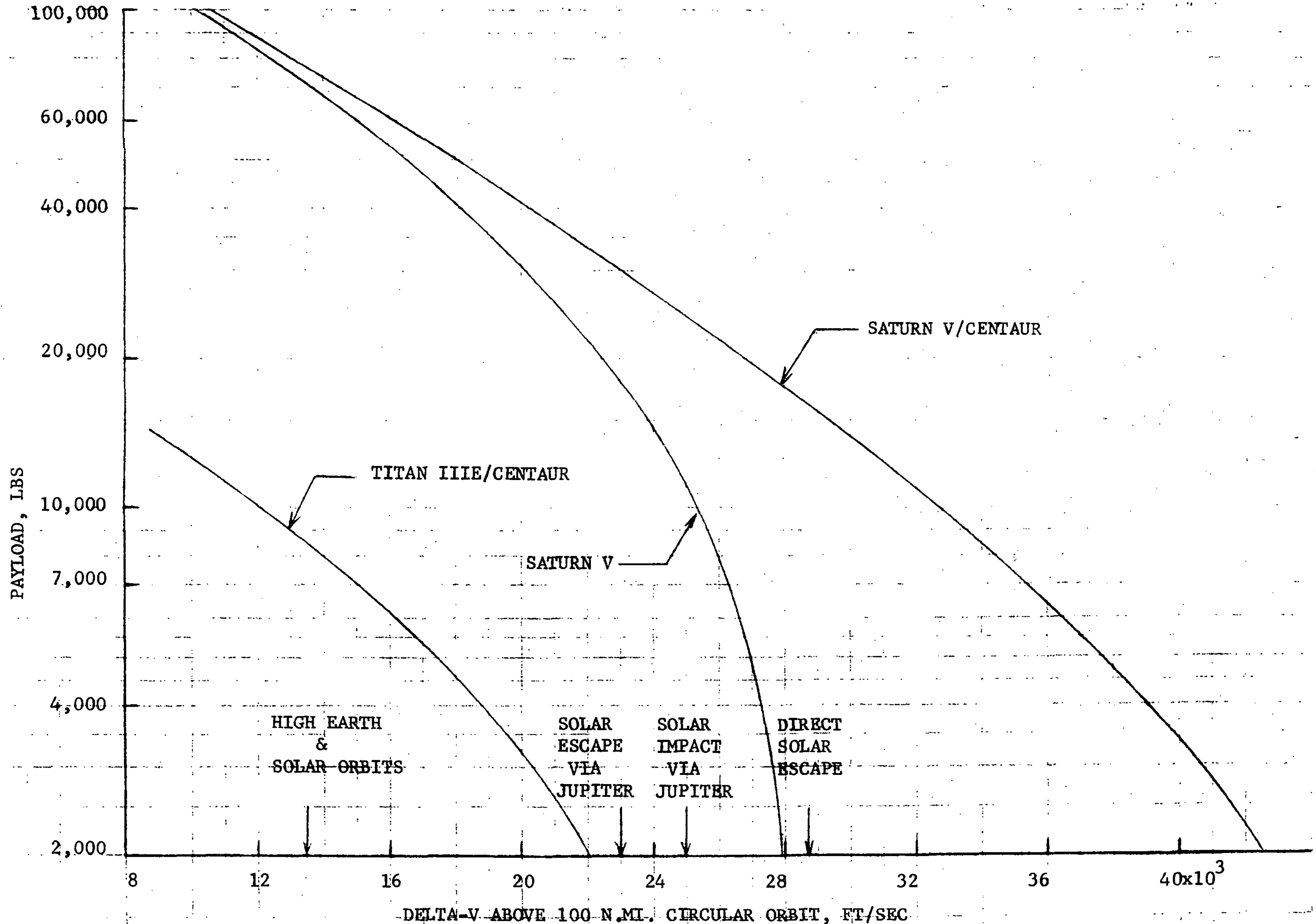


FIGURE 5.—EXPENDABLE LAUNCH VEHICLE PERFORMANCE

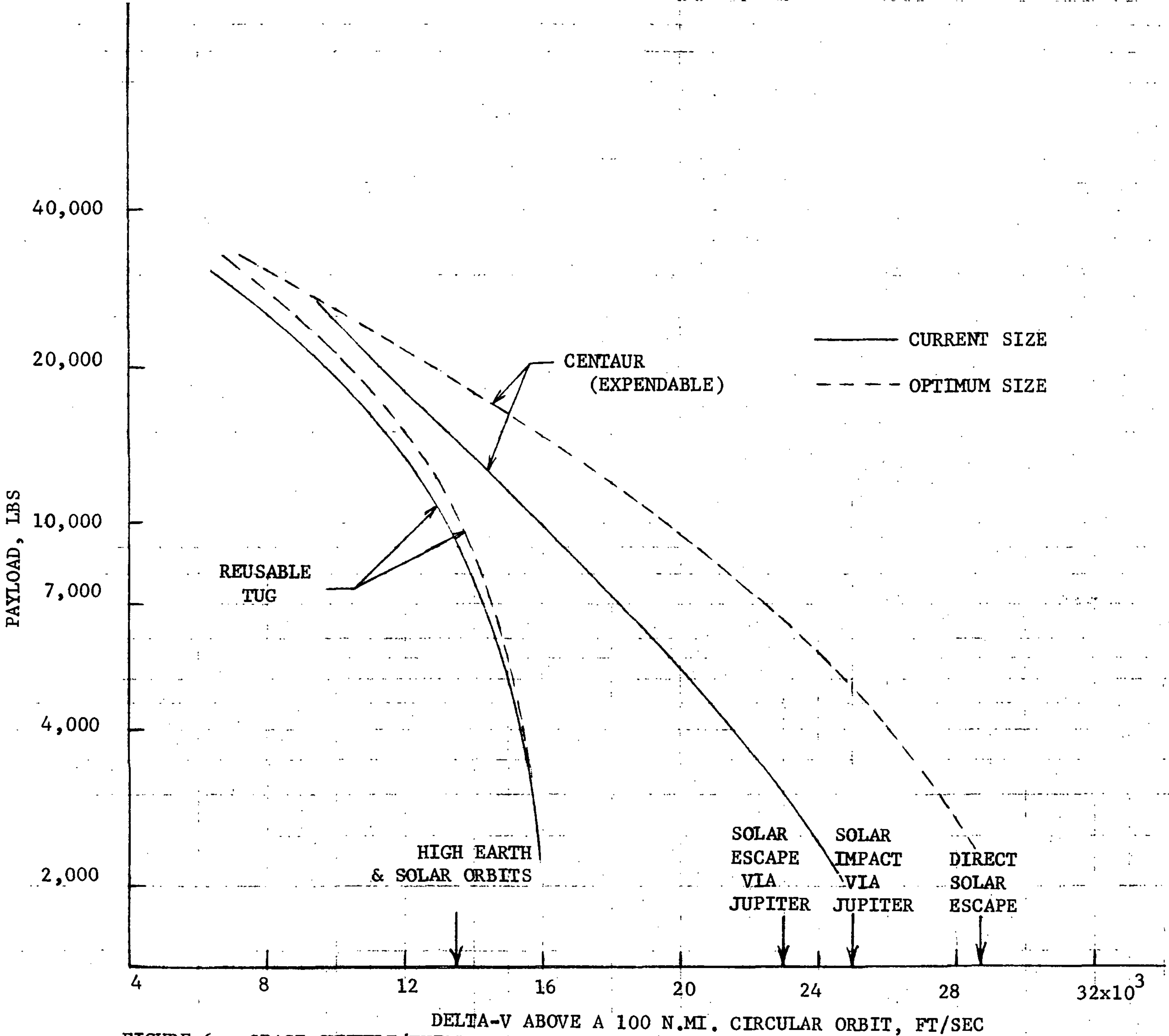


FIGURE 6. – SPACE SHUTTLE/THIRD STAGE PERFORMANCE

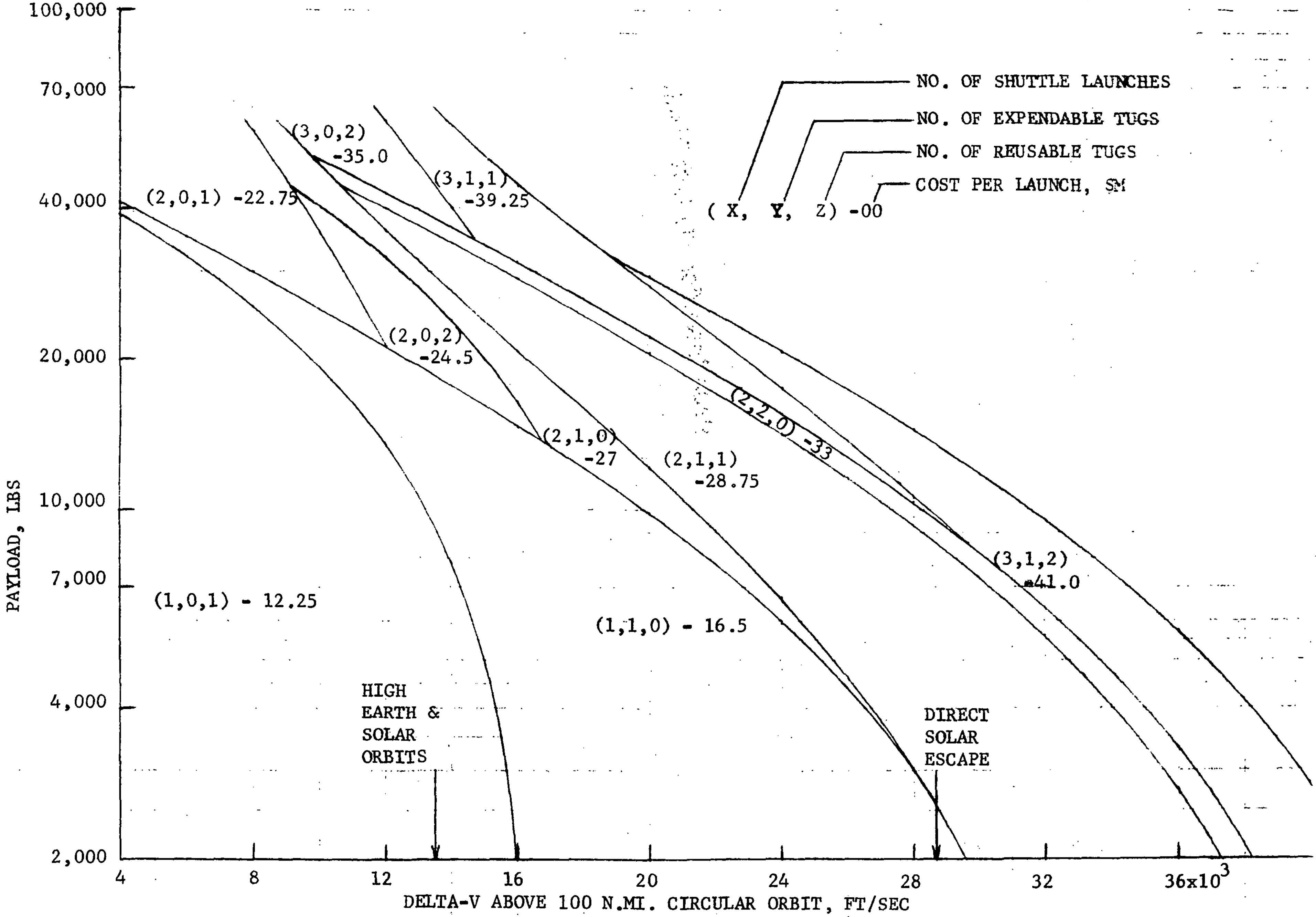


FIGURE 7.— IDEAL PERFORMANCE OF MULTIPLE SPACE TUG VEHICLES. COST PER SHUTTLE LAUNCH, $10.5M; COST PER REUSABLE TUG, $1.75M; COST PER EXPENDABLE TUG, $6.0M