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NUCLEAR ENERGY WASTE-SPACE TRANSPORTATION AND REMOVAL

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16. ABSTRACT

A method for utilizing the decay heat of actinide wastes to power an electric thrust vehicle is proposed. The vehicle, launched by Shuttle to Earth orbit and to Earth escape by a Tug, obtains electrical power from the actinide waste heat by thermionic converters. The heavy gamma ray and neutron shielding which is necessary as a safety feature is removed in orbit and returned to Earth for reuse. The problems associated with safety are dealt with in depth. A method for eliminating fission wastes via chemical propulsion is briefly discussed.

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I. INTRODUCTION

The level of a civilization can, in large measure, be equated with the energy used by the civilization. The energy consumption of the United States, Japan, and other industrialized countries has increased to the point where new sources of energy are required to maintain the present standard of living. More and more, nuclear energy is being relied on to replace energy previously generated from fossil fuel. The earliest accomplished work was from muscles, but this soon was aided by the use of fire. The heat developed from wood allowed the smelting of metals, personal comfort, and eventually the steam engine. A search for new fuels yielded various oils, coal, and natural gas.

An entirely new concept for generating heat came from the discovery that large quantities of energy can be obtained from nuclear fission. The classical terminology of steam plants has been transferred to nuclear engineering, since phrases such as "burnup" and "ashes" are common. In reality, the uranium is not burned, and the ashes are radioactive waste products. The prior concepts of good housekeeping have also carried over to the highly sophisticated nuclear reactor industry and this new technology has produced problems requiring equally sophisticated operations responsibilities.

One of the responsibilities associated with nuclear energy is the elimination of wastes from nuclear reactors. This report will deal with one possible option for elimination of such waste. The system design makes use of the unique physical and chemical properties of the waste to produce a tailor-made solution to a complicated problem.

To better understand the source of the problem, a bit of background is presented. The atomic nucleus is well known as a source of power. The heavy elements, such as thorium, uranium, and plutonium have properties such that if an additional neutron enters their nucleus the nucleus will usually break apart (or fission) into two parts. These parts are usually of unequal mass.

The results of a fission can produce virtually any element in the periodic table, but some elements are so rare as to be negligible. The normal "fission produced spectrum" is a double humped curve with peaks at zirconium and cerium. Thus, fissioning a nucleus produces unequal quantities of various elements which range throughout the periodic table.

The result becomes more complicated from several "real world" situations. First of all, the type fuel used in a reactor (thorium, uranium, or plutonium) will change the fission produced spectrum. Additionally, the number of available neutrons in the reactor, the time that the fuel is used, and numerous other factors will change the characteristics of the fission product spectrum to some degree.

In some cases, the neutron which enters the nucleus does not produce a fission. The neutron is simply accepted into the nucleus, and a new isotope is formed. This isotope is radioactive and, since it is now neutron-rich, tends to decay by negative beta radiation, i.e., it moves up the periodic table. Successive neutron captures move the nucleus up the periodic table and the exotic elements, neptunium, plutonium, americium, curium, etc., are obtained. As a general rule, approximately 2 to 5 percent of the total wastes will consist of these exotic (or superheavy) elements. They are termed "actinides" because all of them fall into a chemical family whose first element is actinium.

The elimination of all these wastes is important because they are highly radioactive and biologically toxic. The properties of actinides and fission fragments vary from each other. The fission fragments tend to isotopes that emit gamma and beta radiation while the actinides are usually alpha emitters. Although alpha particles are easily shielded, they are more biologically toxic than the penetrating gamma radiation.

Another important difference in the fission fragments and the actinides is that fission fragments tend to have much shorter decay times than do the actinides. If fission products could be isolated from the environment for periods on the order of 1000 years, they would be rather harmless. In the case of actinides, the isolation period would be required to be on the order of 250 000 years.

If the actinides could be separated from the fission fragments, then a split disposal scheme could be considered due to the varying properties of the types of waste.

Table 1 shows the areas which were investigated by the AEC as methods for nuclear waste management. In this report the concern is with the space disposal option only.

The destination for waste is important; several options [1] are presented in Table 1. Solar impact is certainly a safe destination, but performance calculations show that it is an enormously expensive target since a characteristic velocity of almost 30 km/s would be required.

Solar orbit and Earth orbit destinations are undesirable because the stability of these orbits cannot be guaranteed for the time periods required to isolate actinides.

Planetary impact (for the nine planets) is unacceptable for several reasons: (1) first of all, targeting these bodies would require sophisticated guidance, (2) secondly, launch opportunities are quite limited due to planetary motion, and (3) finally, natural evolution on most of the planets would make isolation of the waste virtually impossible after impact, and the resultant contamination could hinder future exploration of these bodies.

The primary alternative that remains is to escape the solar system. This is a high energy mission, and the available rocket power dictates that only the actinides (approximately 2 to 5 percent of the waste mass) could be so treated.

It is obviously important to determine how much waste will be generated in the future. This question cannot be answered accurately because it depends upon many future decisions. One estimate, made in Reference 1, shows a possible growth in waste (Fig. 1).

Figure 1 shows the nuclear production waste per year and the accumulated material. More recent data predict that these estimates are high, and it is probable that a multiplier in the range of 0.5 to 0.7 should be applied to each of the graphs.

Although it was mentioned previously that transporting wastes out of the solar system was feasible only for the actinides, it is apparent that any separation of the actinides from the fission fragments will be only partially successful; no chemical separation is ever absolute. The degree of separation impacts performance estimates since the radiation shielding is sized to account for the percentage of fission products (gamma emitting).

TABLE 1. AEC WASTE MANAGEMENT STUDY

On Earth			Off Earth	
Geologic	Sea Bed	Ice Sheet	Space	Transmutation (Elimination)
Mined Cavity Nuclear Cavity Deep Hole Drilled Hole Matrix Man Made Structures in Geologic Formations	Stable Seep Sea Floor Subduction Zones and Deep Trenches Rapid Sedimentation Areas	Free Flow Burial Anchored Burial Ice Surface Facility	Solar Impact Solar Orbit Earth Orbit Planetary Impact Solar System Escape	Accelerator Fission Reactor Nuclear Explosive Fusion Reactor

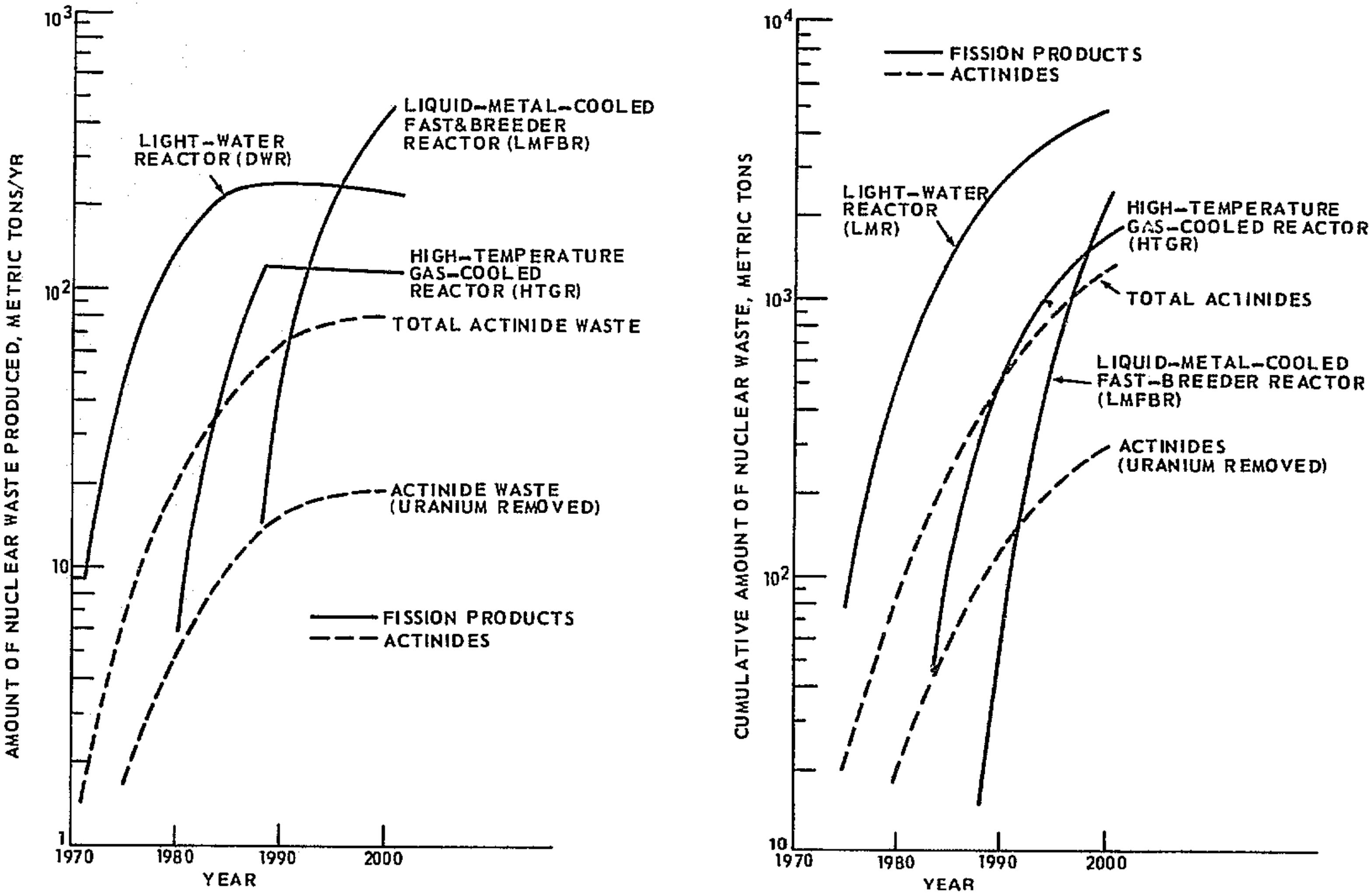


Figure 1. Predicted waste generation.

As a potential scenario for required separation cuts, Claiborne [2] reasoned as follows. Radioactive ore occurs naturally on Earth. If the uranium is extracted from this ore, used for the benefit of mankind, and then fractionated in such a way that the total radiation hazard is actually decreased by usage, then there is an obvious gain.

However, fresh fission fragments are intensely radioactive, so a "cooling off" period is necessary. This cooling off period was taken to be 1000 years since it is rather easy to guarantee geologic stability over such short spans. The question of separation was then quantitatively framed as: "What separation factors of actinides from fission fragments are necessary to reduce the long term hazard of high level waste to a hazard index that is less than 5 percent that of high grade pitchblende" (pitchblende is a high grade uranium ore). The answers to this question are shown in Table 2.

TABLE 2. FRACTIONATION OF WASTES

To reduce the long term hazard (> 1000 years) of high level waste to a hazard index that is less than 5 percent that of high-grade pitchblende ore requires a removal of:

99.99 percent of uranium and plutonium

95 percent of neptunium and protoactinium[a]

99.9 percent of americium and curium

99.5 percent of thorium[a]

from the fission products.

These removal factors are 10 to 100 times better than the currently available technology.

a. Products of high temperature gas cooled reactors.

In summary, the situation with nuclear waste disposal at the present time is that a safe disposal scheme is necessary. It is necessary in the long term because future generations should not be expected to do our housekeeping; they did not receive the benefits of the generated power. It is necessary in the short term because waste disposal is a soft point which the critics of nuclear power have determined as a cause celebré. Space elimination, as stated in Reference 1, is one possibility, but such an elimination will require separation of actinides from fission fragments. The "target point" for space elimination of the actinides is solar system escape. Reference 1 used conventional chemical rockets to accomplish the task.

II. OVERVIEW OF THE NEWSTAR VEHICLE

The use of chemical thrusters to accomplish a given mission has the advantage of established technology and experience; however, the performance of such a system is not particularly good. Performance calculations show that more advanced technology such as electric propulsion yield far higher mass fractions than do chemical systems.

Electric thrust is a system wherein ions (e.g. mercury) are expelled at high velocity using electrical acceleration. The traditional source for the electrical energy is solar radiation impinging upon solar cells.

If an electrically driven vehicle were to be designed to handle only nuclear waste, another possibility opens up. Baselining actinide elimination as a goal, it is well known that the actinides are physically hot (some will boil water). Heat is a source of energy, thus this energy can be tapped to produce electrical power. The methods of producing this power are presented in the remainder of this report.

Rather than introduce subsystems, piecemeal, it is perhaps better to describe the overall NEWSTAR (Nuclear Energy Waste Space Transportation and Removal) configuration and then work with subsystems. NEWSTAR is shown in Figures 2, 3, and 4.

The actinides are packaged in 19 circular canisters which are packaged into a hexagon. (The number 19 is dictated by geometric considerations.) A heat pipe which carries heat backward toward the circular radiation runs through the center of each cannister. The hexagonal waste package is sheathed with several types of shields. One such shield blocks gamma radiation, another shield blocks neutrons, while a third shield retains generated heat within the package. The gamma and neutron shields are removable (in orbit) while the thermal shield is a part of the vehicle.

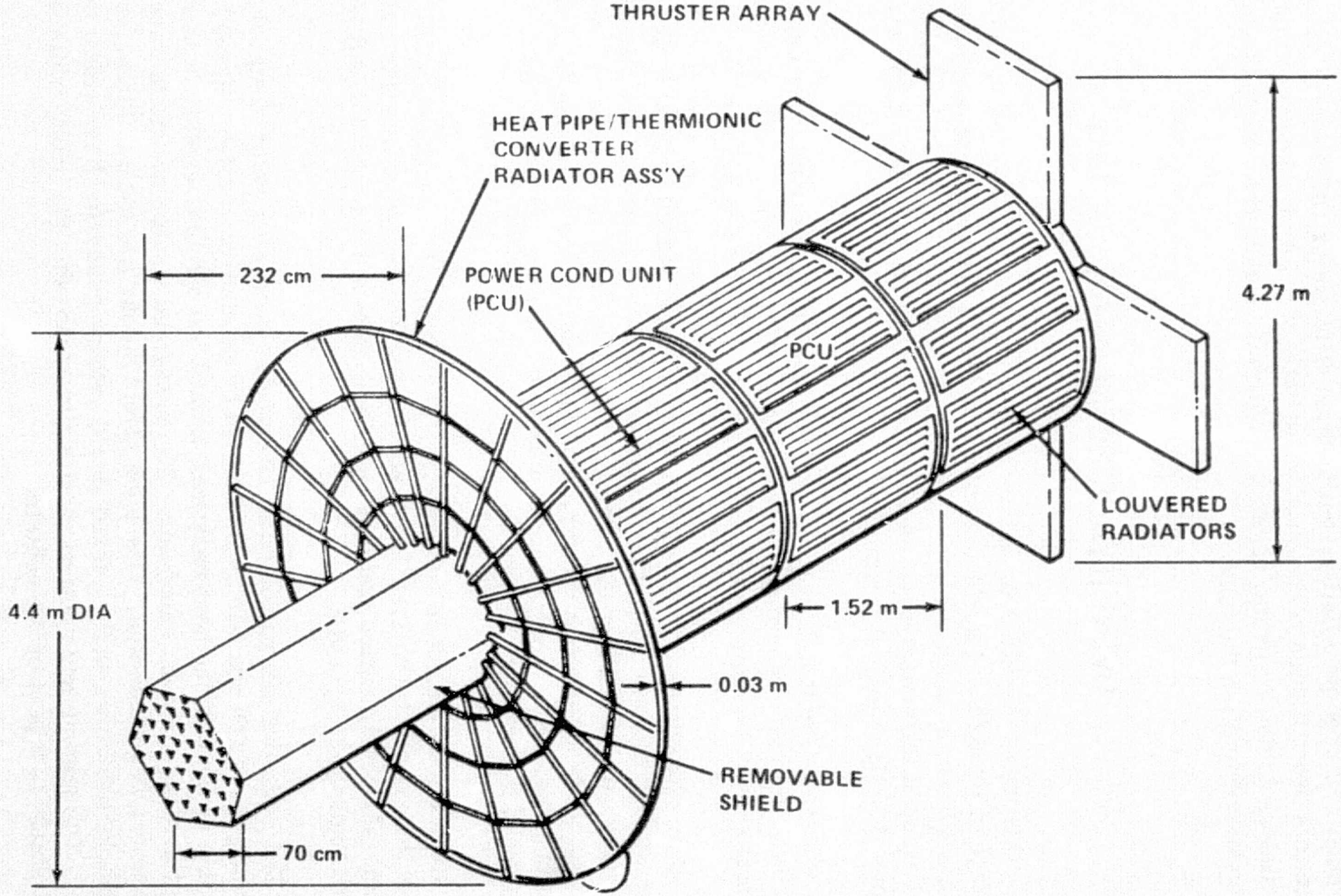


Figure 2. NEWSTAR vehicle concept (front view).

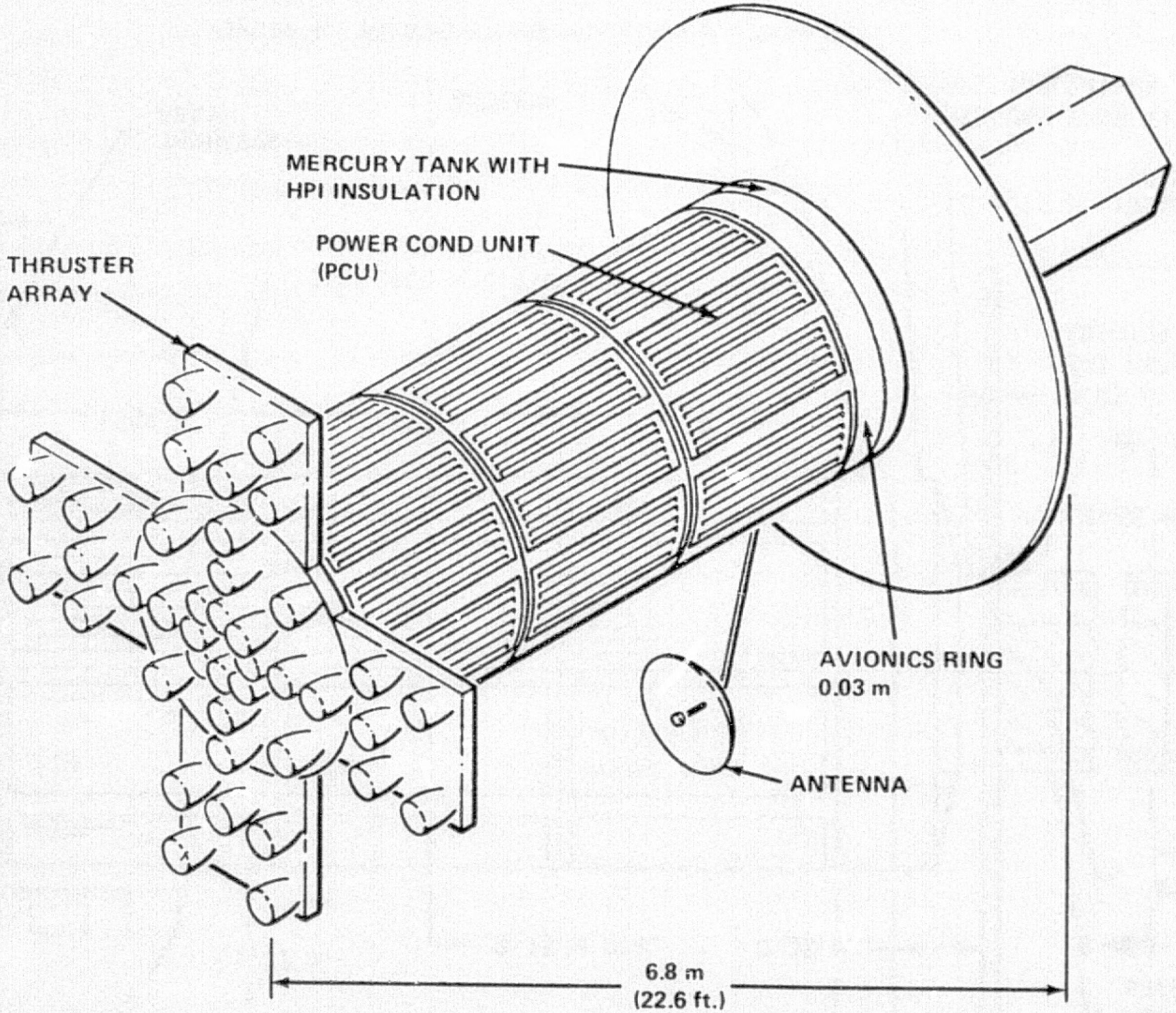


Figure 3. NEWSTAR vehicle concept (rear view).

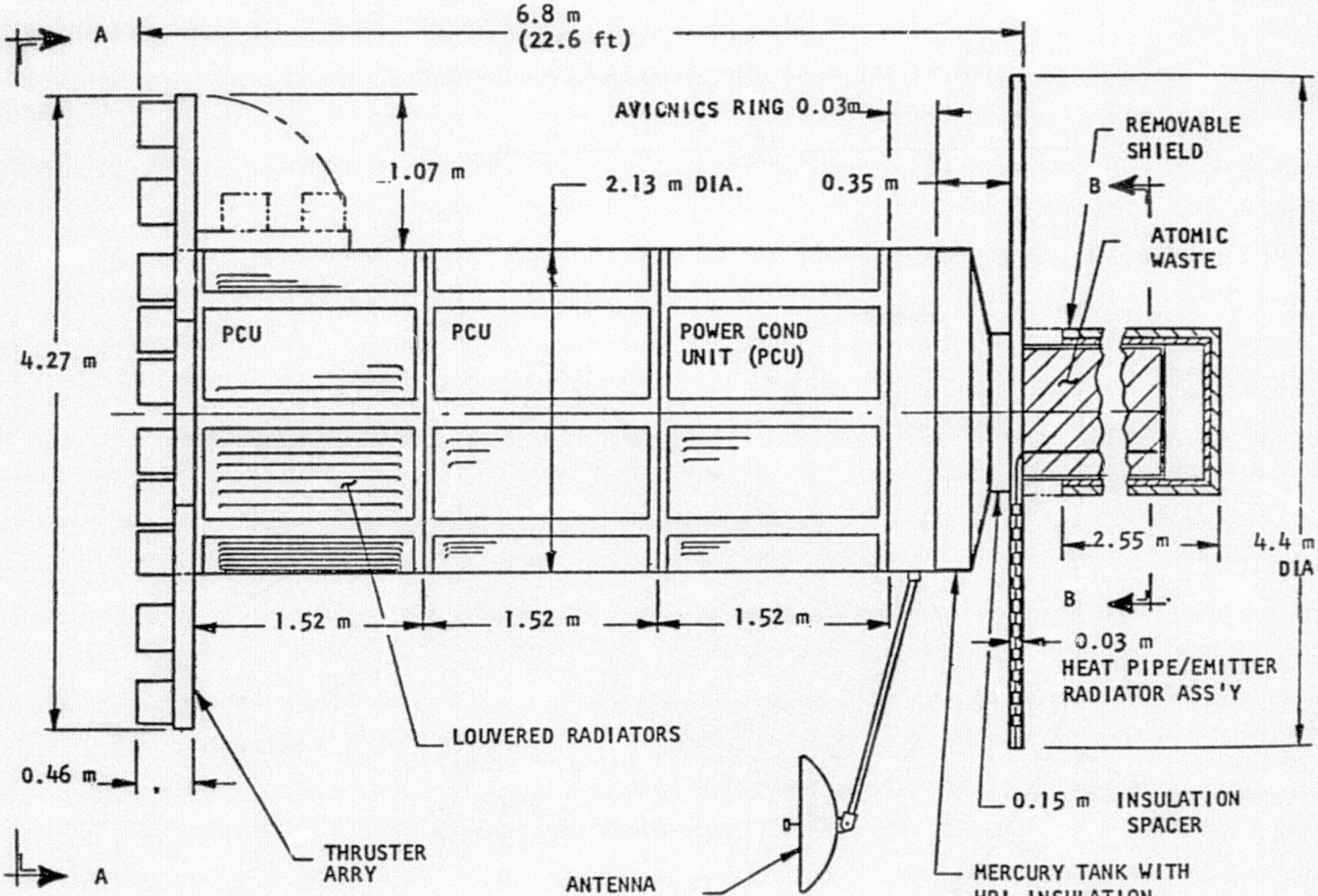


Figure 4. NEWSTAR vehicle concept (to scale).

The heat pipes bend radially outward to travel through the annular radiator, shown as a collar behind the waste package. Thermionic diodes that convert heat to electricity surround the heat pipes. This electricity is then modified via power conditioning units from the original high amperage, low voltage output of the diodes to low amperage, high voltage current used by the thrusters. The power conditioning units are mounted on the large barrel behind the radiator. The ion thrusters are mounted on the cruciform tail of NEWSTAR.

Figure 3 presents a rear view of the vehicle. Additional data shown in this figure include the mercury fuel tank, the avionics ring, and the thrusters. The metallic mercury, a very dense metal, will provide radiation shielding for the avionics over much of the flight.

Figure 4 shows a dimensioned line drawing of the vehicle. The large barrel which holds the power conditioning units is sized to act as a low temperature radiator. It is hollow and quite light. The center of gravity of the vehicle lies in the actinide waste package since most of the mass is concentrated near the fore end.

III. LAUNCH SCENARIO AND WEIGHT STATEMENT

The scenario for the launch of NEWSTAR was investigated for several options. Although it is certainly possible to fire NEWSTAR from low Earth orbit and achieve escape from the solar system, the vehicle will spend much time close to Earth. For this reason, it was decided that a Tug assist would be used. Two Shuttle launches per payload are made. The first Shuttle launch carries a liquid oxygen-hydrogen Tug to Earth orbit, and the second Shuttle launch then performs a rendezvous with the Tug. Following rendezvous, the Tug is mated to NEWSTAR and a systems checkout is performed. The gamma and neutron shields are then removed. The Tug is ignited and places NEWSTAR into an orbit that is free of the Earth.

Once Earth escape is achieved, NEWSTAR thrusters are started and the vehicle is powered to solar system escape.

The gamma and neutron shields are retrieved by the second Shuttle and returned to Earth for reuse. This recovery is necessary due to cost as well as the fact that their uncontrolled reentry would pose a hazard.

This scenario, listed in Table 3, is shown pictorially in Figure 5.

TABLE 3. SCENARIO

1.	Two Shuttle Launches:
	a. First Shuttle carries expendable chemical stage Tug to Earth orbit
	b. Second Shuttle carries high performance electric stage (NEWSTAR) with shielded payload to Earth orbit
2.	Chemical Tug and NEWSTAR mated in Earth orbit
3.	Following checkout, shields are removed
4.	Single burn of the Tug places NEWSTAR to Earth escape
5.	NEWSTAR powers payload to solar system escape
6.	Shields recovered by second Shuttle for return to Earth and reuse

Much of the hardware necessary for the disposal vehicle scenario already exists. The Shuttle (Fig. 6) will be operational in 1981, and Figure 7 shows a possible method of fitting NEWSTAR into the present Shuttle design. (The OMS kit, water kit, and other aspects of NEWSTAR which are shown in Figure 7 are discussed elsewhere in the report.)

Much work has already been accomplished on electrically powered vehicles including the Shuttle. Figure 8 presents an artists concept of a SEPS (Solar Electric Propulsion Stage) which has been studied in detail.

Since much work has been expended on SEPS, it is worthwhile to note that many subsystems of SEPS apply directly to NEWSTAR as is shown in Figure 9. The avionics, thrusters, power conditioning units, fuel, and structure will be either identical or similar between SEPS and NEWSTAR. The SEPS solar panels will be replaced, however, by the payload of actinides.

The weight of the vehicle is fundamental to the performance calculations for elimination of waste products. Since many of the subsystems of NEWSTAR are similar to those of SEPS, the detailed work for SEPS weights is a touchstone

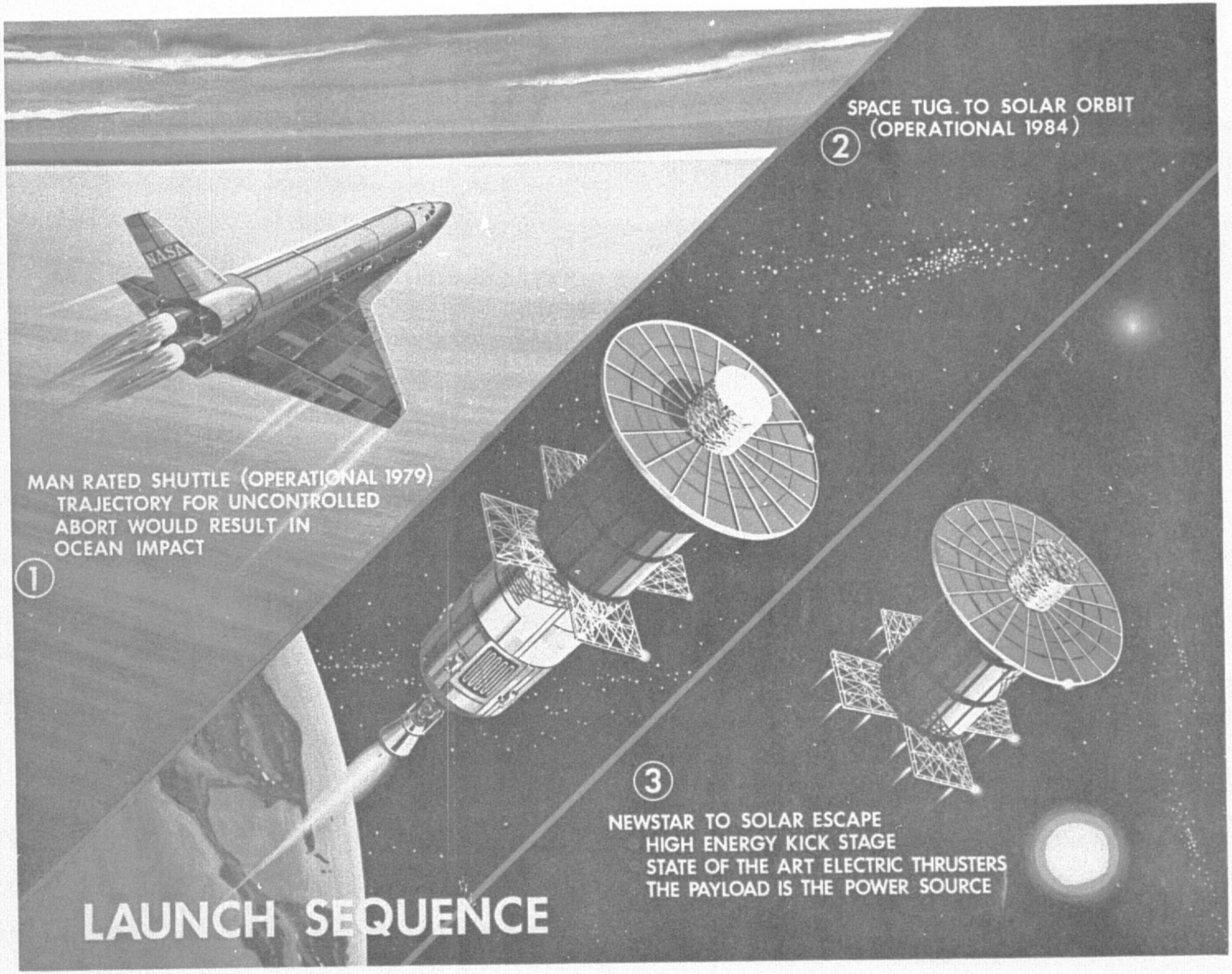


Figure 5. Launch sequence.

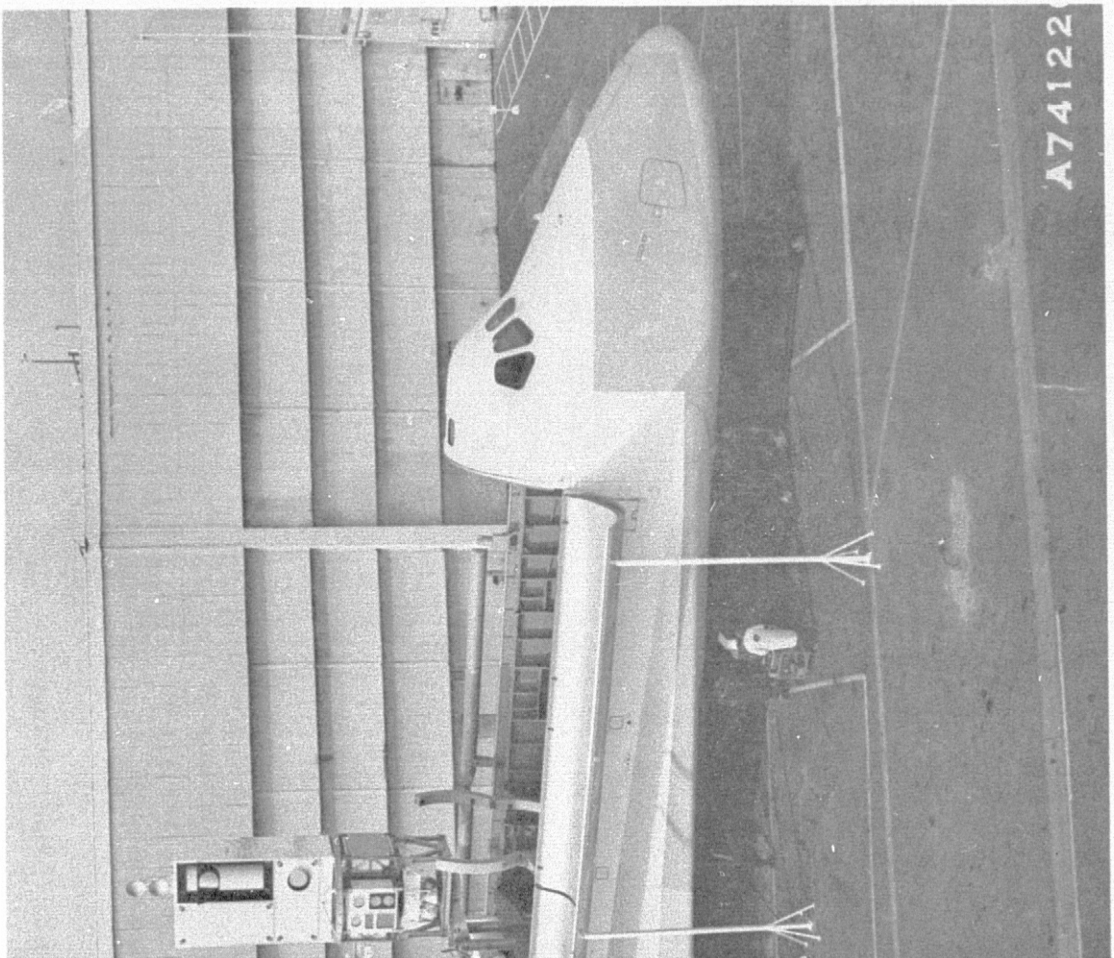


Figure 6. The Shuttle.

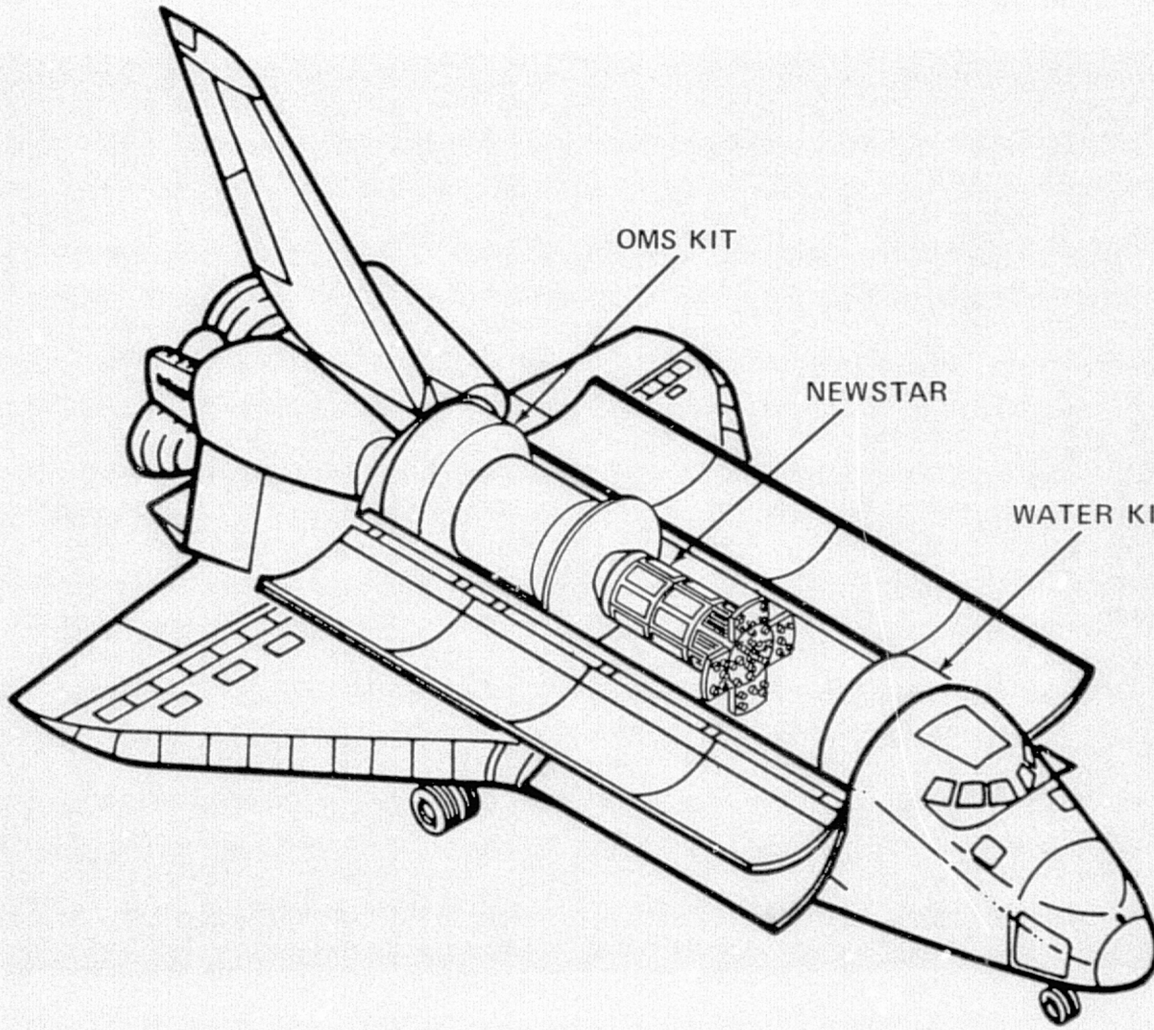


Figure 7. NEWSTAR in Shuttle payload bay.

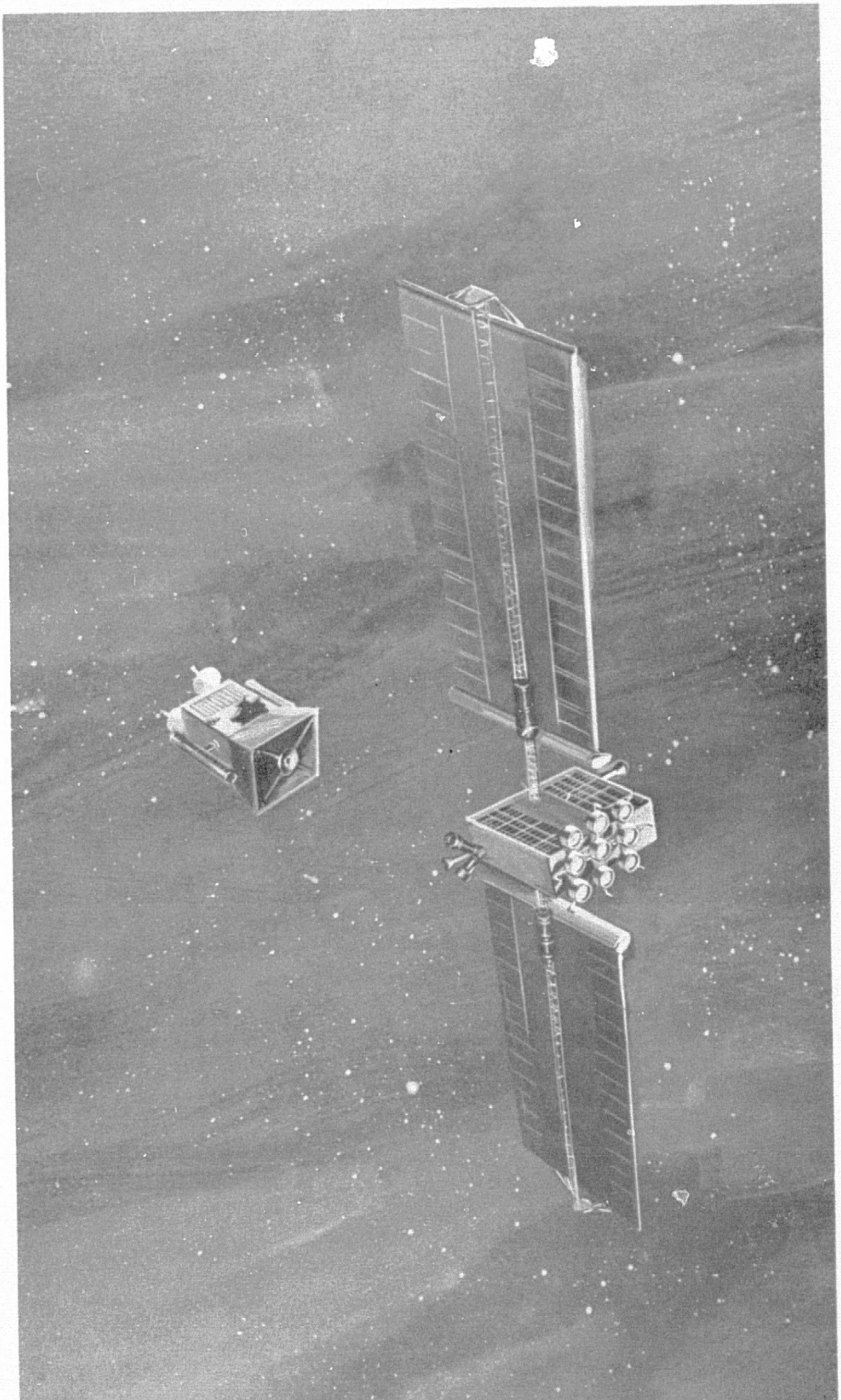


Figure 8. Artist concept of SEPS.

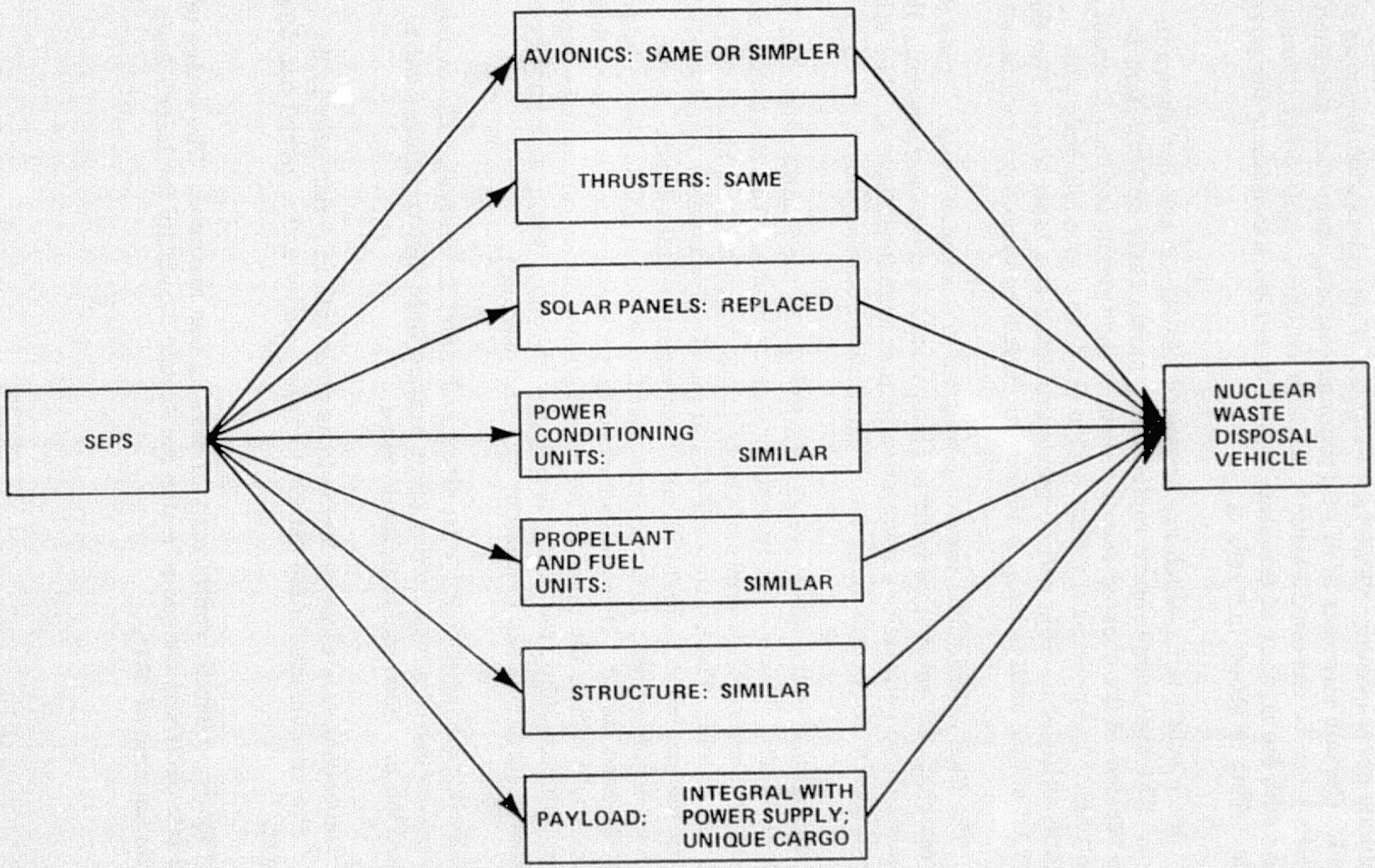


Figure 9. Evolution from SEPS.

to estimate corresponding NEWSTAR weights. This calculation is shown in Table 4. Certain elements of SEPS (communications, computer, guidance, and navigation) can be assumed identical for both vehicles, while other items (which interact with the number of thrusters) must be scaled according to the power outputs. This is shown in Table 4.

Some subsystems which are unique to NEWSTAR are also shown in Table 4. The high temperature radiator is a particularly difficult item to design because of the coupled requirements of lightweight and high thermal conductivity. The present and final design involves a graphite body with beryllium stiffeners. This will be treated in detail at a later time. For the NEWSTAR unique subsystems, a 15 percent weight contingency was allowed.

The final calculations involve propellant and actinide waste. Since these items interact with subsystem weights (the payload is the power source), it was necessary to establish an interactive loop to complete Table 4. The ultimate weight of NEWSTAR comes from the lifting limit of the Shuttle.

In addition to the initial weight of NEWSTAR, the Shuttle must also bear additional weight. Table 4 shows additional components. The removable shield (previously mentioned) consists of two components: a neutron shield and a gamma ray shield. The neutron shield (10 cm of polyethylene) is relatively light, but the gamma ray shield (4 cm of tantalum) is quite heavy. From packaging considerations, it is apparent that the tantalum shield should be inside the polyethylene shield. It is also apparent that a metal which is denser than tantalum would reduce the mass of the polyethylene. However, metals heavier than tantalum are either too costly (platinum, rhenium, etc.) or cannot be fabricated in large masses (tungsten) or both (osmium).

Cooling during ascent (to be discussed later) is critical. The evolved system makes use of a high boiling point organic fluid that transfers heat to water and the produced steam is then vented.

The cocoon is a reentry device to be dealt with in detail later in the report. The attachments to the Shuttle include a pallet and a special handling equipment.

Finally, a Shuttle contingency of 2677 kg was assumed. The entire mass injected into orbit was chosen to match the Shuttle capability for launch from KSC at an azimuth of 108°.

TABLE 4. NEWSTAR WEIGHT SUMMARY (kg)

SEPS subsystems scaled for NEWSTAR		822
• Propulsion (99.7)	253.8	
• Communications (55.4)	55.4	
• Command computer/data handling (32.6)	32.6	
• Guidance and navigation (32.3)	32.3	
• Power storage and distribution (149.6)	270.0	
• Reaction control (11.9)	23.8	
• Propellant system (18.3)	154.3	
NEWSTAR unique systems		3 653
• PC modules	861	
• Thermionic converters	179	
• High temperature radiator	392	
• Actinide packaging (includes heat pipes)	793	
• Structure	450	
• Thermal insulation	438	
• Miscellaneous	63	
15 percent contingency	477	
Propellant (includes 1 percent FPR)		6 285
Actinide Waste		4 140
NEWSTAR initial weight		14 900
Removable shield		4 772
• Polyethylene	789	
• Attitude control kit	25	
• Tantalum	3958	
Ascent Cooling		3 100
• Water	2100	
• Tank, lines, etc.	1000	
Cocoon		2 275
Attachments		1 500
Shuttle contingency		2 677
Total		29 224[a]

( ) SEPS weights

a. Shuttle capability for launch from Cape Kennedy AZ = 108°.

Once NEWSTAR has been sized, performance calculations can be completed (Table 5). It should be noted that the "all up" Tug delivers NEWSTAR to a C_3 (energy) measure of 13.8 km^2/s^2. The flight time of NEWSTAR (848 days) gives a measure of required reliability of NEWSTAR components such as the electric thrusters subsystems, guidance and control subsystems, etc.

TABLE 5. TUG/NEWSTAR WEIGHT SUMMARY (kg)

Tug (I_{sp} = 456 s)	
Burnout weight (includes reserves, losses and adapter)	3 010
Usable Propellant	24 932
Liftoff weight	27 942
NEWSTAR	
Burnout weight	8 615
Propellant	6 285
Liftoff weight (includes actinides and propellant)	14 900
Actinides	4 140
Tug delivers NEWSTAR to C_3 = 13.8 km^2/s^2	
NEWSTAR flight time = 848 days	
Solar escape reached at 4.18 astronomical units	

IV. RADIATION SHIELDING

Figure 10 shows a view of the actinide waste package in the 19 cylindrical cannisters. The shield (tantalum) is shown directly to the right of the cannister bundle. The single end plate of the shield (not shown) is designed to block radiation while allowing fluid flow.

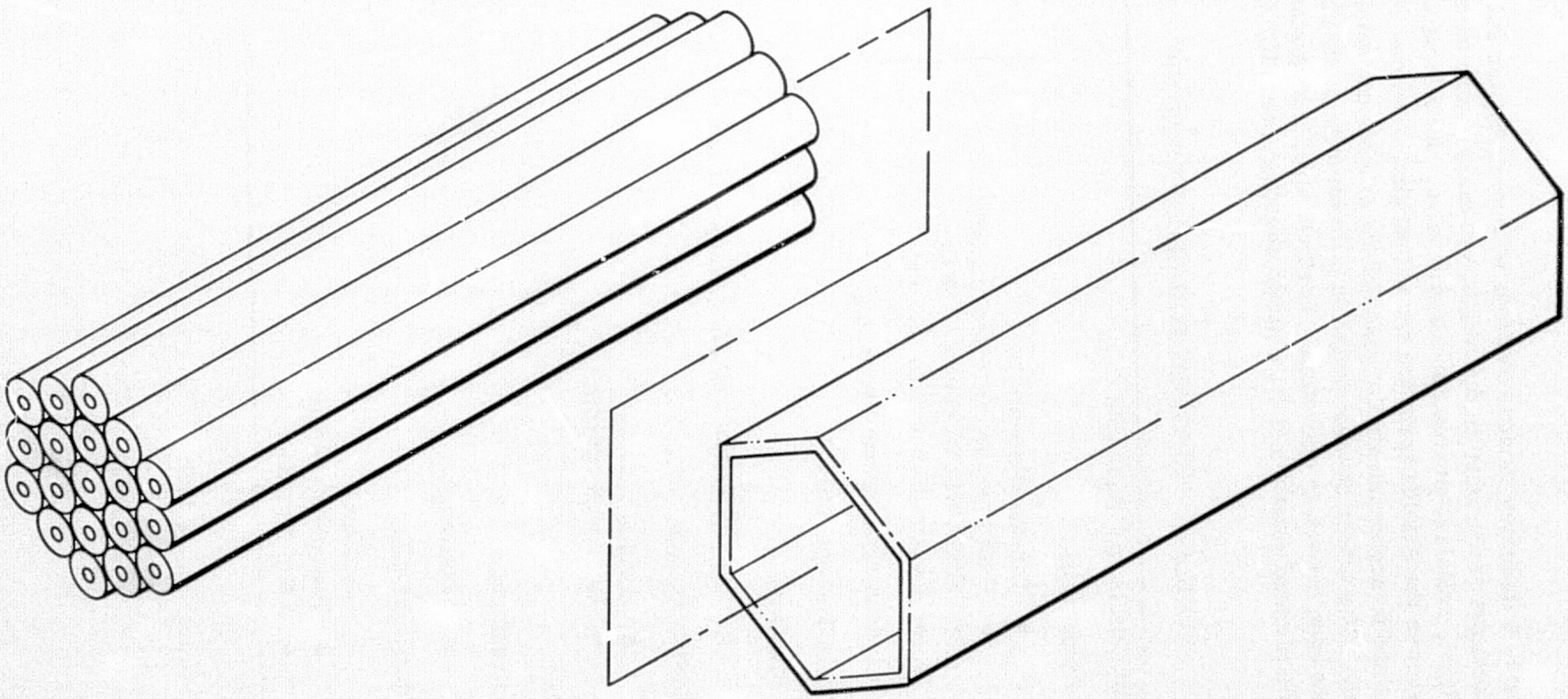


Figure 10. Isometric shield.

Table 6 indicates various methods of recovering the shields. Attitude control packages (mentioned in the weight summary) were baselined because they are light, reliable, proven, and inexpensive. Additionally, they could be used to remove the shields from the waste hexagon. Remote teleoperators have not been sized to accommodate the mass of the shields and would probably be quite heavy. The tether concept presents a problem in momentum management and has not been proven in operation. Furthermore, a long stand-off distance between the manned shuttle and the shields would present difficulties.

TABLE 6. METHODS FOR RECOVERING SHIELDS

Attitude Control Packages (Baseline)

- Advantages
  - Proven concept
  - Could be used in removing shields
  - Slight Weight penalty (19 kg)
  - Cost is $38 000 to $50 000
- Disadvantages: None identified

Remote Teleoperator

- Advantage
  - Capability for restoring shields if necessary
- Disadvantages
  - Weight
  - Unproven concept

Tether

- Advantage
  - Lightweight
- Disadvantages
  - Complex
  - Unproven concept
  - Long distance

V. POWER GENERATION

The use of the actinides as a power source produces very large payload capability. But the specific power which is available (W/gm or kW/kg) is critical. Figure 11 shows the specific power from actinide oxides as a function of time since removal from the reactor.

The long decay times of the actinides provide an almost constant power level after approximately 4 years of initial decay. A specific power level of 0.1 W/gm was chosen. It is assumed that the actinides are used to power NEWSTAR from approximately year +5 to approximately year +8. The "constancy of power" over this time is important because NEWSTAR always works on the power available at mission termination while the radiator must be sized to accommodate the power available at the start of the mission.

The age of the actinides is important but not restrictive since varying age actinides can be blended to achieve the desired power level.

The specific method of converting actinide heat into electricity is open to choice. Four systems that are of known characteristics are shown in Table 7. The overriding parameter shown in Table 7 is the required radiator area. Since thermionic generators reject heat at high temperatures, they require the smallest radiator area. Their efficiency (18 percent shown, 16 percent used in calculations) is adequately high to operate NEWSTAR. Thus, thermionic generators were chosen.

The input power shown in Table 7 (380 kW thermal) is lower than eventually chosen (440 kW thermal) but the system comparisons are valid.

Once the conversion method is chosen, it is necessary to describe a power budget for the vehicle. This has been done in Figure 12. All known losses were reckoned, including line losses. The efficiencies assumed [16 percent for the thermionic converters, 85 percent for the power conditioning units (PCU), and 72.5 percent for the thrusters] are nominal-to-low. The final output power of the stage, 37.2 kW electric, corresponds to a thrust of 2.53 N on NEWSTAR.

The bulk of the thermal energy is dissipated by the high temperature radiator. The PCU radiator (the large barrel of NEWSTAR) dissipates 9.3 kW while the thrusters self-radiate 14.1 kW thermal.

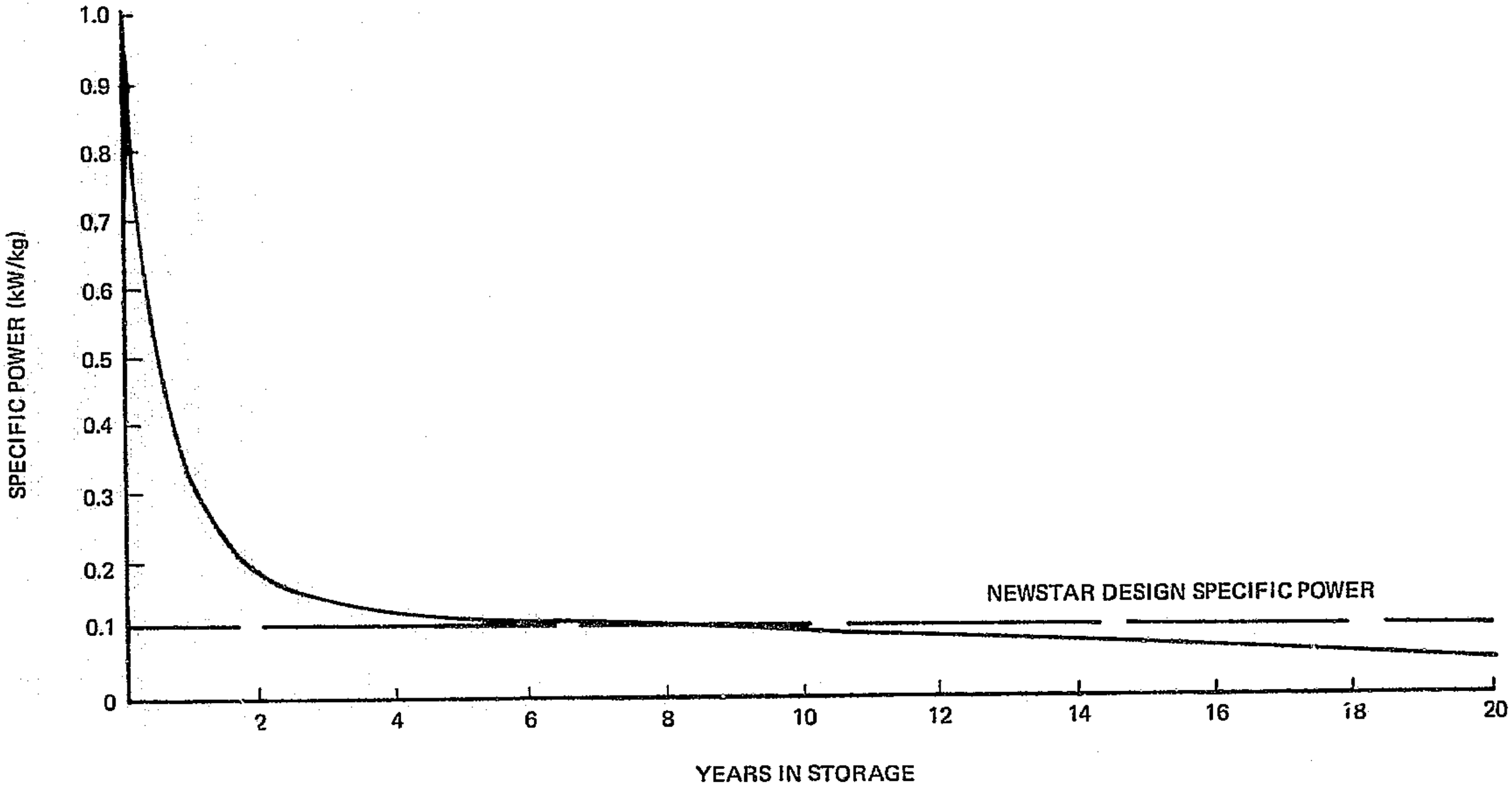


Figure 11. Actinide specific power (oxides).

TABLE 7. NEWSTAR POWER SYSTEM COMPARISON

Parameter	Brayton Cycle	Organic Rankine	Thermionic	Thermoelectric
Input Power, kW thermal	380	380	380	380
Output Power, kW electric	114	76	68	38
Efficiency, percent	30	20	18	10
Weight, kgms	10 370	7370	1200	3460
kgms/kW electronic	91	97	18	91
Source Temperature, K	1 140	640	1800	1070
Rejection Temperature, K	445	445	900	520
Radiator Area, m^2	691	791	13	201
State of Development	1	2	3	1
Cost of Development	2	2	2	1
System Cost	3	3	1	2

Notes: 1. Power conditioning system characteristics not considered.
2. Numerical rankings are relative.
1. Best 2. Second Best 3. Third Best

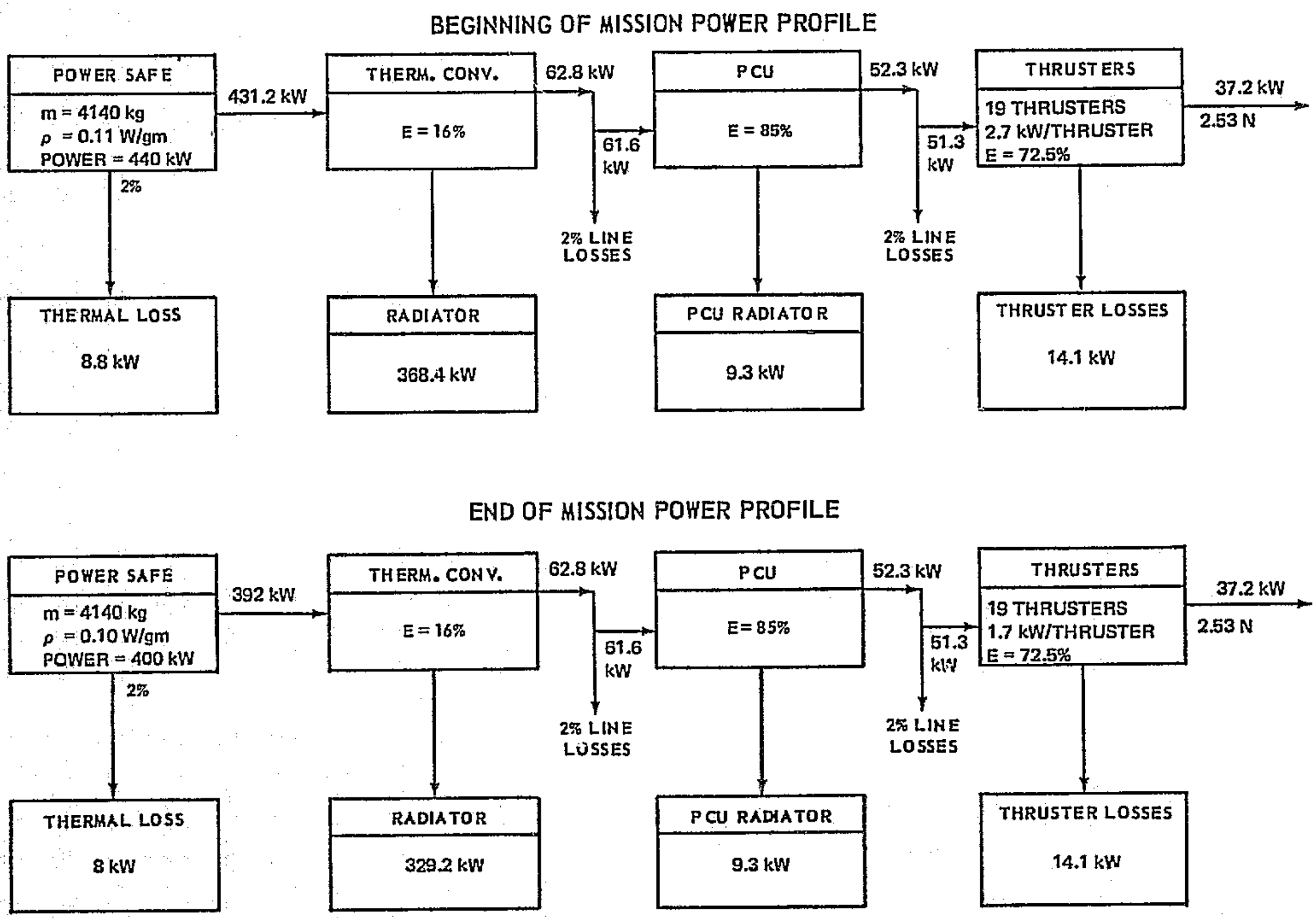


Figure 12. Power profile.

Figure 13 shows a schematic of the converter assembly. A heat pipe which drives 50 thermionic converters comes from each actinide cylinder. These converters, spaced over less than 1 m of the heat pipe, produce 45 V at 80 amp.

The internal arrangement of each thermionic converter is shown in cross section in the lower right hand corner of Figure 13. The internal heat pipe is insulated by alumina surrounded by a tungsten emitter. The cesium converter plasma around the emitter is itself contained in a tungsten trioxide collector. The final wrap is alumina. (The materials listed here are simply candidates: they may change in light of new research.)

Table 8 lists the parameters of the system together with the specifications for the PCU.

Figure 14 illustrates a potential wiring diagram for the converters — PCU — thrusters. If we define a family to consist of thermionic converter assemblies and PCU, then we have three families of 5 and one family of 4. It is possible to switch converter assemblies and PCU within a family. The switching matrix can operate any thruster from any thermionic converter-power conditioning set.

In summary, thermionic converters seem to offer the best approach to conversion of actinide thermal energy to electrical energy. Some development of state-of-the-art of thermionics is necessary but a breakthrough in thermionic converter design appears to be unnecessary.

The efficiencies which have been demonstrated in the laboratory (18 percent) are actually higher than needed, but additional work must be done to ensure long term reliability.

The following conclusions can be drawn from this study:

1. Thermionic system offers the best approach with respect to radiator area.

2. Overall thermionic and power conditioner technology is not presently available but can be developed at reasonable cost within the required time frame.

3. Additional analyses in the area of costs and reliability need to be performed.

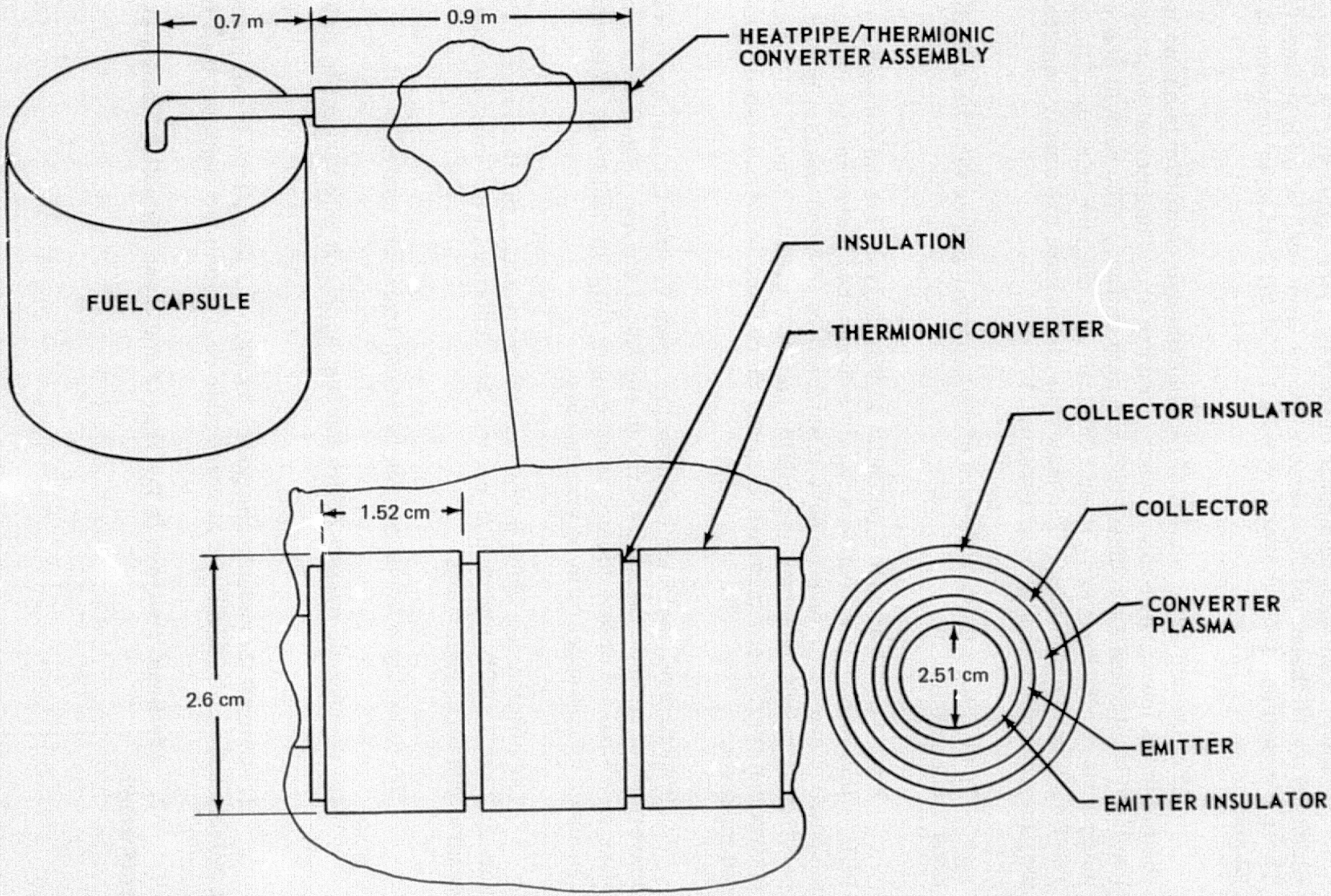


Figure 13. Thermionic power source for NEWSTAR.

TABLE 8. NEWSTAR POWER SYSTEM CHARACTERISTICS

Heat Pipe/Thermionic Converter Assembly
Number: 19 with 50 converters each
Input Power: 20.67 kW thermal
Output Power· 3.31 kW electronic (45 V at 80 amp)
Converter Assembly Length: 81.9 cm
Heat Pipe/Converter Assembly Weight: 9.26 kg
Power Conditioning Unit (PCU)
Number: 23 (includes 4 spares)
Input Power: 3.2 kW electronic (45 V at 72 amp)
Output Power: 2.76 kW electronic
Specific Weight: 13.6 kg per kW electronic output
PCU Weight: 37.54 kg

VI. THERMAL ASPECTS OF NEWSTAR

Because NEWSTAR operates from the heat output of the actinides, it is vital to control heat flow carefully. The thermal wrap which contains the heat within the actinide waste package assures a flow of heat to the thermionics. However, the study of heat flow beyond this point has yet to be given. The following thermal problems in NEWSTAR are discussed:

1. PCU thermal control

2. Heat transport system — actinides to thermionics

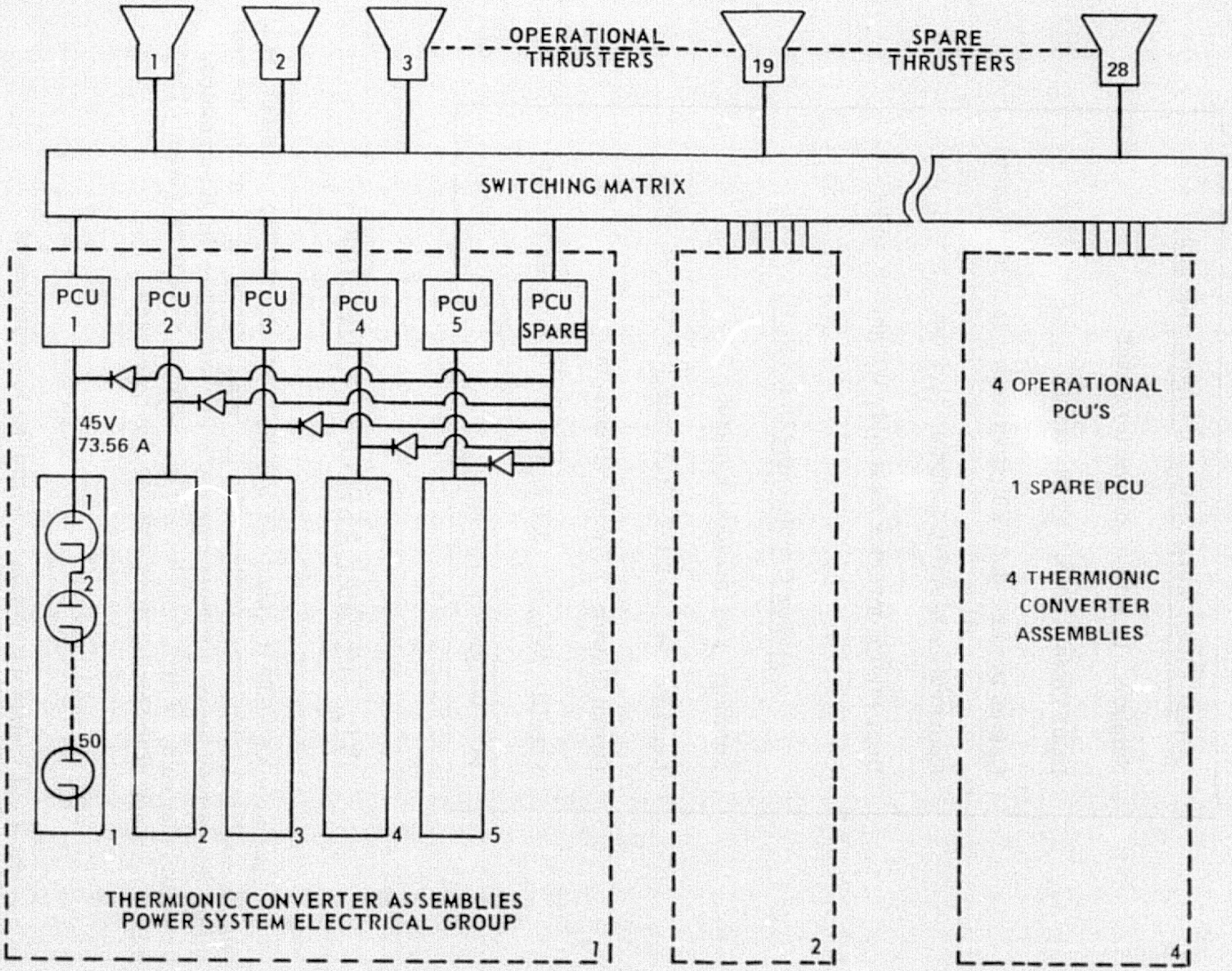


Figure 14. NEWSTAR power and thrust subsystem.

3. On-orbit heat rejection

4. Actinide temperatures — internal thermal packaging

5. Ascent heat rejection

6. Abort/reentry thermal survival

7. Abort/ocean recovery thermal survival

8. Mercury temperature.

Thermal control of the PCU [(1) system: louver/radiator — basically SEPS design; (2) radiator temperature: 55°C; and (3) radiator size easily accommodated within NEWSTAR packaging concept] is quite easy. The barrel of NEWSTAR was sized to facilitate PCU thermal control; i.e., the PCU radiator area per PCU was chosen and the number of PCUs then sized the barrel. Since these units like to operate at about 55°C, and since this temperature can be maintained with little difficulty, no further discussion is necessary.

The method of transporting heat from the actinides and through the thermionics to the radiator was originally thought to be a more difficult problem than it was ultimately found to be.

Single fluid heat pipes carrying no more than 23 200 W per pipe are virtually off-the-shelf items. The operating temperature (~1550°C) is also reasonably standard. The only restriction is with respect to heat pipe length and diameter, and the requirements of NEWSTAR fall within acceptable bounds.

The wall material of the heat pipe is molybdenum alloy and the wick system is standard axial groove with screen.

The working fluid, lithium, has a number of advantages. First of all, it is the recommended material for this heat range. Secondly, it is of very low density so there is not a large weight penalty. Finally, since it must operate in a (low) neutron density, it is fortunate that the "fission fragments" of lithium are only helium atoms, an inert gas. Due to the low neutron density, no significant helium pressure will occur over the life of NEWSTAR.

The heat pipe parameters are shown in Table 9.

TABLE 9. NEWSTAR HEAT REJECTION HEAT TRANSPORT SYSTEM ACTINIDES TO THERMIONICS

- Transport media: heat pipe, single fluid
- Quantity: 19
- Max/min load: 23 200/21 000 W/pipe
- Operating temperature: ~1550°C
- Diameter: 2.6 cm (condenser), 2.6 to 6 cm (evaporator)
- Length: 5 m (max)
- Heat pipe: Fluid: Lithium

  Container: molybdenum alloy

  Wick system: axial groove, screened

  Practical capacity: 30 000 W

Conclusion: Heat pipe state-of-art available for NEWSTAR. Development required for specific application.

It was earlier mentioned that finding the right combination of thermal conductivity and density is important to the design of the high temperature radiator. The radiator description in Table 10 is the result of a rather extensive materials search. The basic material was graphite, and it was assumed that the radiator will be fabricated from pieces that can be formed with known techniques.

The radiator must accept a thermal load of up to 368 500 W and dissipate this heat via radiation. The temperature control of the radiator is by sizing. It is important to note that the radiator is only "one-sided" (thermally). This is due to the fact that the PCU's must operate at approximately 55°C and the radiator would heat them far above this temperature via radiation. Thus, the back of the radiator will be covered by high performance insulation (HPI).

The front of the radiator will "see" the thermally insulated actinide package. This effect will remove a portion of the view area of the radiator, but will actually improve heat retention by the package because the temperature differential will be lowered across the thermal wrap around the actinide package.

TABLE 10. NEWSTAR HEAT REJECTION ON-ORBIT

- Annular disc radiator/one side radiation/no bypass
- Thermal load: 368 500/328 000 W
- Temperature control by area sizing
- Beginning/end temperature (root): 675°C/650°C T = 25°C
- Radiator size: R_o = 2.2 m, R_i = 0.5 m, area = 15 m^2

	Thickness	Weight
• Graphite	1.55 cm	400 kg

It should be noted that the radiator is inoperative at all times until it comes on line in orbit. This is simply accomplished by keeping the lithium in the heat pipes frozen. It is necessary because the graphite will deteriorate at high temperatures in an oxidizing atmosphere.

Figure 15 shows a detailed drafting of the front side of the radiation while Figure 16 shows the aft side. Figure 17 shows section C-C, illustrating the slide joint to allow for thermal expansion of the graphite. Section E-E, shown in Figure 18, demonstrates the heat pipe connection to the radiator graphite while F-F, Figure 19, shows flange interface connections. Detail G in Figure 20 shows a potential method of connecting the radiator to the central support ring. Finally, Table 11 gives a weight breakdown of the radiator components.

The multicannister packaging which leads to a hexagonal waste package is not intuitively apparent; therefore, some explanation of this configuration (which resembles fuel tubes in a nuclear reactor) is in order. The original configuration which was considered was a solid cylinder as shown in Figure 21. Preliminary calculations were concerned with the temperatures that would occur in such a cylinder at those points furthest from the heat pipes (20 heat pipes were used at that time). For heat pipes having a radius of 1.3 cm, it was found that the temperature would rise to approximately 9000°C since actinide oxides have poor thermal conductivity. The melting points of the oxides (approximately 2250°C) are far below this value, so some changes were necessary.

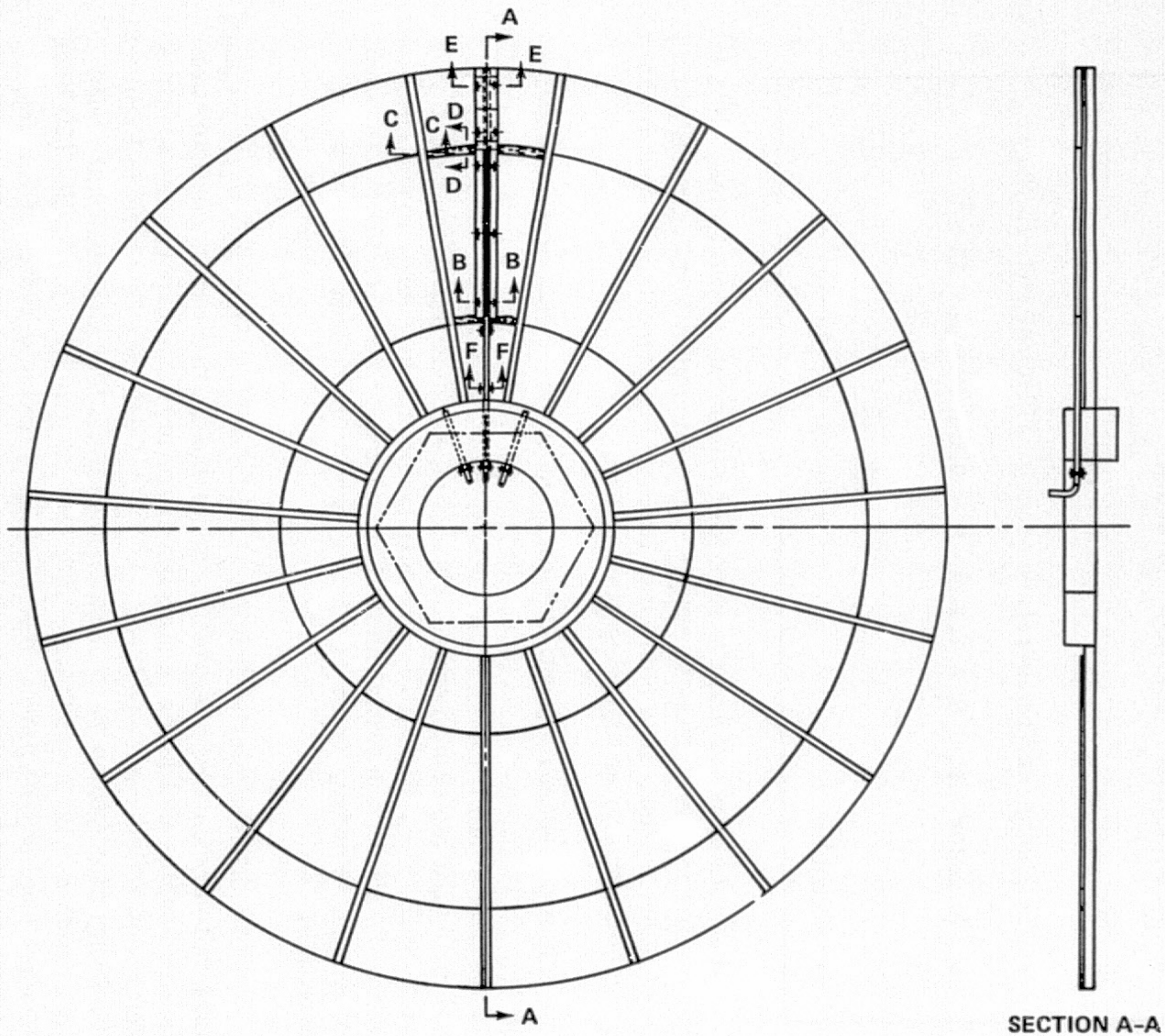


Figure 15. Radiator (front).

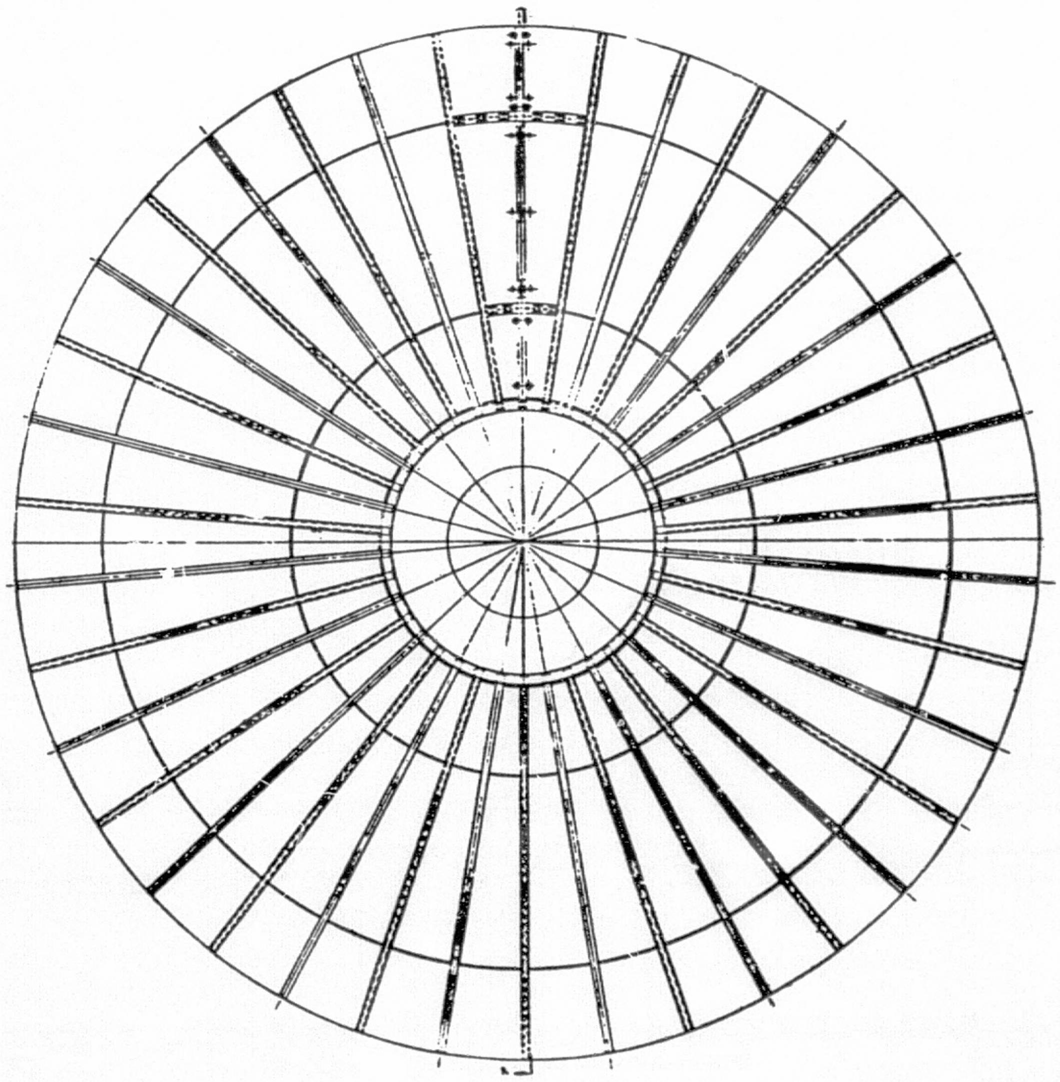


Figure 16. Radiator (aft).

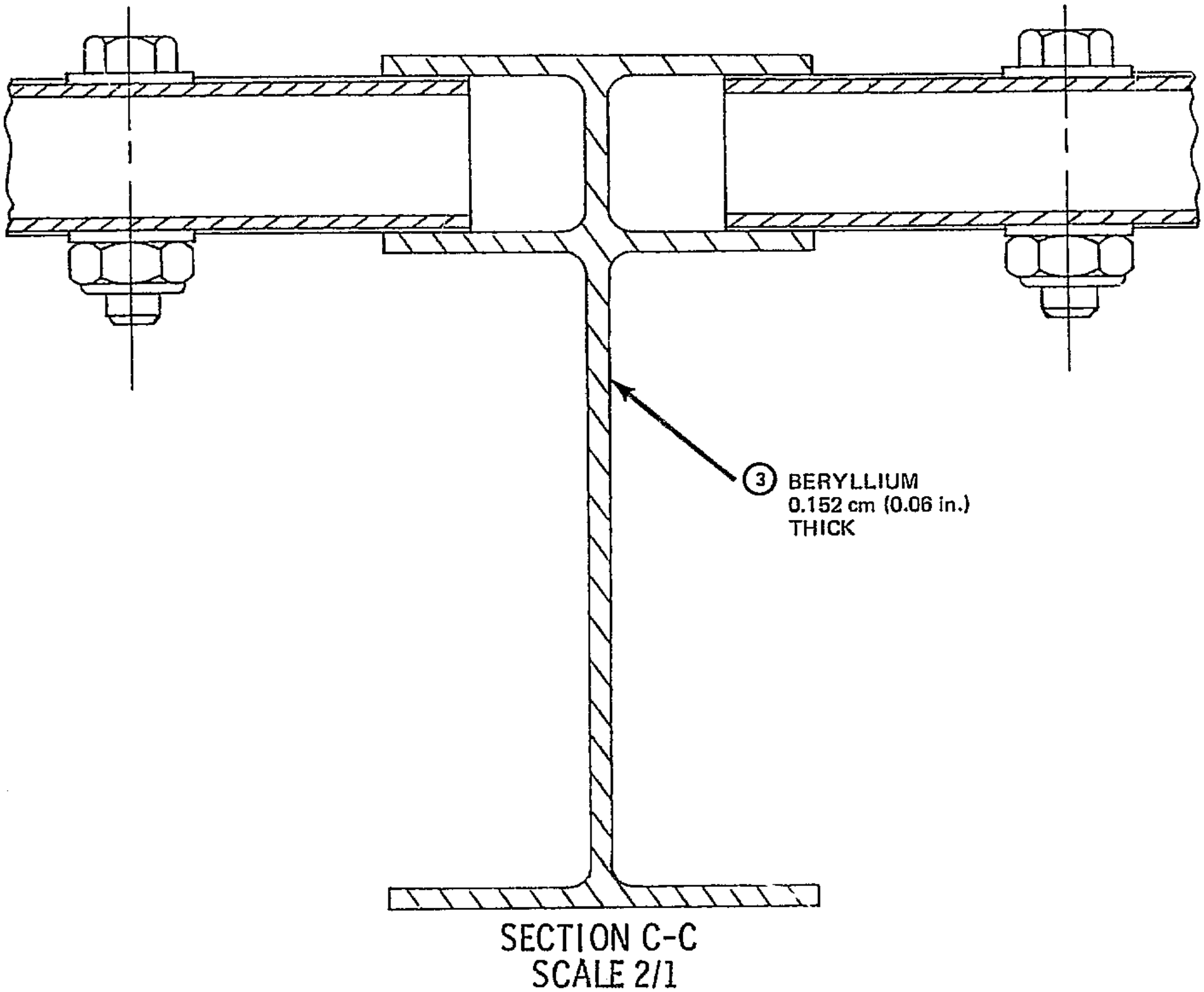


Figure 17. Slide joint to allow for thermal expansion.

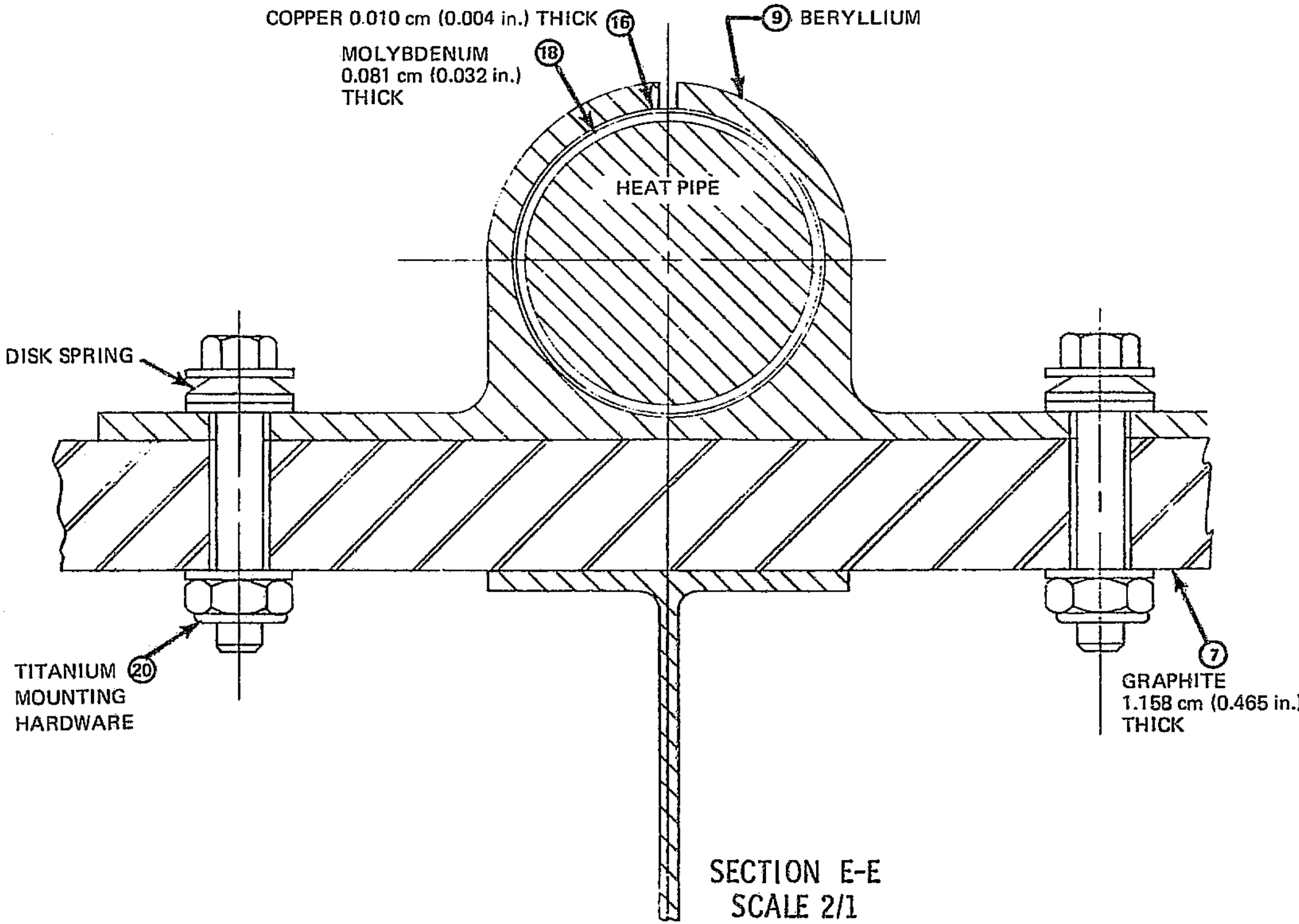


Figure 18. Heat pipe connection to the radiator graphite.

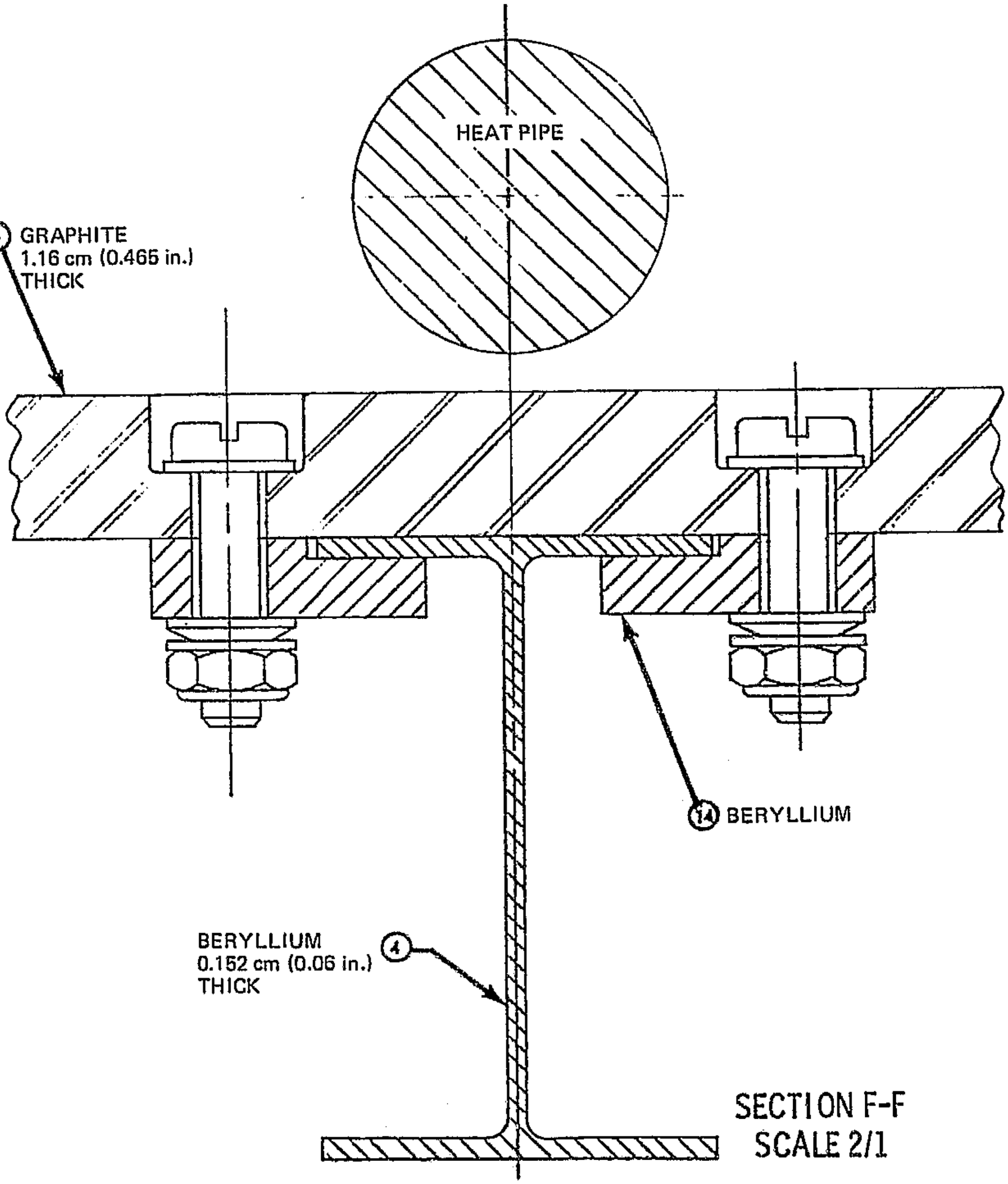
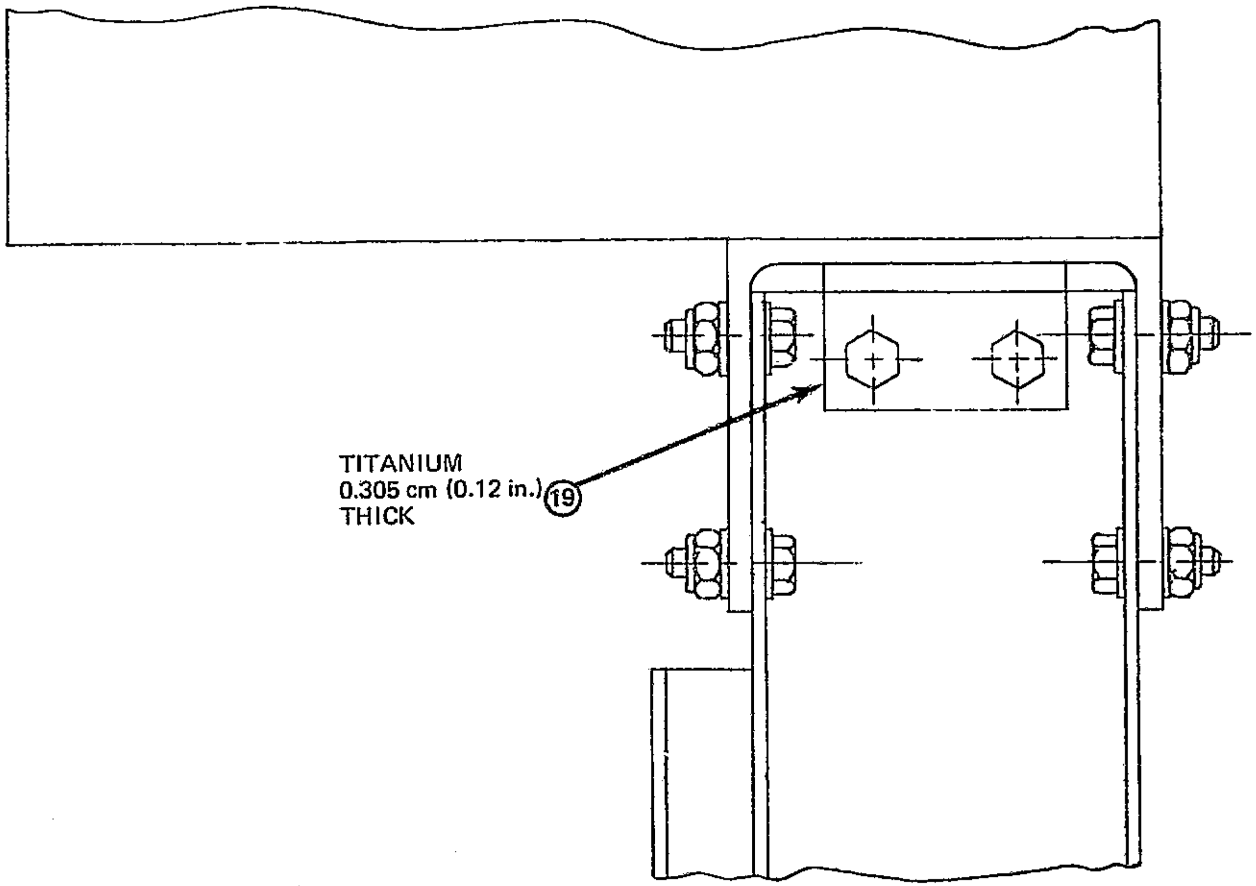


Figure 19. Flange interface connections.



DETAIL G
SCALE 1/1

Figure 20. Potential method of connecting radiator to central support ring.

TABLE 11. RADIATOR WEIGHT SUMMARY

Find No.	Description	Quantity	Unit Weight (kg)	Total Weight (kg)
1	Structural Ring	1	31.63	31.63
2	Support Ring	1	8.02	8.02
3	I-Beam	19	0.71	13.53
4	I-Beam	19	0.51	9.74
5	Web	19	2.05	39.04
6	Web	19	7.87	149.53
7	Web	19	5.25	99.71
8	Heat Transfer Plate	19	0.73	13.96
9	Heat Transfer Plate	19	0.34	6.46
10	Thermal Spacer	19	0.0071	0.14
11	Thermal Spacer	19	0.0039	0.073
12	Joint Plate	38	0.042	1.59
13	Joint Plate	38	0.0227	0.86
14	Retainer Clip	152	0.0041	0.62
15	Outer Spacer Ring	19	0.0630	1.20
16	Outer Spacer Ring	19	0.029	0.55
17	Inner Spacer Ring	19	0.27	5.00
18	Inner Spacer Ring	19	0.26	4.91
19	Support Angle	38	0.16	0.62
20	Mounting Hardware			4.54
				391.73

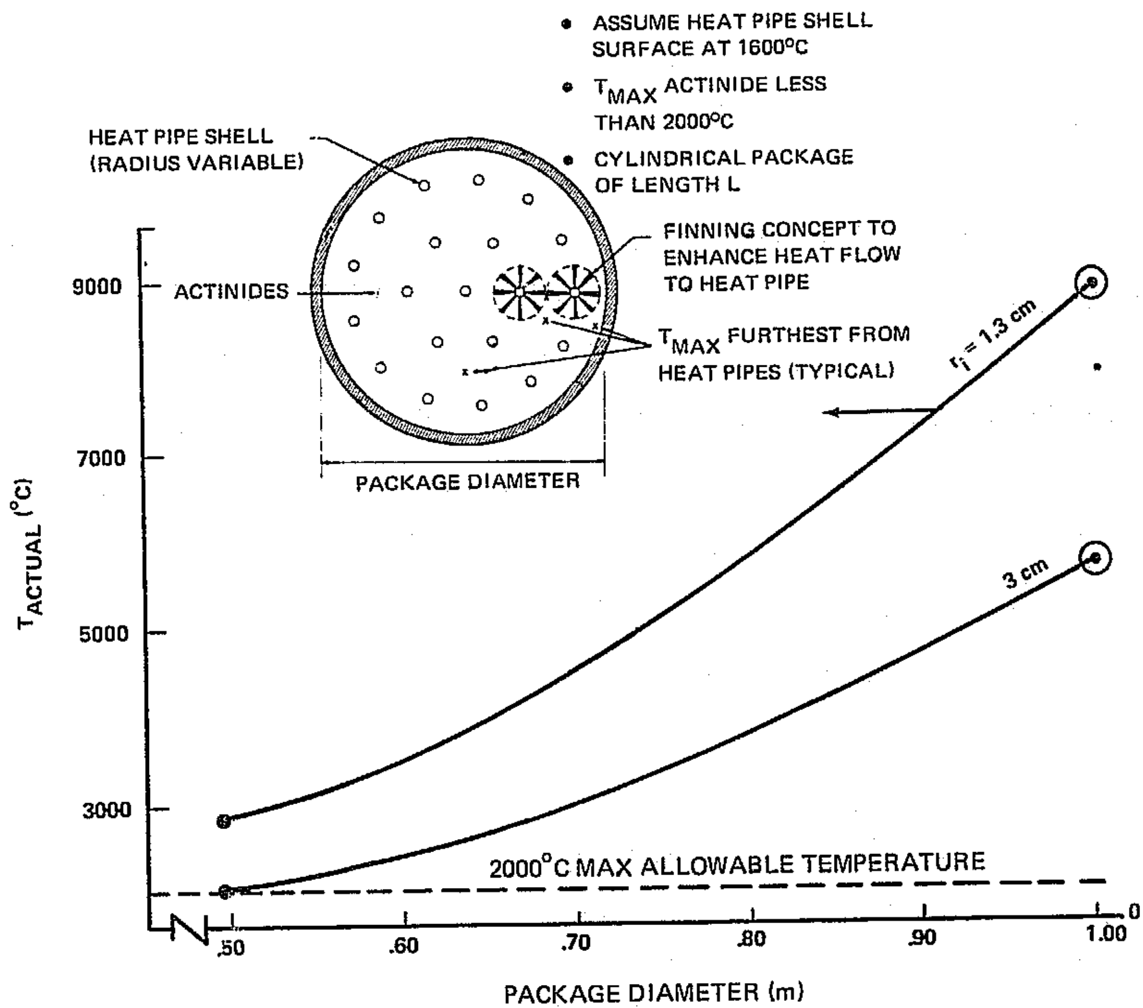


Figure 21. Maximum actinide operational temperature.

The first change was to attempt to decrease the package diameter by bringing the hottest points nearer the heat pipes. While such a change did decrease the temperature (top curve of Fig. 21), the package became quite long and the mass of the tantalum shield increased beyond reasonable bounds.

An increase in the heat pipe radius to the practical upper limit of 3 cm further decreased the temperature as shown in the lower curve of Figure 21; however, with a package diameter of 0.5 m and a heat pipe radius at 3 cm, the weight of the tantalum shield was unreasonable. Thus, the tantalum shield weight implicitly rules out the single cylinder design, and a new configuration, similar to nuclear reactor fuel tubes, was adopted — the hexagonal package.

The multicannister hexagon packaging geometrically eliminates the "hot spots" by eliminating the farthest points. Subsidiary benefits from the "triangular" holes through the package will be discussed in this report.

Figure 22 shows an end view of the waste package. The core of each cannister contains the molybdenum-lithium heat pipe; the actinides (oxides) are packaged around this pipe. The outer wrap of each cannister is baselined as niobium (columbium) since this metal has a high melting point and is rather low in density (approximately equal to the density of iron). The triangular holes that naturally result from the hexagonal packaging are used as coolant flow passages during ascent. This point will be detailed at a later time.

In addition to the actinide waste cannisters, two shields are shown in Figure 22. The inner shield (tantalum) surrounds the actinide package. Finally, a polyethylene shield surrounds the tantalum shield. These two shields will be removed in orbit before firing NEWSTAR to solar system escape.

The actual radius of the actinide cannister will strongly influence the weight of NEWSTAR and the shields. The weight is also dependent upon the radius of the heat pipe.

A calculation is necessary to ensure that the outside wall temperature of the cannisters are within reason. Figure 23 relates these three parameters. A heat pipe radius of 3 cm and a cannister radius of approximately 6.9 cm produced a minimum weight configuration and resulted in an outside wall temperature of 2000°C. This temperature was chosen as being acceptably below the nominal actinide oxide melting point of 2250°C.

To date, it has been assumed that actinide oxides are the chemical form best suited to NEWSTAR, but this point is open to question. The prime disadvantage of the oxides is that they have low thermal conductivities; however other compounds tend toward low melting points, low thermal conductivity, thermal breakdown, and even low density (high density compounds are very important for packaging efficiency).

If metallic alloys of the actinides were available with high density, high thermal conductivity, and high melting points, then a greatly improved NEWSTAR design could be attained. Additionally, there would be added safety in case of abort.

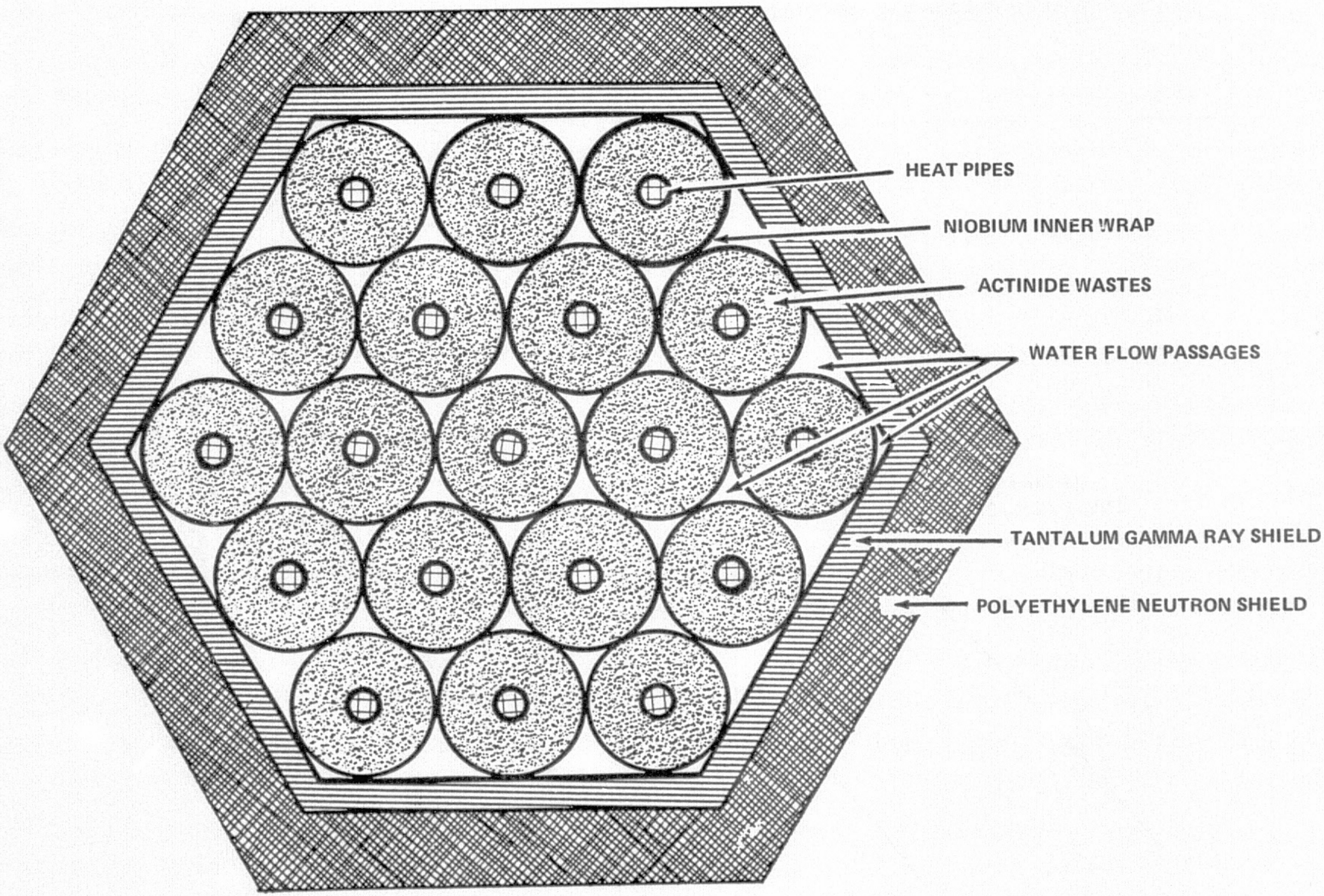


Figure 22. Shield configuration.

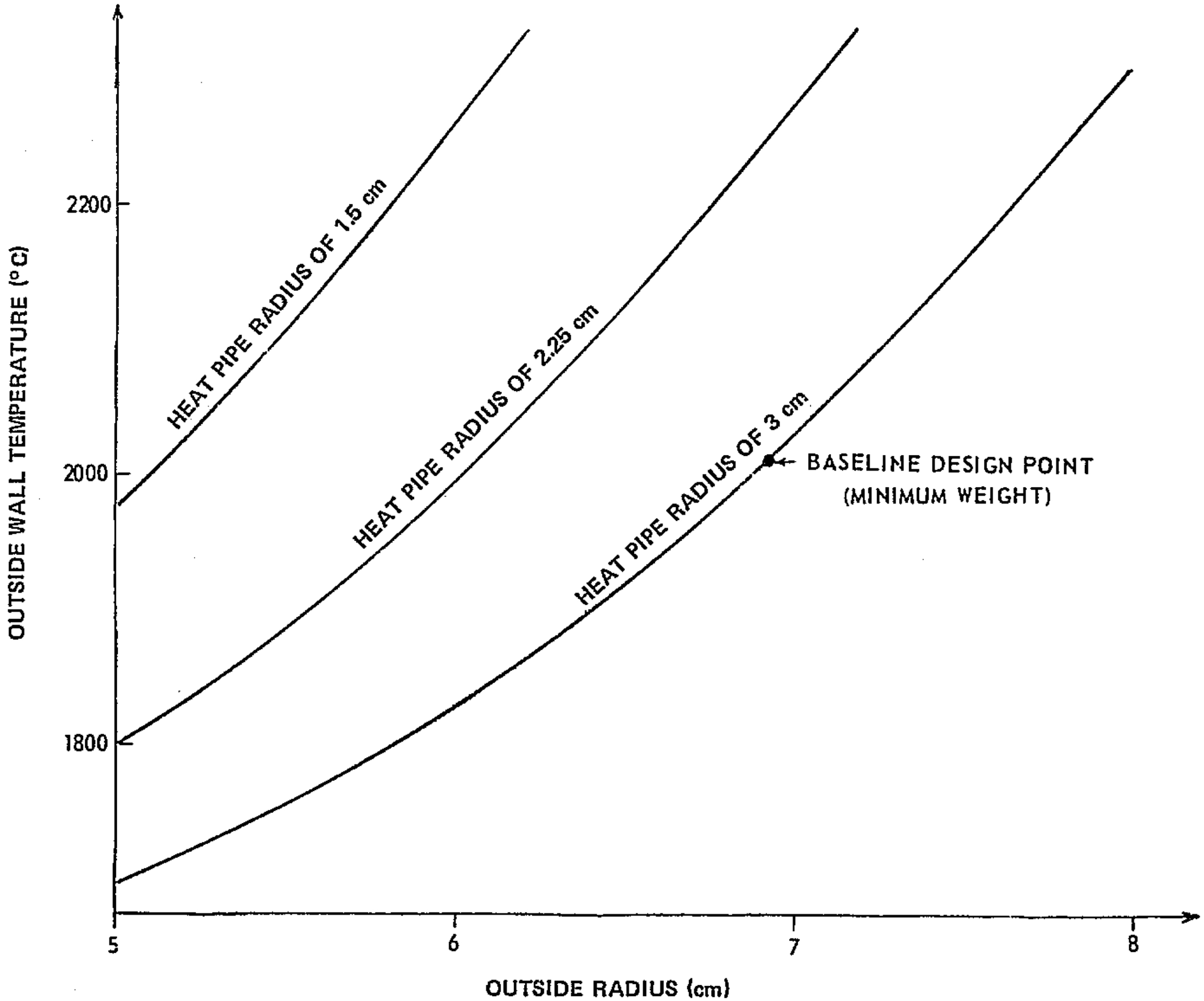


Figure 23. Outside temperature of actinide cylinder versus radius of cylinder (inside temperature of 1600°C).

It must be noted that the alloy under consideration would have to contain a very high atomic percentage of the actinides. That is, only a small weight percentage of inert alloy material could be added to the actinides. Since the properties of actinide alloys are needed, a literature search was conducted to determine these properties — but virtually nothing was found. Lanthanide alloys were sought as an analog, but the industrial uses of lanthanides (semiconductors, phosphors, and lasers) require properties that are not parallel with the properties needed for NEWSTAR.

Although nonoxide compounds offer a promise of an improved NEWSTAR, any data in this direction would probably have to result from a research program. To date, no need has been demonstrated for an actinide compound that has properties ideally suited for NEWSTAR.

The heat produced by the actinides must be carried away by some mechanism when it is not being used to generate electric power. In particular, the actinide heat poses a problem during ascent. Calculations indicated that a prelaunch chilldown was inadequate to handle the thermal load, so an active cooling system was investigated.

The method of thermal control during ascent is shown in Figures 24 and 25. Figure 24 presents a schematic of NEWSTAR within the shuttle bay. A closed-loop organic fluid circulates directly through the holes between the cannisters in the actinide hexagon. This fluid then transfers its heat to water and the resultant steam is vented from the shuttle.

Figure 25 shows a more detailed internal view of the ascent cooling mechanism. The water tank was sized to cool NEWSTAR for 3 hours. For this time period, 2100 kg of water will cool the thermal load of 440 kW.

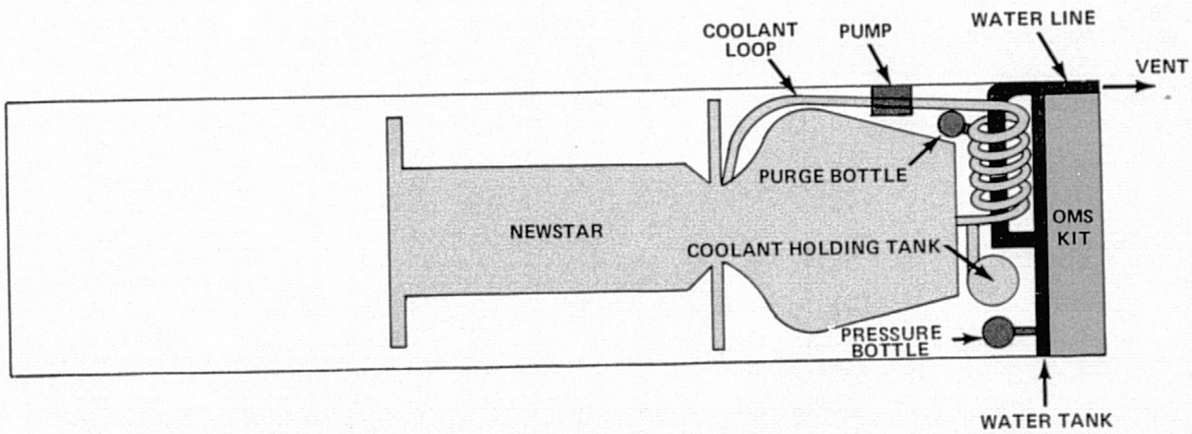


Figure 24. Ascent coolant plumbing.

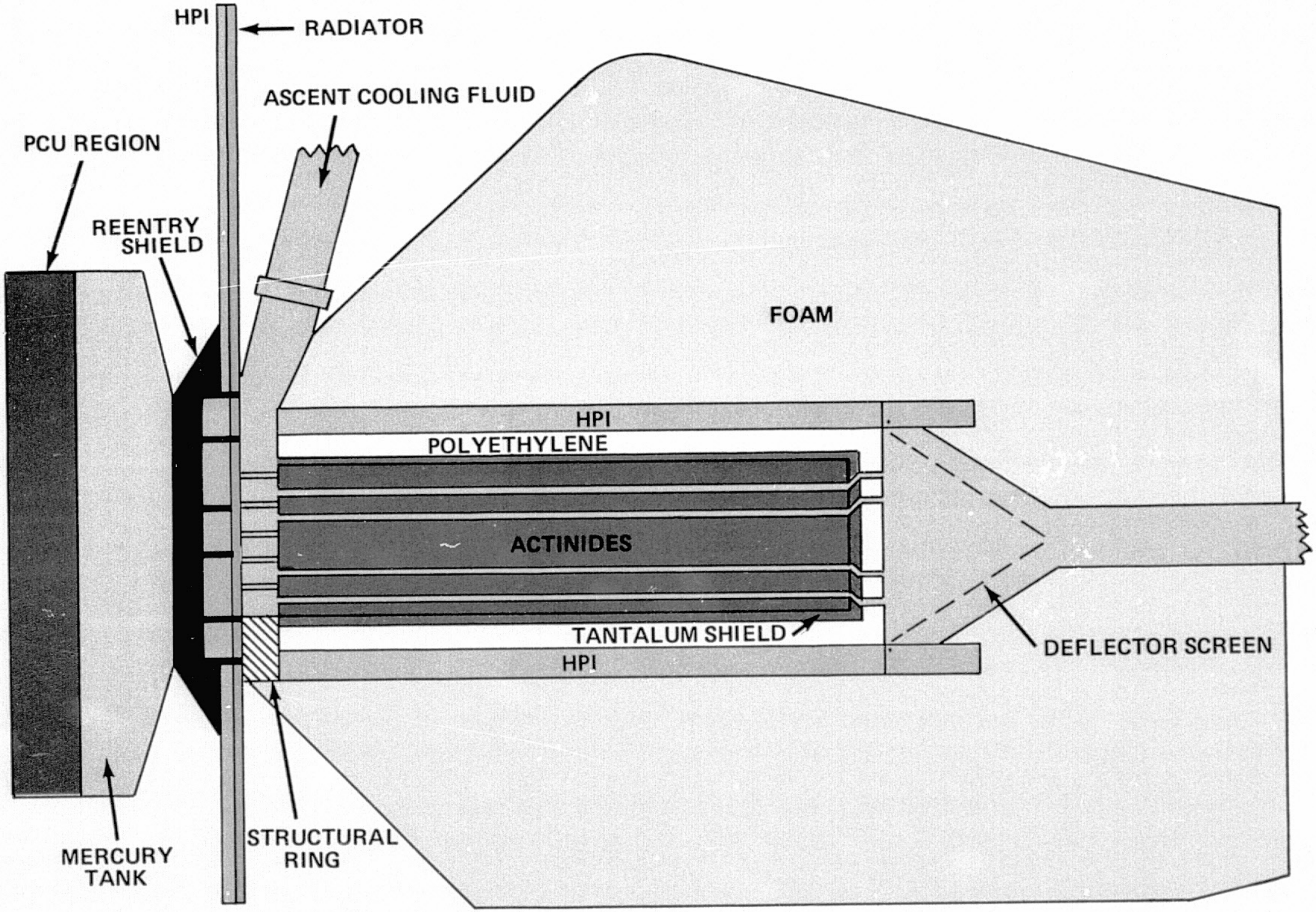


Figure 25. Ascent cooling.

The necessity of an active cooling system raises the possibility of a loss-of-coolant accident. This eventuality will be discussed in the section dealing with safety.

In the event of an abort, it is important to ensure that no actinides escape the package. For this reason, conditions for a severe reentry abort were examined.

A reentry time of 1200 s is approximately maximal, so that value was assumed. During the abort, much of the supporting hardware (such as the barrel, PCUs, radiator, mercury tank heat pipes, etc.) would burn away. An ablative reentry shield behind the payload package would protect the actinides which are still within the various shields and the reentry cocoon.

If it is assumed that all heat which is generated within the actinide package is absorbed by the package, then the rise in temperature will be approximately 405°C. Since the initial temperature of the package was rather low, the reentry will not result in melting of the actinides and/or the shielding material.

In the case of the abort previously mentioned, the actinide package will come to rest in water. Since the package will be held into the cocoon by shear bolts and the reentry cocoon orients the package, the actinides container will break loose from the cocoon at impact. The container, tethered to the cocoon, will then be floated at some depth beneath the surface.

Since the ends of the hexagonal actinide package are open to water flow, one can expect the water which enters the bottom of the holes to be heated and forced upward by convection. The heat flux under these conditions is well below critical, so vapor binding is not a problem. Furthermore, the actinide temperature under these conditions will be lower than the temperature planned for operation in space; no melting of the actinides could occur under such conditions. The combination of heat pipes and voids through the hexagonal actinide package produce a configuration which is compatible with both operation (in space) and abort considerations.

As previously mentioned, the heat pipes in the high temperature radiator will melt during reentry. If a molybdenum alloy heat pipe internal to the package ruptures (behind the heat shield), the actinides could spill into the environment. If such a possibility exists in the final design, it is possible to develop two heat pipes which interface behind the actinide package. This would ensure a completely closed actinide package.

Figure 26 deals with the last critical area of thermal control aboard NEWSTAR, the equilibrium temperature of the mercury fuel. It was found that the temperature of the mercury could be set at almost any desired value by choice of design. Since mercury is a rather good thermal conductor, the fuel will achieve close to the temperature of the mercury tank. The tank acts as a self-radiator, carrying away the heat which flows in from the actinide package. Calculations indicated that approximately 10 cm of high performance insulation would establish a mercury equilibrium temperature of approximately 100°C. This yields adequate mercury vapor pressure for the ion thrusters to operate. The connection between the mercury tank and the front section of NEWSTAR was made with 10 titanium bolts, each having a cross section of 2.54 cm^2. These bolts provided the primary thermal short into the mercury tank. The following is a summary of NEWSTAR heat rejection concepts:

1. Heat rejection is critical design driver.

2. Workable concepts for:

   a. PCU thermal control
   b. Actinide to thermionic heat transport
   c. On-orbit heat rejection
   d. Ascent heat rejection

3. Heat soak during reentry appears acceptable.

4. Individual actinide cylinders recommended for maintaining actinide temperatures below 2000°C for:

   a. Flight-Shuttle ascent
   b. On orbit
   c. Ocean recovery (abort) period.

VII. SAFETY

One of the most important problems associated with NEWSTAR is that of flight safety — a topic not explicitly considered to this point. Figures 27 and 28 are orientation charts showing the near-Earth and far-Earth aspects of a NEWSTAR launch respectively.

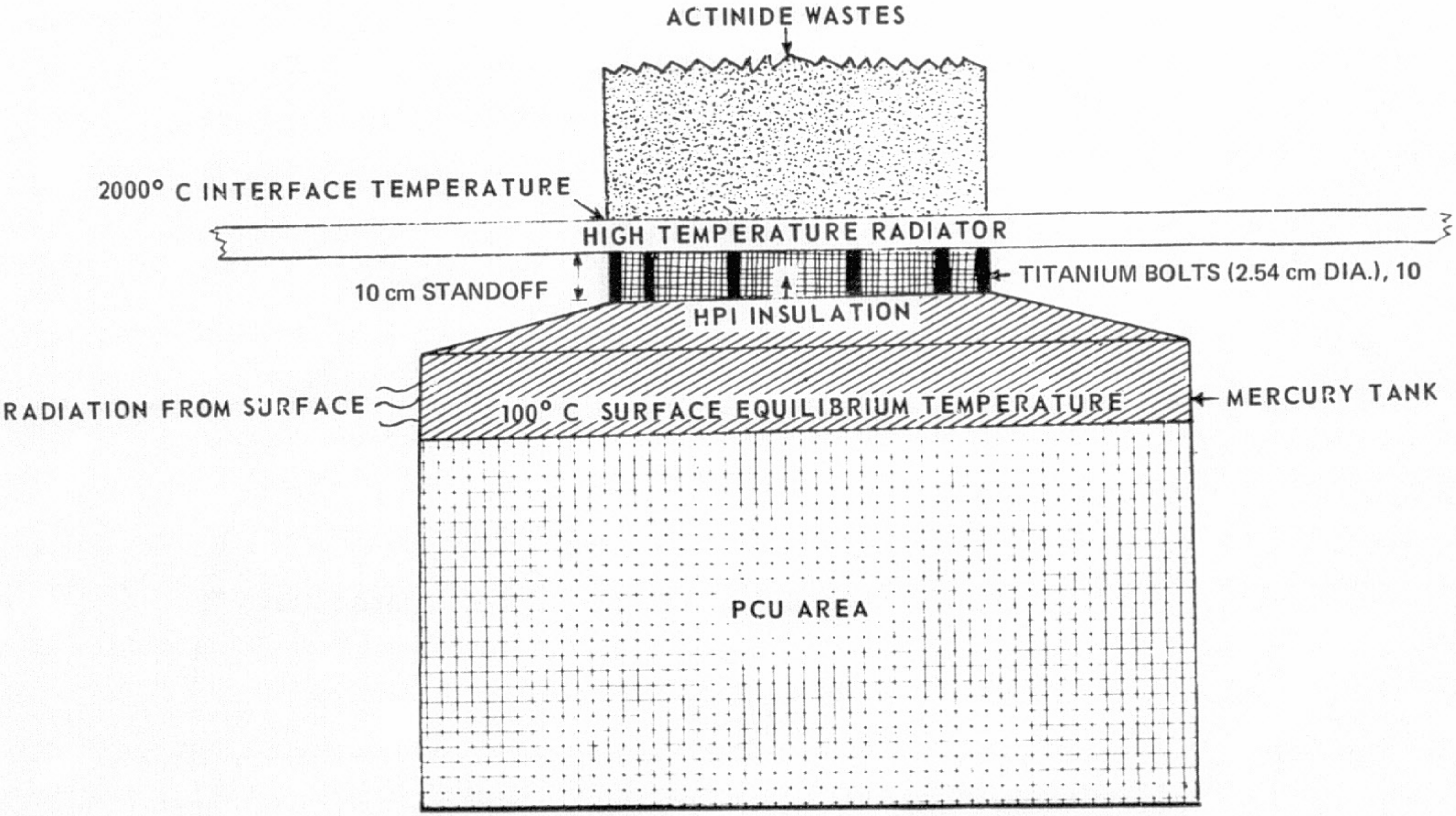


Figure 26. Temperature of mercury.

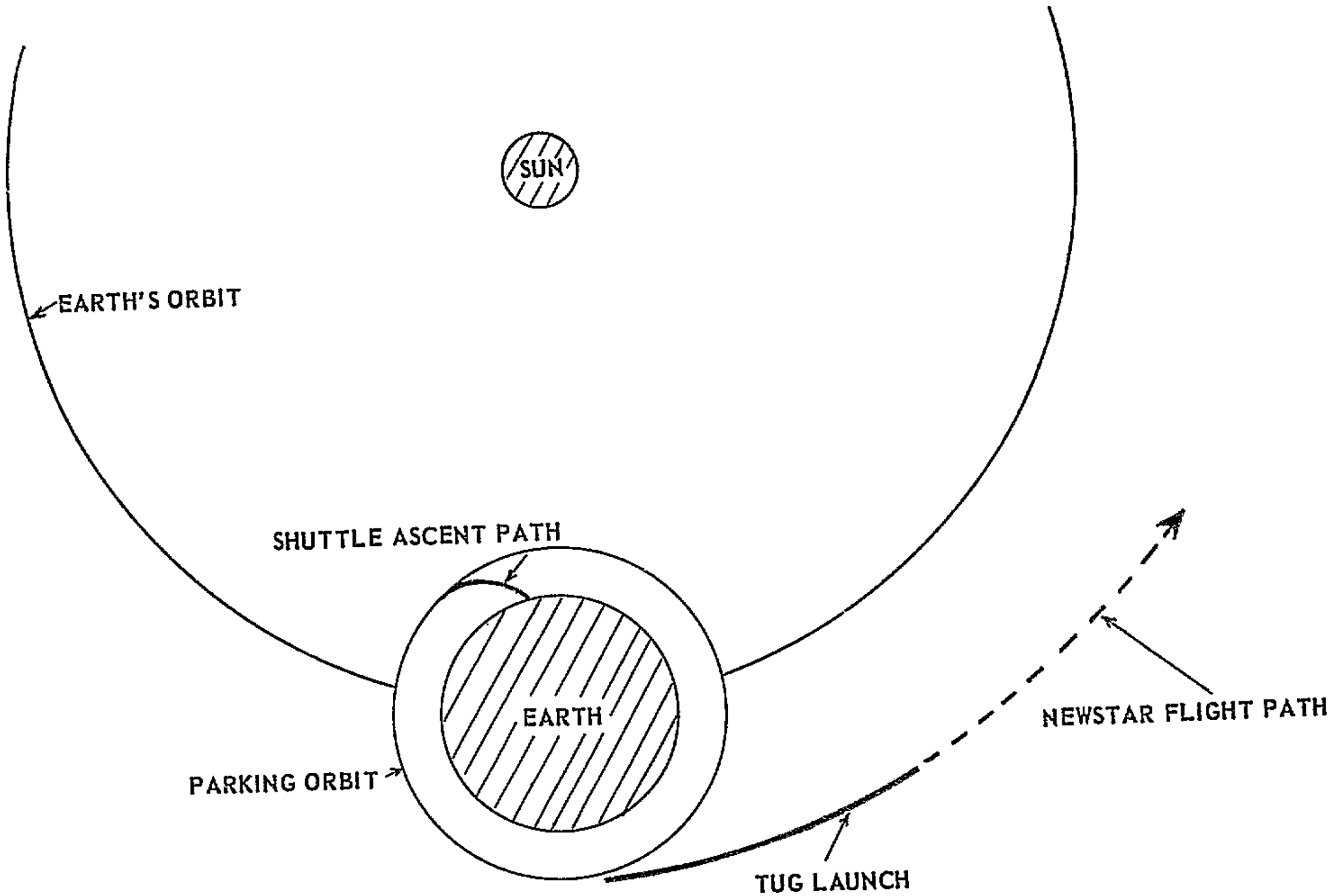


Figure 27. Areas of flight safety.

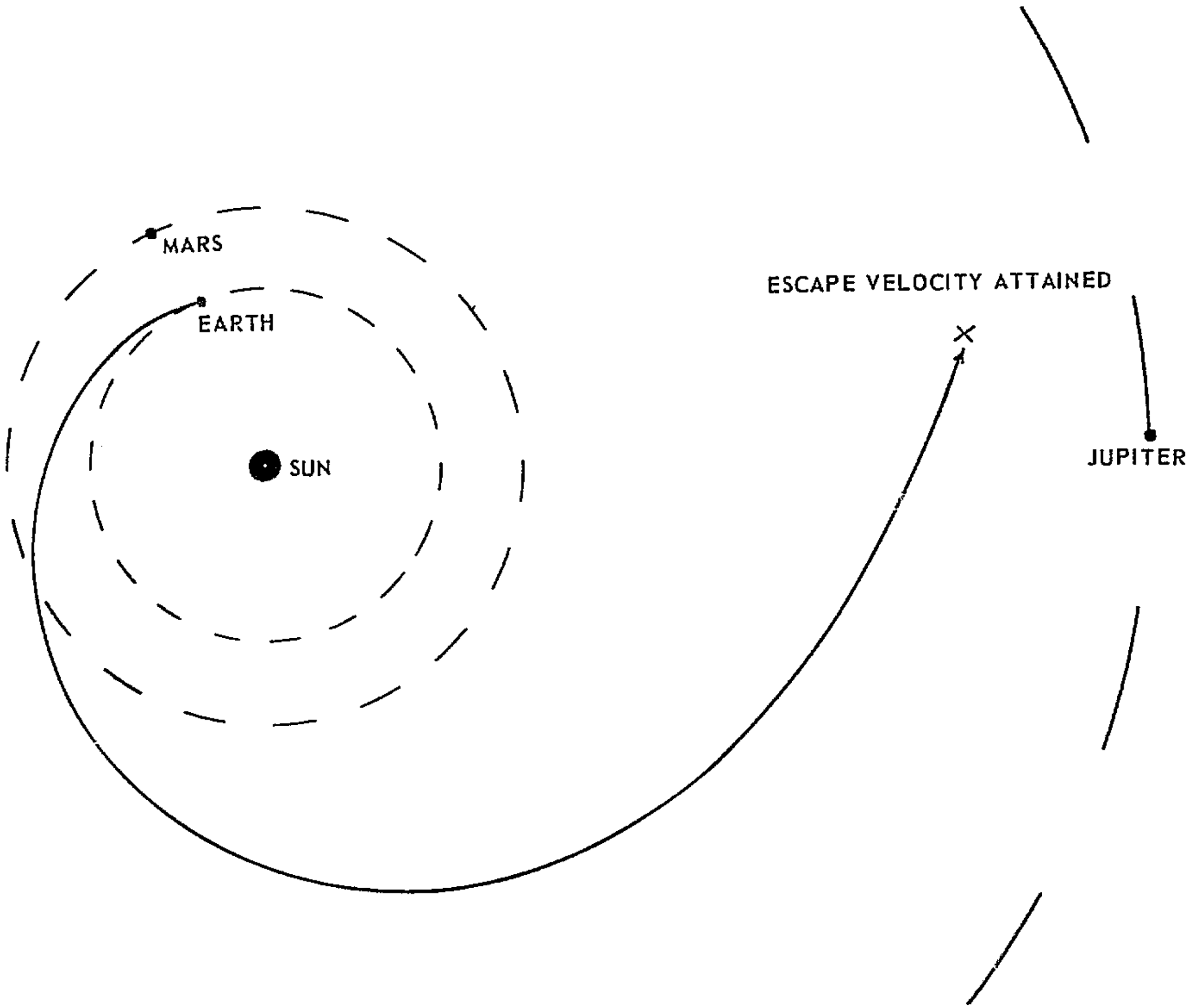


Figure 28. Escape trajectory geometry.

The Shuttle ascent path, parking orbit, Tug launch, and NEWSTAR ignition are shown in Figure 28. Figure 28 shows the NEWSTAR flight profile from Earth to escape. Note that NEWSTAR attains escape velocity inside the orbit of Jupiter. (The position of Jupiter shown in Figure 28 has no relationship whatsoever to a true NEWSTAR launch.)

In this discussion of NEWSTAR flight safety, a general approach to flight safety, contingency design features, NEWSTAR to solar orbit if Tug fails, launch site considerations, and Shuttle modifications are presented.

The design of the waste disposal vehicle was made with emphasis on flight safety. For this reason it can be expected that the inherent system design will mitigate failure modes.

The Shuttle — a man rated vehicle — has a built-in capability for intact abort. Where possible, as ascent abort should be terminated using this capability. For the other cases, the payload would be rejected from the Orbiter and the cocoon used for reentry, flotation, with eventual recovery and relaunch. This technique would also handle a loss-of-coolant accident.

If a failure should occur in low Earth orbit, the Shuttle again has the capability to recover a crippled NEWSTAR and either effect on-the-spot repairs or return NEWSTAR to Earth for renovation and relaunch.

If the Tug, which is used to carry NEWSTAR to Earth escape should fail in a high energy orbit, the best recovery mode would be to start the electric engines and allow NEWSTAR power itself to Earth escape, targeting the most stable solar orbit that can be achieved.

Finally, a failure of NEWSTAR in solar orbit would present a difficult rescue mission. The stability of solar orbits will be examined, however, and the possibility of steering NEWSTAR along a flight path that maximizes orbital stability for any failure time will be investigated. This steering program is probably different from the normal minimum energy excape maneuver.

Figure 29 presents two distinctly different types of information. The left part of the figure illustrates the cocoon and the shear bolt mounting that would be used if an abortive flight has occurred. Notice that NEWSTAR is tethered to the cocoon. Water flow through the holes between the cannisters is shown pictorially.

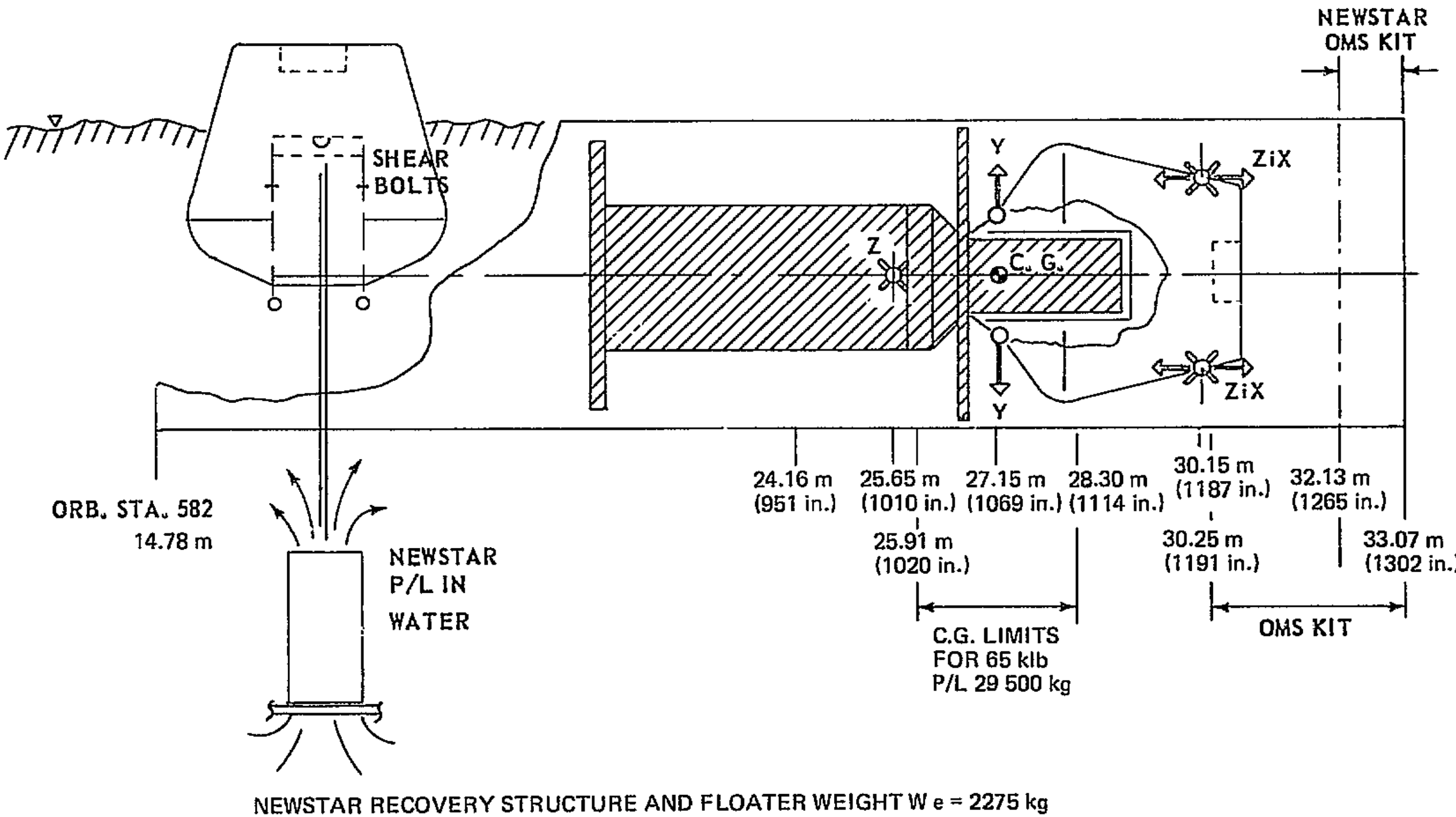


Figure 29. Aerodynamic braking/flotation system.

The other information on Figure 29 illustrates that NEWSTAR can, indeed, be mounted in the Shuttle bay. The center-of-gravity constraints and X, Y, Z loadings can be successfully taken out at established tie-down points.

Although only the reentry cocoon has been mentioned to this point, Figure 30 shows three other concepts that were examined to assure a successful reentry in case of a severe Shuttle abort.

The first of these is the standard cocoon that would impact the water at 150 m/s. This has the advantage of being purely passive and is state-of-the-art.

Since parachutes were used so successfully on the Apollo project, this concept was also studied. Once again a state-of-the-art concept that is perfectly feasible is available if lower impact velocities are needed. A slight weight penalty would be incurred.

Finally, the auto-giro concept was considered. This device is neither totally passive nor is it state-of-the-art. The impact velocity for an auto giro is intermediate between the first two concepts.

Assuming a cocoon reentry body, Figure 31 shows the sequence of events following ejection of NEWSTAR from the Orbiter. This sequence would apply only in the event of a catastrophic abort of the Orbiter.

If it is assumed that an abort has occurred and that a payload ejection has been necessary, and if it is further assumed that the payload hexagon has been detached from the flotation of the cocoon, then the payload will sink into the ocean.

Figure 32 illustrates the available recovery techniques. Virtually any spot on the ocean floor will be accessible with the devices shown in Figure 32 long before NEWSTAR flies. Furthermore, location would not pose a serious problem since transponders would be carried as standard equipment aboard any NEWSTAR payload.

The remote underwater salvage (RUWS) device would be used for the case in which a NEWSTAR payload is lost in very deep water (10 000 to 35 000 ft).

The question of safety is closely tied to the question of launch site. Two possible launch sites were considered, KSC and Mariana Island. The first of these, KSC, is shown in Figure 33. Table 12 details certain advantages and disadvantages of KSC while Figure 33 shows a typical orbit track for KSC launch.

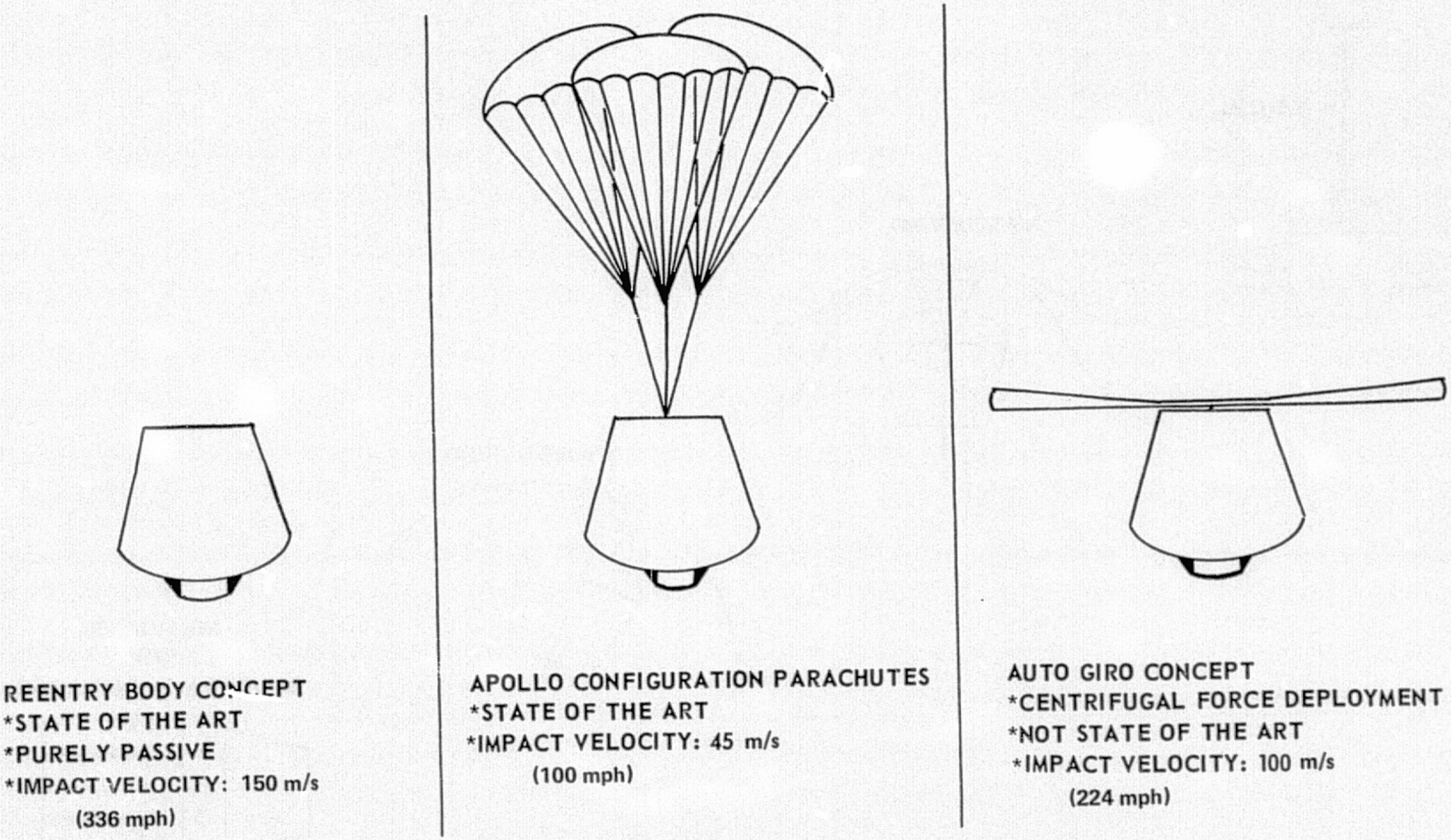


Figure 30. Recovery concepts.

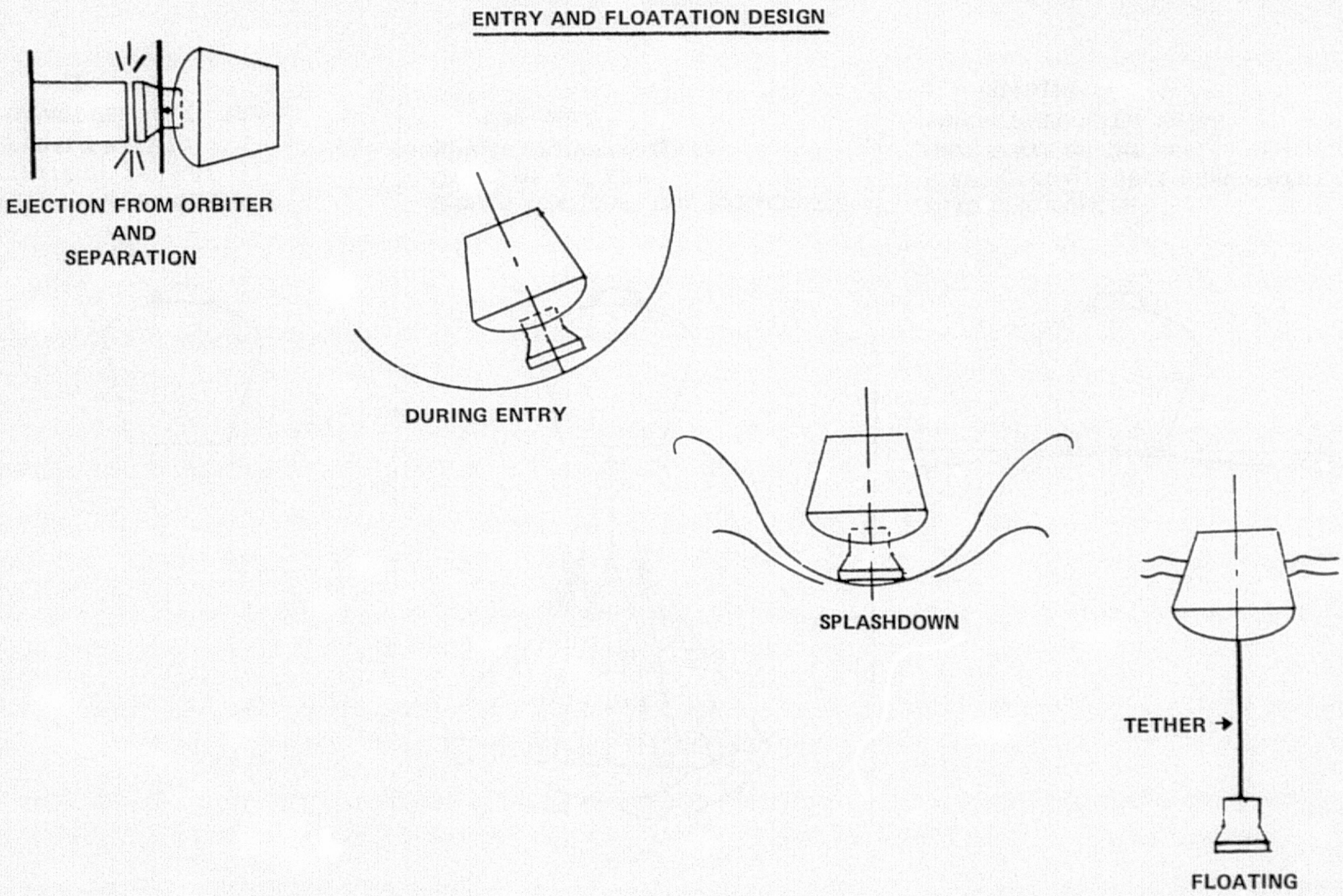


Figure 31. NEWSTAR contingency design features.

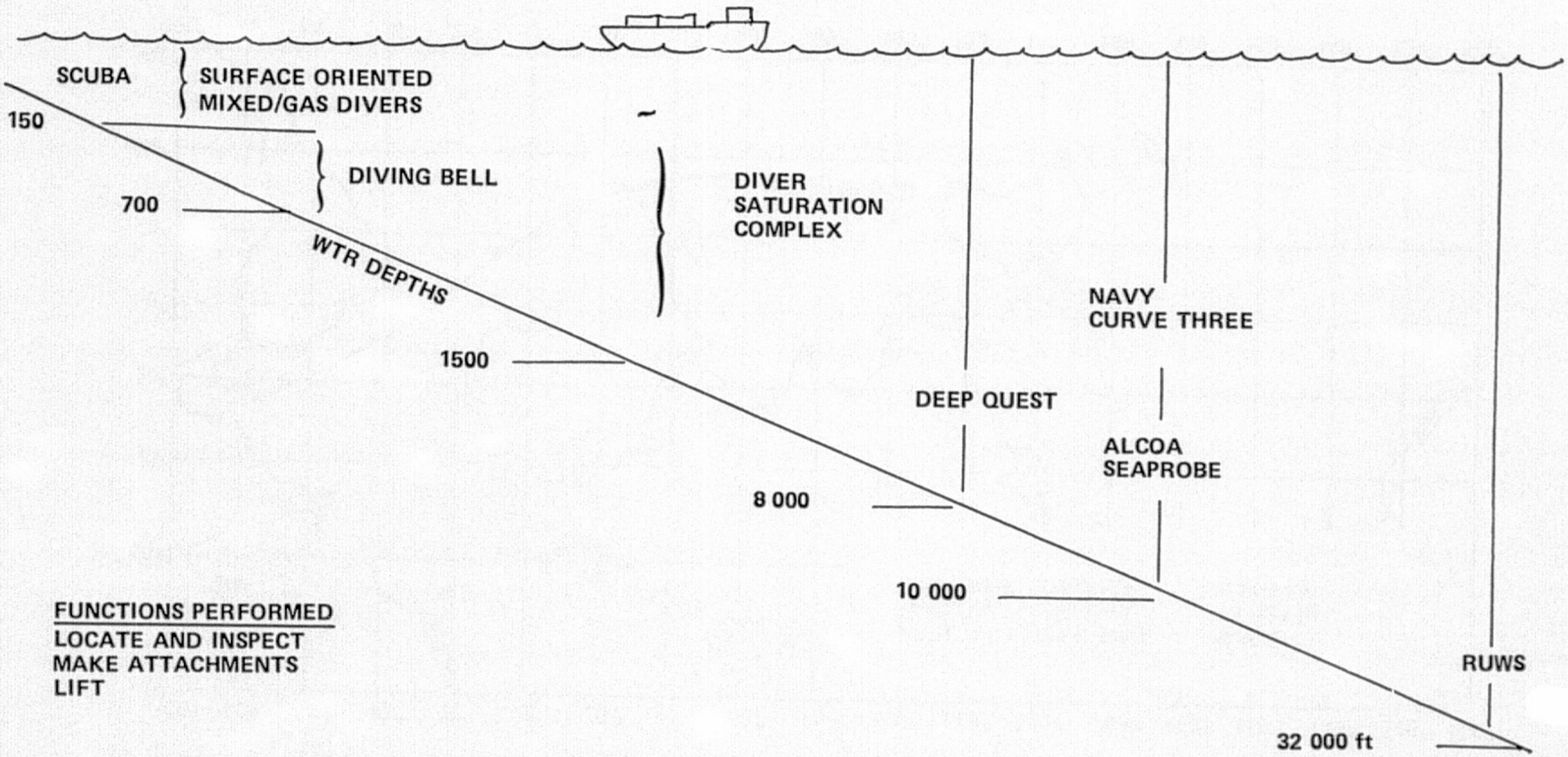


Figure 32. NEWSTAR underwater recovery technology.

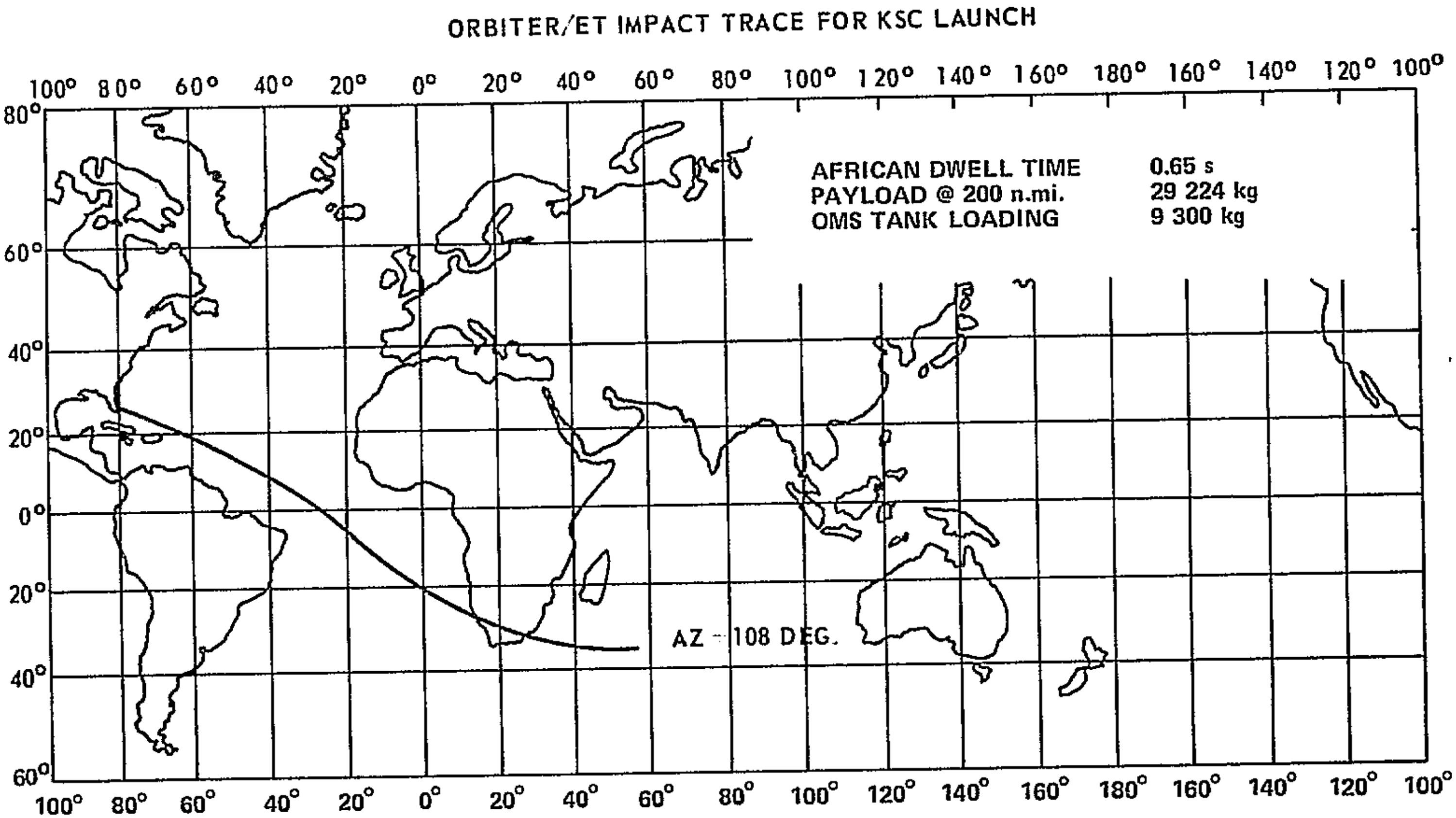


Figure 33. Launch site considerations.

TABLE 12. KENNEDY SPACE CENTER LAUNCH CONSIDERATIONS

Advantages

- Can share some launch facilities
- No OMS kit needed for NEWSTAR flight (full payload bay is available)
- No land impact for a controllable Orbiter

Disadvantages

- Potential nuclear contamination of general Shuttle facilities:
  - Ground storage and loading
  - Launch and landing catastrophes
- African overflight prior to MECO — however, for AZ = 108°:
  - ET and Orbiter do not impact Africa at same time of flight; package can be ejected or stay with Orbiter to avoid land
  - Max cross range from impact trace to water is 480 n. mi., so controllable Orbiter could land in water.

It is worthwhile to note that the "impact window" for Southern Africa is only 0.65 s for the entire flight. In the case of a catastrophic abort, the NEWSTAR payload and the Shuttle vehicle would have differing decent paths due to their different lift and drag characteristics. Thus, during the 0.65 s impact window, the avoidance of Africa is always possible by a simple strategem: if the Shuttle will impact Africa, eject NEWSTAR; if an ejected NEWSTAR would impact Africa, keep NEWSTAR with the Shuttle.

In the event of a noncatastrophic abort, the Shuttle cross-range capability is adequate to easily miss Southern Africa.

Table 13 lists advantages and disadvantages of the Mariana site, and Figure 34 shows a typical launch track from the Marianas.

TABLE 13. MARIANA ISLAND LAUNCH CONSIDERATIONS

Advantages

- Ideal for international launch site
- Dedicated, secure launch facilities
- No land overflight prior to MECO
- No land impact for a controllable Orbiter.

Disadvantages

- Remote from United States (- for U.S.)
- Requires OMS kit to avoid land overflight prior to MECO
- Minimum time from launch through 200 n.mi. to landing is longer (more water required for cooling)

The first large land mass to be encountered, South America, has a much larger impact window than did Africa for a KSC launch. Before main engine cutoff (pre-MECO), no impact of South America is possible; however, a post-MECO impact window of approximately 100 s is possible.

Furthermore, an orbit maneuvering system (OMS) kit (besides the integral OMS kit) is needed for a Mariana launch. While it is certainly true that a launch site near the equator (such as the Marianas) will yield a significant payload boost. The lifting limit of the Shuttle is due to floor loading on the Shuttle; thus, the total gain in payload cannot be readily utilized.

An imaginary (though possible) layout for a NEWSTAR base was designed for Tinian Island in the Marianas. Tinian was chosen arbitrarily as a typical island. Such a facility would include dock facilities, a heavy duty airstrip (4600 by 100 m), an orbiter and external tank processing facility, industrial area, liquid hydrogen and oxygen manufacturing plant, a desalting plant, power station, an engineering and administrative area, and housing and community services area.

Figure 35 shows the modifications that will be made to the Shuttle to accommodate NEWSTAR. These are fairly minor changes and include a possible OMS kit (for Marianas launch), a water kit (for ascent cooling), and an actuator to eject NEWSTAR in case of an abort.

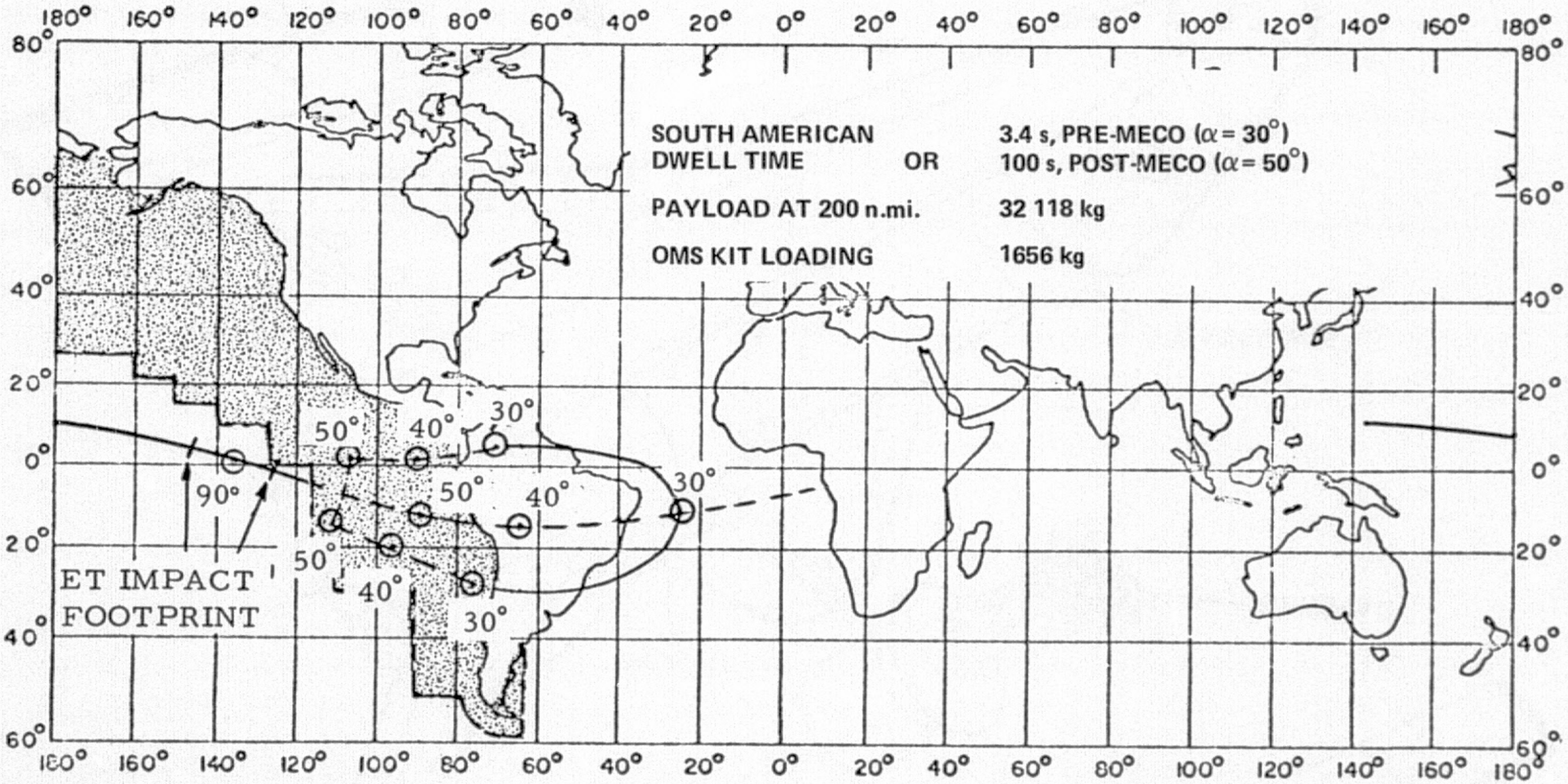


Figure 34. Orbiter/ET impact trace for Mariana Island launch.

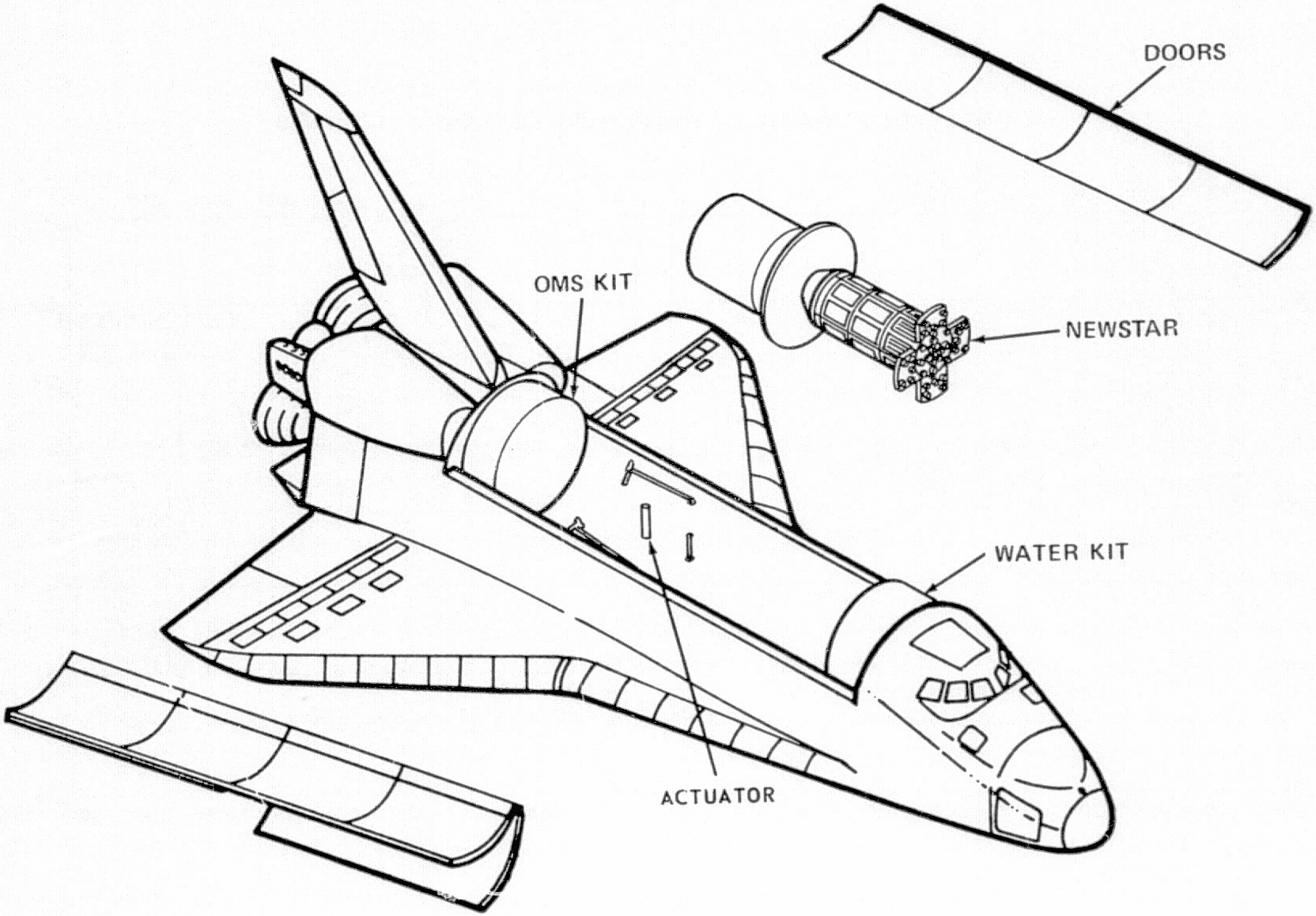


Figure 35. NEWSTAR Shuttle abort.

To summarize the discussion of NEWSTAR flight safety:

1. Safety is recognized as basic design issue and has received more attention than is presented here.

2. Approach is to do what is required to eliminate or minimize all hazards.

a. Fully utilize Shuttle abort capability
b. Minimize Shuttle land overflight
c. Passive safing where required
d. Modify Shuttle as required.

3. Either KSC or Mariana Island launch yields acceptable safety and performance.

4. Adequate safety appears possible through design and operational procedures.

VIII. PERFORMANCE CALCULATIONS AND TRAFFIC DENSITY

Other propulsion techniques for eliminating nuclear waste into space cannot compete with the NEWSTAR concept from an efficiency standpoint. The use of the waste as a power source establishes a very efficient system, and the methods of applying NEWSTAR were varied to optimize the entire mission. Two methods of using NEWSTAR were investigated and these were compared with an all-chemical boost (Fig. 36).

One unique NEWSTAR mode was to use the electric propulsion from low Earth orbit the entire way to escape. The other mode was to use a Tug to achieve Earth escape and then use NEWSTAR ion power to achieve solar system escape. The use of ion thrust from low Earth orbit to escape is certainly feasible and produces excellent performance, only one Shuttle launch is required. However, the main disadvantage to an all-electric launch is that the vehicle will spend much time in the vicinity of Earth (approximately 400 days). For safety reasons, the all-electric mode was dropped.

Once the NEWSTAR vehicle has been configured and a mode chosen, it is then possible to calculate a specific payload that could escape the solar system. Such a calculation shows that NEWSTAR can deliver 4140 kg of actinide oxides to "infinity" in mode 3 (Tug assist).

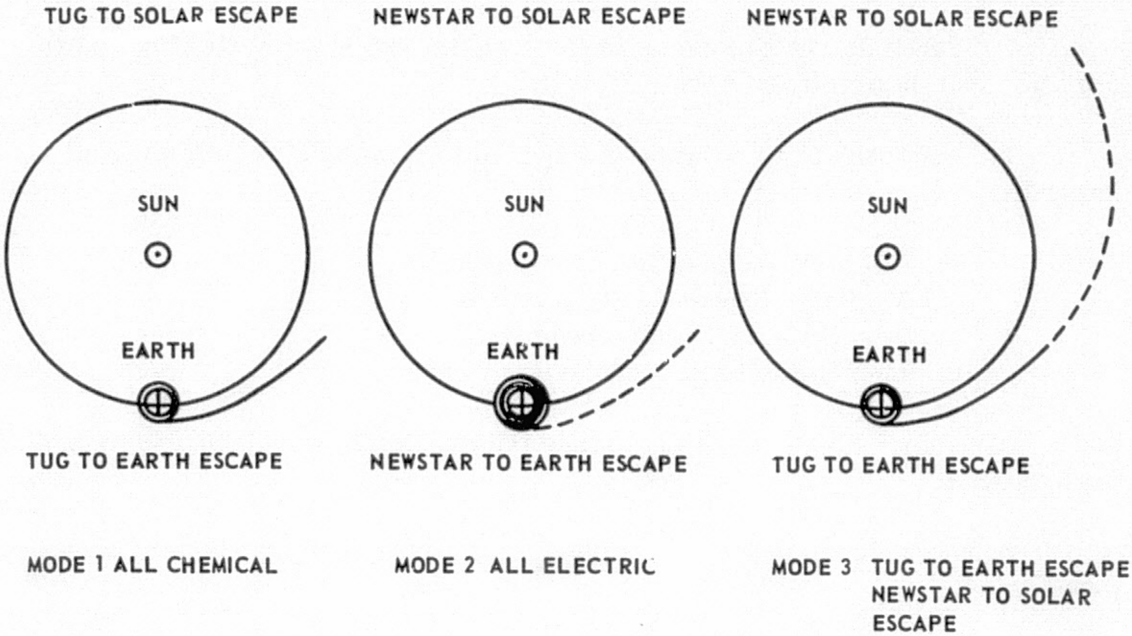


Figure 36. Potential operational modes.

The next question then concerns the number of flights that are necessary to eliminate the actinides that will be generated in the future. To answer this question requires a further discussion of separation that was previously mentioned.

The actinides constitute a very small proportion of the overall fission fragments. But the fission fragments are also only a percentage of the unreacted uranium which remains from the fuel originally charged to the reactor. From this it can be seen that the removal of uranium (which is an actinide) from the residual actinides which we wish to carry aboard NEWSTAR is very important. The mass of the actinides to be carried are shown in Figure 37. If all but 0.1 percent of the uranium is removed, then the upper curve shows the NEWSTAR loads to be carried. If chemical separations can eliminate all but 0.01 percent of the uranium, then the lower curve should be used.

Figures 38 through 41 present parameterizations of the NEWSTAR payload with respect to actinide density, allowable cylinder temperature, heat pipe radius, and actinide thermal conductivity, respectively. If off-nominal values for any of these parameters occur, then these figures illustrate the anticipated changes that will occur in the payloads. It is apparent that the ideal payload would have very high density, thermal conductivity, and melting point.

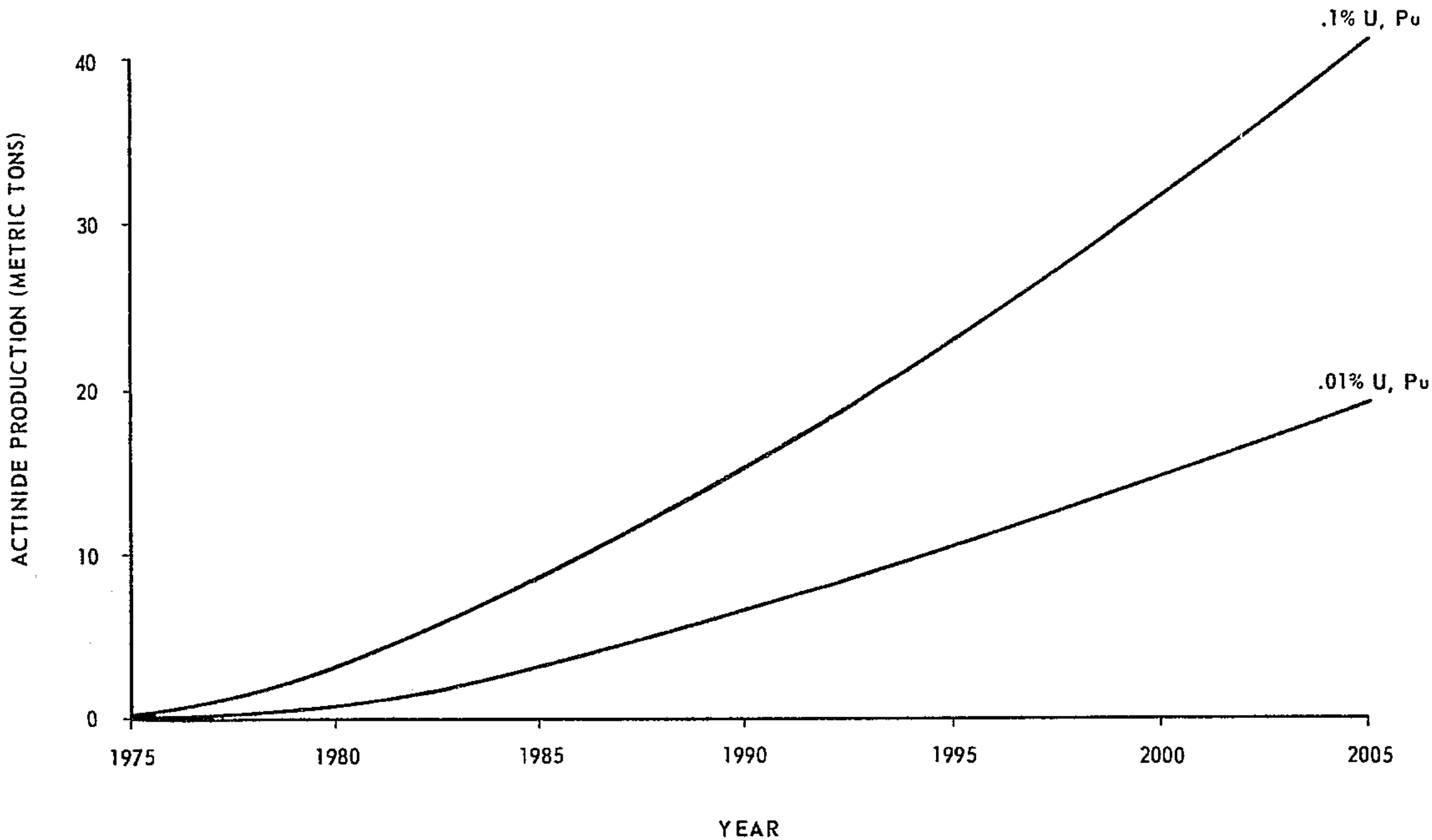


Figure 37. Actinides produced per year.

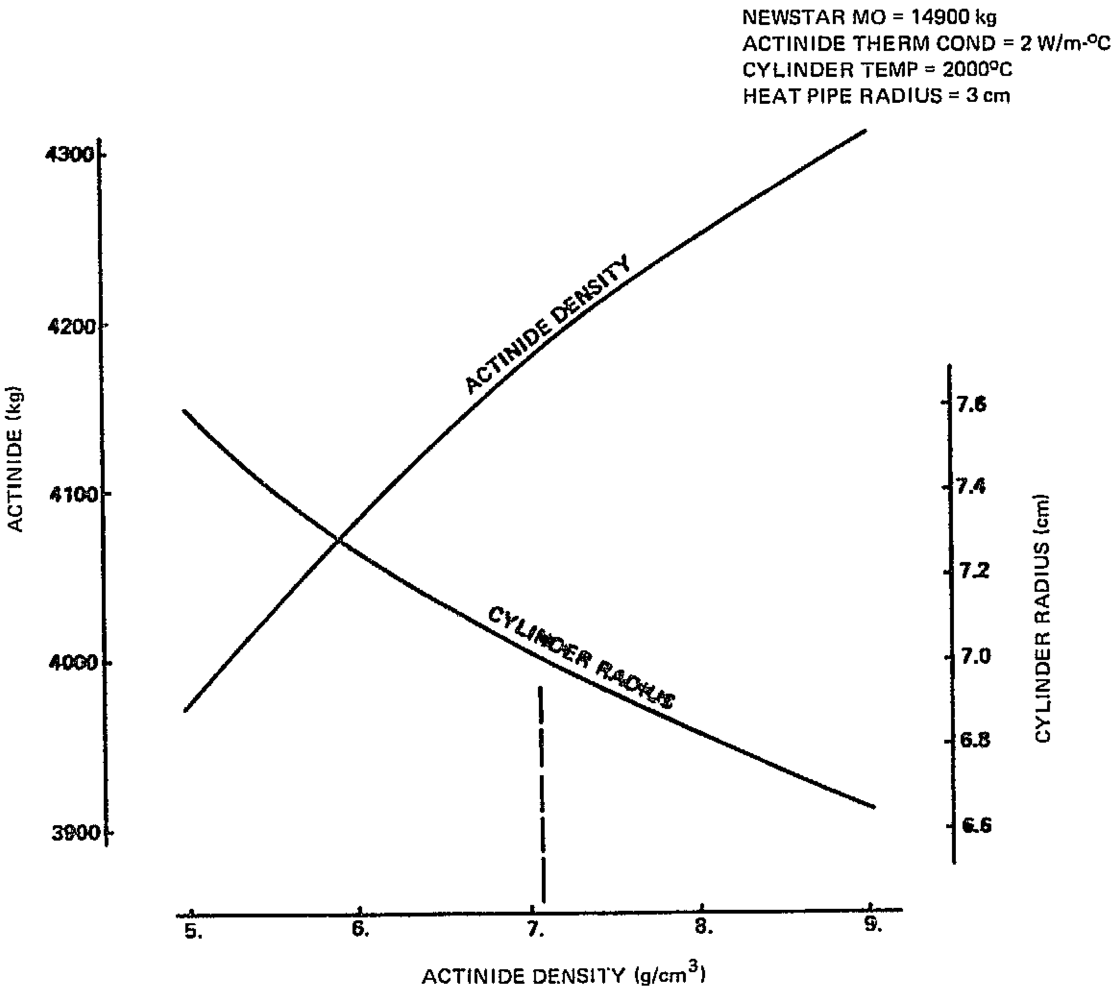


Figure 38. Payload versus actinide density.

The values chosen for each of these parameters influences the payload which NEWSTAR can carry. The figure quoted earlier (4140 kg) corresponds to the baseline values of these parameters. If it becomes necessary to shift the value of these baseline assumptions, Figures 38 through 41 would indicate the payload loss or gain.

If baseline values are used for each of the four parameters treated in Figures 38 through 41, a payload of 4140 kg of actinides is possible. Using this figure and Figure 37 we can now calculate a traffic density for NEWSTAR

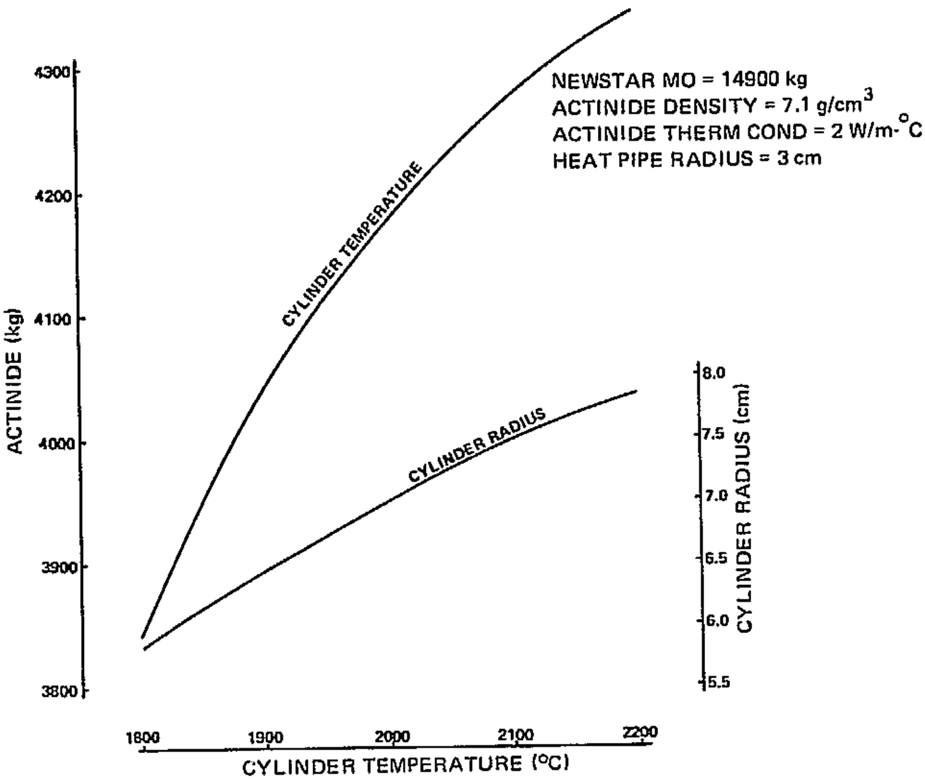


Figure 39. Payload versus cylinder temperature.

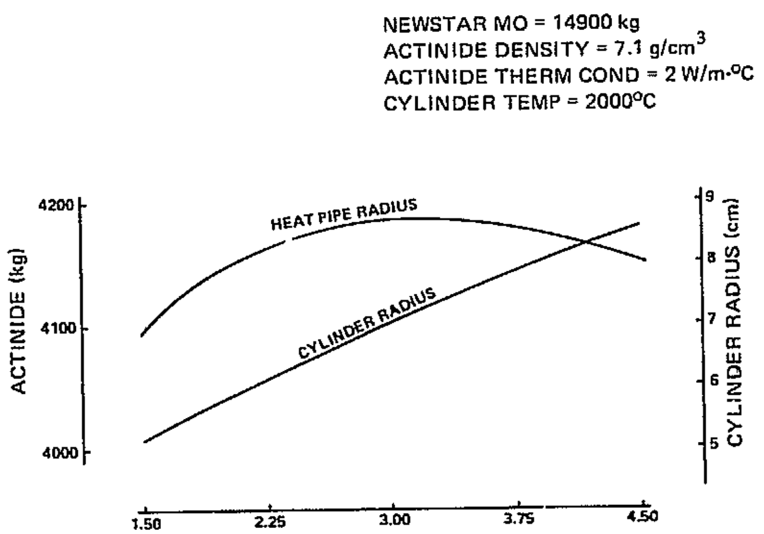


Figure 40. Payload versus heat pipe radius.

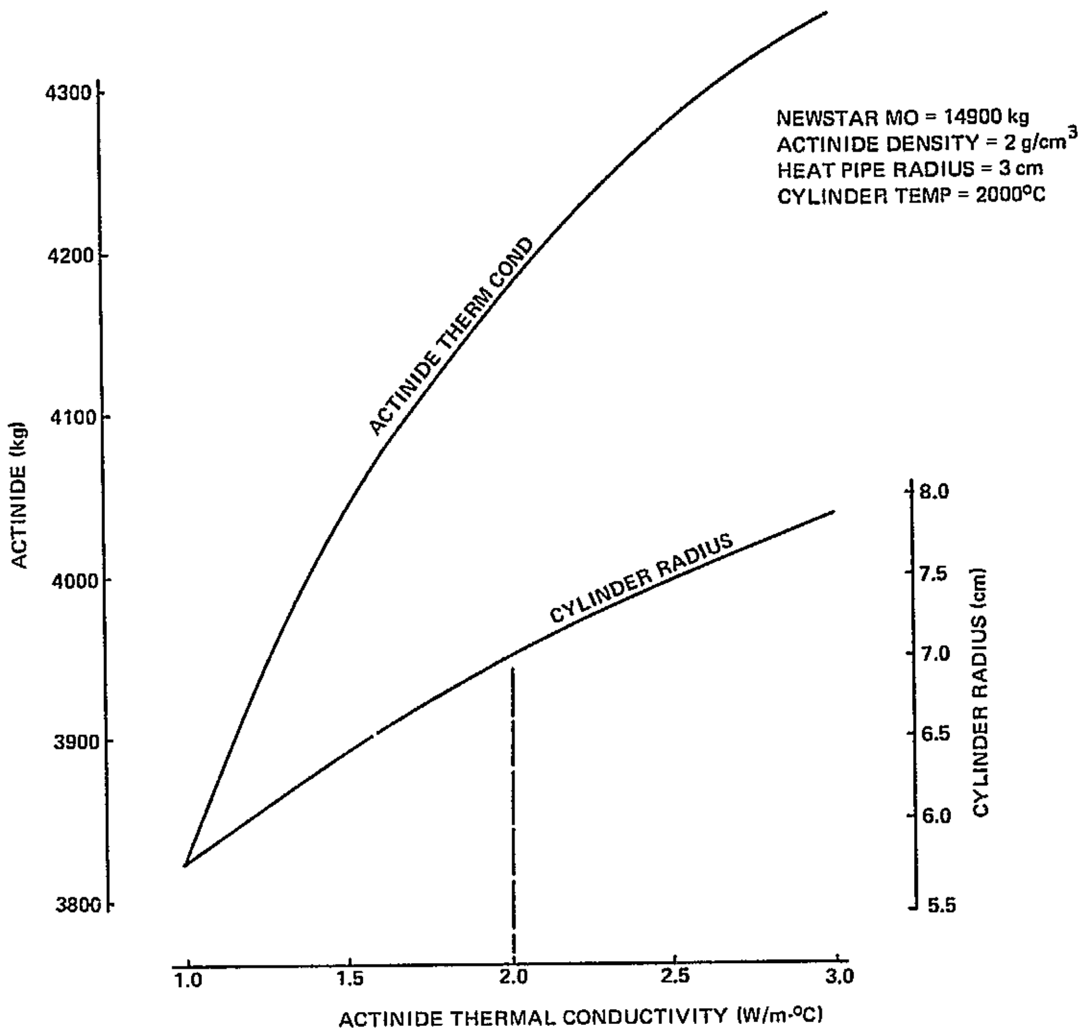


Figure 41. Payload versus thermal conductivity.

launches (Table 14). Two modes (all-chemical and Tug/NEWSTAR) are shown. Additionally, separation factors of 0.1 percent and 0.01 percent for uranium are treated separately.

It should be noted that NEWSTAR demands on Shuttle launch frequency are rather small.

TABLE 14. SHUTTLE TRAFFIC DENSITY FOR WASTE DISPOSAL

Year	Actinide Waste 0.01 percent U. PU		Actinide Waste 0.10 percent U. PU	
	Mode 1 Flights at 1530 kg/flt	Mode 3 Flights at 4140 kg/flt	Mode 1 Flights at 1530 kg/flt	Mode 3 Flights at 4140 kg/flt
1985	5	1	11	4
1986	2	1	4	1
1987	2	1	4	2
1988	2	1	5	2
1989	3	1	6	2
1990	3	1	7	2
1991	3	1	7	2
1992	4	1	7	3
1993	4	2	9	3
1994	4	1	9	4
1995	5	2	11	3
1996	5	2	11	5
1997	6	2	13	4
1998	6	2	13	5
1999	7	3	15	6
2000	8	3	16	5
2001	8	3	18	7
2002	9	3	18	6
2003	9	3	20	8
2004	10	4	21	7
Total Flts	2 × 105	2 × 38	2 × 225	2 × 83
Remaining Waste (kg)	489	3818	1009	1639

Note: Does not include actinide waste produced after the year 2000.

The use of mercury as a fuel for NEWSTAR could be considered an objection from two points of view. The first is that mercury is toxic, and the explusion of these ions from NEWSTAR could eventually result in a significant biospheric accumulation over many years of flight. Choosing Mode 3 eliminates this problem. The Tug burn places NEWSTAR (and its propellant) at escape velocity with respect to the Earth. Any ejected mercury from that point onward cannot return to Earth unless Earth directly intercepts the ion beam. The accumulation from such an event, when beam dispersion is accounted for, is so negligible as to be utterly discounted.

During a catastrophic abort, the entire mercury loading would be dumped into the ocean. But catastrophic aborts are extremely unlikely, and the amount of mercury added to the ocean (deep) would be well below the noise level of background mercury pollution.

The second possible objection to mercury is its availability (Table 15). While mercury is due to become increasingly scarce, NEWSTAR would require only 0.2 percent of the total U. S. demand by the year 2000.

TABLE 15. AVAILABILITY OF MERCURY

Estimated U.S. demand for mercury by year 2000	5.2×10^6 kg
Estimated world demand for mercury by year 2000	15.8×10^6 kg
Estimated world supply at ($43.5 per kg)	1.05×10^9 kg
Mercury required for NEWSTAR (Mode 3) per year	0.042×10^6 kg[a]

a. 0.2 percent of U.S. demand by year 2000.

The technical summary of the work presented to this point is that NEWSTAR disposal of actinides appears technically feasible. Certain areas — such as thermionic diode lifetime will require research and development — but no fundamental breakthroughs are required to construct the waste disposal vehicle.

It has been emphasized that separation of the actinides from the fission wastes and uranium is absolutely critical to the concept. This has been done on a laboratory scale but the process has not been macroscaled. One of the primary difficulties stems from the fact that production line operations must add reagents throughout the process. These reagents, in turn, become contaminated and must be dealt with. Care must be taken that the end product is not a larger, more difficult problem than was the initial product.

IX. ELIMINATION OF FISSION FRAGMENT WASTES

The logic that led to NEWSTAR was that solar system escape was a suitable disposal site for the actinides. The remainder of the waste, the fission fragments, has not been considered to this point; however, they pose a biologic health hazard and must be disposed of in some way.

It has been assumed that a separation is possible between the actinides and fission fragments, and this assumption is still in effect. However, the degree of separation is important, i.e., it is rather easy to make a "dirty cut" via a single stage separation. Each time a higher and higher purity separation is required, the difficulties mount exponentially.

Let us, then, weaken the separation requirements and insist only upon "reasonable" separations of the actinides and the fission fragments. (Reasonable will be undefined at this time — it is to be determined experimentally.) Thus, some fission fragments will remain in the actinides and some actinides will remain in the fission fragments.

The effect of a small percentage of fission fragments in the actinides will be to increase the gamma ray shielding requirements for NEWSTAR — a potential payload degradation. However, the inclusion of a small percentage of actinides in the fission fragments could well preclude geologic storage. Thus, reasonable cuts could well make space disposal of the residual fission fragments necessary.

To return the contaminated fission fragments to a relatively innocuous state will require several thousand years, but not several hundred thousand as is the case with the actinides. We note that solar orbits can certainly have stability guaranteed for a few thousand years.

This comment then opens up the possibility of disposal of (slightly) contaminated fission fragments in solar orbit while the actinides are sent to solar system escape. The advantage of the split disposal is that then small amount of long lived components (actinides) are used to power a vehicle to a very high energy mission — solar system escape. The bulk of the fission wastes (fission products) can then be safely eliminated with a lower energy mission-earth escape. It is reasonable to assume that the previous work done on NEWSTAR provides a basis for design of a vehicle to eliminate fission fragments. A simpler vehicle could be expected, however. One could certainly use the same launch site, ground handing procedures, launch procedures, radiation safety, tracking, underwater recovery, and the design of the bird could make use of the ascent cooling innovations for NEWSTAR. In this case, the waste heat of the fission fragments would not be used to produce power. The heat would be a definite detriment. Electric propulsion for a solar orbit is not needed since the mission is of rather low energy compared to solar escape.

If the heat from the fission fragments is not to be used, it is expedient to allow the wastes to cool for some time before transportation. A cool-down time of 30 years is assumed.

Even after this time, the gamma radiation from the wastes is intense; a shield thickness of 9.3 cm of tantalum is necessary. It was again assumed that the fission wastes were packaged (0.3175 cm steel) into cannisters and 19 of these cylinders were stacked into a hexagon (with 3 cm radius hole through the center of each cylinder) in the same configuration as NEWSTAR. The package size was 92 cm long and 173 cm in diameter. The steel weight was 494 kg. The total shield weight in this case was over 10 000 kg.

Cooling during ascent is provided by the same methods as used in NEWSTAR — i.e., water or an organic fluid is to flow through the holes between and through the hollow cored cannisters. The fission wastes, at 30 years of age, produce only approximately 14 percent of the heat generated by NEWSTAR wastes. If we assume a conductivity of 2 W/m K and use water as the cooling fluid, the hottest point within the cannister will be approximately 214°C (Fig. 42).

One difficulty with transporting fission wastes is that much of the periodic table is represented. While a homogeneous mixture of actinide oxides forms a working basis for NEWSTAR, the fission fragments contain some very difficult elements — such as selenium, rubidium, iodine, tellurium, and cesium. These elements are volatile and/or corrosive in many compounds. The proper chemical form for the space transportation of fission fragments is unresolved. Such solutions as phosphate glass imbedding would probably require too much matrix and too little fission fragments (i.e., the traffic density would become prohibitive).

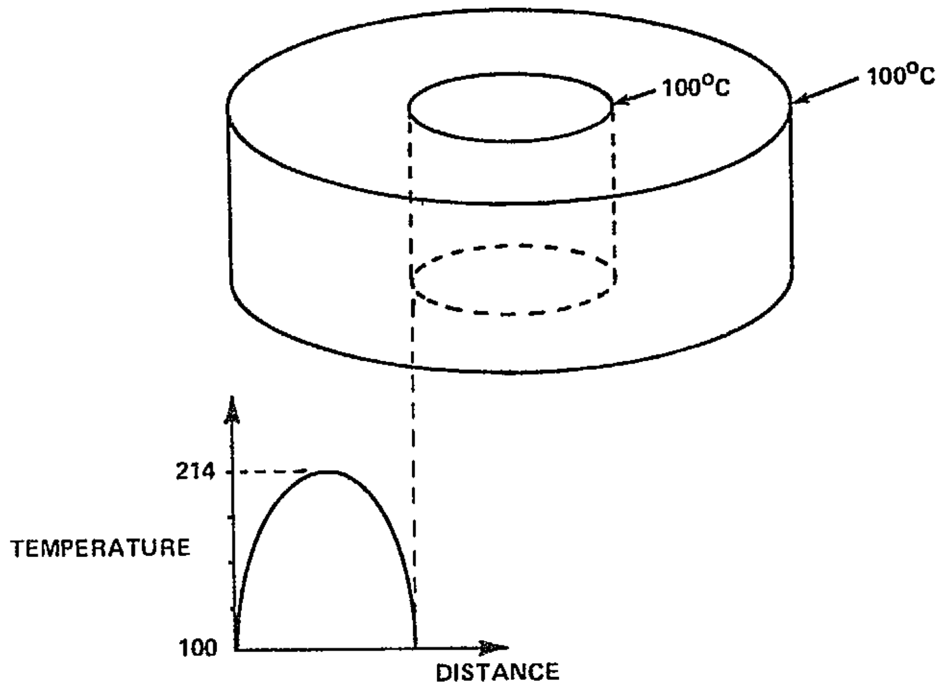


Figure 42. Temperature profile.

We again assume that two Shuttle launches will be made per fission fragment payload. Aboard Shuttle Number 2, the fission fragments require much support equipment. The gamma shield, mentioned earlier, occupies much of the Shuttle lifting capacity (total lifting capacity is 29 484 kg). Additionally, the steel packaging (cannister material) must be carri·d. Cooling water and water handling equipment for ascent cooling must be added. Finally, the cocoon for abortive reentry and a pallet to attach the entire package to the Shuttle must be included in the total weight. A contingency of 15 percent is also included.

When the weights are all accounted for, we have an excess lifting capacity of 7580 kg to Earth orbit. This is a larger payload than NEWSTAR because the radiator, electric thrust system, etc., have been eliminated.

Since electric propulsion is not to be used to achieve the solar orbit, the Tug has been baselined as the most useful stage.

A very respectable solar orbit can be attained with a single burn of the Tug. The apohelion of such an orbit (3.2 AU) would place it between Mars and Jupiter at its furthest point. The perihelion, to a first approximation, would be at the radius of Earth's orbit. Dynamic stability of these orbits would be investigated as work proceeds.

The perihelion could be moved away from the Earth's orbit by a two-burn maneuver, but this may not be possible since no active cooling will be provided to the fission fragment package.

The ultimate temperature of the fission fragment package is not presently known. It is assumed that once the fission fragment package is separated from the second Shuttle, all active cooling will cease. If we assume 2 hours preparation time in orbit and a Tug flight time of 1000 s, the temperature of the package is nominal at Tug ignition. The temperature rise rate is only 150°C/hour even if it is assumed that no heat is lost from the package — a very conservative assumption.

Future work will involve a careful calculation of the ultimate package temperature. Such calculations will determine the feasibility of a two-burn escape to solar orbit.

The Shuttle traffic density for elimination of all fission fragments wastes (Table 16) is obviously going to be much greater than the traffic density to eliminate only the actinides. Since a 30 year cool-down time has been assumed, we would not expect to eliminate wastes generated in 1970 until the year 2000, etc. It must be noted that the figures shown in Table 16 are only for the given year — i.e., we would expect approximately 28 or 29 payload flights in the year 1986.

TABLE 16. TRAFFIC DENSITY (FISSION FRAGMENTS)

Year Waste is Generated	Amount Generated (metric tons)	Year of Launch	Number of Payload Flights	Total Number of Shuttle Flights
1970	9	2000	1+	2
1975	42	2005	6	12
1980	150	2010	20	40
1985	210	2015	28	56
1990	250	2020	33	66

Figure 43 presents two concepts of space disposal of fission wastes. The left side of the figure shows the Tug disposing of fission fragments into solar orbit, and the right side shows NEWSTAR carrying actinides to solar system escape.

It is believed that the material presented here is a reasonable solution to an existing problem. It is a method to resolve the problem of nuclear waste disposal for all time.

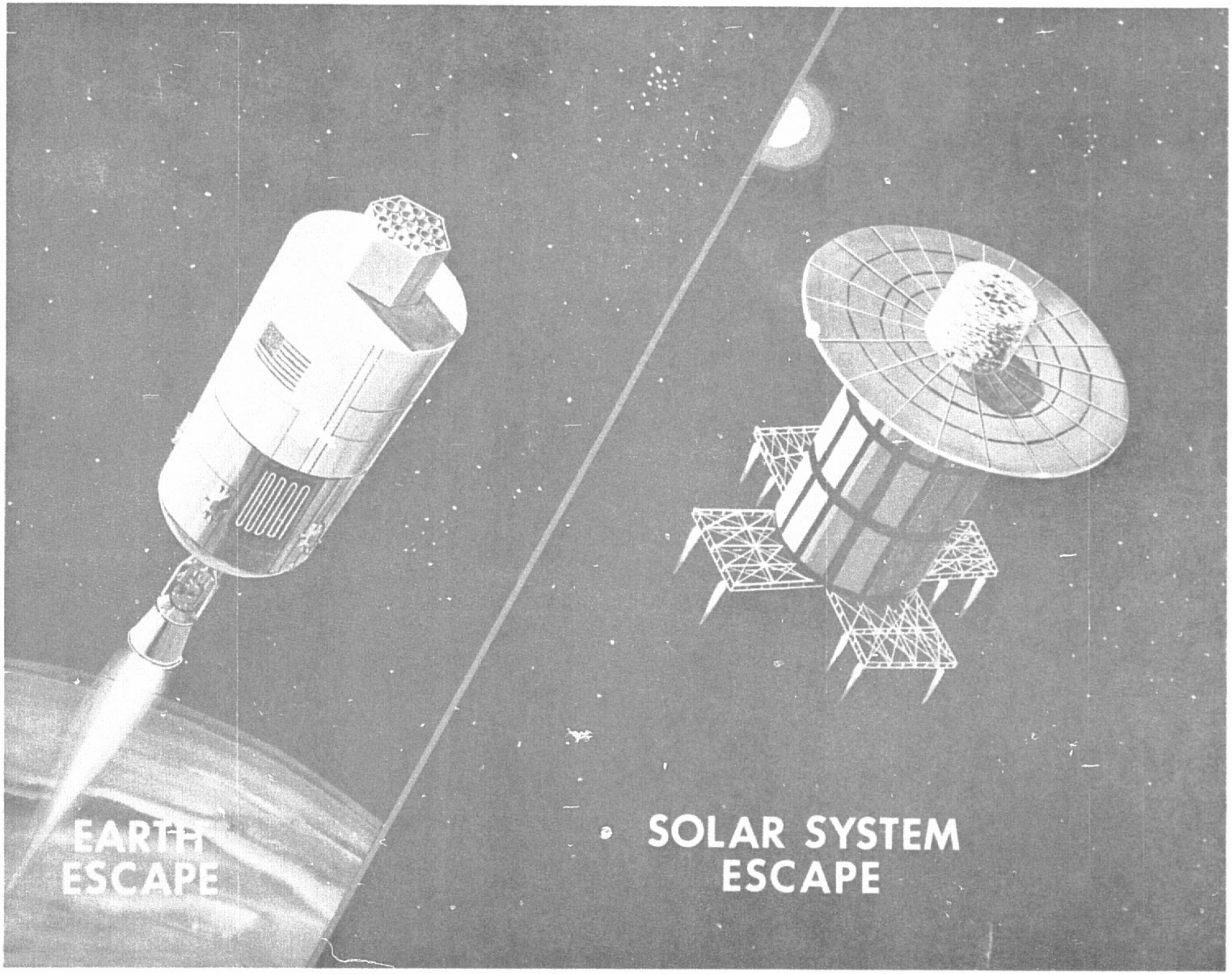


Figure 43. Concepts of space disposal of fission wastes.

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1. Anonymous: Feasibility of Space Disposal of Radioactive Nuclear Waste. Vol. I: Executive Summary; vol. II: Technical Summary. NASA TM X-2912, Lewis Research Center, National Aeronautics and Space Administration, May 1974.

2. Claiborne, H. C.: Effect of Actinide Removal on the Long-Term Hazard of High-Level Waste. ORNL-TM-4724, January 1975.

APPROVAL

NUCLEAR ENERGY WASTE-SPACE TRANSPORTATION AND REMOVAL

By R. E. Burns

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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