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JSC-10674

JSC INTERNAL NOTE NO. 75-ER-1

SPACE DISPOSAL OF NUCLEAR WASTES

NOVEMBER 1975

FUTURE PROGRAMS OFFICE

ENGINEERING AND DEVELOPMENT DIRECTORATE

National Aeronautics and Space Administration
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JSC - 10674

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November 6, 1975

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1.0 INTRODUCTION. The large increase in United States electrical power generation by nuclear fission reactors is projected to result in a total of about 1.2 billion kilowatts of fission power generating capacity and 200,000 cumulative metric tons of spent fuel (raw nuclear waste) by the year 2000 (Reference d.). In addition, a relatively constant, but continuing, waste generation rate of about 13,300 metric tons per year after the year 2000 is estimated in Reference a.

Present nuclear waste disposal techniques of surface storage and continuous monitoring appear unrealistic as a final disposal solution due to the large waste quantity, extremely long radioactive life, and environmental incompatibility of many of the waste components. Consequently, other methods of disposal such as transmutation of dangerous products to benign elements, transportation of the dangerous products to space, and various, special, geological disposal techniques have been under consideration as a permenent solution to the problem.

A program for space disposal of nuclear waste products is defined in this study, and total program cost estimates for a number of the most pertinent transportation systems are produced as an end product. These costs are summarized in Table II.

2.0 STUDY DESCRIPTION. This study is composed of three general parts: a consideration of nuclear power waste generation and waste disposal factors, a study of space transportation vehicles, and the integration of these and other factors into a total program definition and cost estimate.

The first study portion, presented in Section 3, consists of the review, update, expansion, and derivation of new data related to the generation, processing, and handling of nuclear waste materials. This effort addresses such known and significant factors as waste composition, partitioning, environmental safety, disposal requirements and the impact of these factors upon hardware design, mission configuration, operations and ultimate program costs.

Another study portion, presented in Section 5, consists of the definition and conceptual design of the space transportation vehicle system. This is approached in terms of individual vehicle elements as follows: (1) Booster to low Earth orbit - Shuttle, 350,000 pound payload/SSME unmanned booster, and 160,000 pound payload SSME unmanned booster; (2) Nuclear waste payload - design factors and selected configuration; (3) Chemical upper stage - FCT, new Cryo stage, SRM, and pertinent combinations; (4) Ion upper stage - two sizes plus various chemical stages for Van Allen belt transit. The ion vehicle design is based on SEPS technology and hardware.

Finally, Section 4 outlines a baseline program, establishes and integrates the various cost factors from the other two study sections and identifies, analyzes, and integrates other programmatic considerations (such as vehicle R&D and procurement, operations, facility requirements and mission configurations).

All three portions interact in content and overlap in time of accomplishment; they are, however, presented in this sequence for reading clarity.

3.0 NUCLEAR WASTES. A typical nuclear waste space disposal program (Section 4.1) is utilized in this study to explore the impact of various space vehicle design approaches. This program is based on previous nuclear power generation and waste disposal studies, updated and expanded as required, and summarized in this section.

3.1 Waste Components. Nuclear power generating capacity in the United States is projected to increase to 1.2 billion kilowatts by the year 2000, resulting in the generation of 200,000 metric tons of irradiated (or spent) fuel, including 1,270 metric tons of actinides (Reference d.). Reference a. agrees closely, predicting about one billion kilowatts of power, 9,000 metric tons of fission products, and 1,200 metric tons of actinides. These actinides may be reduced to 300 metric tons by removal of essentially all uranium isotopes, and to 100 metric tons if additional in-pile transmutation to short lived components (Reference b.) proves feasible.

3.2 Disposal Requirements. The final, long term solution to the radioactive waste disposal problem is anticipated by ERDA (formerly AEC) to be implemented no earlier than the year 2000 (Reference i.) and to consist of one or more of three general approaches (References i. and d.):

a. Waste deposit in selected seabed areas such as geologically stable ocean floor regions, subduction zones, deep sea trenches, or high sedimentation areas.

b. Transmutation of highly toxic/long-lived components into less undesirable isotopes.

c. Extraterrestial disposal.

In implementation of the latter two options, partitioning (or separation) of the long-lived from the short-lived waste fractions is necessary (Reference d.). In this case, long-lived is roughly considered as possessing important radioactivity after 1000 years. Thus, in the space disposal program, the actinides and possibly samarium, technetium, tin, and iodine fission products and nickel contaminant would be separated, solidified, encapsulated, and transported to a permanent deposit in space (References c. and d.). The remaining short-lived fractions would be candidates for some form of geological disposal or for surface storage and monitor until radiologically safe. In this study, as in Reference a. and as suggested in References c. and d., only partitioning to isolate the actinides as a group and to recover usable uranium is assumed necessary. The final waste for space disposal thus consists of the actinides (except uranium) plus either 1.0 percent or 0.1 percent of the total fission products, depending upon degree of partitioning.

Space options include transportation to high Earth orbit, planetary or lunar orbit, solar orbit, solar impact, and solar system escape. Based on the considerations detailed in Reference a., solar system escape is selected as the prime candidate for space disposal; however, the solar orbit option is also included due to its relatively low ΔV requirements and consequent better compatibility with the Space Shuttle and Full Capability Tug combination.

3.3 Disposal Processing. Since the intent of this study is to show the cost differential chargeable to space disposal, processing functions common to present practices (References d. and i.) are not included. These common functions (Reference d.) include partial uranium recovery, solidification and encapsulation, surface storage (partitioning may require some interim aqueous storage to reduce solvent or ion-exchange media radiation damage), and considerable handling. Actinide partitioning, partial transmutation, and additional handling are new functions required for space disposal.

Partitioning is the biggest factor due to the need for new facilities and high operational costs. Previous estimates originating in Reference c. and noted in Reference a. indicate a total cost per metric ton of irradiated fuel as follows:

a. All actinides plus 1.0 percent of the fission products = $10K

b. Actinides less U plus 1.0 percent of the fission products = $15K

c. Actinides less U plus 0.1 percent of the fission products = $20K

These figures were updated by Reference h. to be $30K, $45K, and $60K, respectively, divided equally between facility and operations costs. For the anticipated program, estimated R&D costs are negligible at about $3M to $5M (Reference d.), and are assumed to be included in the previous figures. It is important to note that there is considerable question about the optimum approach, large scale feasibility, and even theoretical possibility of some of the partitioning factors (References c. and h.). Therefore, the exact nature, extent, and cost of the partitioning process and facilities is only a consensus of opinion among knowledgeable and experienced personnel. This uncertain situation is not expected to improve in the near future, since partitioning R&D has been terminated due to ERDA budget cuts (Reference i.).

This study assumes that substantial (two-thirds) portions of the waste actinides are transmuted by continual recycling in commercially-owned fission reactors (Reference d.). This is shown in the simplified diagram of Figure 1. Thus, there is no requirement for new, expensive, transmutation facilities and the major expense, after partitioning, is a significant increase in handling, a moderate fuel enrichment for Light Water Reactors, and an R&D cost of $75M for actinide recycle engineering (Reference d.). Since these charges are small compared to partitioning and since the partitioning cost estimate is poorly defined and subject to considerable modification, this study assumes that transmutation costs are contained within partitioning cost uncertainties, and therefore, are not additionally defined or included.

Total differential processing costs for space disposal are therefore taken as $45K and $60K/metric ton of fuel, less a credit of $5K/metric ton of fuel for uranium recovery. This results in an $8.0B and $11.0B total program cost estimate for 1.0 percent and 0.1 percent fission products, respectively.

3.4 Disposal Packages. Both actively controlled and essentially passive types of payload packages were considered in this study. In general, the former provides a lighter design, with a waste to total package weight ratio of about 8 to 10 percent as compared to the passive ratio of 3-1/2 percent to 7-1/2 percent. The latter design, developed in Reference a., has been selected for this study because of its higher inherent reliability and lower cost resulting from its passive re-entry and hard landing features. See Section 5.1 for additional considerations of the packaging design which is shown in Figure 2.

The design consists of a central aluminum-copper matrix with lithium hydride particles. This matrix provides the solidified and encapsulated actinide wastes with mechanical support, efficient heat removal, and some radiation shielding. Spherical tungsten and lithium hydride shells around the matrix complete the radiation shielding, and inner and outer stainless steel impact shells provide a passive, hard landing capability. This capability has been demonstrated by testing which reveals no structural failure during payload and reinforced concrete block impacts at velocities to 320 meters per second (1050 FPS). The sperical waste container within a passively stable re-entry vehicle and ablative heat shield forms the total payload package. Although not mentioned in Reference a., it is noted that a small radio and possibly sonar beacon and associated power source is required in the waste package for location and recovery in the event of a malfunction during launch or upper stage propulsion. The beacon and power source should be as long-lived as possible to provide recovery after long delayed Earth re-encounter, such as might occur after a propulsion failure which places the waste package into a high Earth or one A.U. sun orbit. The weight penalty of such a recovery system is negligible compared to the total waste package.

4.0 WASTE DISPOSAL PROGRAMS. This section applies various space transportation systems developed in Section 5 to a standardized and typical waste disposal program based on the preceeding sections's considerations. Results consist of a space program cost estimate for each vehicle system selected for consideration.

4.1 Baseline Program Description. The program baselined for this study, as derived from Section 3 and 5 considerations, consists of processing all expended fuel generated up to the year 2000 and transporting the resultant 100,000 KG of accumulated actinides and 0.1 percent or 1.0 percent of the total fission products to either solar system escape or to solar orbit. The program is designed to reach completion in the year 2010 to allow at least 10 years of pre-partitioning aqueous storage of the waste material. Sections 3.1 through 3.3 discuss these factors in detail. Figure 3 presents a proposed actinide disposal rate which establishes, in conjunction with payload size, the required launch rate for each transportation system. Note that the program start date, in conjunction with the end date, allows a reasonable build-up to a steady disposal rate of 6-2/3 metric tons per year. This corresponds to the steady-state actinide generation rate anticipated after about 2000, and allows disposal of accumulated wastes and transition into a continuing program disposal rate after 2010 without a peak in vehicle flight rates. The end point of the 17-year baseline study program simply establishes the point at which non-recurring costs are amortized.

4.2 General Program Factors. In determining program costs chargeable to space disposal of nuclear wastes, the following equation incorporates the pertinent cost factors and has been used for each transportation system:

$$\text{Cost} = \frac{\text{Process} + (\text{Veh. Proc.})\ (\text{No. Flts.}) + \text{Veh. R\&D} + (\text{Ops.})\ (\text{No. Flts.})}{\text{Elect. Energy}}$$

Process is the total facilities and operations waste processing cost chargeable to space disposal.

Veh. Proc. is the summation of vehicle procurement costs within each space transportation system.

No. Flts. is the total flights required to transport the waste actinides of the program.

Veh. R&D is a summation of development costs for the space transportation system.

Ops. is the summation of per flight operational costs.

Elect. Energy is the total energy developed by the nuclear reactors producing the waste for space disposal. Dividing by this quantity gives the cost in terms of an electricity surcharge. The program cost may be reduced slightly if the surcharge is levied at an early date and placed in an interest generating trust fund. Conversely, the cost may be increased if the surcharge is delayed and money borrowed for the waste disposal program. This study assumes a surcharge application near the disposal program start date and negligible interest benefits or penalties. See Section 4.2.4.

4.2.1 Waste Processing. As indicated in Section 3.3, total space disposal processing charges, which are equated to partitioning charges, are based solely on the irradiated fuel quantity. This is not strictly correct, since the waste flow rate directly impacts the facility size and cost. The flow rate, however, is expected to stabilize at about 20,000 KG of actinides (excluding uranium and resulting in 6,670 KG for space disposal after transmutation) per year after 2000 (Reference a.), and the estimated charge of \$8.0B and \$11.0B as applied to the waste accumulated by the year 2000, appears reasonably compatible with the flow rate and appropriate at this time as a first estimate.

4.2.2 General Vehicle Considerations. Cost considerations that are common to each type and size of vehicle include the single unit procurement cost, the development cost, and most elements of the operations cost. Table 1 summarizes estimated values for each vehicle considered in this summary report. Very briefly, these figures were derived as follows:

Vehicle Procurement and Operations. These two items are discussed together since a significant portion of reference source cost data is in terms of total recurring costs. These sources include the following:

a. Outlook for Space summary report (Reference j.) and associated, unpublished supporting studies for recurring booster costs.

b. 1971 Shuttle recurring cost of $10.5M; verbally acquired from JSC/BW.

c. Expendable FCT single unit procurement cost of $11.0M; verbally acquired from MSFC/PF02.

d. 1972 Centaur launch cost of $5.8M from Reference a.

In applying these sources, all costs were translated to FY 1975 dollars on the basis of 10 percent, 8 percent, 5 percent, and 5 percent inflation during the four preceeding years. In addition, all costs were separated for this study into vehicle procurement and total (ground and flight) operating costs by defining and separating the procurement cost based on previous in-house studies. This separation allows better adaptation of costs to fit and account for each vehicle's individual configuration pecularities.

Regarding Reference j. and supporting studies, level III booster (400K pound payload) designs and estimates by Withee/Jones of General Dynamics, Kelly/Goodman of Grumman, and Tischler, a private consultant, were found to be particularly pertinent for the new 315K and 160K boosters. These are shown in Table III and Figure 4. Note that for the space nuclear waste disposal program, the relatively steady and predictable launch schedule essentially eliminates the need to maintain an inventory for the transportation vehicles. Instead, direct shipment from manufacturer to launch area is assumed, and only a small portion of the annual capability maintenance cost is included in operations to allow for brief perturbations of the launch schedule.

Table I shows costs for single vehicle procurement: however, considerable savings are anticipated in the large quantity production of propulsion vehicles on a predetermined schedule. This saving is presented in Appendix A for the FCT, and is applied as the same percentage saving to all predominently cryogenic stages and the new boosters. In addition, one-half of the percentage saving is applied to SRM vehicles, with the smaller value attributed to the more nearly off-the-shelf status of the solids, resulting in a less favorable "learning curve."

Finally, the requirement for additional Shuttle vehicle purchases is somewhat indeterminent since it depends not only on number and time of waste disposal flights required, but also on quantity and schedule of other space packages competing for transportation. For the 17-year program outlined in 4.1, however, solar orbit, which requires a total of only 126 and 183 flights (Table II) for 0.1 percent and 1.0 percent fission product payloads, respectively, can be accommodated within the present Shuttle complement. On the other hand, 524 and 885 flights required for solar system escape (SSE) require a set of Shuttle vehicles for exclusive waste disposal use. To this end, 3 and 5 vehicles at $320M each (derived from $250M in 1971 dollars - Reference, JSC/BW) are included in the Shuttle SSE program.

Vehicle Flights. Payload size for each transportation system establishes the actinide load and, consequently, the total number of flights to carry the 100,000 KG of program generated actinides. These flights, shown in Table II, are divided by 15 (total program length less two years for buildup) equivalent program years at the steady state level to derive the steady state flight schedule or missions per year.

Vehicle R&D. The lump sum R&D cost estimate for each vehicle is shown in Table I. The estimate for large boosters was derived by modifying non-recurring cost figures from Reference j. and from Table III/Figure 4 to reflect individual vehicle configuration variations. Table III is a copy of estimates derived by the Outlook for Space Working Group V Forecasters in support of data presented in Reference j. Again, designs and estimates by Withee/Jones, Kelly/Goodwin, and Tischler proved to be most pertinent.

In the case of the upper stages, the Cryo vehicle estimate is based upon, and extrapolated from, Apollo and Centaur experience; and the ion stages are based upon SEPS study data. In both cases, the availability of proven hardware and technology is anticipated.

4.2.3 Operations Facility Requirements. New mission control and launch requirements will be determined by the frequency and length of waste disposal flights, utilization of existing facilities by competing space programs, and unique vehicle or mission requirements. A numerically rigorous cost estimate of new facilities thus requires establishment of available facilities throughout the program's time period and the detailed and reasonably accurate design and cost estimate of new facilities for each transportation system. Such an effort is beyond the scope of this study, but will be required once a detailed program study has been initiated.

Broad cost impact factors have been identified, however, and their probable impact on the program predicted in general terms. This gives a fairly useful indication of facility cost trends and relative magnitudes for the various vehicle configurations. These considerations are as follows:

Existing Facility Availability. Based on present NASA planning, it appears reasonable to assume a moderate availability of present and authorized launch and mission control facilities. Quantitatively, this is assumed to translate to two Shuttle or unmanned launches per month and no more than a few days (possibly 5) of intensive tracking, control, and monitor per month. Relative to the cost magnitude of the baseline program, the costs of launch and mission control facility modifications and expansions within these utilization rates appear to be small, and are therefore not included.

Solar Orbit Missions. Expansion of existing launch facilities can probably handle the solar orbit missions, although the highest launch rate of 24.4 Shuttle vehicles per year (for 12.2 missions per year as indicated in Table II) exceeds the 2 per month limit just defined. ~~Note, from Table II, that the very strong candidate transportation system of two Shuttles and one FCT with 1.0 percent fission product payload requires only 1.1 Shuttle launches per month.~~

Significant new mission control facilities are probably not required, either, since each mission requires only two relatively short periods of intense tracking, monitor, and control. These periods occur throughout launch operations and during solar orbit insertion, about 6 months after launch. Facility utilization requirements are estimated at 3 and 2 days for Shuttle or unmanned vehicle launch, respectively, and 1 day for solar orbit insertion. It is anticipated that each vehicle can be placed into a low activity mode during the 6-month coast period, and that ground monitor can be accomplished on an intermittent and possibly automatic basis with a very low increase in facility utilization. Thus, the highest utilization amounts to about 4 days per month.

Solar System Escape - Chemical Propulsion. For chemical propulsion out of the solar system, new launch facilities of significant magnitude appear to be required for all but two vehicles, the new 160K booster + 2 FCT and the new 315K booster + 2 Cryo + 2 SRM, each vehicle with the 0.1 percent fission product payload. These vehicles have launch rates of about 1-3/4 and 1-1/2 per month, respectively.

Intensive mission control is estimated to be required for 2 and 1 days during Shuttle and unmanned vehicle launch, respectively; and for one additional day during inflight trajectory correction. Again, it is anticipated that each vehicle can be placed into a low activity mode with intermittent and perhaps automatic ground monitor between launch and trajectory correction maneuvers. Thus, no new mission control facilities appear necessary for the two vehicles just identified. Of the remaining vehicles, one requires no new facilities and five require moderate to extensive additions to existing facilities.

Solar System Escape - Ion Propulsion. Transportation systems incorporating an ion propulsion stage all have low launch rates and require no significant new launch facilities. The ion stage mode of operation, however, is continuous thrusting over very long periods, such as several years. Thus extensive, new, dedicated mission control facilities will be required to handle the long term control of each vehicle and the resultant high vehicle density. This density will range from 11 to 35 simultaneous vehicle operations depending upon launch rates and assuming a 2-year operating time for each vehicle. See Section 5.4 for additional ion stage discussion.

4.2.4 Electrical Energy Surcharge Estimating Basis. For a surcharge to pay for the space disposal of nuclear waste, total cost of the 17-year baseline program is divided by the quantity of electrical power associated with the specified actinides and multiplied by 1000 to convert dollars to mills. Total electrical energy is 73.4×10^9 KWH, as derived from the Reference a. estimate of 0.409×10^{-8} KG actinides (excluding uranium isotopes) generated per KWH.

5.0 VEHICLE DESIGNS. This section describes the booster and upper stage space transportation vehicles which are considered most appropriate for meeting program cost and performance objectives. Table II gives nine vehicle system configurations, each with payloads of actinides plus 0.1 percent and 1.0 percent of the original fission products. These were not all of the configurations studied, but were selected for this report to show particular vehicle sizes, combinations, or designs of particular interest or to demonstrate important points of consideration. In addition, particular vehicle designs were selected to achieve good compatibility among the largest number of vehicles and systems.

5.1 Nuclear Waste Payload. Section 3.4 gives a general description of the nuclear waste payload package and identifies its design source. Selection of a payload configuration has a large impact upon propulsion vehicle requirements and designs, and hence upon total program costs. This section, therefore, identifies and discusses specific factors leading to the payload design selection.

All but one of these factors, (i.e., pre-partitioning storage), ultimately leads to a trade-off between waste disposal reliability (or Earth environment safety) and program cost. Since the entire point of the space disposal program is the final and complete isolation of the extremely long-lived and dangerous waste products from the Earth's environment, it is self-defeating to significantly compromise reliability for cost. Therefore, such trade-off decisions within this study are biased toward safety. Significant system study effort will be needed to treat all aspects of mission completion reliability and to define abort procedures.

5.1.1 Design for Earth Re-encounter. Table IV, derived from Reference a., shows the weight distribution for several waste package sizes and percentages of fission products.

Note that the combination of core matrix, re-entry heat shield, and double impact shells form about one-half of the total package weight. This combination is designed to maintain structural integrity throughout Earth atmosphere re-entry (including both low and high velocity and entry angle modes) and after surface impact with rock or concrete at a sea level velocity of 300 meters per second (984 FPS). This velocity is based on atmospheric entry at 11 KM per second (36,090 FPS). Thus, by maintaining the structural and heat shield configuration throughout the propulsion phases, considerable protection is provided against a vehicle failure causing widespread actinide distribution in the atmosphere or ocean. This holds true even after extreme periods of time such as might result from propulsion failure near Earth escape velocity. Although the weight penalty is high, such protection appears necessary and commensurate with the program safety philosophy, and has accordingly been retained in the study.

5.1.2 Thermal Considerations. The waste package is designed for passive thermal control utilizing radiative heat dissipation in space and radiation plus natural convective/conductive cooling while on Earth. In both cases, the highly conductive core matrix provides efficient heat removal from the package center and a package size limitation of 6,400 KG (14,080 pounds) reduces the probability of thermal-structural failure with a landing and burial in soft, low heat conductivity soil. This size results in about 34 KW of heat per 0.1 percent fission product package, assuming 10-year pre-partitioning waste storage as described in the next section. These temperature control techniques are incorporated in this study to maintain a reasonable level of structural integrity.

5.1.3 Pre-partitioning Waste Storage. As mentioned in Section 3.3, aqueous surface storage of the waste may be required prior to partitioning to control solvent or ion-exchange media damage. Such storage also reduces the weight penalty for radioactive shielding and allows a more efficient, larger package size due to lower waste heat levels. The 10-year storage period and resulting thermal energy level as calculated in Reference a. has been assumed in this study. Figure 10, which is also derived from Reference a. information, shows typical power density decay with time for waste from two types of fission reactors. Heat characteristics of this study's waste packages appear to fall closest to the lower, LWR curve. Note that elimination or significant reduction of the waste storage period results in an extreme increase in the thermal energy density. This essentially excludes the passive, high reliability design approach, since extensive and active thermal cooling is required while in space, during atmospheric re-entry, and on the surface while awaiting recovery. Since loss of active cooling results in package destruction and actinide release, the 10-year waste storage period and passive design approach appears to be mandatory.

5.1.4 Radiation Shielding. The radiation shield provides personnel protection during prelaunch handling, during manned booster launch, and after Earth landing following certain modes of transportation failure. Since the probability of vehicle failure and landing in a populated area is extremely low, removal of the radiation shield in low Earth orbit may provide an acceptable risk means of greatly increasing the actinide payload. Such a concept retains the re-entry shield and impact shell as protection against uncontrolled and widespread distribution of the actinides.

Table IV shows that the radiation shield, composed of a lithium hydroxide and a tungsten shell, accounts for roughly 40 to 50 percent of the total payload package weight. Of this, the tungsten component, providing high density gamma shielding, accounts for about 90 percent of the total shield weight. Since the lithium hydride shell is lightweight and provides important neutron shielding for any event except package structural failure, it is recommended that it be retained throughout each mission. Thus, the possibility exists for a substantial increase in actinide weight per package, perhaps as much as 3 to 5 times, provided that safety considerations permit the payload to be redesigned for tungsten shell removal.

The trade-off of the tungsten shell removal or retention prior to upper stage flight is again one of cost versus safety, and additional study is required to resolve six major considerations:

a. Radiation Shield Design: Since an early, upper stage propulsion failure would strand the payload in Earth orbit, the shield must be designed for replacement prior to actinide package recovery as well as for removal during normal operations. This requirement applies to both manned and unmanned modes of shield manipulation.

b. Re-entry Shield: Establish the design and program impact of the new heat shield package configuration.

c. Operational Impact: Establish the increase in operations and crew/ground control training for manipulation and handling of the highly radioactive package during shield removal and possible replacement.

d. Reliability: What is the increase in failure probability and what are the modes and probable consequences of a failure due to the increased hardware and operational complexity?

e. Environmental Safety: Assuming a failure during any part of the mission and successful re-entry and Earth landing, what is the probable effect on the Earth's environment and inhabitants of a randomly placed, concentrated, long-lived, high level source of gamma radiation?

f. Tungsten Shield Recovery: Is it cost effective to recover individual shields by single purpose Shuttle flights? What are the design and operational factors associated with storage of a number of shields in Earth orbit and subsequent Shuttle recovery?

In view of the major effort required to resolve these considerations, this study assumes that the waste package shielding will be retained throughout each mission.

5.2 Boosters. Figures 5, 6, and 7 show the Shuttle and two unmanned boosters of 160K and 315K pounds to low Earth orbit payload capability, selected for presentation within this report. The two unmanned vehicles both utilize Shuttle SRM, SSME, and modified propellant tank hardware and the Shuttle's hardware recovery concept. This minimizes development, production, and new GSE costs and allows as direct a comparison as possible of the program impact from two upper stage designs and various payload sizes. Since the design characteristics of all three vehicles are based on established Shuttle program hardware, expected performance and program factors are known or easily predicted. Design activity other than shown in the figures was not accomplished within the scope of this study.

Another version of a Shuttle derived, heavy-lift launch vehicle (HLLV) is shown in Figure 8 and described in Reference k. It provides about 150K pound payload to low Earth orbit capability, and has a 5 SRM first stage, one SRM second and third stage, and Earth-storable liquid propellant fourth stage (inadvertantly omitted from the drawing) configuration. Serial operation is used for all four stages. This vehicle was not included in Table II, however, since it provided no performance advantage and appeared less reliable than the selected 160K booster due to 4 stage complexity.

5.3 Chemical Upper Stages. Figures 5 through 8 show various upper stage configurations which are all combinations of two basic, cryogenic propellant vehicles plus tailored sizes of SRM's.

The "full capability" cryogenic propellant space tug (FCT) with a performance capability as shown in Figure 9 and Appendix A was considered because of its potential availability and because of its size and performance compatibility with payloads, launch systems, and mission requirements. Note that only an expendable version of the tug is utilized in this report. This decision was based upon calculations showing a significant cost advantage in applying the full capability to the payload deployment mission rather than reserving enough capability for return of the tug to low Earth orbit and Shuttle recovery. This was true, even assuming only half the cost of a Shuttle flight for FCT recovery. The new Cryo stage largely utilizes existing hardware components and is based on proven techniques and designs. This vehicle was primarily sized for Shuttle/SSE operation in a two Shuttle per mission mode; however, it also demonstrates excellent compatibility with transportation systems utilizing the new 315K booster in SSE missions.

As mentioned, SRM selections are sized to provide necessary velocity increments within available system weight allotments. These stages are extrapolated from off-the-shelf catalog units and from the large, Shuttle, solid booster motors. Although they are not strictly off-the-shelf, the cost differential for amortizing development costs over large quantities of motors is very small and is not included as a factor.

5.4 ION UPPER STAGE

5.4.1 Ion Stage Design. The large ion stage design shown in Table V and Figure 12, is based upon a considerably modified version of the SEPS mercury propellant vehicle and the Jupiter orbiter and Saturn missions described in Reference e. Major differences, in addition to the twelve-fold increase in total weight, include the elongated, open, lightweight structure; the four panel, longitudinally stowed solar array; a 9-foot parabolic antenna; increased low thrust and RCS propellant supplies; and improved mercury/electron bombardment ion thrusters, estimated as available by the early 1990 need date. It is considered important to predict ion thruster improvements because of the high level of effort and rapid advances currently being made in the state-of-the-art. This prediction, derived from information in References f. and g., results in the following thruster parameters: 45 cm size; 80 percent efficiency; 6,400 sec. specific impulse; 20,000 hour (2.28 year) life; and perhaps most important to this program, an extremely high reliability throughout the specified life period.

Ion thrusters utilizing propellants other than mercury may be available by the program need date and may prove superior because of propellant availability or environmental compatibility. It is specifically noted that the 55 to 95 tons per year required for the basic program constitutes a significant portion of the total world's production. Mercury propulsion appears valid for this study, however, for the following reasons:

a. Earth environment contamination is expected to be very small due to the high orbit for ion thrust initiation and the short thrust duration within close proximity of the Earth. Contamination from this 10,000 N.M., and outward orbit was considered by applying the same basic factors as presented in Reference e.

b. Mercury propulsion performance and hardware characteristics are better defined than for other systems (such as argon) and are believed to be reasonably representative, within the requirements of this study, of other ion propulsion types.

This study's design approach consisted of calculating the SEPS vehicle's propellant requirements for low thrust Solar System Escape (SSE) and modifying, extending, and replacing portions of the design to accommodate the larger payload and unique mission and hardware requirements and limitations. One such limitation is the total allowable propulsion period. This is determined from GN&C and propulsion system reliability and life characteristics, and is estimated at no more than 2.0 years with the required high reliability. The increase in allowable propulsion time from the 1.18 years of the SEPS SSE mission to 2.0 years allows a 40 percent relaxation in the average thrust (or electric power) to mass ratio. One perturbation to this approach is the decrease in available solar energy at extended solar distances beyond normal SEPS operations, which results in a nominal increase in total propulsion time beyond the indicated limit. Thrusters are the critical life limited components, however, and may be shut down and reserved as spares as the incident solar energy declines. Therefore, this is not a serious impact to the total mission, but should be defined in detail during later iterations of this study.

The design shown in Table V and Figure 12, which is sized for operation with the new 315K booster, provides 174 KW of solar power and about 5 KW (with a slight variation depending upon fission product concentration) of payload waste heat power early in the mission and at one A.U. from the Sun. Ion propulsion utilizes 177.5 KW of this power and a constant 1.5 KW is required for other subsystems. Thus, thruster system electrical power to mass ratio is 2.14 watts/lb., a 37 percent reduction from the 3.39 watts/lb. for the SSE SEPS.

Figure 13 shows an alternate design in which the four solar panels are stowed across the bottom of the vehicle rather than along the longitudinal edges. This allows a smaller and lighter structure, but results in 97.5 meter (320-foot) long solar panels. Note that the panel width limitation, which leads directly to the length problem, has been eased as much as possible by allowing a 9.1 meter (30-foot) diameter fairing. This results in a hammer-headed payload with the 8.2 meter (27-foot) diameter, 315K booster of Figure 6. Since the long body design, also placed within a 9.1 meter (30-foot) fairing for comparative purposes, results in 54.0 meter (177-foot) solar panels, it is recommended for the large ion vehicle.

Table VII presents a small, half payload size version of the previous vehicle for utilization with the smaller, 160K booster of Figure 5. Note that both boosters maintain the 8.2 meter (27-foot) diameter, and that provision of the 9.1 meter (30-foot) fairing requires the hammer-head payload configuration. With the 50 percent reduction of required solar power, solar panel lengths reduce to 48.8 meter (160 feet) and the alternate short body design becomes the recommended approach. Later studies can resolve the larger-fairing/shorter solar panel versus the straight line form/longer solar panel trade alternates.

5.4.2 Transportation Systems. Table VI and VIII show calculated weights for all elements of the large and small ion stage transportation systems, respectively. Velocity requirements and propulsion characteristics are also noted for each burn of the mission. These values are reasonably self-explanatory and straight-forward in their derivation. It can be noted, however, that the 280 KM (150 N.M.) LEO of the large ion stage is considered a minimum altitude to ensure adequate orbital stability for in-orbit checkout and possible repair, recovery, or other emergency action. In addition, chemical propulsion to the 18,500 KM (10,000 N.M.) circular parking orbit is provided to protect the solar panels from Van Allen Belt radiation damage and to allow a final ion stage checkout in an orbit that is still accessible from Earth.

5.4.3 Payload Considerations. Figures 12 and 13 show payload waste packages of 8,545 KG (18,800 pounds) each, which is the maximum size, after adding 145 KG (320 pounds) for waste heat energy recovery, presented in Reference a. This size, when loaded with 0.1 percent fission product waste, exceeds thermal limits when buried in certain types of soil. For this reason, all packages of Table II are limited to the 6,400 KG recommended in Section 3.3.3, Thermal Considerations.

The drawings also show each payload with a SRM, which is sized to provide 300 meters per second (1,000 FPS) of velocity to the separated payload. This extra capability may be used during flight emergencies to minimize the safety threat of a non-optimum performance, or it may be reserved as a final SSE kick at large solar distances when power is low and solar panels are degraded from long term space exposure.

5.4.4 Waste Heat Utilization. Section 5.1 considers possible payload variations within the context of Earth environment safety and arrives at the conclusion that only two configurations may be acceptable at this time. These configurations are the original passive design of Reference a. and a modification of this design to allow orbital removal of the tungsten gamma ray shield. For the large ion stage payload of Table V, total waste actinide heat energy, as derived from Reference a. and Section 5.1 considerations, is as follows:

a.	Reference a. waste package design:	0.1 percent fission products - 88 KW 1.0 percent fission products - 60 KW
b.	Removable gamma shield design:	0.1 percent fission products - 246 KW 1.0 percent fission products - 276 KW

For the waste disposal application, reliability considerations rule out the relatively high efficiency, thermal-mechanical-electrical power conversion approach. The relatively inefficient, passive, highly reliable thermoelectric (example: ALSEP with a 4 percent efficiency) or thermionic diode types remain as prime candidates. The latter is selected for this study due to its higher projected efficiency of 15 percent. Total power system efficiency, including power conditioning (80 percent), and all other items (90 percent), becomes about 10.8 percent.

Applying this efficiency figure to the preceeding power figures results in available waste heat electricity as follows:

a.	Reference a. waste package design:	0.1 percent fission products - 9.5 KW 1.0 percent fission products - 6.5 KW
b.	Removable gamma shield design:	0.1 percent fission products - 26.5 KW 1.0 percent fission products - 29.8 KW

Thus, within the Earth environment protection philosophy discussed in Section 5.1, utilization of waste heat electrical energy appears useful as a long-lived, reliable, relatively stable supplement to solar power, but does not begin to approach levels commensurate with elimination of the solar power system. Doubling of the power conversion efficiency, as has been predicted for advanced heat-pipe-thermoionic conversion systems presented in Reference m., still fails to achieve the required power levels by a factor of about three, for the removable shield, 1.0 percent fission product case.

6.0 ADDITIONAL PROGRAM CONSIDERATIONS. Some factors uncovered and investigated during the study deviate somewhat from the specific study goal of defining and comparing competitive systems and programs for the space disposal of nuclear waste materials. These factors are very briefly included in this section, however, for completeness and general interest.

6.1 Unpartitioned Nuclear Waste Disposal. Most studies, including this one, have assumed the obvious: that disposal of the combined unpartitioned fission and actinide (excluding uranium) waste products, is not economically feasible. To test this supposition, a large ion stage and four payload packages of 9,400 pounds each in the new 315 K Booster + Cryo + SRM + Ion Stage + P/L SRM configuration can be considered. It was found that 26,587 flights were required which resulted in a program cost of $1,563B and a surcharge of $21.3 mills/KWH. This estimate disregarded the need for new launch, mission control, and tracking facilities. The partitioning requirement assumption, therefore, appears to be valid.

6.2 Booster Exhaust Pollution. As indicated in Table II, launch rates vary from 3 to 59 per year, with one to three per month being representative of the lower cost, all chemical transportation systems. In view of present concerns with the atmospheric pollution by SRM exhaust products, these SRM firing rates may be considered by some to be unacceptable, particularly when added to other SRM-type space launches. A change from the proposed liquid/solid boosters to all liquid boosters has no effect on the relative merits of the various transportation system configurations for the SSE mission. For the solar orbit mission, however, the Shuttle option loses its status as the minimum cost program if development of the new Shuttle booster is charged totally to the waste disposal program. SSE program calculations for the all liquid 315K + 4 SRM booster/0.1 percent product payload configuration shows a small program cost increase of less than 5 percent over the liquid/solid booster design.

6.3 Vehicle R&D Sharing. This study assumes that the full R&D burden for the new booster and upper stage vehicles falls upon the nuclear waste disposal program. This is somewhat pessimistic, since other programs will undoubtedly utilize the new hardware and should pay a proportionate share. If this consideration is factored into the program, total program and surcharge estimates are reduced for all but the solar orbit Shuttle configuration, and systems with the greater number of new vehicle types show the biggest improvement. Quantitative figures are difficult to estimate at this time since they depend upon exact vehicle utilization by future and, in many cases, ill defined programs. It appears reasonable to assume, however, that the Shuttle advantage for solar orbit missions will probably disappear entirely; and that the relative merits of ion stage systems may improve significantly.

6.4 Fusion Reactor Transmutation. As in Reference a., this study has assumed the use of fission reactor transmutation to reduce by two-thirds the quantity of actinides requiring space disposal. This is supported by Reference d. which suggests the possibility of significant reductions in the cumulative toxicity index* of actinides by continuous recycling through fission reactors. This reduction in the long-term toxicity index may be by a factor of 50 or more, depending upon actinide separation efficiency, reactor irradiation, and reactor type.

Reference d. also indicates that transmutation in the blankets of fusion reactors may reduce the actinide cumulative toxicity index by an additional factor of 10 or more, and may significantly reduce the total radioactive toxicity for some fission products. Exact reduction amounts are not known at this time due to uncertainties in nuclear reaction data for these elements and in the characteristics of actual, successful fusion reactors. Typically, reductions may be as much as 10^8 for I-129 and only 2 to 5 for Cs-137.

Thus, successful and timely development of fusion reactors may well obviate or drastically reduce the need and desirability for space disposal of nuclear waste materials. It is suggested that this possibility be carefully considered and widely coordinated before committing significant funds to the space disposal program.

7.0 CONCLUSIONS AND RECOMMENDATIONS. Information resulting from the study activity is summarized in the following comments:

a. Unknown factors with the biggest impact on the space disposal program lie in the nuclear waste management area and consist of the Earth environment issue and the waste partitioning process. The former directly impacts the selection of space as a means of disposal and the payload package design impact upon vehicle design, flight quantities, and mission characteristics. The latter injects a question of technical feasibility, waste product separation efficiency, and facility/operations costs.

b. It is not yet necessary to make detailed and definitive space disposal studies. ERDA generally considers the final solution of nuclear waste management as a year 2000

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* Toxicity index as used here is equivalent to dose calculations.

or later type requirement and has cancelled funding of studies associated with the unknown factors mentioned in the preceeding paragraph.

c. It is recommended that definition and resolution of the Earth environment safety requirement, because of its extensive program impact, be given top priority in future considerations of nuclear waste space disposal.

d. As may be seen from Table II, program costs for the 18 vehicle-payload-mission configurations presented within this report vary over a factor of 3, from the $16.29B and $0.222 mills/KWH of the solar orbit-Shuttle configuration to the $48.77B and $0.664 mills/KWH of the solar system escape-Shuttle configuration. Based on Earth environment safety considerations discussed in Section 5.1, waste disposal by solar system escape is indicated. Recommended vehicle configurations for these missions are the 315K Booster + 4 SRM or the 160K Booster + 2 FCT, each with 0.1 percent fission product payloads. Corresponding program costs are $27.76B ($0.375 mills/KWH) and $28.62B ($0.389 mills/KWH), respectively.

Note in Table II that the manned Shuttle is the highest cost option for solar system escape, with a program cost of $36.03B ($0.490 mills/KWH) for the 0.1 percent fission product payload. In addition, ion stages are not recommended, since the cost figures of Table II do not reflect significant, new, dedicated facility requirements. See conclusion i. of this section.

e. Disposal of nuclear wastes to 0.9 A.U. solar orbit costs approximately 40 to 45 percent less than solar system escape disposal for the lower cost options of each mission. Note that if the Earth environment safety problem of solar orbit can be satisfactorily resolved in the future, the Shuttle + FCT + SRM and 1.0 percent fission product payload becomes the lowest cost selection of all nuclear waste disposal options considered within this study.

f. For the solar system escape, actinide partitioning to a remaining fission product equal to 0.1 percent of the total fission products is moderately to significantly more cost effective than partitioning to 1.0 percent. For solar orbit, actinide partitioning to 1.0 percent remaining fission products is slightly more cost effective.

g. A new 160,000 or a new 315,000 pound payload to low Earth orbit booster is indicated for solar system escape. Assuming no R&D or additional Shuttle-Orbiter vehicle procurement costs, the Shuttle is about 3 to 10 percent more cost effective than unmanned boosters for the solar orbit program.

h. Within the recommended Earth environment safety considerations, ion stage payload waste heat is insufficient, by a wide margin, to meet engine and supporting subsystem electrical power requirements.

i. Without regard for the probable new launch and tracking facilities requirement, an ion stage powered by a solar plus waste heat energy source appears to be most cost effective for solar system escape waste disposal. Table II, Program Cost Summary, shows a cost advantage of about $1B to $2B for the ion versus the all chemical propulsion approach.

Considering the extended duration of powered flight requiring extensive control, however, this advantage is expected to be lost as the details of the operation are developed. Thus, a new 315K booster plus 4 SRM or a 160K booster plus FCT design is recommended since the ion approach requires new, dedicated tracking and control facilities and additionally poses a reliability/safety question due to the 2-year operating period of each ion stage.

j. Shuttle recovery of upper stages from Earth orbit does not appear to be cost effective for this mission.

8.0 GLOSSARY

ALSEP	Apollo Lunar Surface Experiments Package
CRYO	Cryogenic
ERDA	Energy Resource and Development Administration
FCT	Full Capability Tug
HLLV	Heavy Lift Launch Vehicle
LEO	Low Earth Orbit
LMFBR	Liquid Metal Fast Breeder Reactor
LWR	Light Water Reactor
P/L	Payload
SEPS	Solar Electric Propulsion Stage
SRM	Solid Rocket Motor
SSE	Solar System Escape
SSME	Space Shuttle Main Engine
STS	Space Transportation System

9.0 REFERENCES

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TABLE I

VEHICLE COSTS, FY 1975 DOLLARS

VEHICLE	SINGLE UNIT PROCUREMENT*	GND & FLT OPERATIONS COST/FLT*	R&D COST*
SHUTTLE	0.0	$13.0 M**	0.0
315 K BOOSTER	$20.0 M**	$ 8.5 M	$ 4.5 B
160 K BOOSTER	$17.0 M**	$ 8.0 M	$ 4.0 B
FCT (EXPENDABLE)	$11.0 M	$ 7.2 M	NEGLIGIBLE
CRYO	$15.0 M	$ 7.8 M	$ 2.0 B
ION STAGE (LARGE)	$20.0 M	$ 9.5 M	$ 4.0 B***
ION STAGE (SMALL)	$18.0 M	$ 9.0 M	$ 4.0 B***
P/L 7.2 K POUND	$ 1.0 M	$ 0.25M	NEGLIGIBLE
10.0 K POUND	$ 1.5 M	$ 0.35M	"
14.0 K POUND	$ 2.0 M	$ 0.50M	"
SRM 160 K	$ 1.04 M	"	"
80 K	$ 0.84 M	"	"
40 K	$ 0.56 M	"	"
30 K	$ 0.46 M	$ 0.30M	"
20 K	$ 0.34 M	"	"
10 K	$ 0.21 M	"	"
ALL LIQUID 160 K BOOSTER	$19.0 M	$ 9.0 M	$ 4.5 B
ALL LIQUID 315 K BOOSTER	$22.0 M	$ 9.5 M	$ 5.0 B

* SEE TEXT, SECTION 4.2.2 FOR DERIVATION.

** INCLUDES RECOVERY AND RE-USE OF SRM AND SSME COMPONENTS.

*** ASSUMING UTILIZATION OF PROVEN SEPS HARDWARE

TABLE II

PROGRAM COST SUMMARY

VEHICLE	FLIGHT TRAJECT	WASTE PKG QUAN/LBS EA	FISSION PROD	NO. FLTS	MISSIONS PER YR	VEH PROC COST/FLT	VEH R&D	OPS COST	PROGRAM COST	SURCHARGE MILLS/KWH
NEW 160K BOOSTER + 2 FCT	SOLAR SYS ESCAPE	1/12.1K	0.1%	312	20.8	$20.8M	$4.0B	$ 7.15B	$28.62B	0.389
	"	"	1.0%	527	35.2	$19.2M	$4.0B	$12.07B	$34.20B	0.465
NEW 315K BOOSTER + 4 SRM (76K LB EACH)	"	1/7.2K	0.1%	524	34.9	$12.4M	$4.5B	$ 5.61B	$27.76B	0.375
	"	"	1.0%	885	59.0	$12.1M	$4.5B	$ 9.47B	$32.67B	0.445
NEW 315K BOOSTER + 2 CRYO + 2 SRM (12K LB EACH)	"	2/7.2K	0.1%	262	17.5	$27.7M	$6.5B	$ 6.60B	$31.36B	0.430
	"	"	1.0%	442	29.5	$25.4M	$6.5B	$11.14B	$36.87B	0.502
2 SHUTTLE + CRYO + SRM (13.5K LB)	"	1/7.2K	0.1%	524	34.9	$ 7.9M	$2.0B	$16.16B	$36.03B	0.490
	"	"	1.0%	885	59.0	$ 7.7M	$2.0B	$27.35B	$48.77B	0.664
NEW 160K BOOSTER + FCT + ION STAGE + P/L SRM (2.5K LB)	"	2/9.4K	0.1%	158	10.5	$28.2M	$8.0B	$ 3.98B	$27.44B*	0.373
	"	"	1.0%	261	17.4	$26.3M	$8.0B	$ 6.58B	$29.44B*	0.401
NEW 315K BOOSTER + CRYO + SRM (66K LB) + ION STAGE + P/L SRM (5K LB)	"	4/9.4K	0.1%	79	5.3	$40.0M	$10.5B	$ 2.05B	$26.86B*	0.365
	"	"	1.0%	131	8.7	$37.6M	$10.5B	$ 3.46B	$27.07B*	0.368
NEW 160K BOOSTER + FCT	SOLAR ORBIT	3/14.0K	0.1%	90	6.0	$22.5M	$4.0B	$ 1.50B	$18.53B	0.252
	"	"	1.0%	152	10.1	$21.4M	$4.0B	$ 2.54B	$17.79B	0.242
NEW 315K BOOSTER + 2 FCT	"	6/14.0K	0.1%	45	3.0	$31.7M	$4.5B	$ 1.17B	$18.09B	0.246
	"	"	1.0%	76	5.1	$30.7M	$4.5B	$ 1.97B	$16.80B	0.229
2 SHUTTLE + FCT + SRM (32K LB)	"	3/10.0K	0.1%	126	8.4	$11.1M	0	$ 3.93B	$16.75B	0.228
	"	"	1.0%	183	12.2	$10.8M	0	$ 5.71B	$16.29B	0.222

* EXCLUDING NEW MISSION CONTROL AND TRACKING FACILITIES; SEE SECTION 4.2.3

TABLE III

LEVEL III COST ESTIMATES - 400 K BOOSTERS

Forecaster	Concept	Nonrecurr. Costs $B	Annual Capability Maint. Costs $M/YR	Payload to Orbit Recurr. Costs $/LB
Akridge	VTOVL SSTO	6 ± 1	25 ± 5	20 ± 10
Chamberlain	(1) Larger Baseline Shuttle	15.4	250	113
	(2) Larger Baseline Shuttle with Flyback Booster	28.4	250	39
Edgecombe	2-Stage with Unmanned Modular 2nd stage and Flyback Booster	$2^{+1}_{-.5}$ (Δ to 11)	100 ± 50 (Δ to 11)	15^{+15}_{-1}
Gore	Rhombus 1 1/2-Stage VTOVL (1992 IOC)	7.2 ± 1.5	300 ± 5	37^{+37}_{-3}
Hammock	Larger Baseline Orbiter with Flyback Booster	9.24	78	6.73
Henry	VTOVL 2-Stage, Series Burn 1st Stage Strap-on Booster	9.1 ± 1.3	360 ± 50	22 ± 5
Kelly/Goodman	(1) Shuttle Derived Unmanned HLV (III Δ-PL = 160K)	1.26 ± .15	52 ± 6	63
	(2) 2-Stage, Recoverable 2nd Stage Engine, Flyback Booster	9.1 ± 1.8	52 ± 10	16
Nansen	VTOVL SSTO (Ballistic Recovery)	10.6 ± 1.5	30 ± 6	14 ± 2
Odom	VTOHL SSTO	15.5 ± 2.7	150 ± 22	24 ± 6
Salkeld	(1) SSTO VTOHL	11.8 ± 2	40 ± 10	21
	(2) VTOVL (Unmanned)	8.5 ± 2	40 ± 10	16
Paustian	3 Stage-1st 6 Shuttle SRB's 2nd S-1C with 3 F-1's 3rd S-11 with 3 SSME's	1.165 ± .2	45	662
Tischler	1 1/2 Stage, VTOVL Ballistic Recovery	10.13 ± 2	300 ± 60	30 ± 6 w/o rec. 40 ± 8 w/rec. ≈ 36 ± 12
Withee/Jones	2 Stage - 1st Stg, 4 SRB's 2nd Stg. Recoverable Engines	4.8 ± .5	240 ± 60	90

TABLE IV

WASTE PACKAGE WEIGHT DISTRIBUTION

WASTE PKG KG (LBS)	FISSION PROD.	PERCENTAGE OF TOTAL PACKAGE WEIGHT					
		ACTINIDES	FISSION PROD.	CORE MATRIX	RADIATION SHIELD	RE-ENTRY SHIELD	IMPACT SHELL
2800 (6,160)	0.1%	5.3	0.2	17.8	43.0	13.2	20.2
	1.0%	3.5	1.2	14.8	48.6	13.2	18.0
3270 (7,200)	0.1%	5.9	0.2	19.1	41.8	12.9	19.6
	1.0%	3.5	1.2	15.1	49.4	12.9	17.3
8400 (18,400)	0.1%	7.6	0.3	24.8	38.5	12.4	15.4
	1.0%	4.6	1.6	19.7	47.6	12.4	13.4

TABLE V

LARGE ION STAGE WEIGHTS

ION STAGE (Long Body/Short Solar Panel Option)

Structure	2,400 LBS
Electric Propulsion	6,000
Communications (Ant. & Elect.)	100
Command Computer/Data Handling	30
GN&C	100
Reaction Control	250
Solar Array (174 KW & 21,230 ft^2)	6,000
Power Control & Distribution	900
Thermal Control	500
Margin (10%)	1,630
Ion Stage, Dry	17,910 LBS

PROPELLANTS

RCS Hydrazine	530 LBS
RCS Nitrogen	120
Mercury (60,100 FPS, Isp = 6,400, 1% Resid.)	21,500
Liquid Propellants	22,150 LBS

PAYLOAD

Four - 9,240 LB Waste Pkgs + 160 LB thermocouples, wiring, fittings, etc.	37,600 LBS
P/L Adapter & Radiators + 10%	1,870
P/L SRM (1,000 FPS)	4,900
P/L Spin Thrusters & Control	200
Ion Stage P/L	44,570 LBS

TOTAL VEHICLE

Σ Dry Ion Stage + Propellant + P/L	84,630 LBS

TABLE VI

LARGE ION STAGE TRANSPORTATION SYSTEM - NEW 315K BOOSTER + CRYO + SRM + ION + P/L SRM

WEIGHTS

P/L, Adapter, & P/L SRM	44,570 LBS
Ion Stage & Propellants	40,060
Adapter, Ion Stage to SRM (3%)	2,540
SRM (4,700 FPS Circularize at 10,000 N.Mi)	65,810
Adapter, SRM to CRYO (3%)	4,590
CRYO (6,400 FPS, LEO to 10,000 N.MI.)	134,000
Adapter, CRYO to Booster (3%)	8,750
P/L & Ion Stage Fairing	4,500
Total to LEO, 150 N.Mi.	304,820 LBS

VELOCITY REQUIREMENTS

Launch to LEO = 150 N.Mi.	25,700 FPS
LEO to 10,000 N.Mi. Elliptical	6,600 FPS
Circularization at 10,000 N.Mi.	4,700 FPS
Low Thrust to SSE (Includes Gravity Loss ΔV)	60,100 FPS

PROPULSION CHARACTERISTICS

SSE: Mercury - Ion Propulsion, Isp = 6,400 sec.

Propellant Weight = 21,290 LBS + 1% residuals for 60,100 FPS

Circularize at 10,000 N.Mi.

Solid Propulsion, Isp = 290

Propellant Weight = 60,540 LBS for 4,700 FPS

LEO to 10,000 N.Mi.

LOX/H_2 Propulsion, Isp = 460

Propellant Weight = 105,000 LBS for 6,607 FPS

Emergency Spare or SSE Injection

Solid Propulsion, Isp = 290

Propellant Weight = 4,512 LBS for 1,000 FPS

TABLE VII

SMALL ION STAGE WEIGHTS

ION STAGE (Short Body/Short Solar Panel Option)	
Structure	700 LBS
Electric Propulsion	2,970
Communications (Ant. & Elect.)	100
Command Computer/Data Handling	30
GN&C	100
Reaction Control	120
Solar Array (87 KW & 10,615 ft^2)	3,000
Power Control & Distribution	450
Thermal Control	250
Margin (10%)	770
Ion Stage, Dry	8,490 LBS
PROPELLANTS	
RCS Hydrazine	260 LBS
RCS Nitrogen	60
Mercury (60,100 FPS, Isp = 6,400, 1% Resid.)	10,560
Liquid Propellants	10,880 LBS
PAYLOAD	
Two - 9,240 LB Waste Pkgs + 160 LB Thermocouples, Wiring, Fittings, etc.	18,800 LBS
P/L Adapter & Radiators + 10%	850
P/L SRM (1,000 FPS)	2,450
P/L Spin Thrusters & Control	100
Ion Stage P/L	22,200 LBS
TOTAL VEHICLE	
Σ Dry Ion Stage + Propellant + P/L	41,570 LBS

TABLE VIII

SMALL ION STAGE TRANSPORTATION SYSTEM - NEW 160 K BOOSTER + FCT + ION + P/L SRM

WEIGHTS

P/L, Adapter, & P/L SRM	22,200 LBS
Ion Stage & Propellants	19,370
Adapter, Ion Stage to FCT (3%)	1,250
FCT	56,500
Adapter, FCT to Booster (3%)	2,980
P/L & Ion Stage Fairing	2,000
Total to LEO, 400 N.Mi.	104,300 LBS

VELOCITY REQUIREMENTS

Launch to LEO = 400 N.Mi.	26,600 FPS
LEO to 10,000 N.Mi. Elliptical	5,600 FPS
Circularization at 10,000 N.Mi.	4,650 FPS
Low Thrust to SSE (Includes Gravity Loss ΔV)	60,100 FPS

PROPULSION CHARACTERISTICS

SSE: Mercury - Ion Propulsion, Isp = 6,400 sec.

Propellant Weight = 10,560 LBS for 60,100 FPS

LEO to 10,000 N.Mi. Circular Orbit

LOX/H_2 Propulsion, Isp = 460

From Figure 10: For 42,820 LB P/L, ΔV = 10,250 FPS Via FCT

Emergency Spare or SSE Injection

Solid Propulsion, Isp = 290

Propellant Weight = 2,256 LBS for 1,000 FPS

TRANSMUTATION WASTE MANAGEMENT

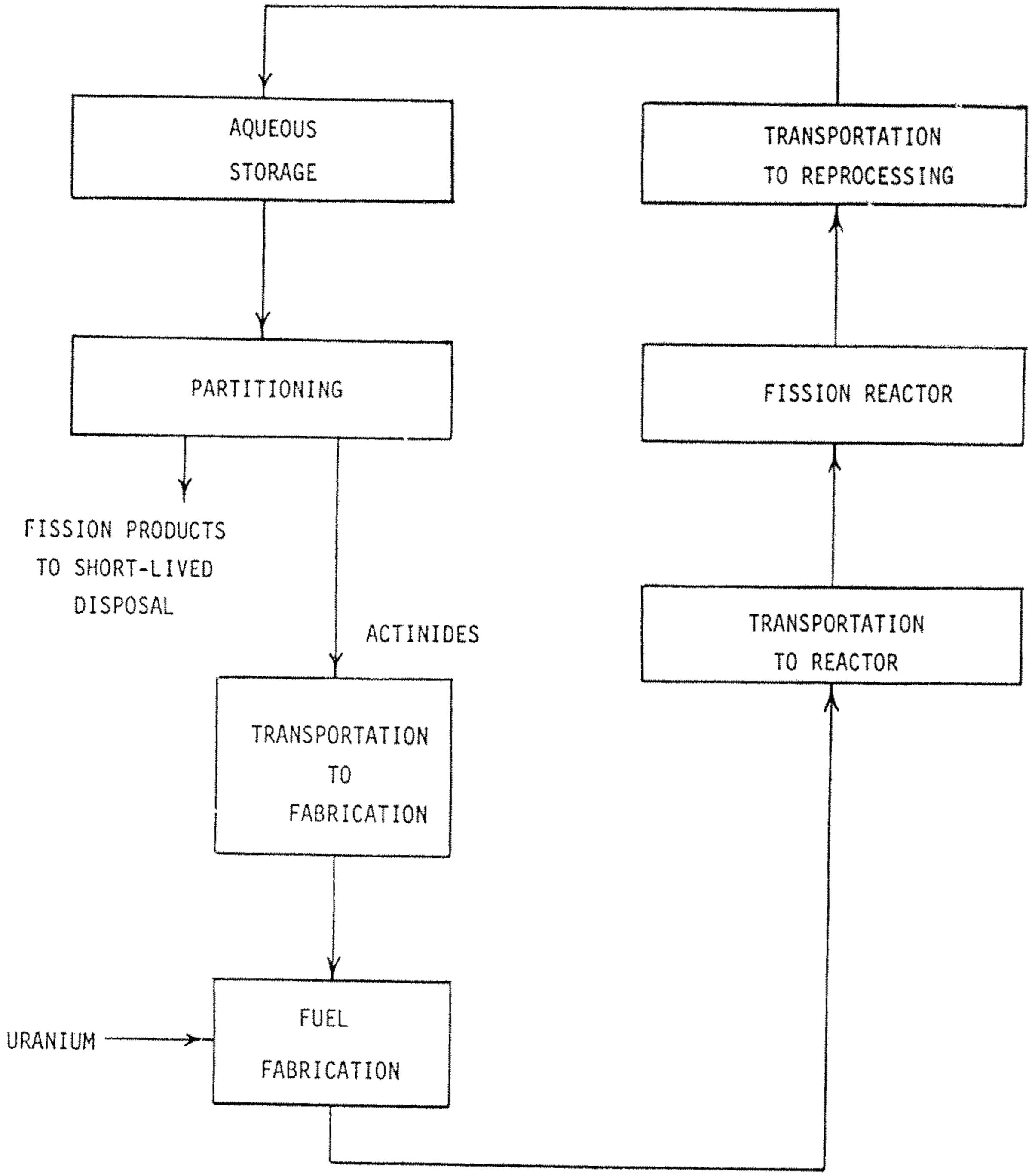
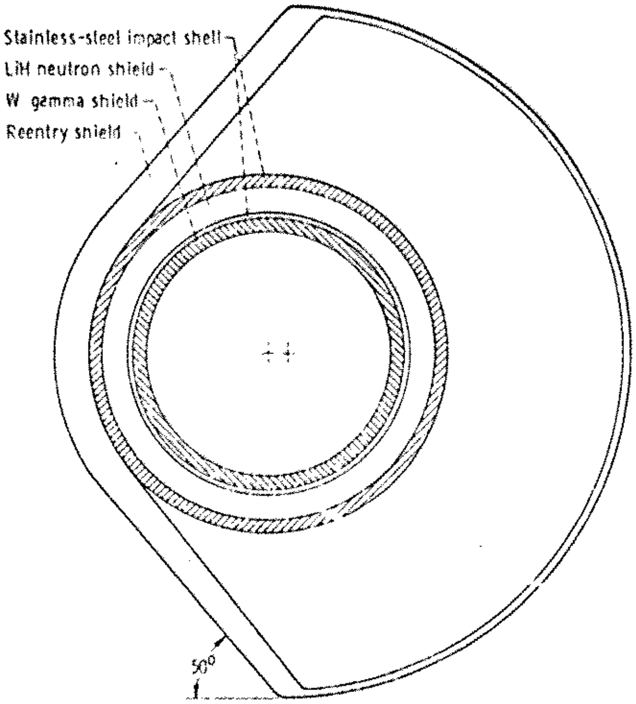


FIGURE 1

ACTINIDE WASTE PAYLOAD CONFIGURATION



TYPICAL PAYLOADS

TOTAL PAYLOAD - 3,270 KG (7,194 LBS)

ACTINIDES - 191 OR 113 KG (420 OR 249 LBS) FOR 0.1% OR 1.0% FISSION PRODUCTS, RESPECTIVELY

TOTAL PAYLOAD - 8,400 KG (18,480 LBS)

ACTINIDES - 634 OR 384 KG (1,395 OR 845 LBS) FOR 0.1% OR 1.0% FISSION PRODUCTS, RESPECTIVELY

FIGURE 2

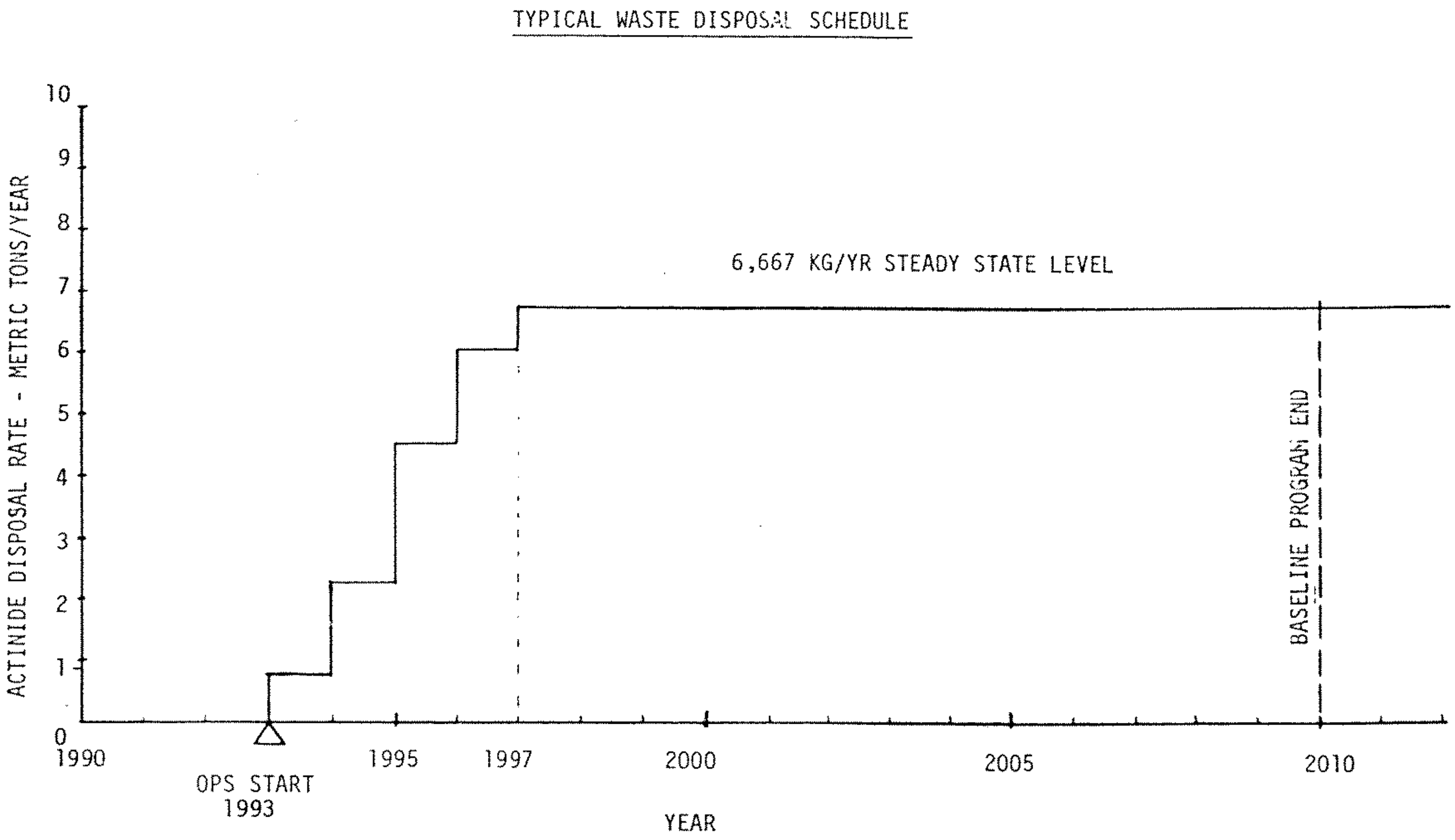

TYPICAL WASTE DISPOSAL SCHEDULE
ACTINIDE DISPOSAL RATE - METRIC TONS/YEAR
10
9
8
7
6
5
4
3
2
1
0
6,667 KG/YR STEADY STATE LEVEL
BASELINE PROGRAM END
1990
1995
1997
2000
2005
2010
OPS START
1993
YEAR

FIGURE 3

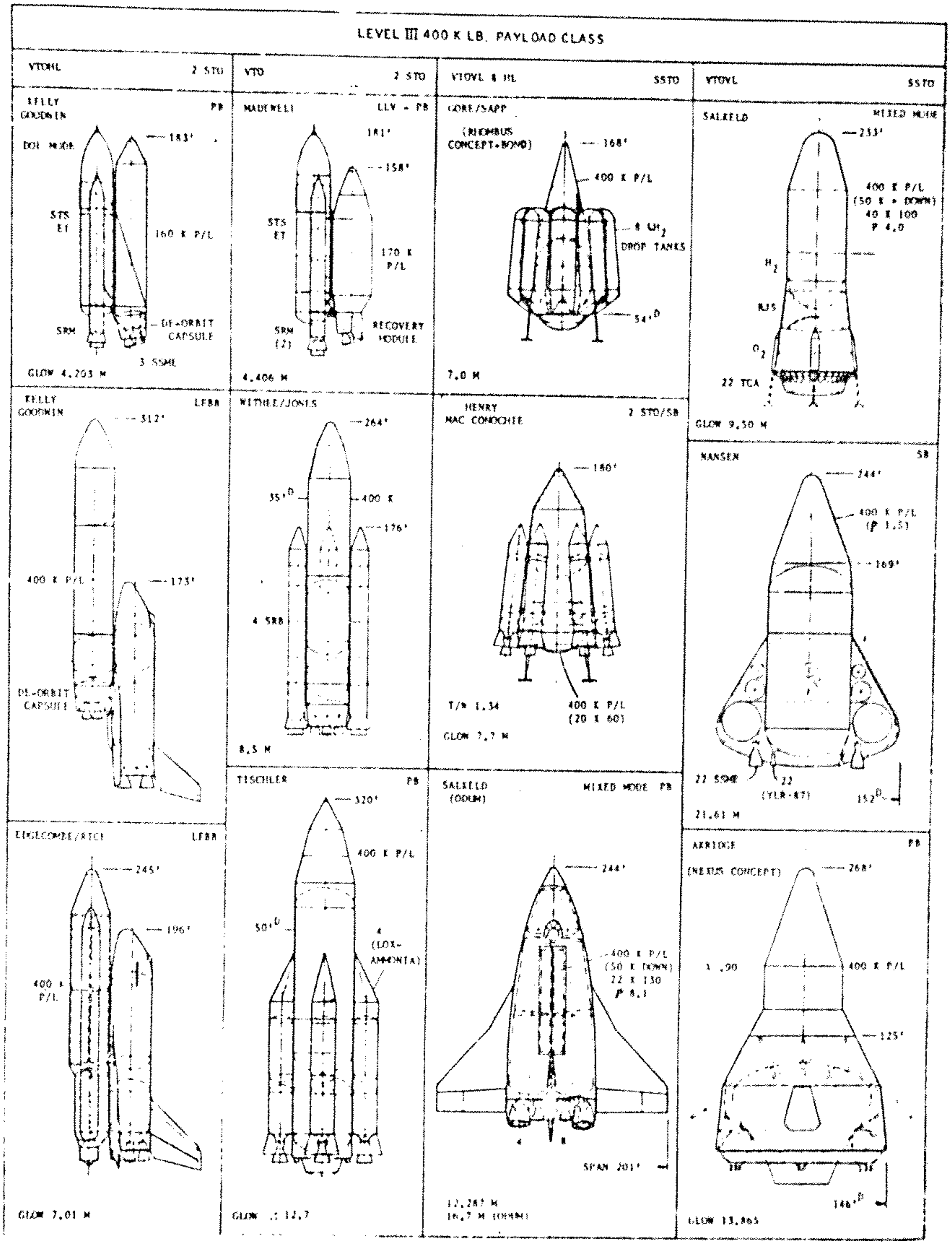

LEVEL III 400 K LB. PAYLOAD CLASS
VTOHL
2 STO
KELLY
GOODWIN
PB
DOI MODE
183'
STS
ET
160 K P/L
SRM
DE-ORBIT
CAPSULE
3 SSME
GLOW 4,203 M
KELLY
GOODWIN
LFBB
312'
400 K P/L
173'
DE-ORBIT
CAPSULE
EDGECOMBE/RICE
LFBB
245'
196'
400 K
P/L
GLOW 7,01 M
VTO
2 STO
MAUDWELL
LLV - PB
181'
158'
STS
ET
170 K
P/L
SRM
(2)
RECOVERY
MODULE
4,406 M
WITDLE/JONES
264'
35'D
400 K
176'
4 SRB
8,5 M
TISCHLER
PB
320'
400 K P/L
50'D
4
(LOX-
AMMONIA)
GLOW :: 12,7
VTOVL & HL
SSTO
GORE/SAPP
(RHOMBUS
CONCEPT+BOND)
168'
400 K P/L
8 LH2
DROP TANKS
54'D
7,0 M
HENRY
MAC CONOCHIE
2 STO/SB
180'
T/W 1,34
400 K P/L
(20 X 60)
GLOW 7,7 M
SALKELD
(ODUM)
MIXED MODE PB
244'
400 K P/L
(50 K DOWN)
22 X 130
ρ 8,1
4
8
SPAN 201'
12,287 M
16,7 M (DOWN)
VTOVL
SSTO
SALKELD
MIXED MODE
233'
400 K P/L
(50 K + DOWN)
40 X 100
ρ 4,0
H2
RJS
O2
22 TCA
GLOW 9,50 M
HANSEN
SB
244'
400 K P/L
(ρ 1,5)
169'
22 SSME
22
(YLR-87)
152'D
21,61 M
AKRIDGE
PB
(NEXUS CONCEPT)
268'
λ ,90
400 K P/L
125'
146'D
GLOW 13,865

FIGURE 4

NEW 160K BOOSTER + CRYO + SRM

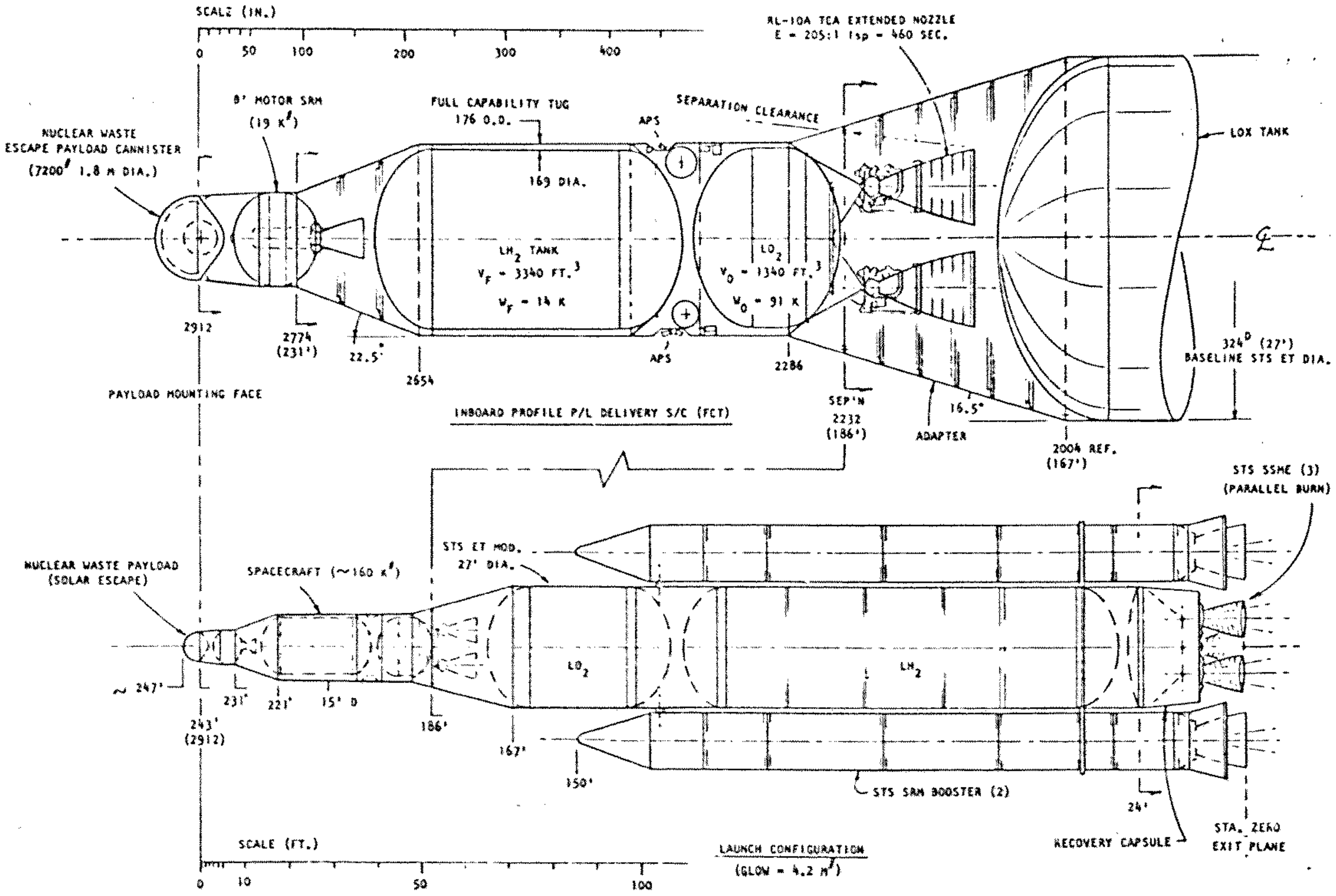


FIGURE 5

NEW 315K BOOSTER + 4 SRM

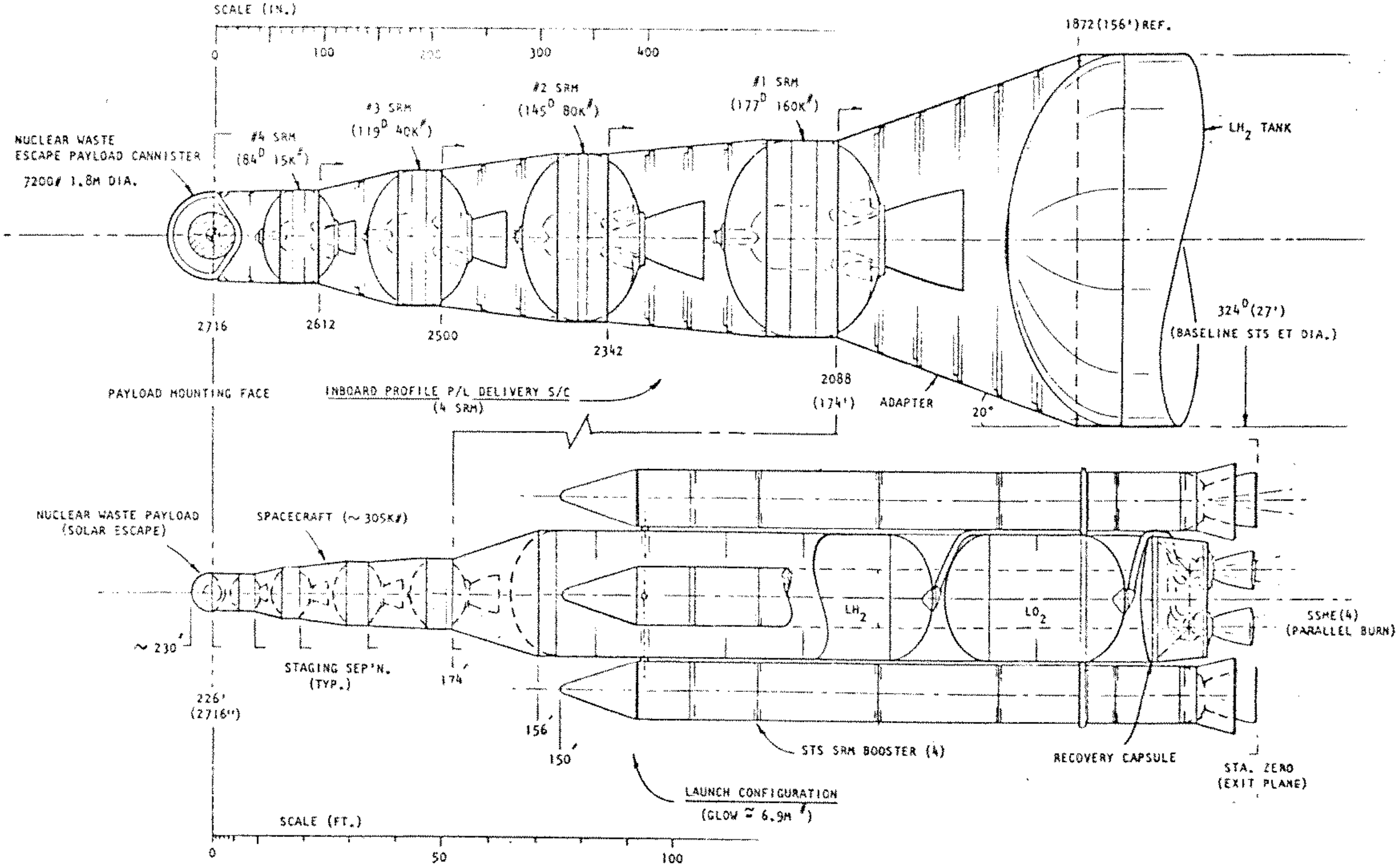


FIGURE 6

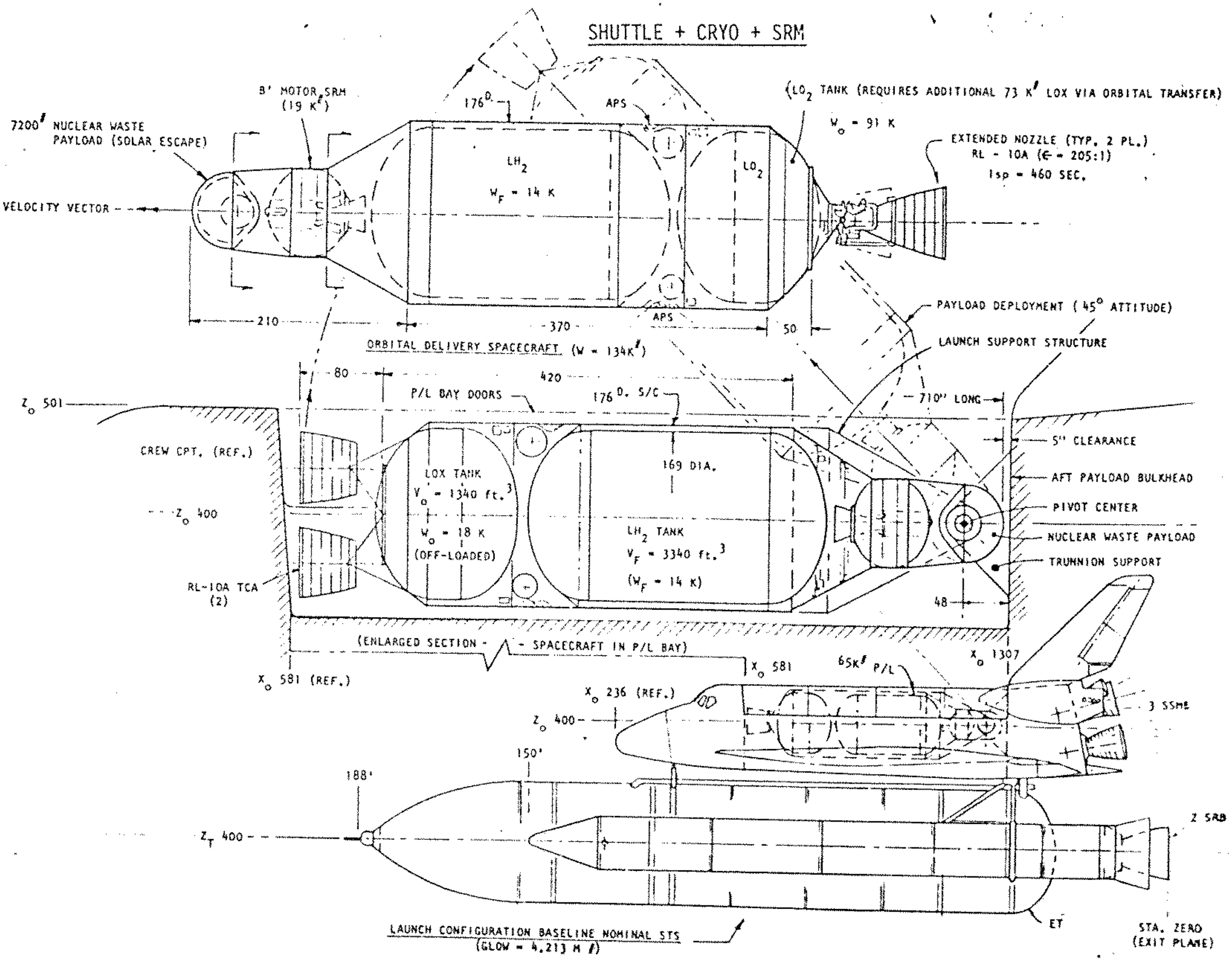

SHUTTLE + CRYO + SRM
8' MOTOR SRM (19 K#)
7200# NUCLEAR WASTE PAYLOAD (SOLAR ESCAPE)
VELOCITY VECTOR
176 D.
APS
LH2
WF = 14 K
LO2
(LO2 TANK (REQUIRES ADDITIONAL 73 K# LOX VIA ORBITAL TRANSFER)
Wo = 91 K
EXTENDED NOZZLE (TYP. 2 PL.)
RL - 10A (ϵ = 205:1)
Isp = 460 SEC.
210
370
50
APS
ORBITAL DELIVERY SPACECRAFT (W = 134K#)
PAYLOAD DEPLOYMENT (45° ATTITUDE)
LAUNCH SUPPORT STRUCTURE
80
420
P/L BAY DOORS
176 D. S/C
710" LONG
Zo 501
CREW CPT. (REF.)
Zo 400
LOX TANK
Vo = 1340 ft.3
Wo = 18 K
(OFF-LOADED)
169 DIA.
LH2 TANK
VF = 3340 ft.3
(WF = 14 K)
5" CLEARANCE
AFT PAYLOAD BULKHEAD
PIVOT CENTER
NUCLEAR WASTE PAYLOAD
TRUNNION SUPPORT
48
RL-10A TCA (2)
(ENLARGED SECTION - SPACECRAFT IN P/L BAY)
Xo 581 (REF.)
Xo 581
65K# P/L
Xo 1307
Xo 236 (REF.)
Zo 400
3 SSME
150'
188'
ZT 400
2 SRB
ET
STA. ZERO (EXIT PLANE)
LAUNCH CONFIGURATION BASELINE NOMINAL STS
(GLOW = 4.213 M #)

FIGURE 7

DUAL FCT UPPER STAGE

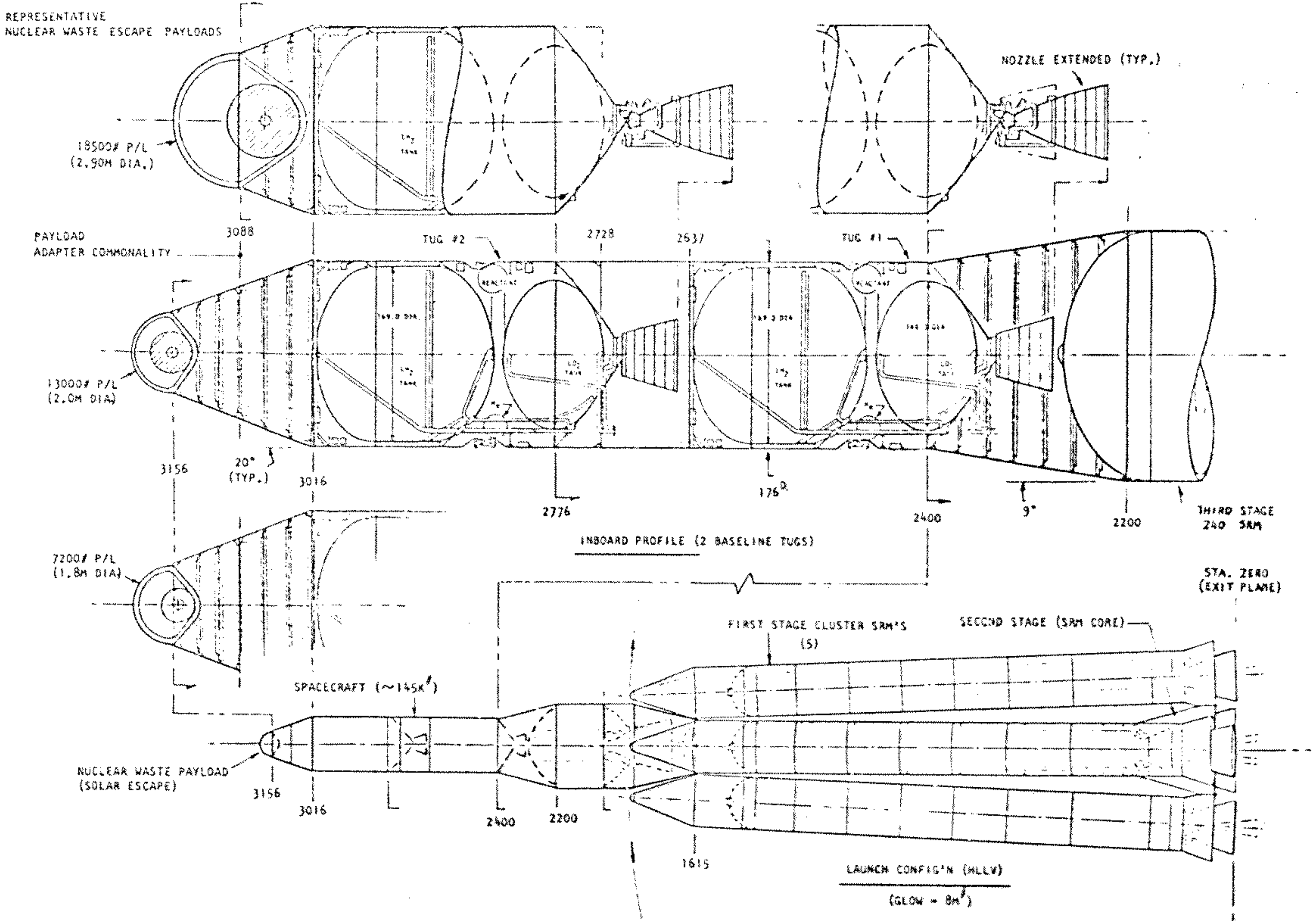
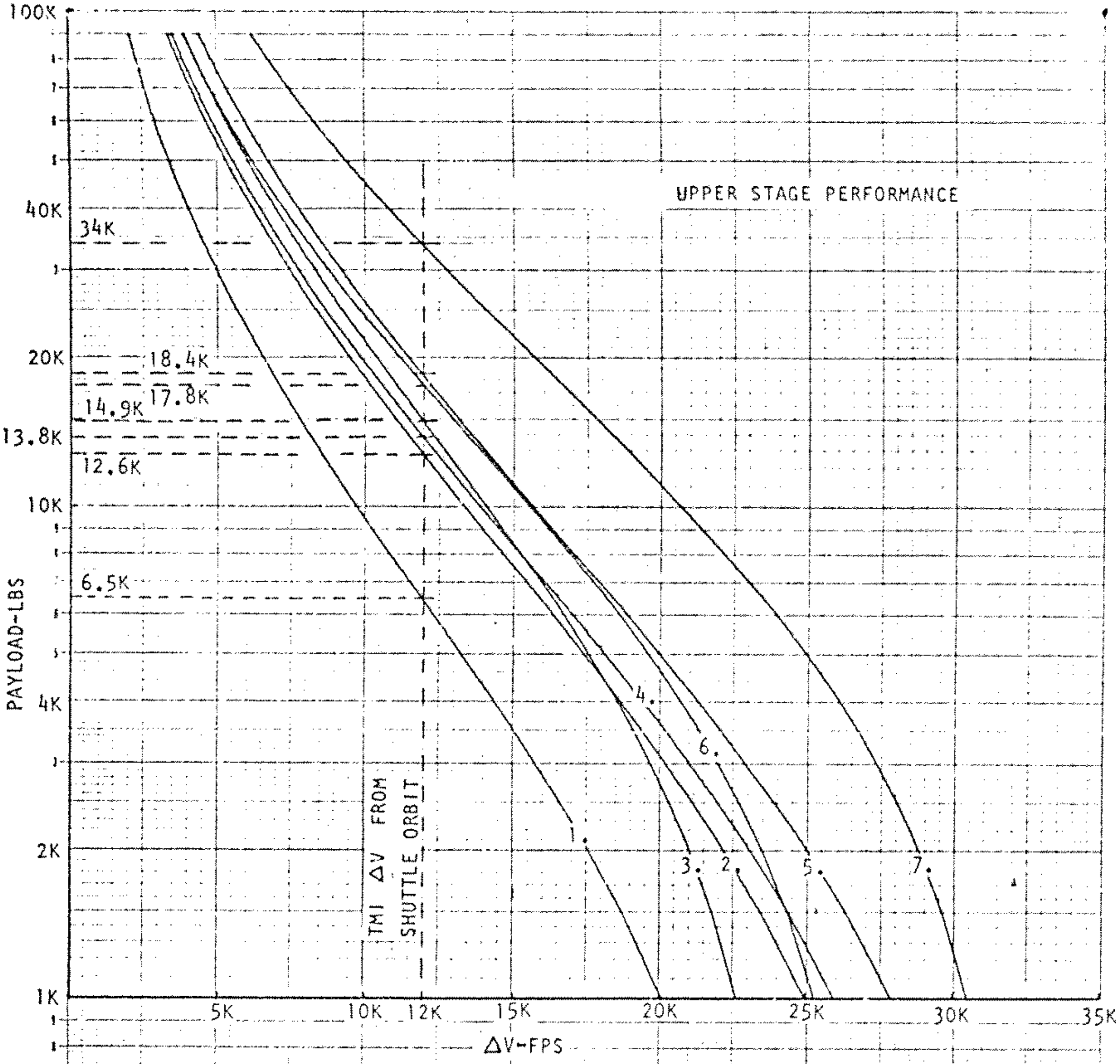


FIGURE 8



	STAGE	LENGTH	WEIGHT AT IGNITION	PAYLOAD LBS
1.	SRM B + A	14.7 FT	25,914 LBS	6.5 K
2.	SRM B + B + A	22.8 FT	45,409 LBS	12.6 K
3.	DUAL TRANSTAGE	42.5 FT	54,061 LBS	14.9 K
4.	AGENA + 4 MM III STG	20.9 FT	47,607 LBS	13.8 K
5.	AGENA + 6 MM III STG	20.9 FT	63,727 LBS	17.8 K
6.	CENTAUR D - 1S	29.0 FT	35,143 LBS	18.4 K
7.	FCT_c	30.0 FT	56,479 LBS	34.0 K

FIGURE 9

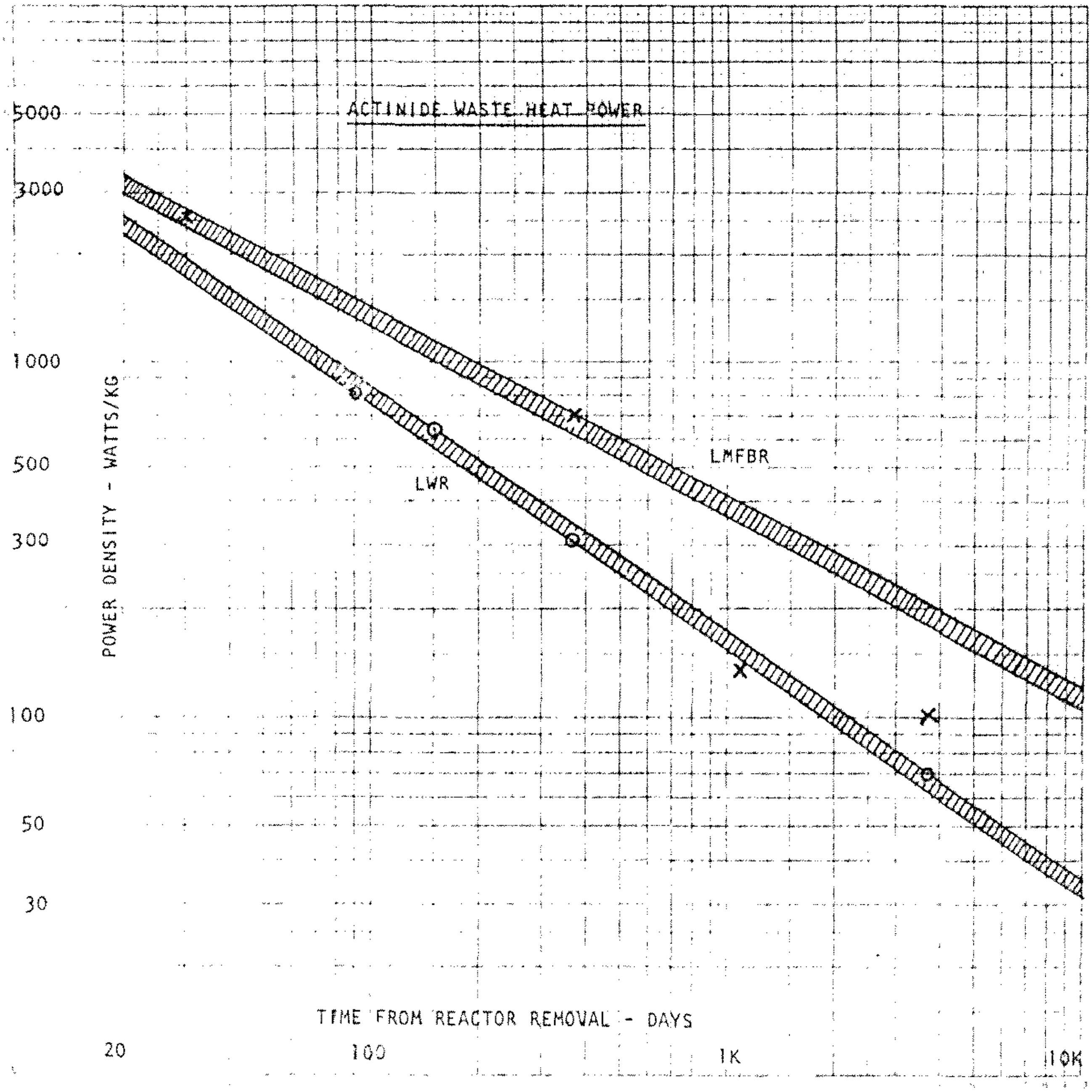
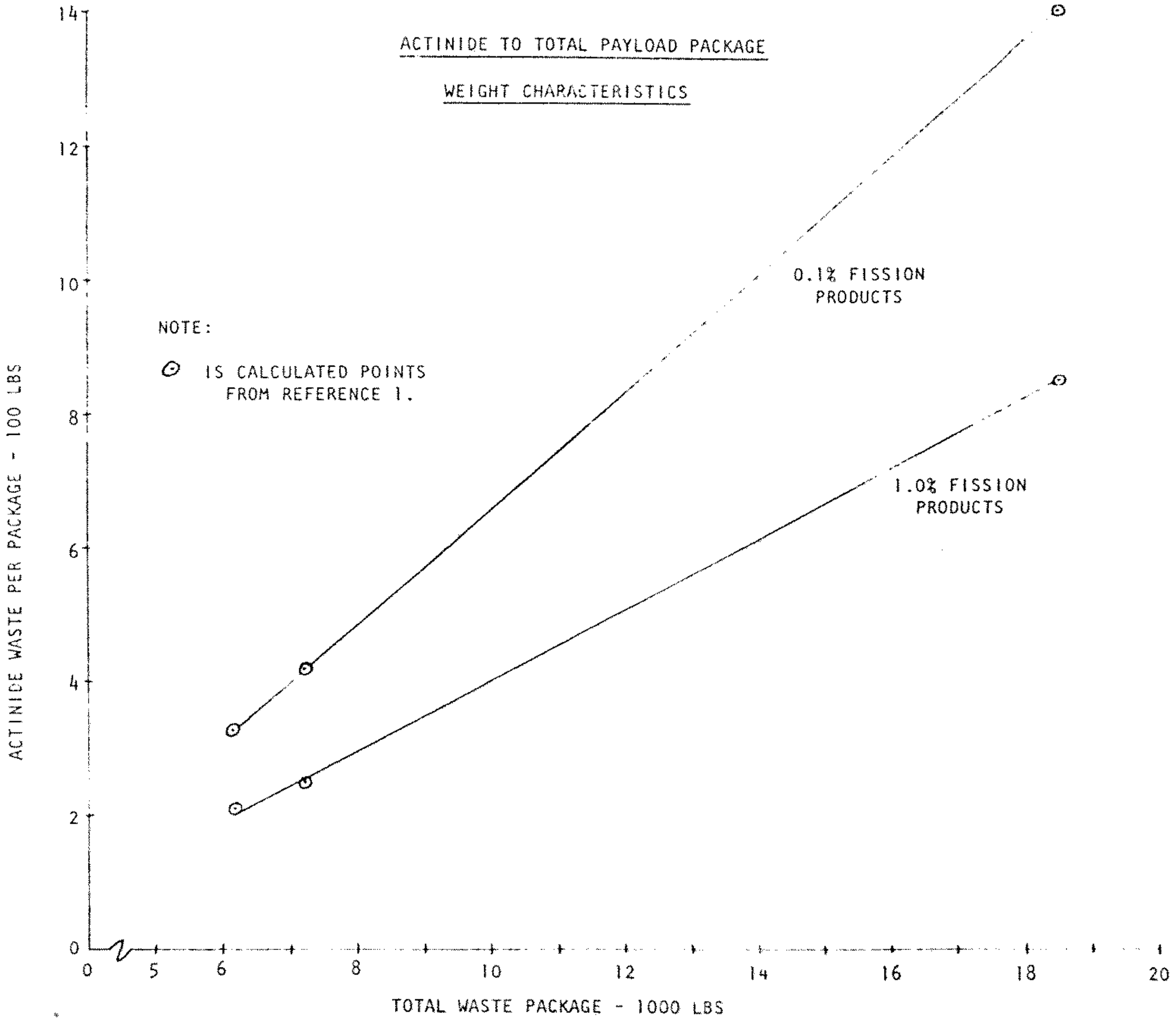

ACTINIDE WASTE HEAT POWER
5000
3000
1000
500
300
100
50
30
POWER DENSITY - WATTS/KG
LMFBR
LWR
TIME FROM REACTOR REMOVAL - DAYS
20
100
1K
10K

FIGURE 10



ACTINIDE TO TOTAL PAYLOAD PACKAGE

WEIGHT CHARACTERISTICS

NOTE:

⊙ IS CALCULATED POINTS FROM REFERENCE 1.

FIGURE 11

ION STAGE AND PAYLOAD

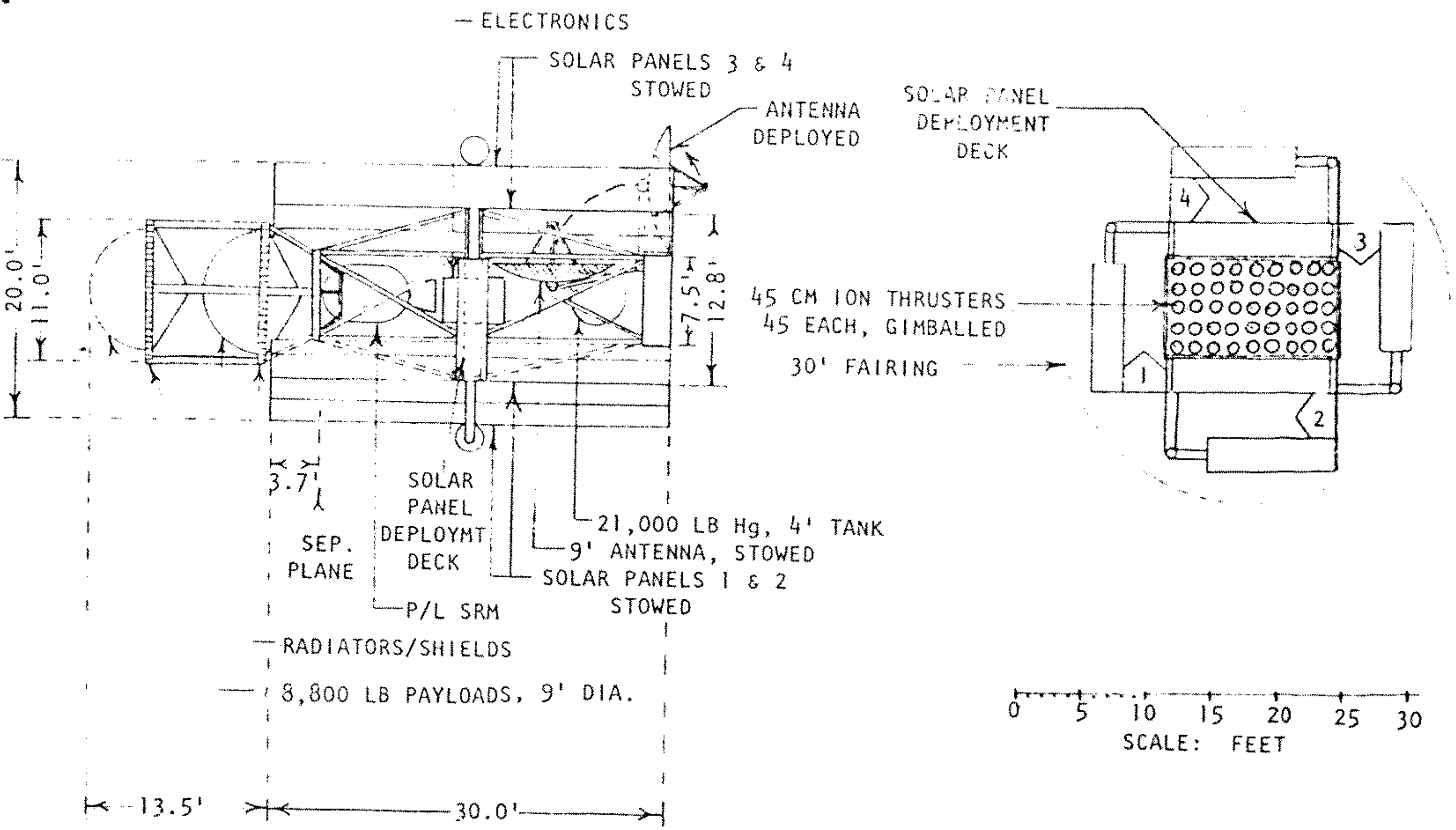


FIGURE 12

ION STAGE ALTERNATE

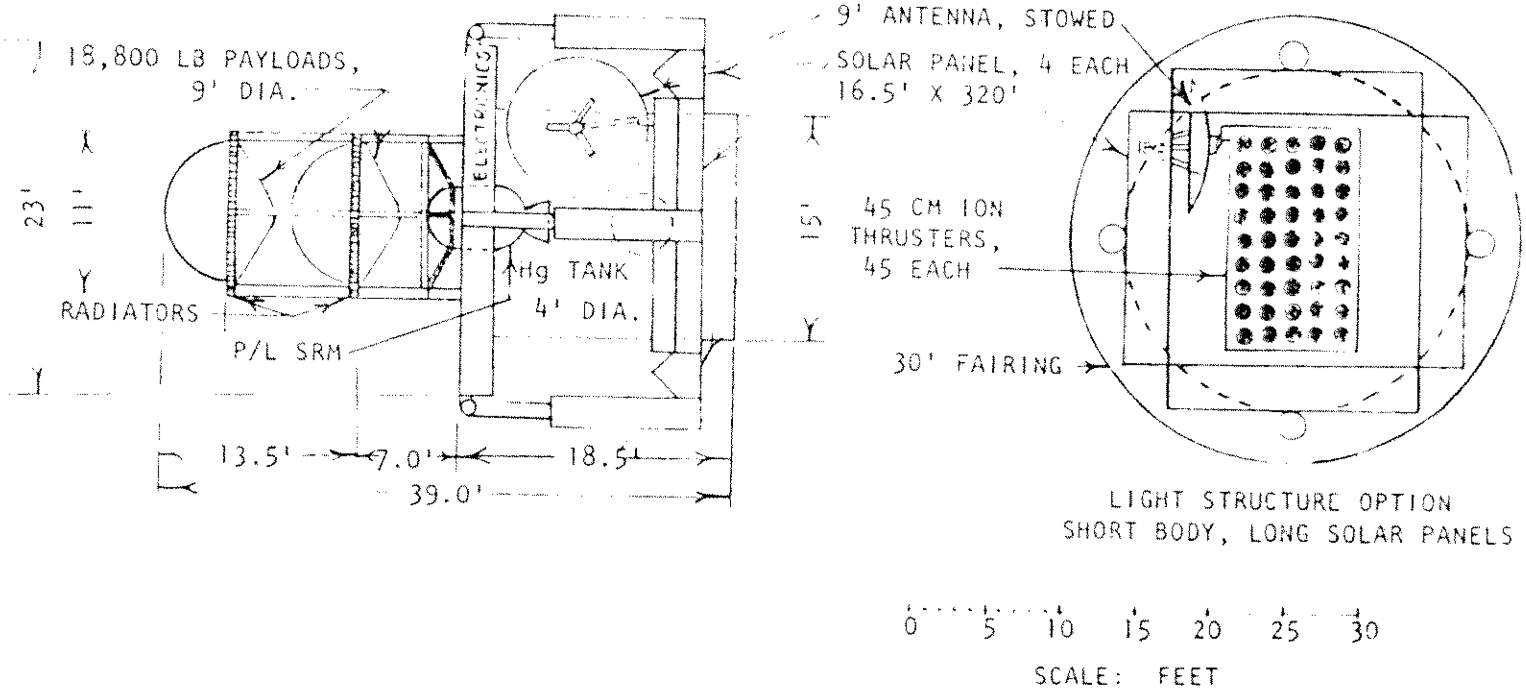


FIGURE 13

APPENDIX A

FCT COST AND PERFORMANCE DATA

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

MA[illegible]

REPLY TO
ATTN OF: PF02

TO: Johnson Space Center
Attn: ER/Hubert P. Davis

FROM: PF02/W. G. Huber

SUBJECT: Full Capability Tug Performance and Cost

REF: Letter ER-75-027, Full Capability Tug Cost and Performance Data, dated February 21, 1975

Attached are the performance and cost data for the Full Capability Tug requested in your referenced letter. The costs are those that I discussed with Mr. Perlich earlier this week. If you have any further questions, please do not hesitate to call.

W. G. Huber
Deputy Manager
Space Tug Task Team

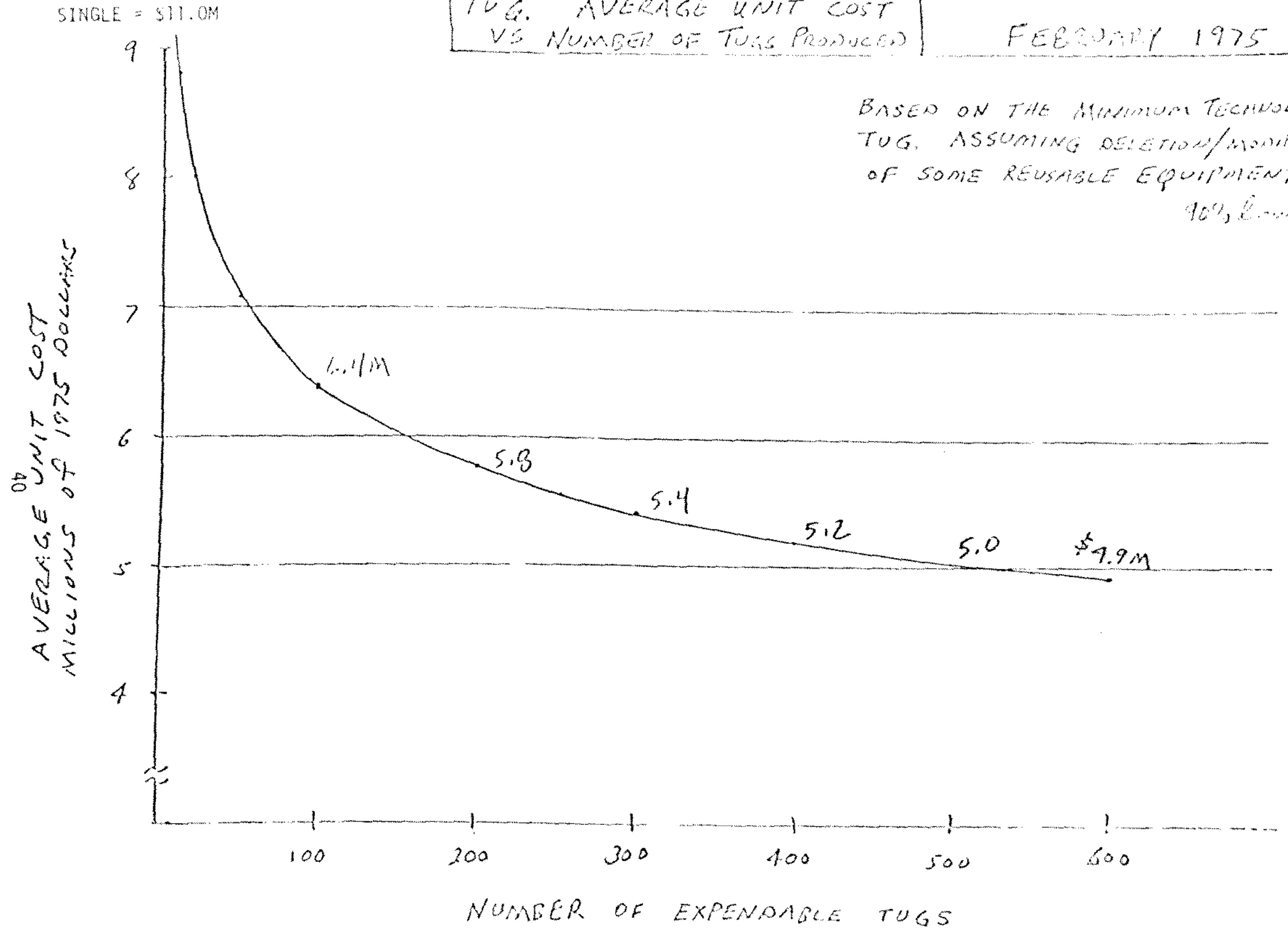
Enclosure

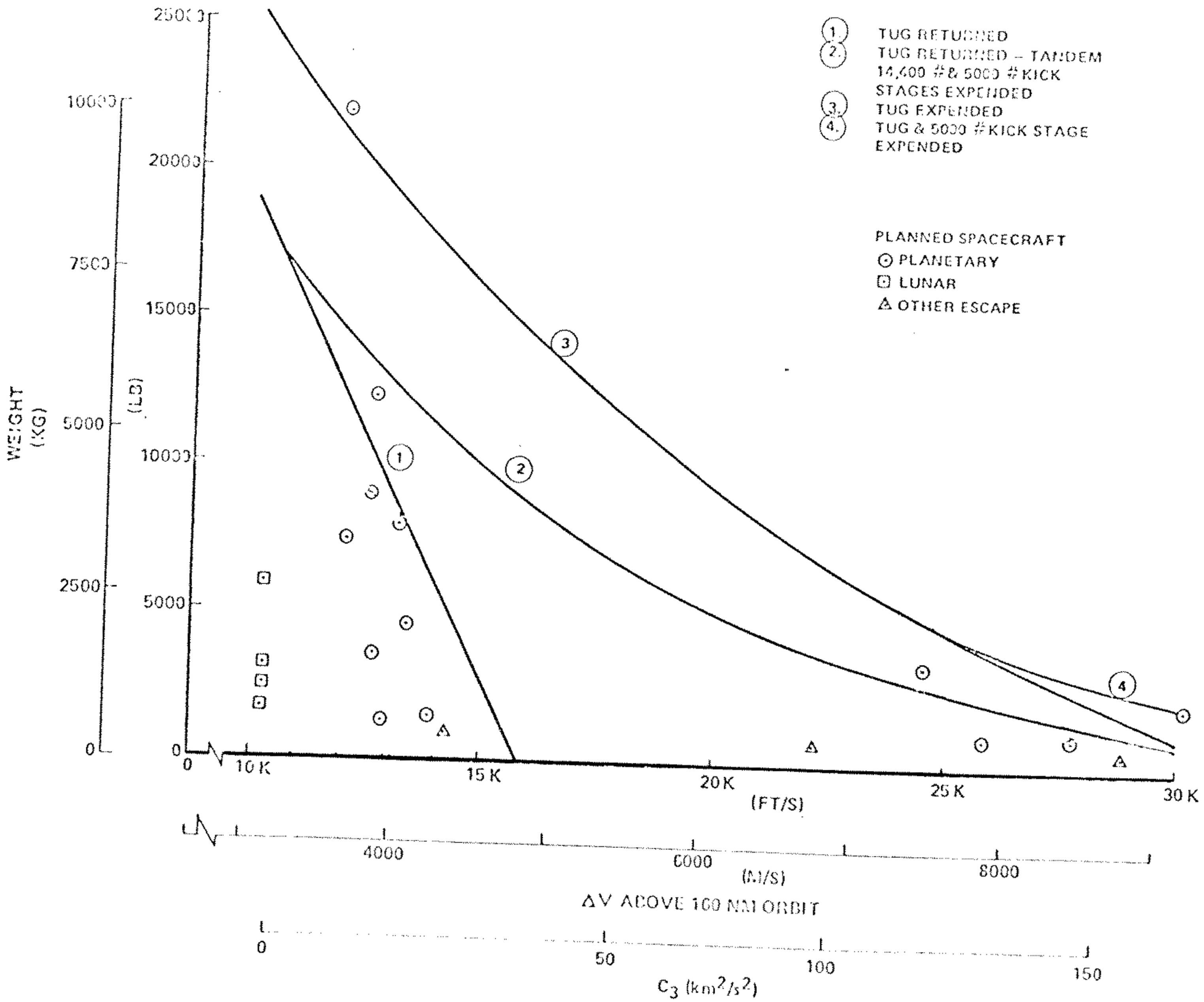
EXPENDABLE LOW TECHNOLOGY
TUG. AVERAGE UNIT COST
VS NUMBER OF TUGS PRODUCED

PP03

FEBRUARY 1975

BASED ON THE MINIMUM TECHNOLOGY
TUG. ASSUMING DELETION/MODIFICATION
OF SOME REUSABLE EQUIPMENT.
90% learning curve





Space Tug delivery capability for escape trajectories departing from Shuttle in 28.5° inclination orbit.