NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-664

Advanced Design Concepts in Nuclear Electric Propulsion

M. L. Peelgren
J. F. Mondt

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
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PREFACE

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

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ABSTRACT

This report represents the final documentation of several conceptual design efforts which were in progress at the time the nuclear propulsion programs were terminated in January 1973. Three major areas of investigation were (1) design efforts on spacecraft configuration and heat rejection subsystem, (2) high-voltage thermionic reactor concepts, and (3) dual-mode spacecraft configuration study. No conclusions will be drawn since none of the efforts were completed. Rather, the goal is to archive the material in a concise, complete, and logical manner so that it is available for any future developments or application of Nuclear Thermionic Reactor Power or Nuclear Electric Propulsion.

I. INTRODUCTION

The Thermionic Reactor Systems Project at the Jet Propulsion Laboratory included several areas of investigation at the time of termination on January 5, 1973. This report will confine itself to presenting the objectives and status of the advanced system and subsystem design concepts being directed under that project. There were three major efforts involved.

The first major effort addressed the questions of spacecraft configuration and the heat rejection subsystem for the reactor. The configuration evolved into two separate cases: (1) a planetary spacecraft injected into its trajectory by means of a Centaur stage injection from ~260-n-mile Earth orbit, and (2) a planetary spacecraft capable of spiraling out from ~260-n-mile Earth orbit into a heliocentric transfer trajectory. The power requirements are ~120 kWe for case 1 and >240 kWe for case 2. Earlier baseline designs showed the heat rejection subsystem as either a tube and fin radiator or, later, as a pumped primary loop with heat pipes brazed to it and to each other to form the radiating area required. The designs discussed herein represent an extension of the heat-pipe-radiator concept into integral heat-pipe-radiator panels entirely without brazes. In addition, the support structure and radiator sizing were accomplished as part of the configuration design effort.

The second of the major design efforts was directed toward the investigation of conceptual ways in which the thermionic reactor output voltage could be raised from the nominal value of $\tilde{2}3$ V to something approximately double that value without a loss in reactor reliability. A corollary to this was to increase the reliability of the reactor by eliminating any source of single-point failure.

A third major effort was the study of NEP spacecraft useful for dual mode operations. Specifically, this means operation both in a geocentric mode as an orbit-raising NEP Tug and as a NEP planetary spacecraft. The geocentric mode predicted large variations in payload mass, and placed some rather formidable constraints on the configuration regarding the center of gravity of the NEP Tug with respect to the thrust vector.

II. BACKGROUND

The purpose of this report is to present, in permanent record, the objectives and status of the design studies of the project. This does not include information or data that already is a part of existing or planned documents. Reports are available (Refs. 1 - 6) which give the background on the work discussed in detail below. In addition, a brief history of the evolution of spacecraft configurations is included as Appendix A.

III. CONFIGURATIONS AND HEAT REJECTION SUBSYSTEM

The design effort on heat rejection radiators was essentially a low-level, continuous, part-time complement to various studies which brought up such questions as power vs payload tradeoffs, injected vs spiral-out trajectories, folding vs telescoping configurations, and maximum power options. The heat rejection subsystem was configured in parallel with the various spacecraft configurations and, in addition, was studied for continuing improvement from a structural and performance standpoint. This included the questions arising from fabrication methods for the many heat pipes which are part of the heat rejection subsystem. The early evolutionary configurations are given in Appendix A.

The chief drivers of spacecraft configuration, both early and late, have been (1) launch vehicle and/or launch configuration, (2) power level, (3) specific mass, and (4) payload-propulsion system interactions. Secondary effects include various changes in high- and low-temperature radiator rejection temperatures, reactor configuration, shield size, number of thrusters, trajectory parameters, and science. These secondary drivers, though important, did not usually change a basic generic configuration. Aside from those illustrated in the appendix, the following descriptions and drawings represent the later work in this area.

The side thrust configuration, illustrated in Appendix A, represents the preferred arrangement for planetary missions. In support of the NASA-AEC Advanced Propulsion Comparison (APC) Committee's work involving geocentric missions (Ref. 7), several configuration drawings were made. Examples of these are given in Figs. 1 and 2. Figure 1 is a 120-kW, axial thrust configuration; Fig. 2 is a 240-kW, axial thrust configuration. Both are folded during Shuttle launch. As a follow-on to this work, some investigations were made to see if configurations could be improved. Figure 3 is an example of a configuration which has several advantages over former configurations:

(1) Payload is concentric to Shuttle bay and Tug interface adapter.
(2) P/C panels are planar for good thermal control.
(3) There is a greater payload envelope for given power level.

The same applies to Fig. 4 except that it is sized to completely fill the Shuttle bay. While this precludes any payload being delivered on first launch, it enables greater performance on subsequent orbit-raising operations. Both configurations employ the axial thrust concept. Additionally, Fig. 4 illustrates a 400-kWe growth version of the 240-kWe NEP system. This growth is based on:

(1) A 60% increase in the power output from a 324 TFE, 240-kWe reactor. This has been demonstrated in a laboratory converter test.

(2) A 60% increase in the current density of the 30-cm ion engine by increased uniformity in ion discharge velocity. This also has been demonstrated with laboratory-type thrusters.

Initial efforts in the design of the heat rejection subsystem (HRSS) indicated the desirability of the use of high-temperature (~760°C) sodium heat pipes in a radiator for the thermionic reactor waste heat rejection. Advantages of heat pipes are (1) micrometeoroid shielding of reactor coolant manifolds, (2) redundancy (no single-point failures), (3) nearly isothermal operating conditions (less area required), (4) lightweight (lighter than stainless steel flow-through radiators with beryllium armor and fins), and (5) after failure operation as fins for adjacent pipes (if bonded or brazed together). The brazing of many heat pipes to a primary coolant loop and to each other is not easily accomplished (Ref. 8). In an attempt to alleviate the braze problem a design was conceived whereby the entire heat pipe radiator is one integral unit with no brazes. This means the fabrication became a process of machining and welding and therefore more amenable to quality control. Interestingly enough, the weight is also less due to the absence of braze fillets, the smaller metal wall thickness between heat pipes, and the preferential thinning of walls not required to meet meteoroid nonpuncture criteria. Furthermore, heat transfer between the primary coolant loop and between heat pipes is better due to the absence of brazes. This concept was referred to as an integral heat pipe panel and is illustrated in Figs. 5 and 6. One figure shows a configuration as a flat panel. The other figure shows a cylindrical configuration which acts as a monocoque structure additionally. The cylindrical integral panel could also be fabricated with circumferential heat pipes instead of longitudinal, as shown, if it were required.

During the study of integral heat pipe panels, it was learned that the Shuttle wing leading edge was being designed to use an array of heat pipes (brazed together) to transmit the heat from the wing's leading edge stagnation point to an area removed from the edge to radiate heat and maintain a reasonable wing leading edge equilibrium temperature. From the in-house design work done on integral heat pipe panels a conceptual design of a leading edge test panel was drawn and is shown in Fig. 7. Obviously, this design concept has no relation to the thermionic program objectives but is included to show applicability of the integral heat-pipe concepts to other uses.

IV. HIGH-VOLTAGE CONCEPTS: THERMIONIC REACTOR

This investigation was being conducted by Gulf-General Atomics (GGA) under contract to JPL. The primary objective of the study was to screen and investigate concepts which indicated a potential for yielding a higher voltage output from the reactor. In addition to providing a higher output voltage from the reactor, there were other considerations in the design effort. Design flexibility was desired to the extent of not being tied to a particular number of thermionic fuel elements (TFE's) per string. Also, the reduction of sites for single-point failures was an objective. The discussion of these concepts is included as Appendix B and represents a summary of the effort completed prior to contract cancellation. It is used verbatim from the last Gulf-General Atomic Technical Progress Report (GULF GA-C 12065, 1/73).

Only the first phase of the work was completed, that of conceptualizing alternative approaches. Forty designs were offered, aimed at increasing voltage and/or reliability objectives. Only preliminary screening comments are offered.

V. DUAL MODE NEP SPACECRAFT CONFIGURATION STUDY

The objective of this study was to investigate the feasibility of designing a dual mode spacecraft, that is, one which could be used not only for a planetary vehicle but also in a geocentric mode as an orbit-raising Tug operating between the Shuttle orbit and a synchronous orbit, for example. The incentive for doing this is the fact that a spacecraft capable of performing both functions may find wider applicability than a single-function, specialized vehicle. The rationale was simply to study autonomous vehicle configuration(s) that would permit attachment to a passive or inoperative payload (or no payload at all) and be capable of slight modification to enable "science" to become the payload and also provide all the support, communication, guidance, and control to enable the science to become part of a planetary spacecraft.

This configuration study was being conducted by a design team of specialists at JPL. Three basic configurations were considered as shown in Figs. 8, 9, and 10. The study termination did not allow sufficient effort to select a "preferred" configuration. Instead, the work is summarized as follows:

(1) Thermal control comments and general comments on the configurations.

(2) A matrix comparing the pros and cons of the three configurations (Table 1).

(3) Weight lists for the three configurations (Table 2).

(4) Shuttle CG locations for each (Table 2 and Fig. 11).

VI. THERMAL CONTROL COMMENTS AND GENERAL COMMENTS

The following discussion documents the thermal comments and general comments concerning the Nuclear Electric Propulsion Spacecraft Configurations. Three configurations have been developed for comments during this task. In two of the configurations (Figs. 8 and 10, respectively), the ion engines thrust toward the end of the spacecraft which contains the reactor, while in the other configuration (Fig. 9) the ion engines thrust in a direction away from the end which contains the reactor.

The configurations thrusting toward the reactor end have several unique features. These configurations maintain a "clean" end of the spacecraft where science instruments may be located. The end of the spacecraft which contains the reactor would also be "contaminated" by the ion engine exhaust. These configurations are preferred from the temperature control viewpoint. The high-temperature components (i. e., the reactor and primary radiator) are located at one end of the spacecraft, with the cooler components (i. e., ion engines and power conditioners) located near the middle of the spacecraft and the coolest components (i. e., spacecraft and science electronics and the science instruments) located at the other end of the spacecraft. These configurations therefore offer the greatest thermal isolation of the components with different temperature requirements. Additionally, these configurations allow science data taking during thruster operation. These configurations also lend themselves well to a geocentric space tug. The spacecraft to be thrusted could be attached to the "clean" end of the space tug. The thermal interface with the spacecraft to be thrusted is also simplified with these configurations.

The remaining configuration has the desirable feature that all of the thrust developed is used, whereas in the other two configurations some thrust is lost due to the cosine effect of tilting the thrusters. In this configuration the thrusters are easier to temperature-control, but this is offset by increased science temperature control problems. This configuration has a distinct disadvantage in that the thrusters must be turned off during science data taking. This configuration also does not lend itself to a geocentric space tug. The thermal interactions between the space tug and the spacecraft are greatest in this configuration.

From a temperature control viewpoint, all three configurations are thermally feasible. Several potentially significant items have not been investigated. The internal thruster design has not been reviewed. However, sufficient area does exist to radiate the power dissipated by the ion engines. The heat generation in the lithium hydride has not been investigated. Sufficient thermal radiation area for the primary radiator exists in all three configurations. The power conditioners have sufficient radiation area in all three configurations.

Thermal testing of any of the three configurations poses special problems. The power levels and temperatures encountered in these spacecraft far exceed current experience. If a temperature control model test is performed, the heat generation is normally simulated by electrical resistors. This amount of power required would seem to offer problems. The cold wall in the space simulator would be required to handle this large quantity of dissipated power. It is questionable if current space simulators could be used unmodified. Temperature control coatings currently in use at JPL would not be satisfactory at some of the elevated temperatures. However, high-temperature coatings and surface treatments do exist, and their implementation does not seem to pose any unsolvable problems.

Testing of the flight spacecraft poses many of the same problems as testing the temperature control model. Additionally, the problems of using a "live" reactor must be considered. Developmental tests using the reactor must also be considered, since the high-temperature insulations which may be used to separate the reactor from the lithium hydride may require a vacuum for proper operation.

In conclusion, all three Nuclear Electric Propulsion Spacecraft configurations are feasible from a temperature control viewpoint. The thermal design and analysis can be performed using existing techniques. Existing construction techniques of temperature control hardware are sufficient for the low-temperature components. High-temperature insulation and surface coatings which will be necessary for these spacecraft do exist, but their suitability for this application is not known. Heat pipes may be required in areas where a large amount of heat is dissipated in a small area (i.e., the ion engines). Finally, with respect to preflight checkout, the spacecraft must be flown based largely on analysis or else the capability of the thermal testing facilities must be greatly increased.

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7. Advanced Propulsion Comparison Study, Geocentric Mission Analysis Progress Report, Lockheed Missiles and Space Company, Inc., October 1972.

8. Kikin, G.M., and Peelgren, M.L., "Test of a 50-kw Heat Pipe Radiator," ASME Paper No. 71-WA/HT-16, November 1971.

Table 1. NEP Spacecraft Comparison Matrix

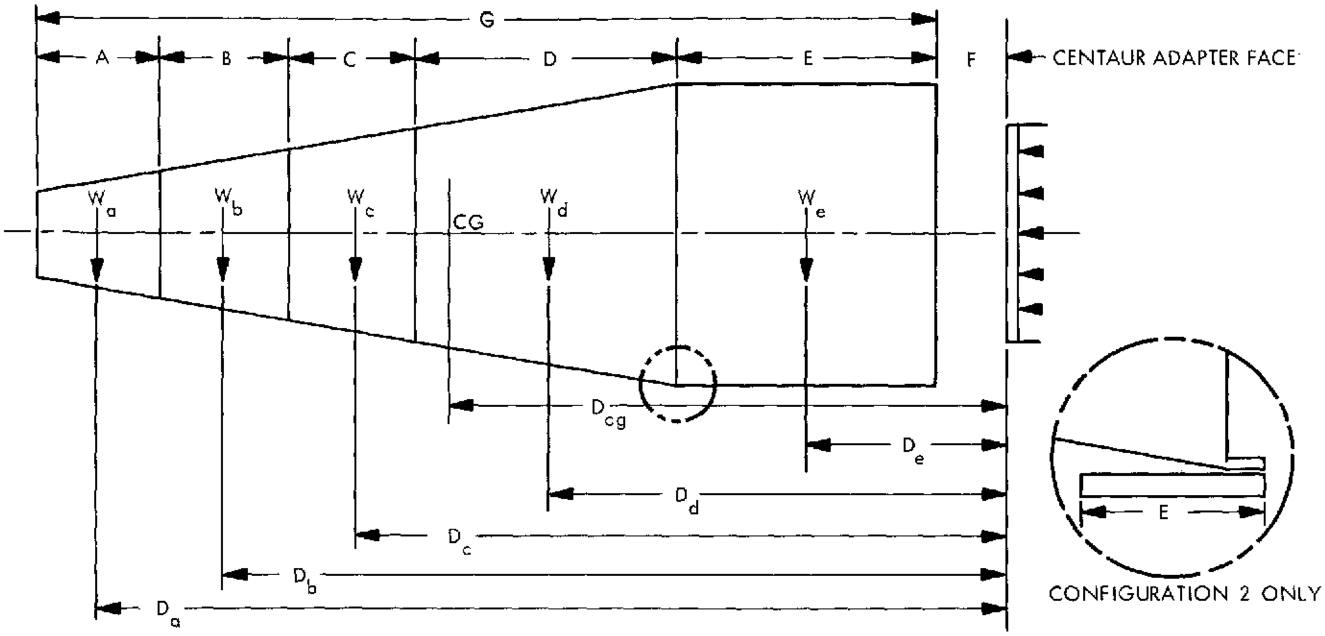
Comparison of three configurations in these categories	Configuration 1: Telescoping power conditioner (thrust over reactor)	Configuration 2: Shortened spacecraft (thrust opposite reactor)	Configuration 3: Power conditioners over Centaur (thrust over reactor)
1. Integration with the proposed Centaur/Shuttle launch system.	Fits in Shuttle bay with no overhang on Centaur. No Centaur pallet modification. Can be supported at reactor end to meet CG requirements. Reactor forward launch CG and emptied Centaur landing CG beyond limits (Fig. 1).	Fits in Shuttle bay with no overhang on Centaur. No Centaur pallet modification. Can be supported at reactor end to meet CG requirements. Reactor forward launch CG and emptied Centaur landing CG beyond limits (Fig. 1).	Power conditioners overhang Centaur. Modification of Centaur pallet no major problem. S/C cannot be supported at reactor end with Centaur due to length. Reactor forward launch CG and emptied Centaur landing CG beyond limits (Fig. 1).[a]
2. Mission profile penalties associated with each configuration due to thrust axis, system mass, escape velocity.	Lesser spacecraft mass increases excess escape velocity (Centaur burn), and decreases trip time during ion propulsion. However, thruster angle increases trip time during ion propulsion. (Angle can possibly be reduced.)	Greater spacecraft mass decreases excess escape velocity (Centaur burn) and increases trip time during ion propulsion. No thruster angle loss. Possible increase in trip time due to turning thruster off for science gathering.	Greatest spacecraft mass decreases excess escape velocity (Centaur burn) and increases trip time during ion propulsion. Also, thruster angle increases trip time during ion propulsion. (Angle can possibly be reduced.)
3. Integration of science onto spacecraft.	Clean end of spacecraft looking away from thrust direction. Greater than hemispherical view for science. Any science that needs deployment can be left deployed. Thrusting can be continuous. Therefore, greater mission reliability.	All science must be relatively close to spacecraft during thrusting and deployed, if necessary, while thrusters are off. Science flexibility and visibility may be limited. Multiple turning off thrusters and any multiple science deployments reduces mission reliability.	Clean end of spacecraft looking away from thrust direction. Greater than hemispherical view for science. Any science that needs deployment can be left deployed. Thrusting can be continuous. Therefore greater mission reliability.
4. Adaptability of spacecraft as geocentric tug with minor modifications.	Full diameter of Shuttle available with Centaur to a length of 1.5 meters maximum. Science and high gain antenna on payload.	No space available with Centaur. Can be adapted to shorter booster by using ion shields protecting payload. 3.5-m-diameter available. Science and high-gain antenna on payload.	No space available with Centaur. Full diameter of Shuttle available. Science and high-gain antenna on payload.
5. Payload-carrying adaptability for outer planet missions.	Is adaptable because of clean end (minimum ion and nuclear radiation contamination). Payload mounted aft of power conditioners.	Not as good for cruise instruments.	Is adaptable because of clean end (minimum ion and nuclear radiation contamination). Payload mounted aft of power conditioners.
6. Requirements and difficulties of articulating structures.	Spacecraft articulation required. Cabling problems during articulation severe. Articulation takes place while Centaur connected to Shuttle. Therefore, if mission failure occurs, recovery may be possible.	No spacecraft articulation required. Antenna needs one deployment; some science may need multiple deployments during mission which affects science reliability.	No spacecraft articulation required. Science and antenna need deployment only once.

[a] Configuration 3 cannot be adapted to Shuttle/Centaur launch.

Table 1 (contd)

Comparison of three configurations in these categories	Configuration 1: Telescoping power conditioner (thrust over reactor)	Configuration 2: Shortened spacecraft (thrust opposite reactor)	Configuration 3: Power conditioners over Centaur (thrust over reactor)
7. Load paths and relative weight penalties associated with spacecraft/ Centaur/Shuttle combinations.	Centaur adapter can attach to neutron shield. Centaur needs structural help from Shuttle attach points and/or Centaur pallet. Weight = 10657 kg	Centaur adapter can attach to neutron shield. Centaur needs structural help from Shuttle attach points and/or Centaur pallet. Weight = 11035 kg	Centaur adapter must attach to high-temperature radiator. High loads through high-temperature radiator from mass of propellant, shield, and reactor. Centaur needs structural help by Shuttle picking up spacecraft CG. Weight = 11320 kg
8. Mercury tank integration and relative efficiency as shield.	Effective mercury thickness = 5.95 in. May require additional shielding.	Effective mercury thickness = 4.32 in. Will probably require additional shielding.	Effective mercury thickness = 4.36 in. Will probably require additional shielding.
9. Requirement of erosion shield and penalties associated.	Shield required. Weight is 320 kg. Need better erosion rates on shield.	No shield required.	Shield required. Weight is 300 kg. Need better erosion rates on shield.
10. Spacecraft adaptability to larger radiating areas for high-temperature radiator and power conditioner.	Capable of growth.	No growth capability within Shuttle/ Centaur constraints.	Capable of growth.
11. Spacecraft adaptability to thrust vector pointing.	Two-axis gimbaling may be required.	Translating array or 2-axis gimbaling may be used. Deployment interference with science and high-gain antenna.	Two-axis gimbaling may be required.

Table 2. Nuclear Electric Propulsion Spacecraft; Dimension and Weight Summary



Drawing Number	J10059996	J10059995	J10059997
Item	Configuration 1	Configuration 2	Configuration 3
A	1230 mm	1230 mm	1230 mm
B	480	480	480
C	540	540	540
D	4170	3030	3320
E	3540	2740	3540
F	0	0	-1090
G (length stowed)	6880	8020	8020 (to mtg.) 9110 (overall)
D_a	6250	7390	7390
D_b	5396	6536	6536
D_c	4910	6050	6050
D_d	2390	4471	3958
D_e	1450	1600	1550
D_{cg}	4356	5599	5408
W_a	1647 kg	1653 kg	1652 kg
W_b	1228	1508	1494
W_c	4991	5254	5260
W_d	1014	1300	1207
W_e	1777	1320	1707
W (total weight)	10657	11035	11320

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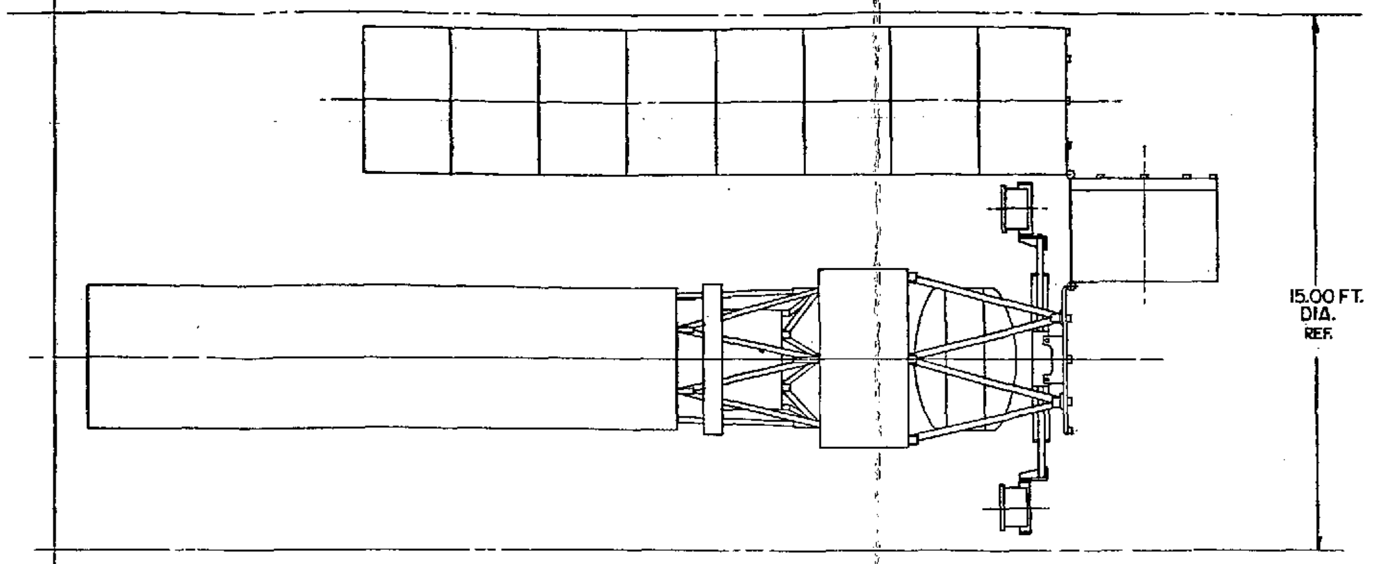
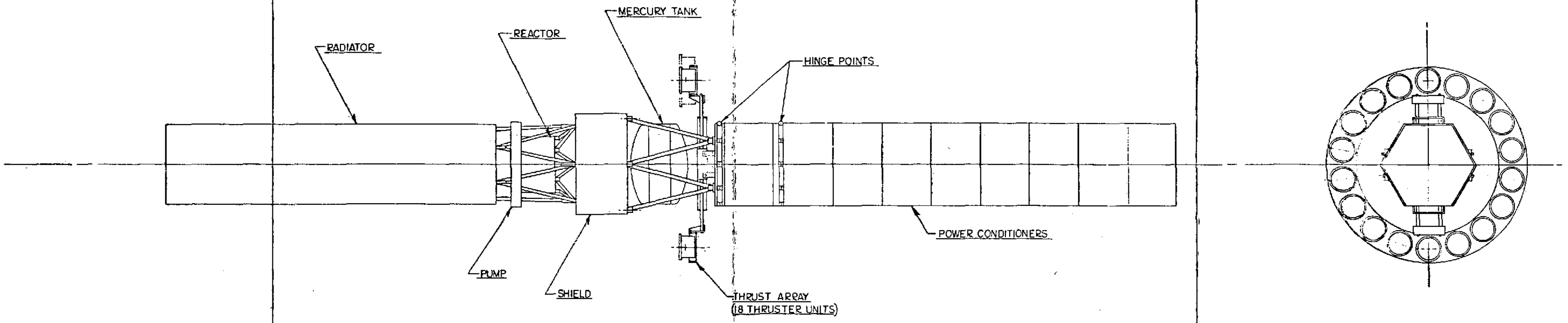


SPACECRAFT (FOLDED)



120 KW_e NUCLEAR ELECTRIC PROPULSION SPACECRAFT

LENGTH, FT. ——50.00
DIAMETER FT. ——9.75

Figure 1
Configuration "A" Thermionic Reactor Spacecraft

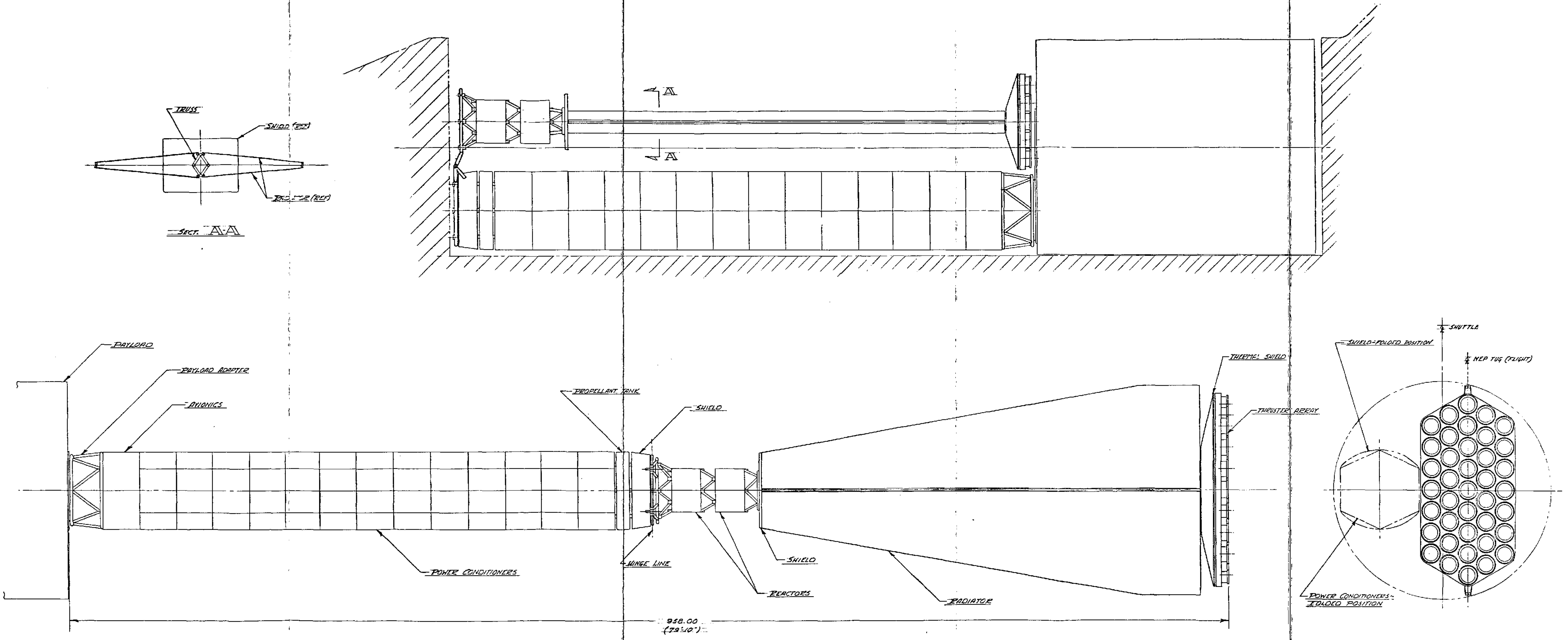


Figure 2
Configuration "C" NEP Tug

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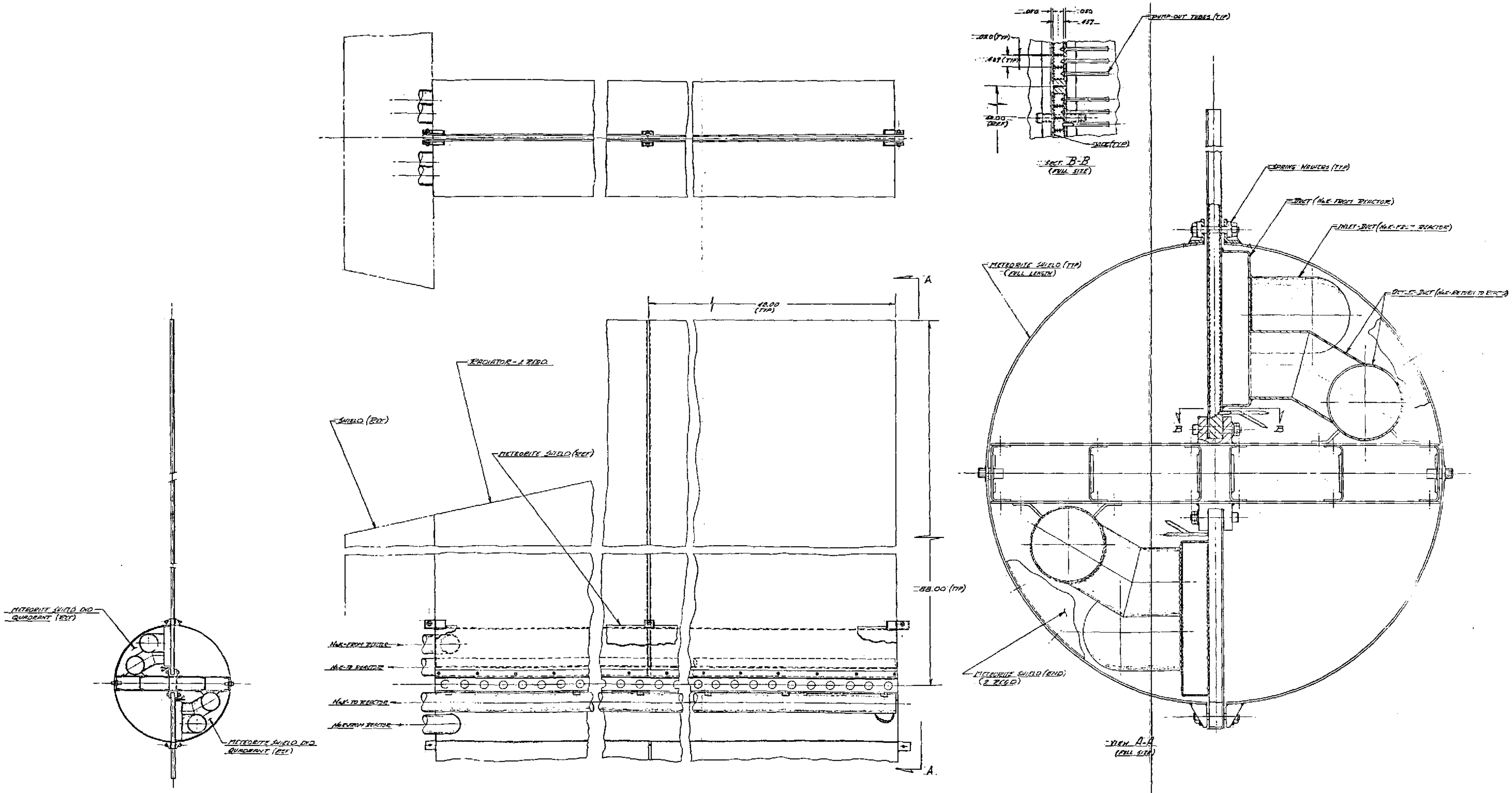


Figure 5

Radiator Assembly - High-Temperature Heat Pipe

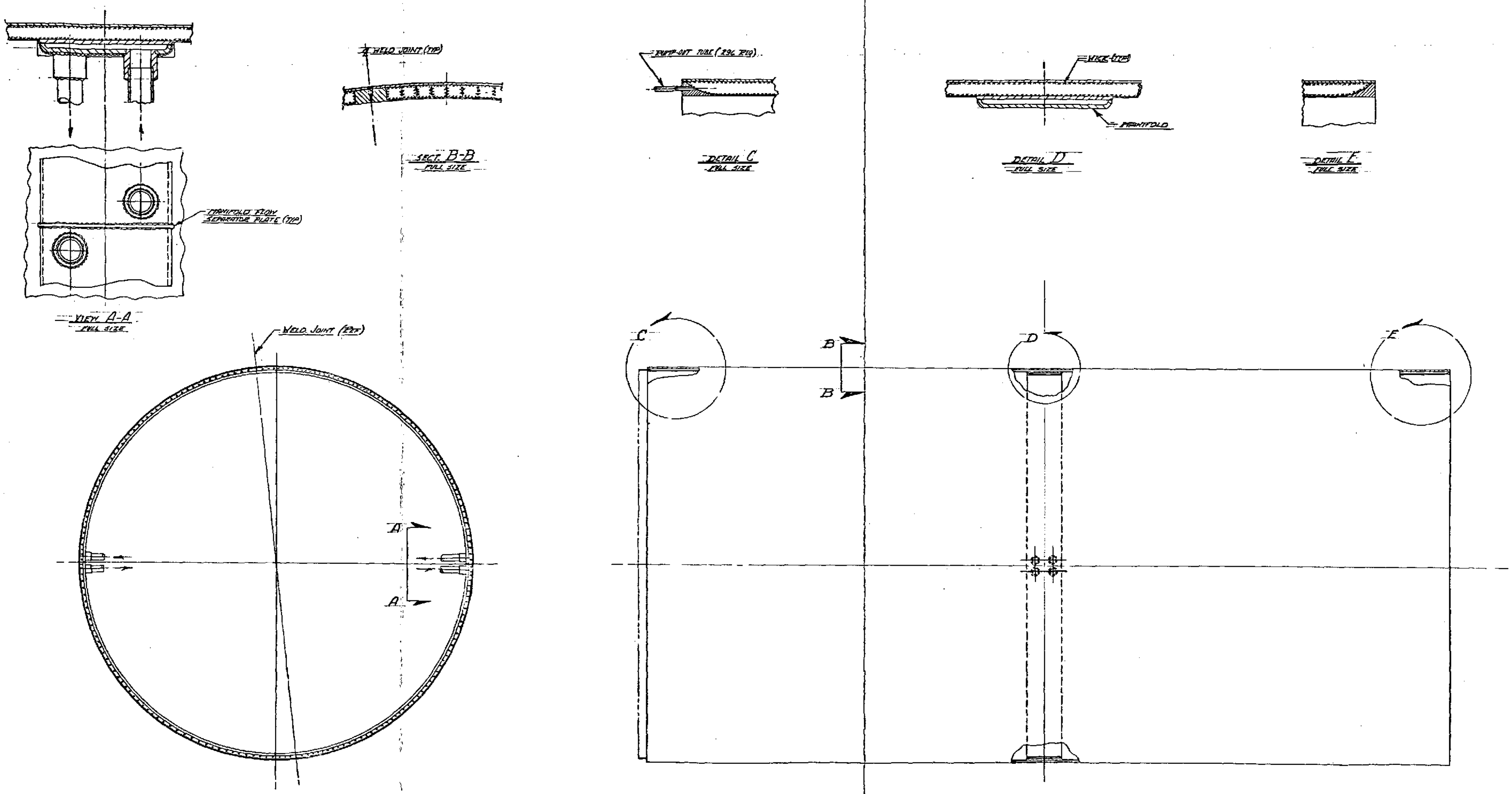


Figure 6

Radiator - High Temperature NEP TUG

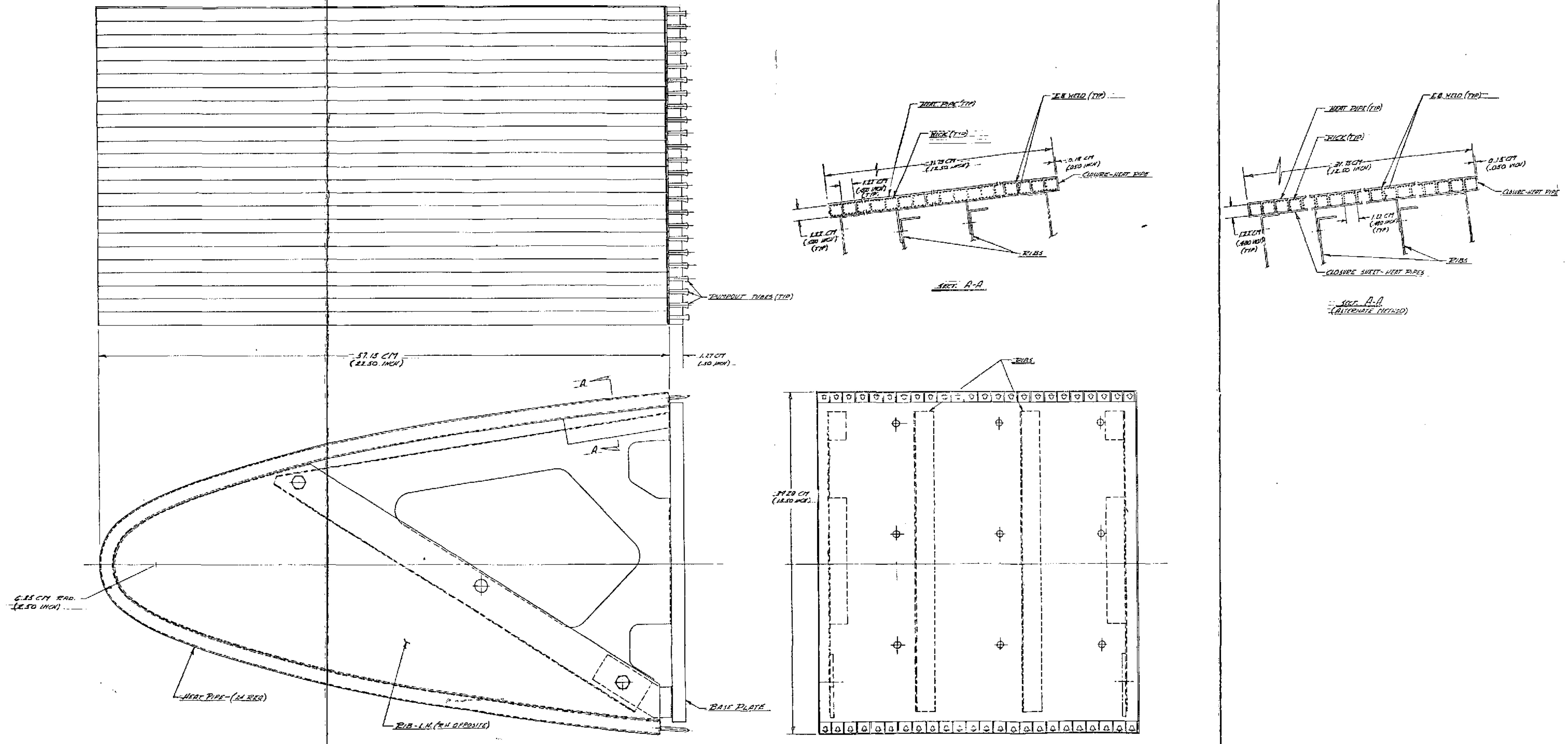


Figure 7

Proposed Heat Pipe Leading Edge Assembly (Test Section)

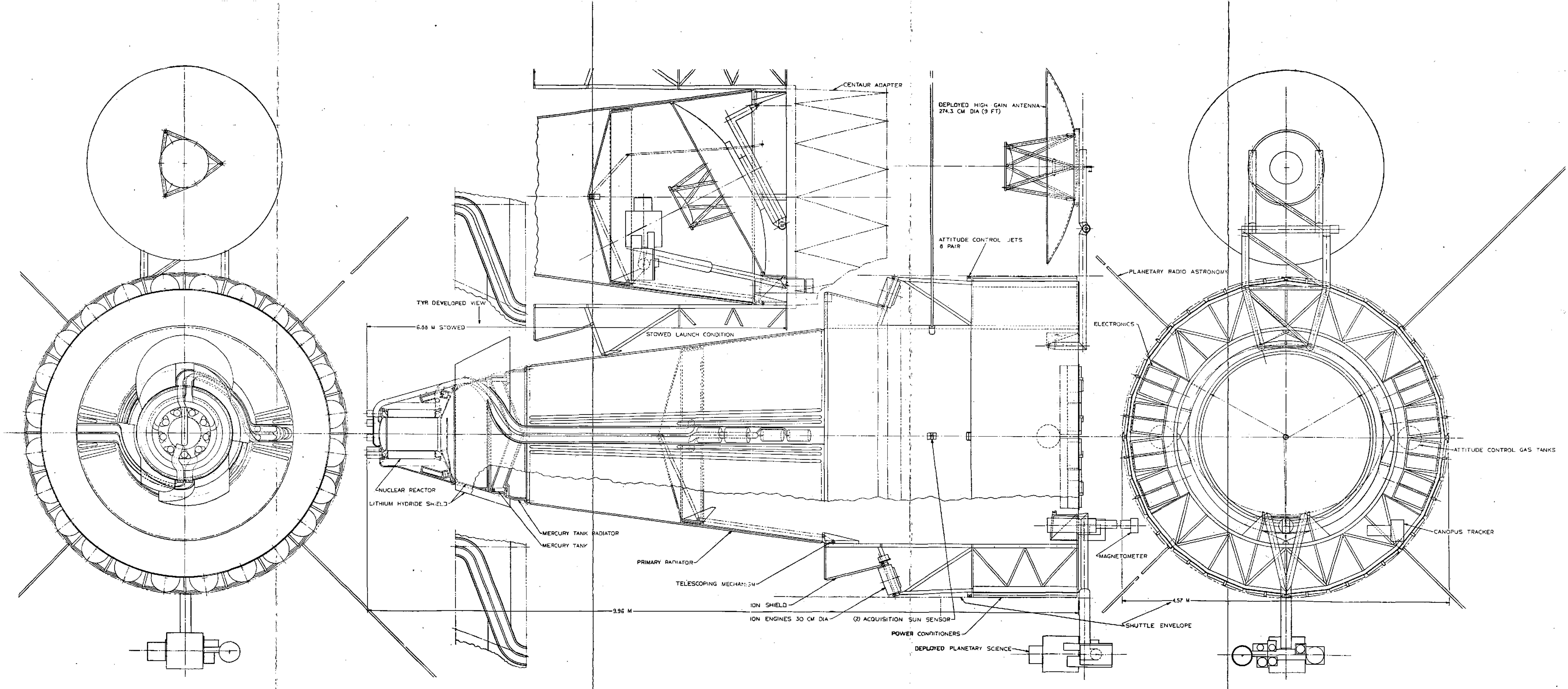


Figure 8

Nuclear Electric Propulsion End Thrust Spacecraft-U/N Flyby Mission-Configuration

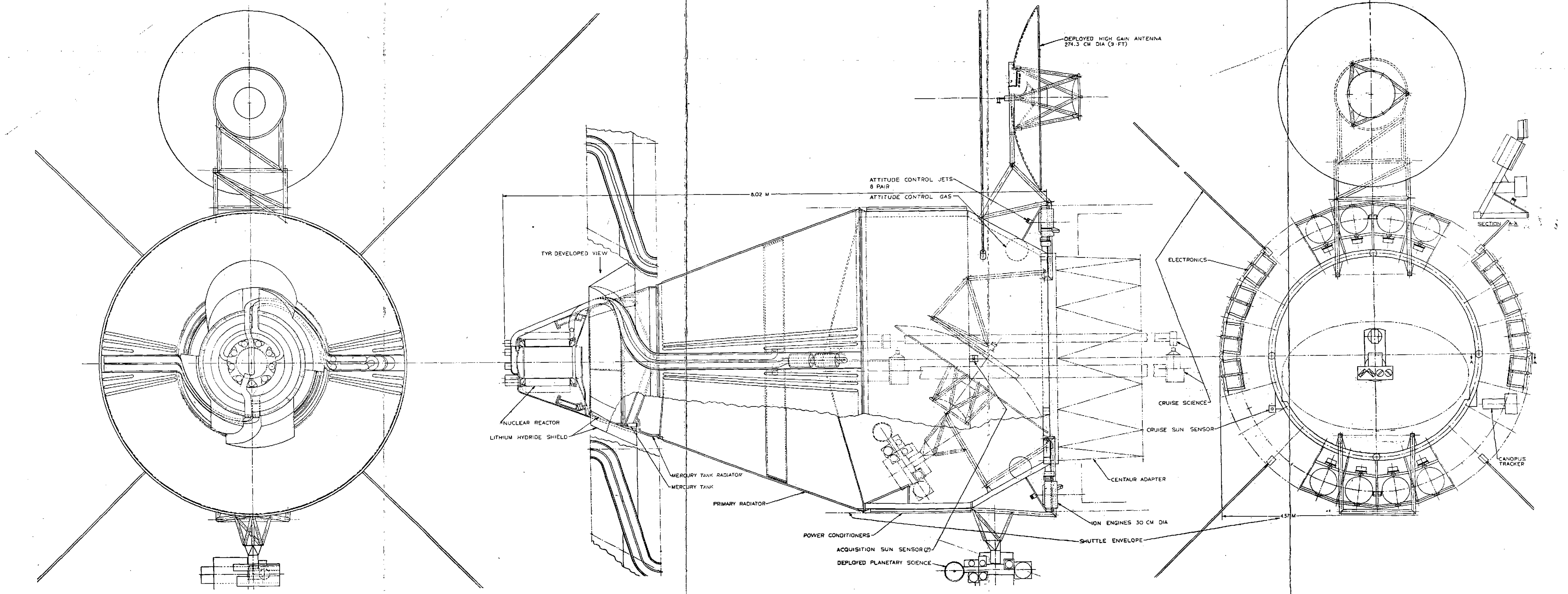


Figure 9

Nuclear Electric Propulsion End Thrust Spacecraft-U/N Flyby Mission-Configuration 2

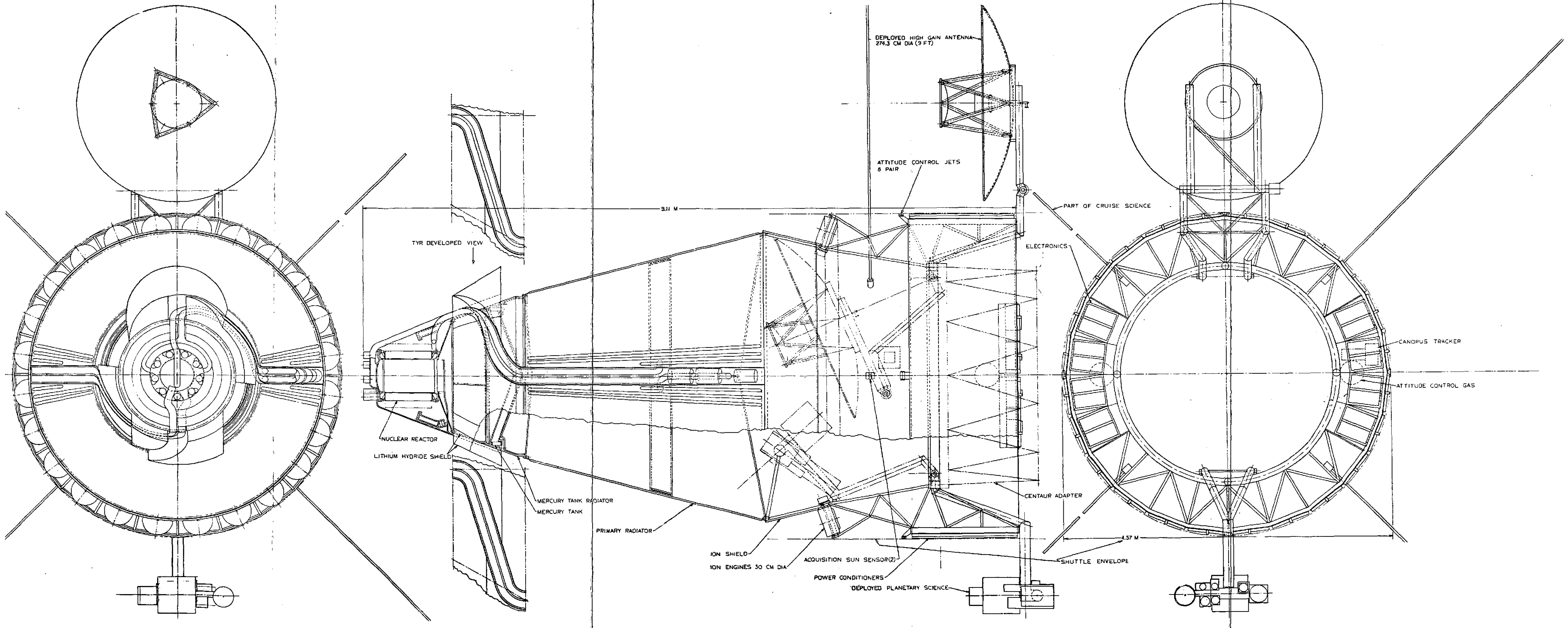


Figure 10

Nuclear Electric Propulsion End Thrust Spacecraft-U/N Flyby Mission-Configuration 3

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

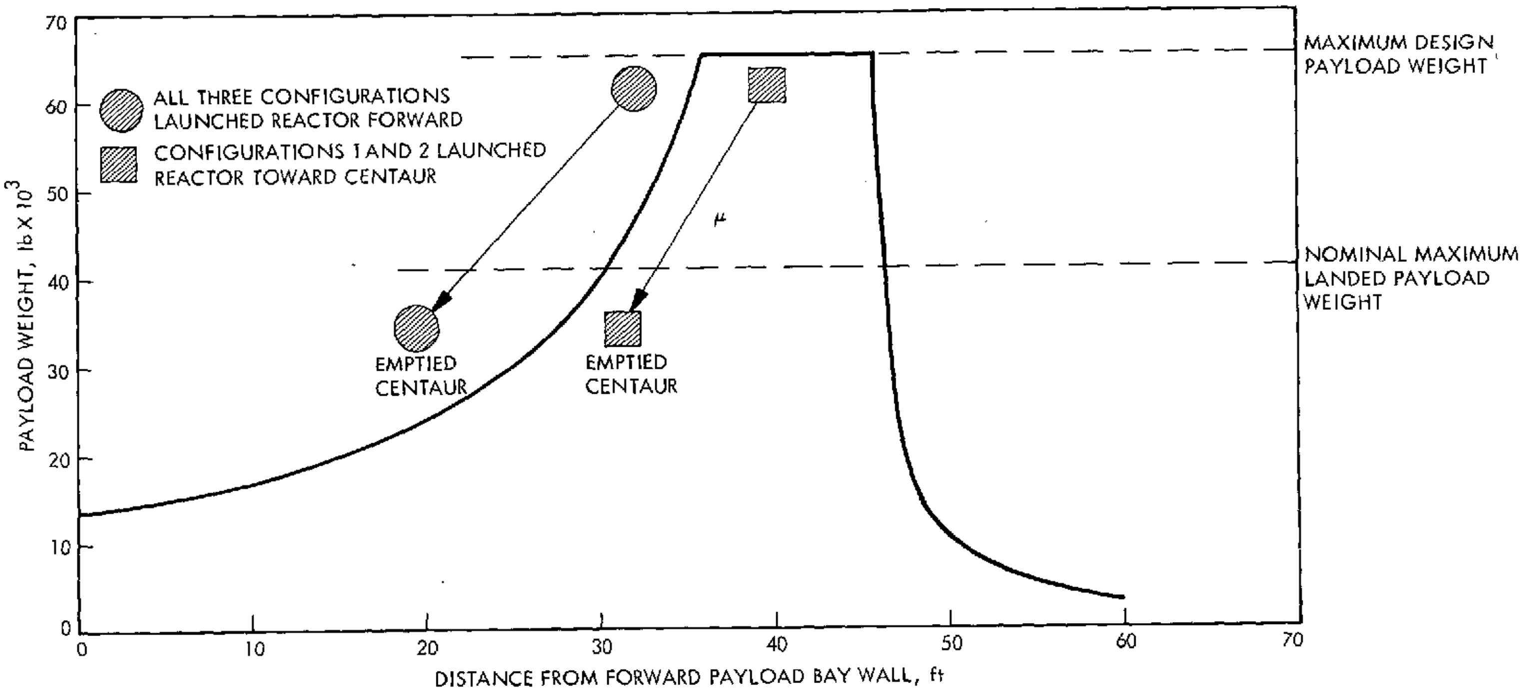
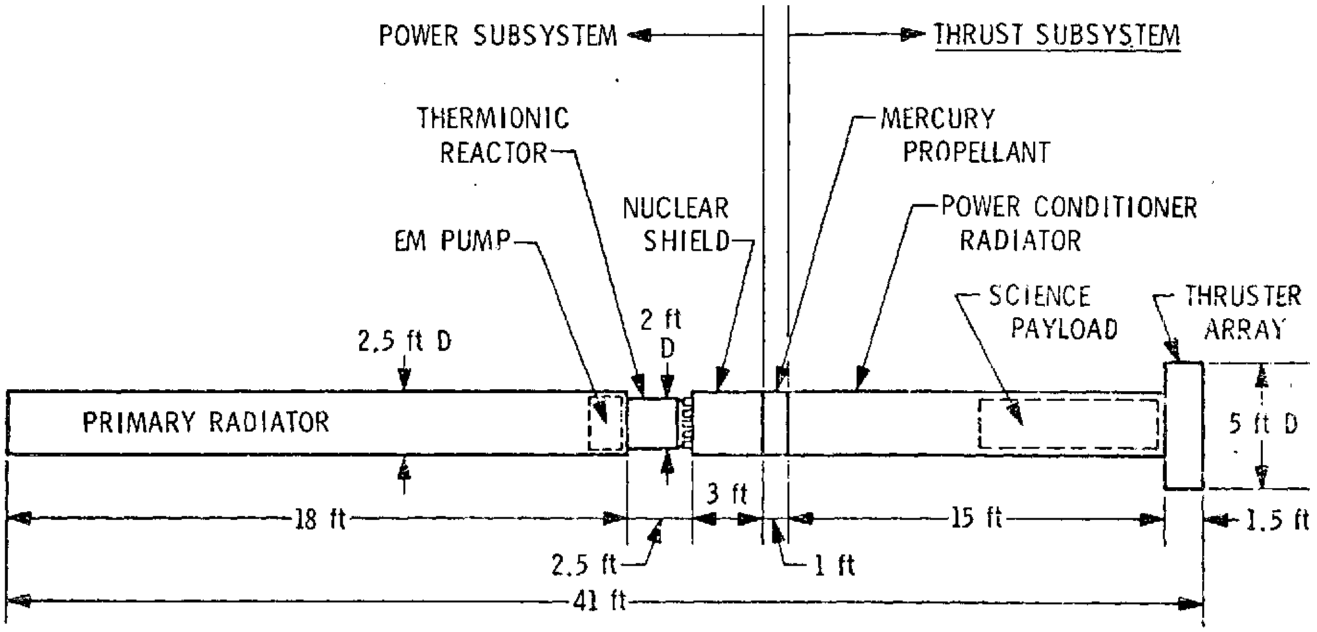


Figure 11. Payload Longitudinal Center-of-Gravity Limits

APPENDIX A

A BRIEF HISTORICAL SURVEY OF NEP SYSTEMS USING THERMIONIC REACTORS AS A POWER SOURCE

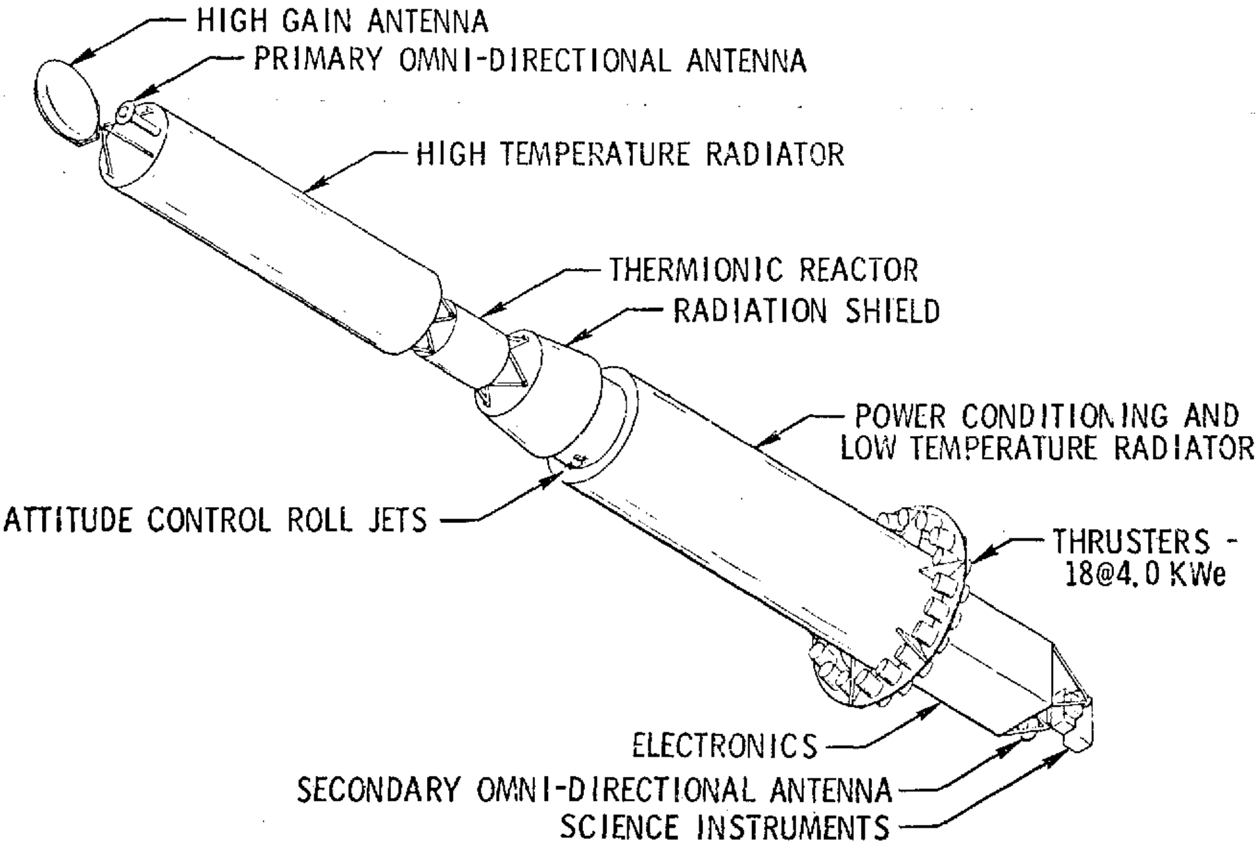


EARLIEST NONCONICAL CONFIGURATION

~70 KWE

TITAN FAMILY LAUNCH VEHICLE

ADVANTAGES:	LOW SHIELD WEIGHT
	HIGH TEMPERATURE COMPONENTS SEPARATED
	SHORT LOW VOLTAGE BUS RUNS
DISADVANTAGES:	THRUSTERS NEAR SCIENCE (EMI)
	SCIENCE SUFFERS FROM TUNNEL VISION
	ANTENNA (?)
	EM PUMP NEEDS HEAT REJECTION AREA

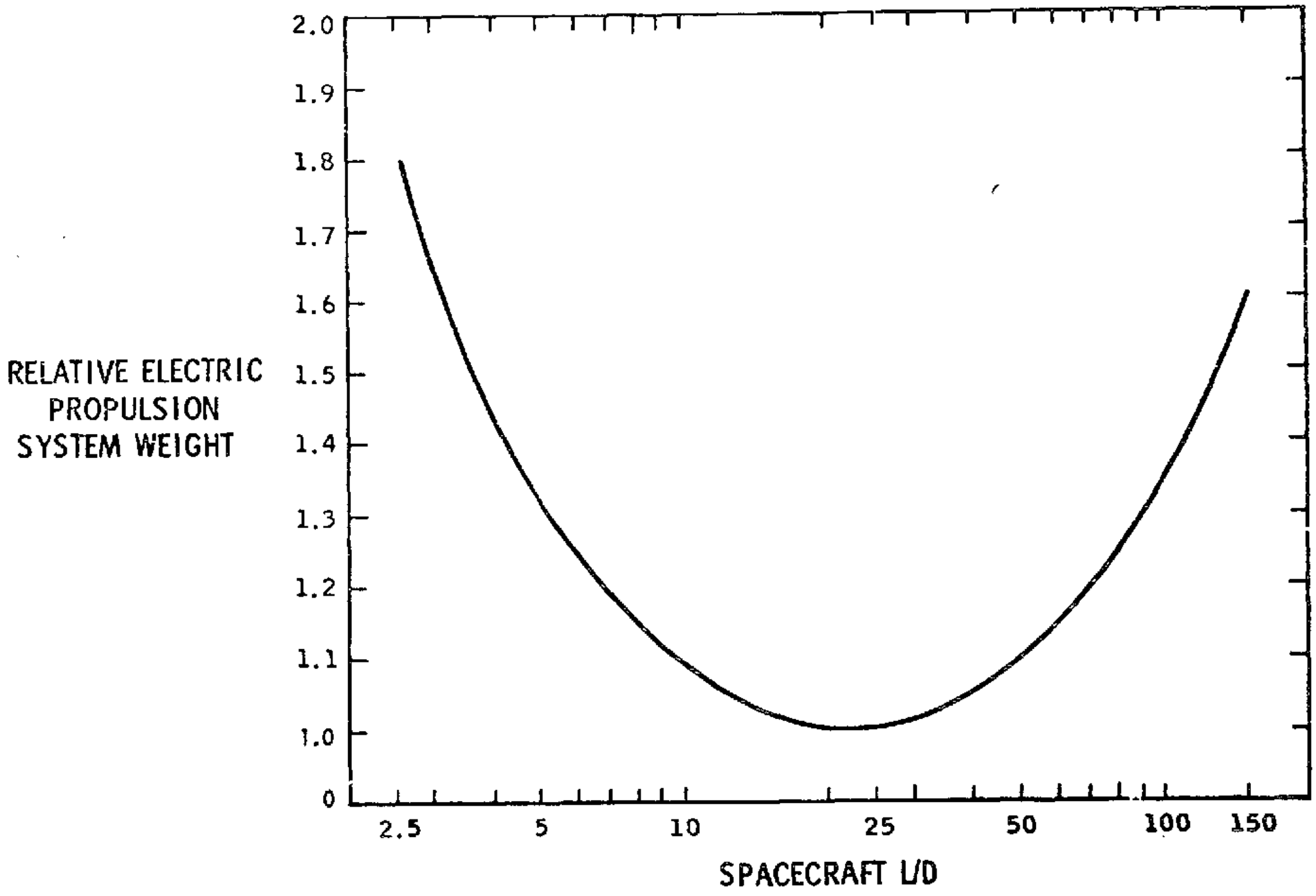


AXIAL THRUST CONFIGURATION

~70 KWE

TITAN LAUNCH VEHICLE

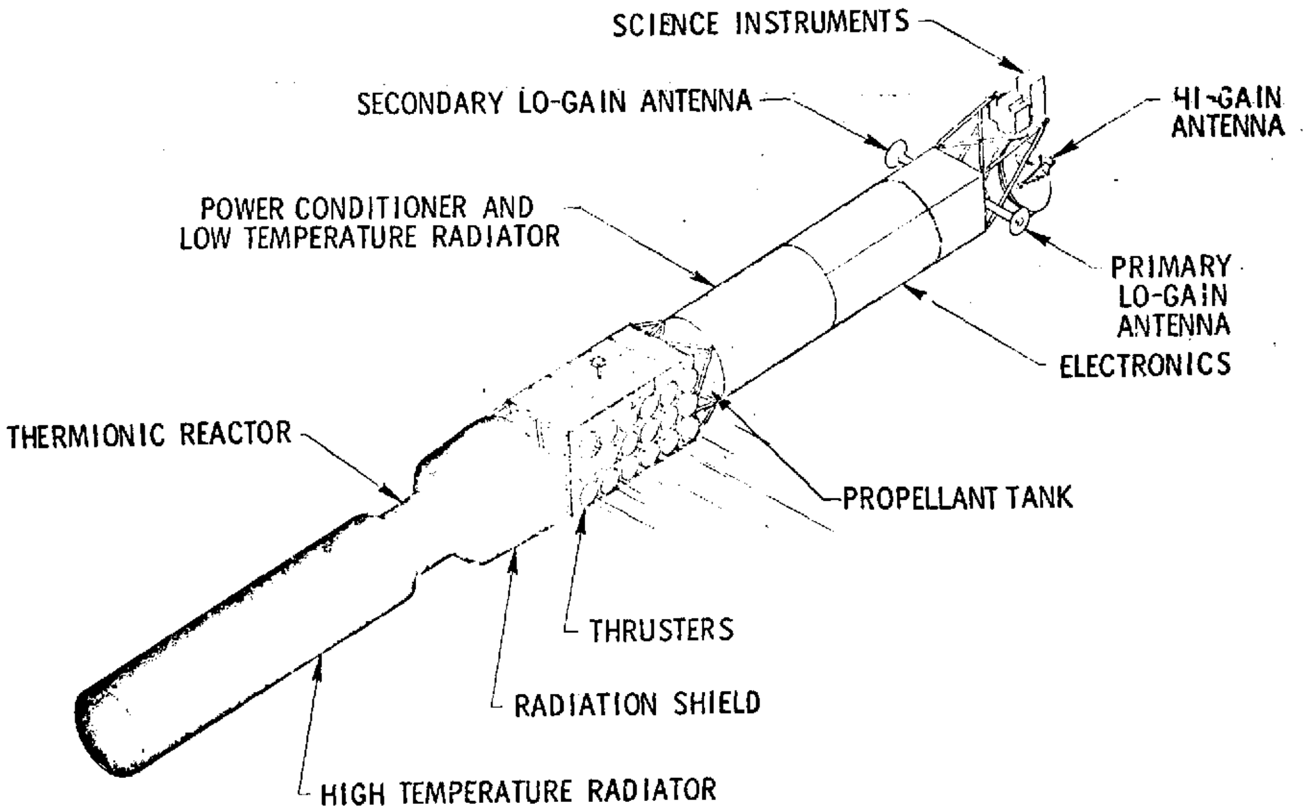
ADVANTAGES:	LOW SHIELD WEIGHT
	HIGH TEMPERATURE COMPONENT ISOLATION
	SHORT LOW VOLTAGE BUS RUNS
	GOOD FIELD OF VIEW FOR SCIENCE PLATFORM
	LOW SHIELD WEIGHT
DISADVANTAGES:	ANTENNA ON HIGH TEMPERATURE RADIATOR
	ELECTRONICS IN THRUSTER PLUME
	EM PUMP REQUIRES HEAT REJECTION AREA



WEIGHT VS. L/D CURVE

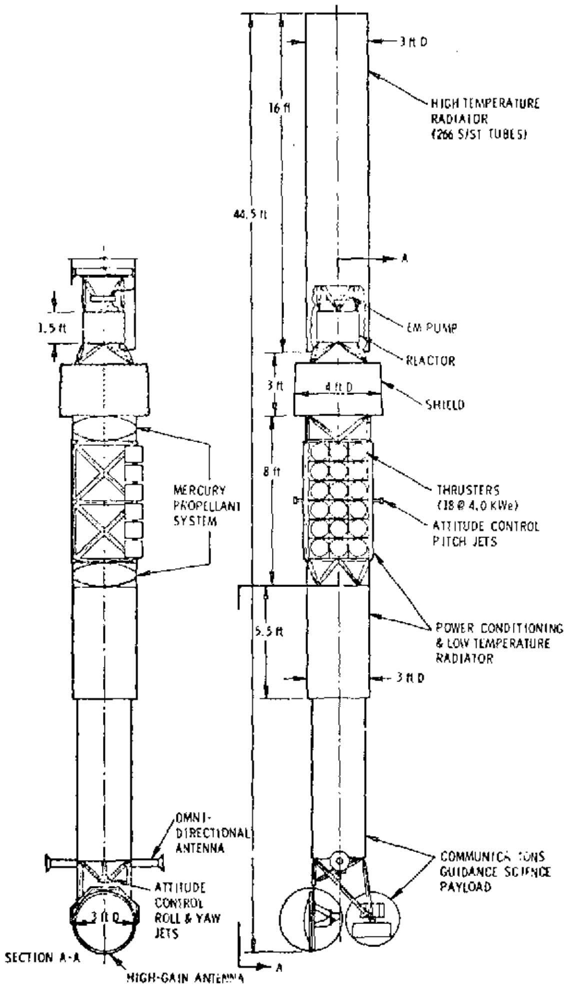
HIGH SHIELD WEIGHTS CAUSE INCREASE IN WEIGHT AT LOWER L/D's

HIGH STRUCTURE WEIGHTS CAUSE INCREASE IN WEIGHT AT HIGH L/D's



SIDE-THRUST CONFIGURATION ISOMETRIC

SEE FOLLOWING PAGE FOR DISCUSSION



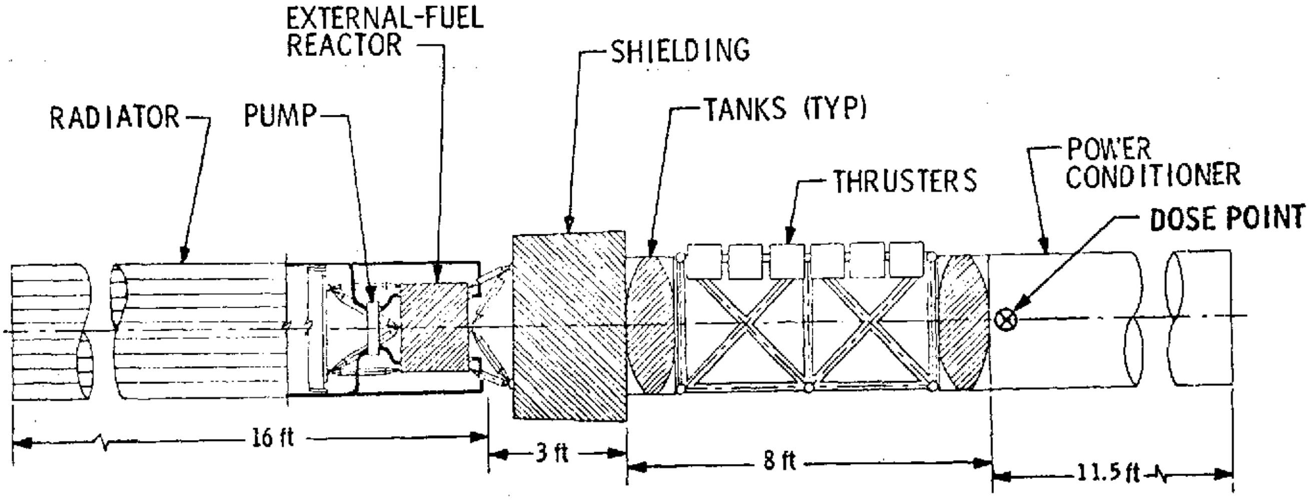
SIDE-THRUST CONFIGURATION

INCORPORATES ALL PREVIOUS ADVANTAGES

RESOLVES ALL PREVIOUS DISADVANTAGES EXCEPT EM PUMP HEAT REJECTION

DISADVANTAGES: SLIGHTLY LONGER LOW VOLTAGE CABLE RUN
C.G. SHIFTS WITH PAYLOAD MASS AND C.G., AND AFTER PROBE/LANDER DEPLOYMENT

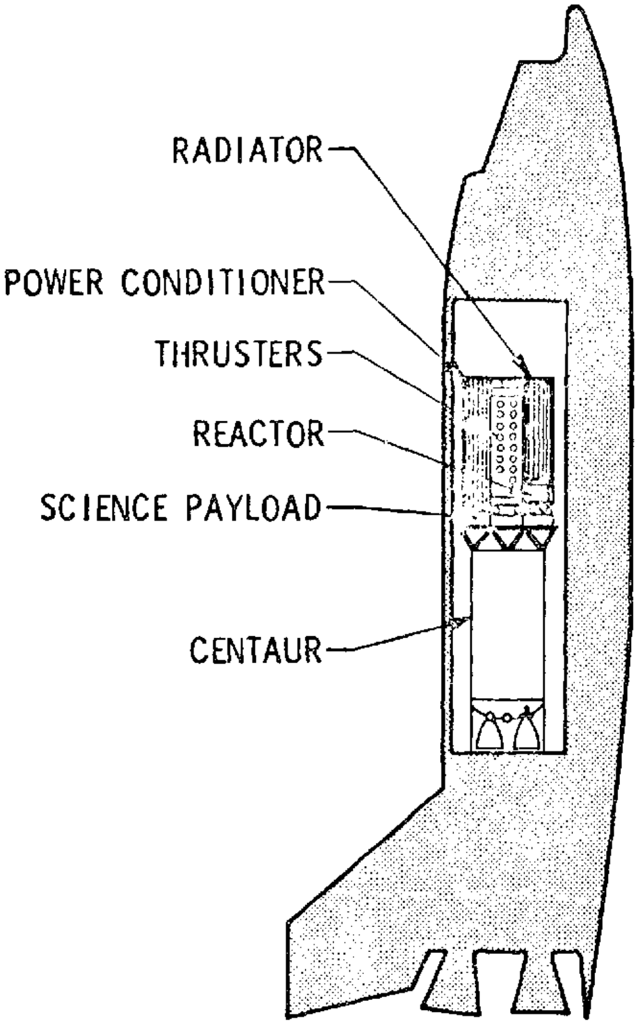
SOME VARIATIONS SHOW HINGES FOR FOLDING DURING LAUNCH IN VIKING SHROUD



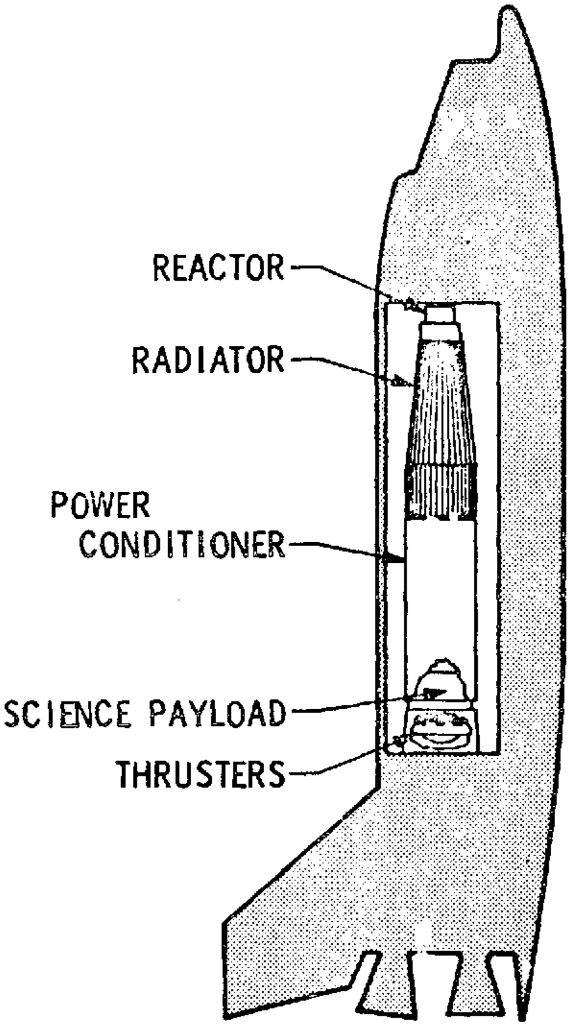
SHIELD ARRANGEMENT

NEUTRON SHIELD: ~2 FT. OF LiH CAST INTO SS CONTAINER.
INTERNAL VOLUME OF SHIELD IS HONEYCOMBED SS FOIL.

GAMMA SHIELD: THIS CONFIGURATION USES Hg AS GAMMA SHIELD.
WHERE THIS IS NOT POSSIBLE OR PRACTICAL, ~1.5-2 INCHES OF TUNGSTEN THICKNESS MAY BE SUBSTITUTED.



120 KWe NEP/CENTAUR

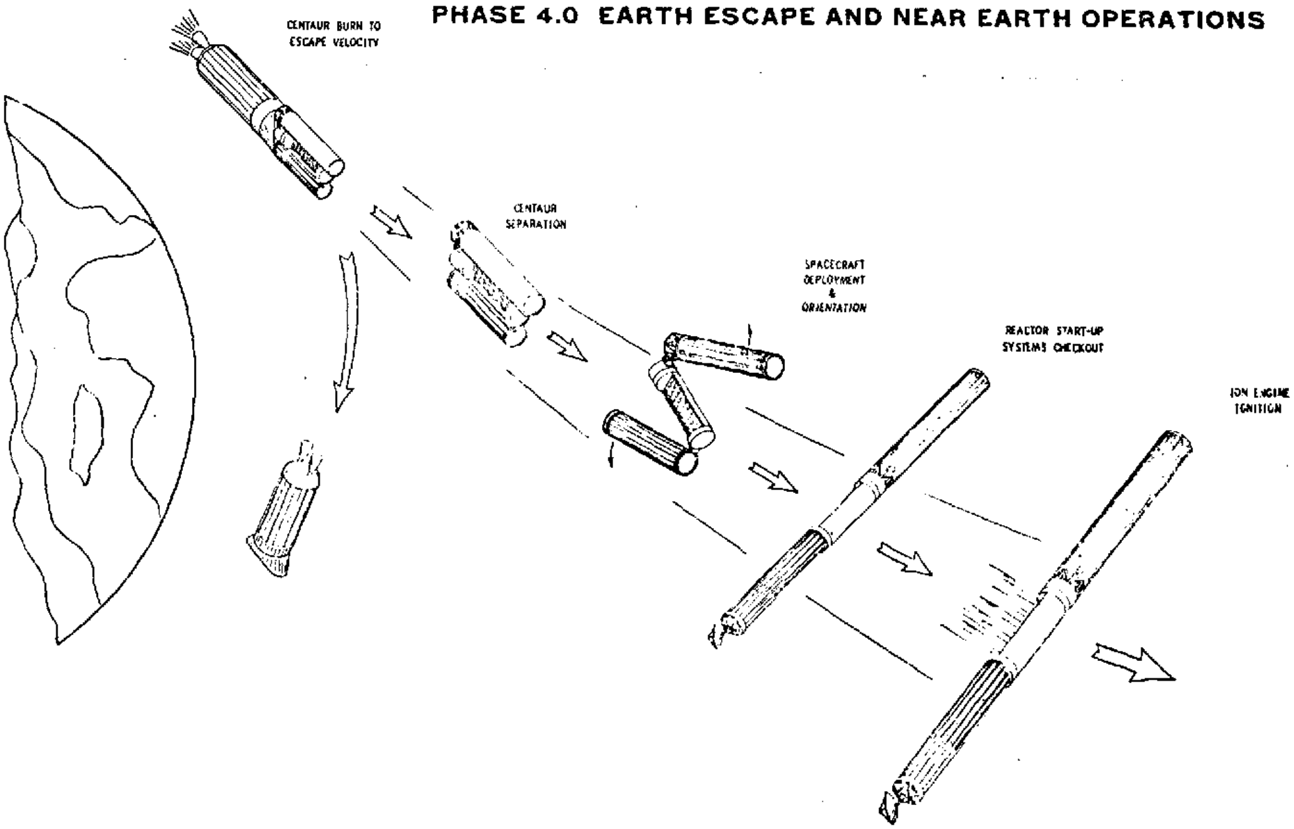


240 KWe NEP

SHUTTLE/CENTAUR INTEGRATION

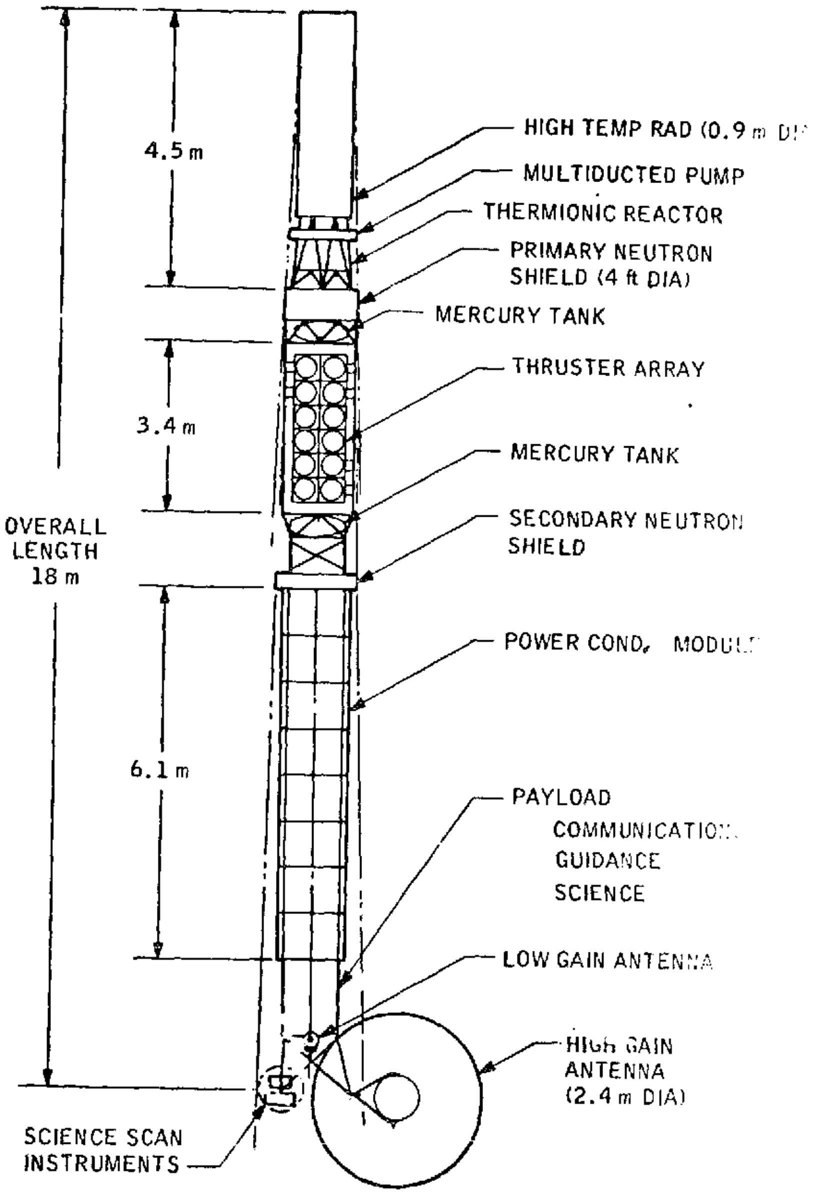
SIDE-THRUST CONFIGURATION (120 KWE)

~120 OR 240 KWE (NO CENTAUR REQUIRED WITH 240 KWE)


PHASE 4.0 EARTH ESCAPE AND NEAR EARTH OPERATIONS

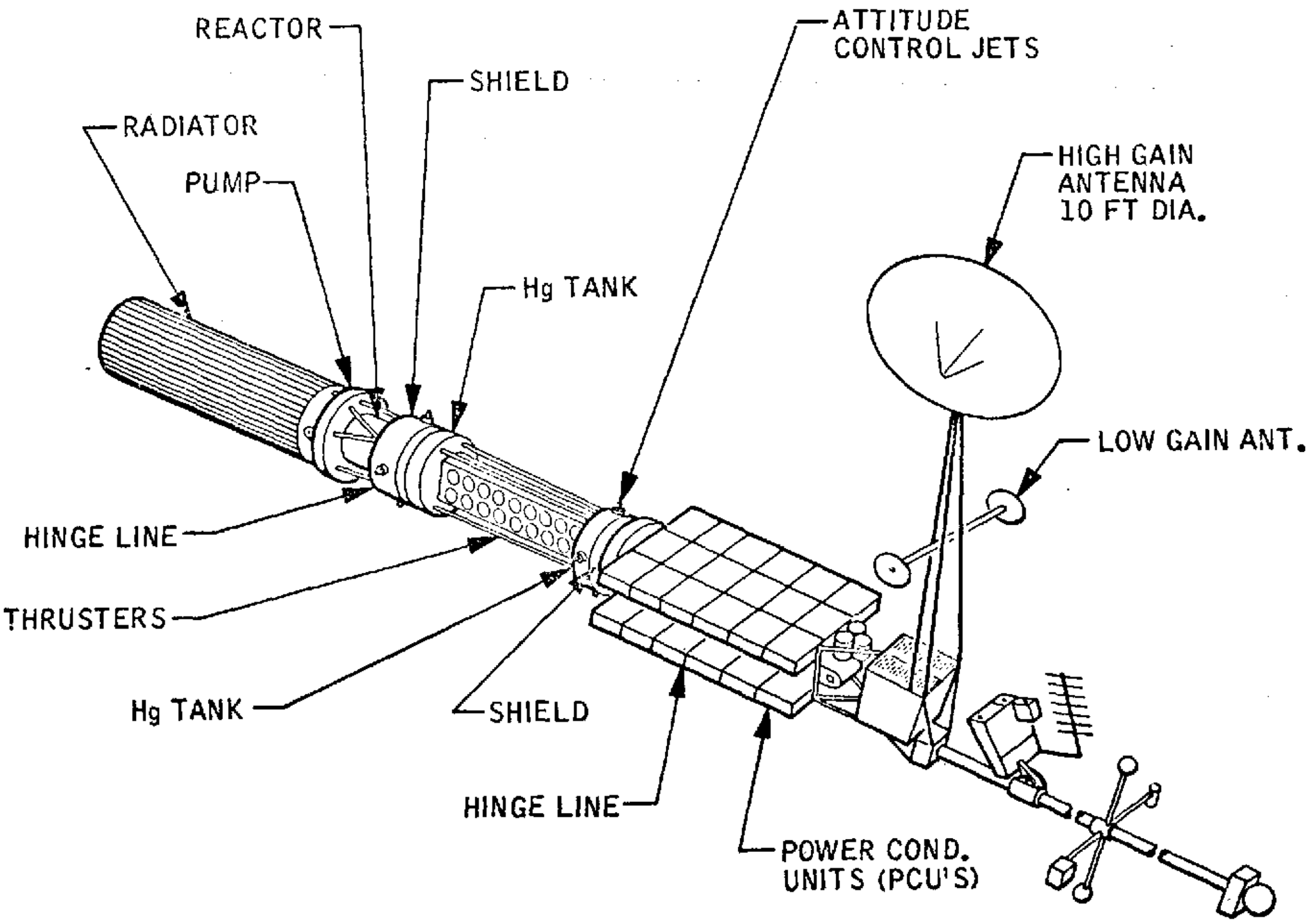
NEP SHUTTLE SEPARATION

IT APPEARS DESIRABLE TO DELAY SEPARATION UNTIL AFTER DEPLOYMENT AND REACTOR STARTUP. THESE FUNCTIONS WOULD THEN BE ACCOMPLISHED BY CENTAUR POWER AND CONTROL SYSTEMS.



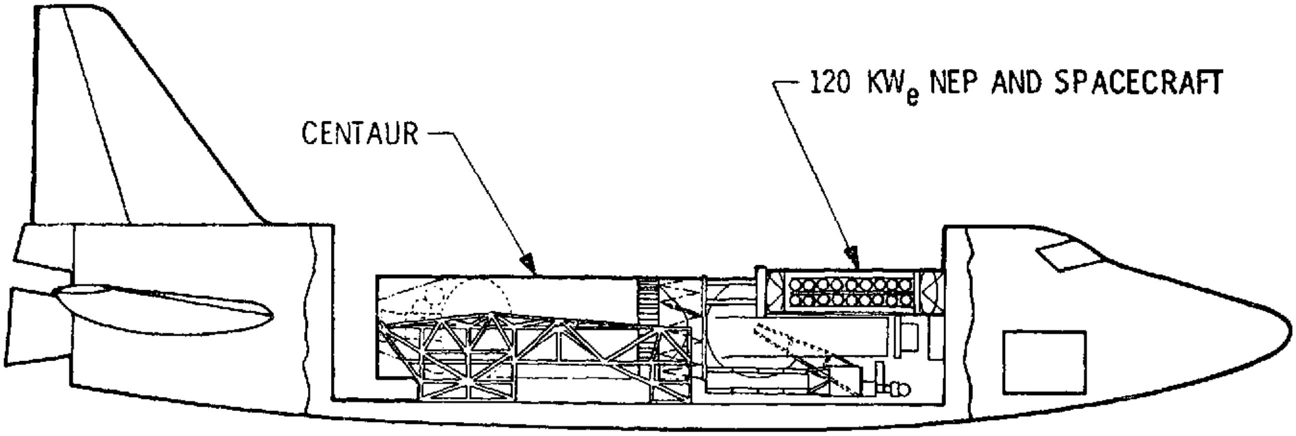
SIDE-THRUST CONFIGURATION

ADDITIONAL FEATURE HERE IS THE SPLIT NEUTRON SHIELD. THIS ALLOWS SOME ACCOMMODATION OF DIFFERENT SPACECRAFT MASSES BY DISTRIBUTED WEIGHT OF SHIELD CHOSEN FOR C.G. CONTROL. STILL DOES NOT ALLOW FOR C.G. CONTROL AFTER PROBE/LANDER DEPLOYMENT.



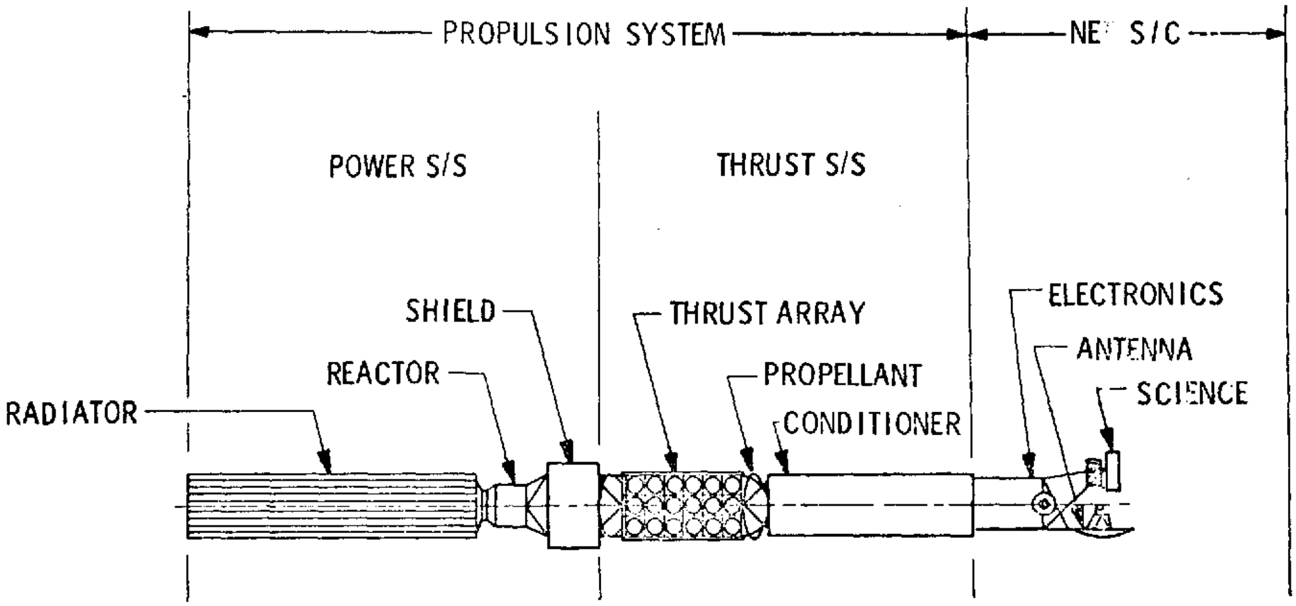
APC SIDE-THRUST CONFIGURATION

THE ADDITIONAL FEATURE OF THIS CONFIGURATION IS THE PLANAR ARRAY OF THE PCU's. THIS ALLOWS BETTER T/C IN THE PCU's. THRUSTING IS POSSIBLE IN ALL DIRECTIONS WITHOUT SOLAR HEATING EFFECTS.

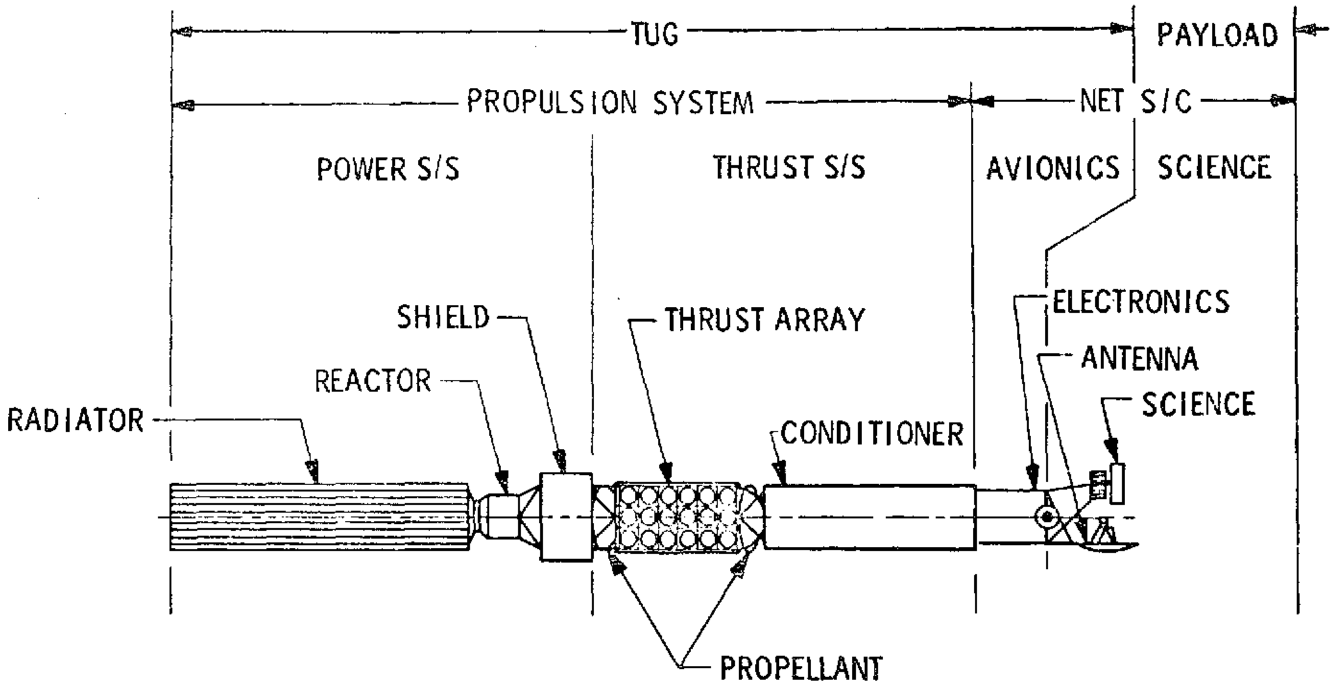


LAUNCH INTEGRATION FOR APC SIDE-THRUST CONFIGURATION WITH SHUTTLE/CENTAUR

NEP SYSTEM DEFINITION



CONCEPTUAL ARRANGEMENT



NEP SYSTEM DEFINITIONS

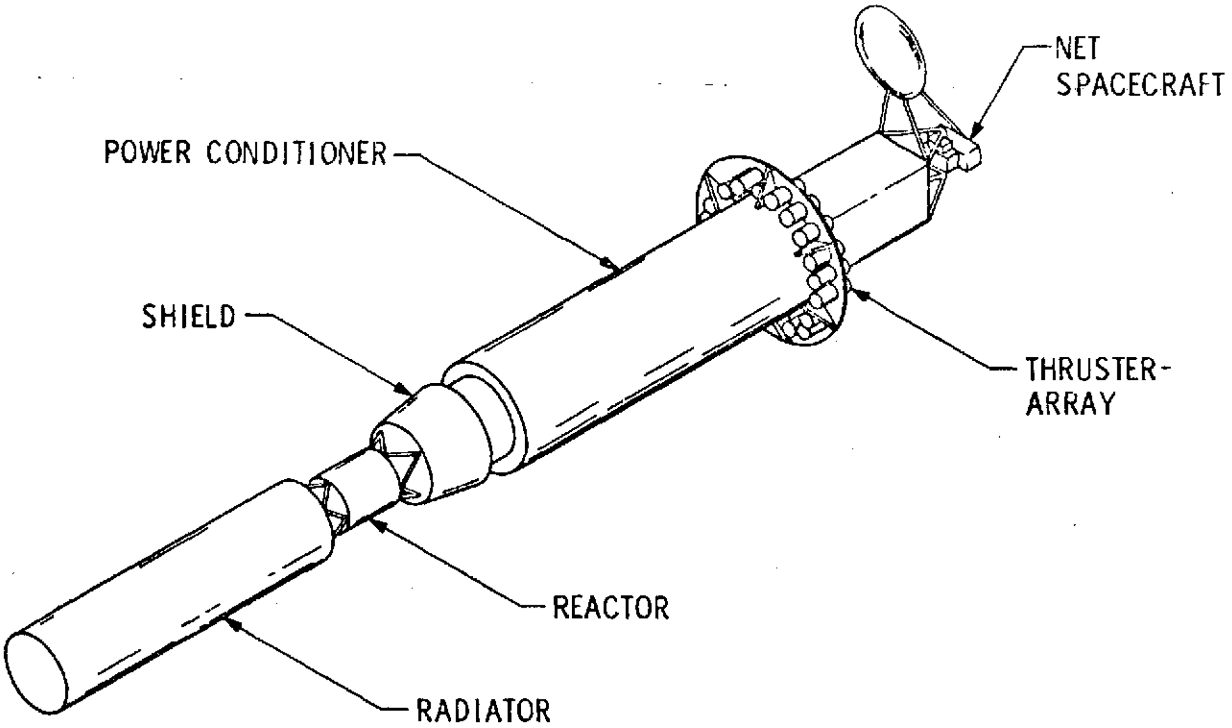
PROPULSION SYSTEM/NET SPACECRAFT IS TYPICAL PLANETARY DESIGNATION

TUG/PAYLOAD IS MORE APPROPRIATE TO GEOCENTRIC MISSIONS

AVIONICS (IN TUG) INCLUDES GUIDANCE AND CONTROL, DATA AND COMMUNICATIONS

WHEN APPLIED TO A PLANETARY MISSION, PAYLOAD MEANS SCIENCE

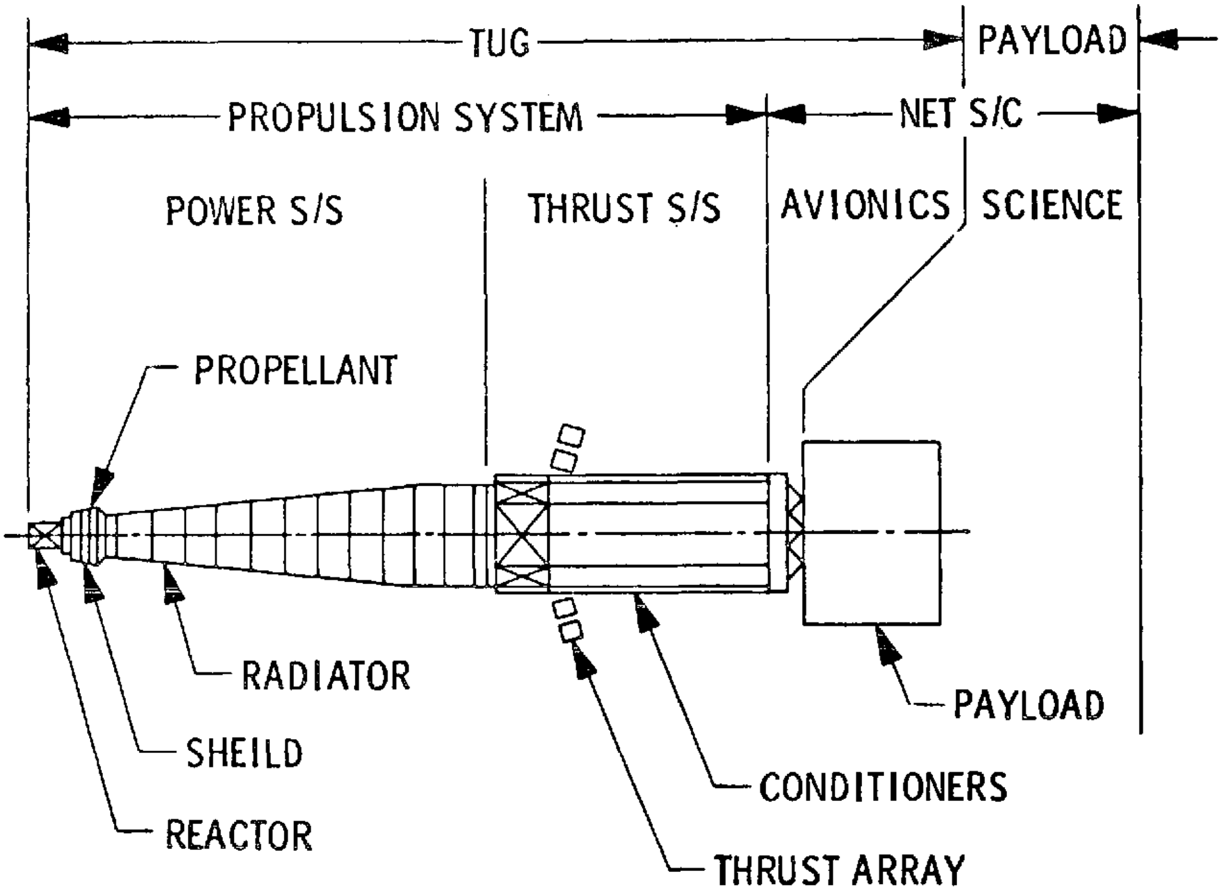
OTHER SPACECRAFT SUBSYSTEMS ARE IN AVIONICS



AXIAL THRUST CONFIGURATION

SIMILAR TO EARLIER AXIAL THRUST EXCEPT Hg PLUME IS TOWARD HIGH TEMPERATURE RADIATOR

α/ϵ OF PC RADIATOR WILL BE EFFECTED BY ION ENGINE PLUME



AXIAL THRUST CONICAL

TELESCOPING DEPLOYMENT MAY BE USED

THRUSTERS' PLUMES SEE ONLY HIGH TEMPERATURE RADIATOR

LOW VOLTAGE CABLES HAVE LONGER RUNS

Hg TANK IN HOT ZONE - MAY REQUIRE DIFFERENT FEED SYSTEM

NEP SYSTEM CONFIGURATION AND DEFINITION

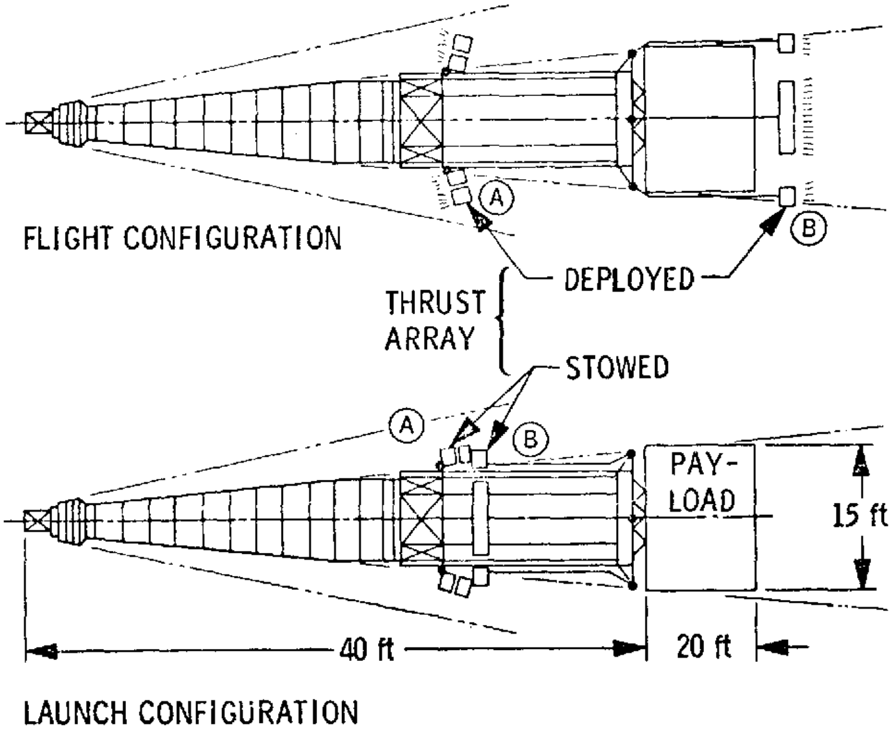
GROWTH NEP (384 kwe)

324 TFE
THERMIONIC REACTOR
(1625°C)
384 kwe-46 Vdc

"G" SERIES TFE
1.6 kwe/TFE
AND 8 V/TFE

36 IMPROVED
30cm ION ENGINES
SAME ISP
INCREASE BEAM
CURRENT 60%

α = 25 kg/kwe
TT = 30,000 hours



NEP SYSTEM WEIGHT BREAKDOWN (Kg)

	120 KWe	240 KWe
POWER SUBSYSTEM	2600	4120
REACTOR	**1080**	**1600**
RADIATOR	**760**	**1500**
SHIELD	**700**	**920**
MISC STR	**60**	**100**
THRUST SUBSYSTEM	1000	1880
THRUSTER	**250**	**500**
CONDITIONER	**550**	**1100**
CABLES	**100**	**180**
MISC STR	**100**	**100**
TOTAL PROPULSION SYSTEM	3600	6000
SYSTEM SPECIFIC WEIGHT	30 Kg/KWe	25 Kg/KWe

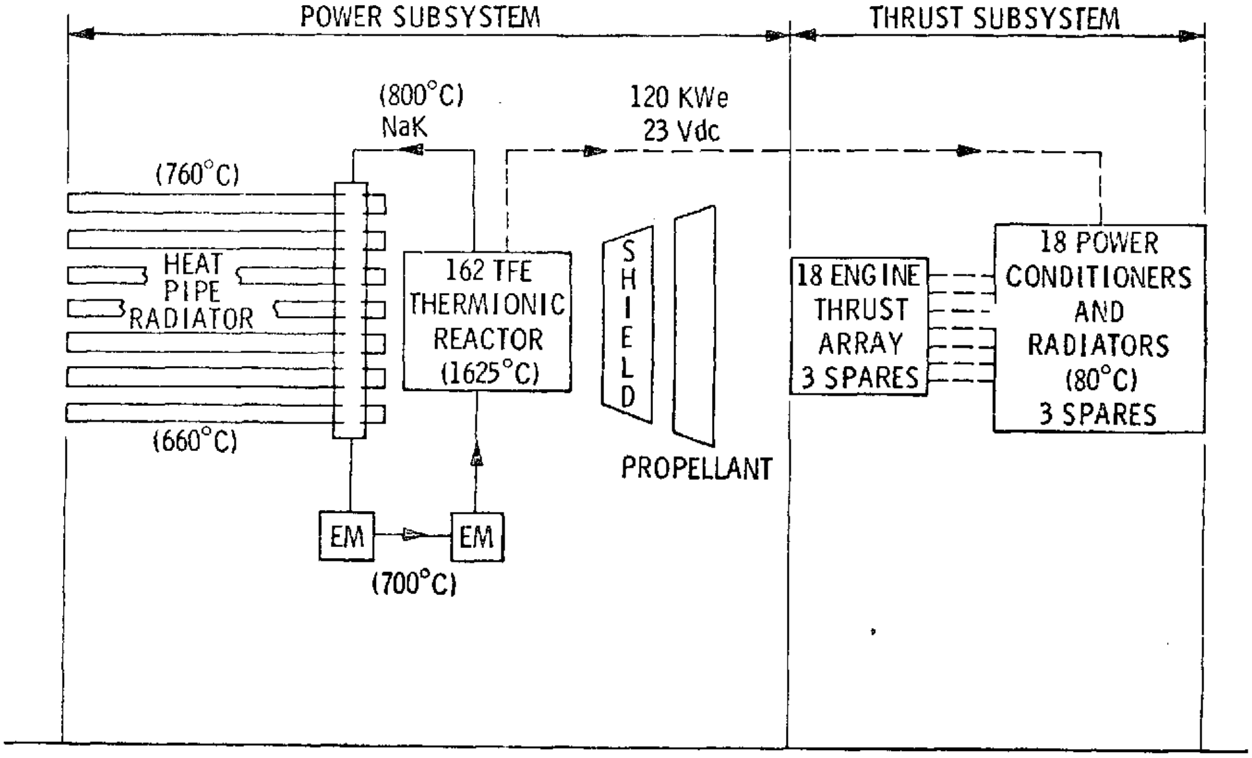
WEIGHT SUMMARY
BASELINE 40-VOLT FLASHLIGHT REACTOR SPACECRAFT

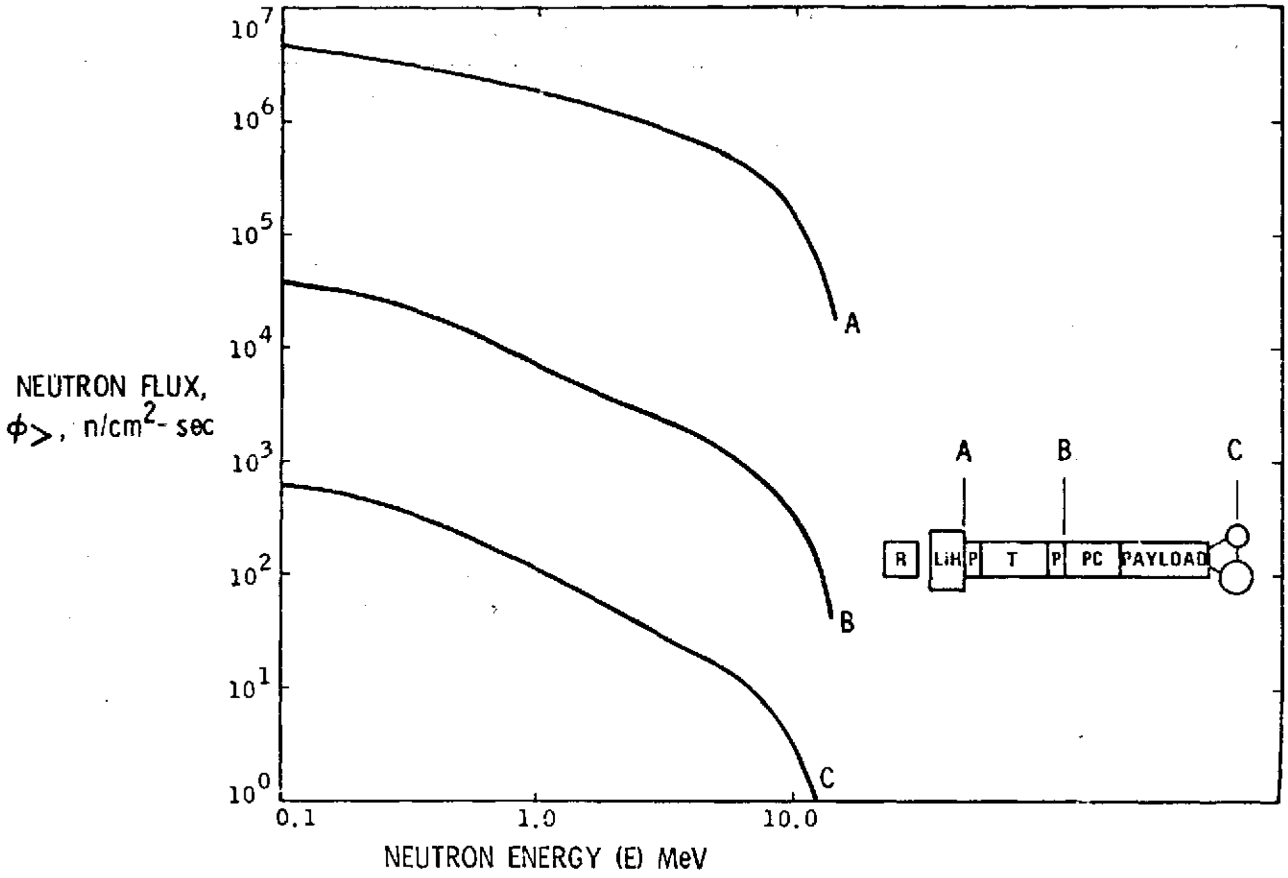
COMPONENTS	WEIGHT, KG		
PROPULSION SYSTEM			3066
POWER SYSTEM		2197	
REACTOR	1062		
HEAT REJECTION	535		
NEUTRON SHIELD	520		
HOTEL POWER CONDITIONING	31		
HOTEL POWER CONDITIONING RADIATOR	5		
PUMP LOW VOLTAGE CABLE	1		
STRUCTURE	43		
THRUST SYSTEM		869	
THRUST ARRAY	213		
POWER CONDITIONING	310		
POWER CONDITIONING RADIATOR	105		
LOW VOLTAGE CABLE	154		
HIGH VOLTAGE CABLE	3		
STRUCTURE	84		
PROPELLANT SYSTEM			3770
PROPELLANT		3660	
TANKS AND DISTRIBUTION		110	
NET SPACECRAFT			662
FLIGHT SHROUD WEIGHT PENALTY			690
LAUNCH VEHICLE PAYLOAD REQUIREMENT			8188

KEY PROPULSION SYSTEM WEIGHT ELEMENTS ARE:

- REACTOR
- HEAT REJECTION
- NEUTRON SHIELD
- POWER CONDITIONING
- THRUST ARRAY

NEP SYSTEM CONFIGURATION AND DEFINITION
SYSTEM SCHEMATIC (120 kwe)





NEUTRON FLUX VS. NEUTRON ENERGY

TO FIND FLUX ABOVE PARTICULAR ENERGY AND AT PARTICULAR POINT IN SPACECRAFT

EXAMPLE: FOR NEUTRONS WITH ENERGY GREATER THAN 1 MEV, THERE ARE ~100 N/CM-SEC AT POINT C, ~ 9 X 10^3 N/CM-SEC AT POINT B AND ~1.5 X 10^6 N/CM^2-SEC AT POINT A

APPENDIX B

HIGH VOLTAGE CONCEPTS: THERMIONIC REACTORS

I. INTRODUCTION

The creative design phase was completed for the conceptual design of several high-voltage configurations. Forty ideas were proposed by 18 participants in brainstorming sessions held over a one-week period. A departmental technical review was held to discuss the design concepts. Seventeen of the concepts were illustrated in sketch form and presented to JPL personnel on 15 January. (The 17 concepts were chosen from the 40 as the simplest concepts to put into graphical form, given the limitations of schedule.)

The following section describes the concepts, including those illustrated before termination of effort.

II. STATUS AT TERMINATION

A. CURRENT REACTOR DESIGN

In the current reactor design, TFEs of alternating polarity are grouped in strings of six connected in series. Twenty-seven such strings make up the 162-TFE core. Two TFEs in each string are grounded to the NaK coolant in which all are immersed. One could alternatively look at the 162 as 54 groups of 3 TFEs arranged so that half the groups produce a voltage above the reactor ground and half below. The arrangement is illustrated in Fig. B-1. The details of connection within the TFE are shown in Fig. B-2. The alternating polarity is achieved with the identical six-converter assemblies by internally inverting the assembly in alternate TFEs.

The possibility of a voltage limitation inherent in the concept arises in the area of the top cells in the extreme TFEs in the groups of 6. There, half of the reactor output voltage is imposed across the trilayer and from the insulator-seal to the sheath tube. This volume is part of the fission product routing space. Details of the converter are shown in Fig. B-3. Flaws in the trilayer or in the insulative coating of the insulator-seal could, in the presence of ionizable fission products, arc and lose power. The magnitude of such a loss would be higher if one of the seals in the TFE breaks and cesium vapor leaks into the fission product venting system from the interelectrode space. (The TFE continues to operate but at lower output in the event that an envelope failure puts the two spaces in communication.)

The high current dc output power of the thermionic reactor is converted to high voltage ac and dc for the power requirements of the nuclear electric spacecraft. The power conditioning and distribution is schematically represented in Fig. B-4.

The objective of the creative design phase was to list all reactor redesign concepts for higher voltage output as they came to mind. A secondary objective was to design higher reliability into the reactor cooling concept. The present design consists of one vessel penetrated by the stem of each of the 162 TFEs. This configuration offers both a large surface area of the vessel and a considerable length of weld path where the TFEs meet the vessel, where a single point coolant failure is possible.

The 40 designs are discussed below. No ideas offered in this first phase have been discarded. Some offer higher coolant reliability without regard to higher output voltage, but they do not exclude the possibility of incorporating some of the high-voltage features of other concepts. The study was to have taken the best of the design concepts and features offered in this phase and combine them into several system designs.

B. FIRST GROUP OF CONCEPTS (17)

Of the 17 concepts looked at most closely, 7 different techniques of generating higher voltage are identified.

Concepts numbered 1 through 9 achieve higher output voltage by floating the cell strings, isolating what is in the current design, the ground potential from the maximum output voltage.

Concept 1 is illustrated in Fig. B-5. In this concept, the TFE penetrates both ends of the reactor vessel. Rather than increasing the coolant reliability, this concept reduces it by doubling the number of welds of TFEs to the vessel. There was no consideration in the concept for differential expansion of the TFEs and the vessel.

In Concept 2, 7 TFEs are grouped together and electrically connected into either a series or parallel cluster. The electrical connections between TFEs are made in hexagonal junction boxes at the ends of the core, and from each box a current feedthrough is welded into the vessel. This has been called a "septafoil" arrangement. This concept offers higher reliability in that only two vessel penetration welds are needed for each seven TFEs. The assembly is straightforward, since the core can easily be subdivided into hexagonal groups of 6. The leads from each "septafoil" must penetrate opposite ends of the vessel, however, and hence the concept shares the differential expansion problem with Concept 1.

Concept 3 is a core of TFEs brazed together with heat pipes of cuspoidal cross-section in the space between them. The heat pipes transfer the waste heat in the direction of the TFE axes. Within the TFEs the converters are isolated from the sheath. Each TFE is accessible at both ends for connection. An alternative to this would be NaK flowing in the cuspoidal spaces to remove the heat.

For Concept 4 the same TFEs as in Concept 3 are aligned in rows separated by ribbon ducts. Between the TFEs in each row are two cuspoidal heat pipes for circumferential thermal conductance. The entire structure is brazed together. The concept is similar to the "pancake reactor" concept except that instead of several layers of "unit cells, " the reactor is one "layer" of TFEs.

The TFEs are assembled into "Siamese twins" by a weld along their length as the basic building block in Concept 5. These pairs are then welded together along their lengths to build a hexagonal structure (a triangular array with every third site empty). Bundles of heat pipes and driver fuel elements would be welded into the hexagonal cavities. Static NaK will conduct heat from the TFEs and driver rods to the heat pipes. TFE cooling should be redundant to the degree that some heat pipes or NaK could be lost without serious effect. The TFE again has a sheath isolated from the converters, and its leads are accessible at both ends.

Concept 6 puts the same converter assemblies into two "sheath tubes." The first is circular and bonds to the converters all around. The second is elliptical and bonds to the inner sheath tube along two lines of contact. The two resulting lenticular spaces between the sheaths are axial heat pipes extending away from the core. Each TFE is sprayed with a ceramic coating outside the elliptical sheath so that the TFEs are insulated from each other. The individual sheaths, and hence the heat pipe pairs, are at floating potential. Electrical connection is again external to the core.

In Concept 7, the same assembly of converters with floating sheath and leads at both ends is assembled into a core which is one heat pipe, the outside surface of each TFE being the wick and boiler. The walls of the reactor vessel are the condenser. Heat is removed from the reactor by redundant NaK circuits enveloping the vessel. This envelope can be counted as a double containment of the vapor in the core-sized heat pipe, which is the primary coolant.

Figure B-6 illustrates Concept 8. For this concept, fins and flats are incorporated in the outer sheath of the TFE. The reactor core is assembled by brazing, welding, or diffusion-bonding together these TFEs with rectangular heat pipes. Of the 17 concepts, this one dilutes the currently designed core the most.

Concept 9 makes use of flat-plate electrodes. The sandwiched emitter/fuel/emitter "pucks" retain fission products. The flat converter elements are stacked in a tube creating a "TFE." The flat circular surfaces of the emitters emit to disc/fin collectors bonded into the sheath tube at their edges. All are insulated from ground by a tube-length trilayer. Emitter-collector connections are by spot-welded or brazed wires. The "TFEs" are all connected in parallel at the reactor ends, since a considerable output voltage can be generated from the stacked converters.

The preceding nine concepts all attained a higher voltage output by eliminating the grounding of any converter in the TFE. The next two concepts reduce the possibility of a parasitic arc to ground by increasing the distance from insulator-seal to grounded sheath. Both are early (1968 vintage) flashlight alternatives.

Concept 10 is the flat seal converter. It is shown in Fig. B-7. This is one concept which has as a result an increase in reactor core fuel volume fraction over the current design.

Figure B-8 shows Concept 11. This concept takes radial space outside the converter assembly, between it and the sheath. This space is filled with an inert gas, possibly a pressurized gas, for arc suppression.

The twelfth and thirteenth concepts are thermionic reactors in which each converter is floating and the user has accessibility at the ends of the reactor core to all of the converter leads.

Concept 12, illustrated in Fig. B-9, requires a core four cells high. The leads from two cells go in each direction to the face of the reactor through a "nine-o-layer" sandwiched concentric sheath-insulator. Note that different emitter lengths compensate for the different diameters for the same electrode areas.

The "pancake" reactor is offered as Concept 13. The layout of this concept is incomplete, but is included as Fig. B-10, since the detail of the electrical, cesium, and fission product connection is shown clearly. The ribbon ducts can be segmented axially to the degree required for redundancy of collector cooling. One set of tubulations could be eliminated if the converters were operated with mixed cesium and fission products. This and the preceding design (and only these two) could incorporate integral sorption cesium reservoirs without degrading reliability.

Concept 14 uses double insulation between collectors and the ground potential. The resulting configuration is the equivalent of a pentalayer. The pentalayer can be accomplished in two ways. First, a full-length (core height) pentalayer with an interrupted inner layer (collector) could be used. Emitters are dropped in from the top and welded to the collectors. The other method is to fabricate the converters as an assembly of six and bond them into a full-length trilayer. For either case the middle niobium layer in the five-layer structure is always floating at neither converter potential or ground. It also has no structural support function. As a result it can be a plasma-sprayed layer of minimal thickness. The separation of cesium and fission products is not prohibited by this design. Small holes can be made in the ceramic for fission product venting, or a central chimney venting scheme* can be employed.

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*A version of this concept was discovered in the literature. It could not be reproduced due to copyright limitations. The configuration is amply illustrated in "An Engineering Evaluation of Advanced Nuclear Thermionic Space Power Plants," Progress in Astronautics and Aeronautics, Vol. 16, Space Power Systems Engineering, AIAA, by P. Bolan, R. Cohen, and G. Bordner, Pratt and Whitney Aircraft, East Hartford, Conn., published by Academic Press, N. Y. (1966).

The novelty of Concept 15 is the incorporation of two separate reactor vessels and coolant loops (Fig. B-11). The two vessels are insulated from each other, and the TFEs are connected as shown in the figure. This concept produces double the voltage from the reactor technology of the current concept. Trisecting the core could result in tripling the output voltage.

Concept 16 approaches the problem of high voltage by reducing the required voltage output of the reactor in eliminating the transistor stage of the power conditioning. The TFE provides alternating current directly to the voltage step-up transformer. The TFE is illustrated in Fig. B-12. It is a regular converter assembly with the addition of a "triode" of two emitters on the top. The thermionic condition in the interelectrode gaps (two) of the triode are such that they operate in a bistable regime. A pulse on the TFE output line switches the output of the regular converters from lead 1 to lead 2 (as the leads are labeled in the figure) to produce the ac. This switching can be accomplished at fairly high frequency. The proposed advantage of the triode over a switch of more simple concept is that it contributes power to the TFE output.

The last of the 17 concepts incorporates an intermediate, nonstructural sheath as the inside layer of a full-length trilayer sheath. This is bonded to the outer layer of the conventional trilayer collectors in the converter assembly. (This is, as described so far, like one of the methods for fabricating Concept 14.) This middle sheath is grounded at the bottom of the TFE to the outermost sheath and, hence, to the coolant as in the current design. It is also connected to the TFE output lead at the top of the TFE. The middle sheath is so thin in the intercell axial space that the resulting leakage current is small; however, the potential seen on this sheath by the insulator seals and across the trilayer as it divides the TFE output voltage is the same as the local converter operating voltage. As a result, there are no significant voltage differences from converters to ground.

The 17 concepts are compared in Tables B-1 through B-4. The first table indicates whether the high voltage concept has an inherent feature of higher reactor coolant reliability against single point failure. If the concept does not, the question is asked if it is compatible with any one of the methods described for the other concepts.

Table B-2 categorizes the methods for greater coolant reliability of those concepts having it.

Table B-3 indicates which of the concepts uses the current bonded outer sheath tube in its design, and the following three questions are asked for each design: Is the electrical connection completely flexible for series/parallel connection? Is the pentalayer an inherent feature of the design? Do the TFEs and the reactor have leads at both ends?

Table B-4 grades the effect of the design on volume fraction of fuel in the reactor core compared to the current design.

C. SECOND GROUP OF CONCEPTS (23)

The remaining 23 design concepts and comment on the features of each follow:

Concept 18 calls for a higher output voltage from each converter by improved thermionic performance. As a result, the converters would be more efficient, and a reactor of the same size would have greater redundancy to compensate for losses caused by the high voltage.

Concept 19 is to reduce the internal resistance in the TFE to accomplish the same as Concept 18.

Concept 20 is to use spherical emitters and collectors. It could not be explained concisely how this configuration would contribute to the goals of the study.

Concept 21 proposes integral cesium reservoirs. Their incorporation would halve the complexity in plumbing within the TFE, but for "flashlight" configurations the integral cesium reservoir reduces reliability. These reservoirs contain so little cesium that a slight leak will open-circuit a converter. The open-circuit failure of one converter turns off the entire TFE string of 36 converters.

Concept 22 proposes cuspoidal ceramic heat pipes outside the collectors such as in Concept 3.

Concept 23 is to find better insulating coatings for the outside of the insulator seal.

Concept 24 is to impose a high-pressure gas or high-pressure cesium vapor in the fission product space to suppress any arcs. The pressure of high-pressure gas outside the interelectrode space could cause creep rupture of the insulator-seal as presently designed, and it would extinguish the thermionic output if it leaked into the interelectrode space.

Concept 25 calls for an annular heat pipe around and fabricated integrally to each TFE to remove heat axially. Cuspoidal driver rods bonded to the resulting element would fit into the open spaces in the triangular lattice and recover the fuel volume fraction lost to the annular heat pipe. High voltage would be accomplished by isolating each of these elements with an external insulating coating.

Concept 26 is a fuel element whose converters have annular emitters and two collectors. This converter is a hybrid of the externally and internally fueled concepts. It could not be explained concisely how this configuration would contribute to the goals of this study.

Concept 27 proposes that the TFEs produce pulsed dc by varying cesium pressure. The pulsed dc would eliminate the requirement for switching voltage output by the amount of loss in the transistors. The power output of a pulsed TFE would be at most half that of a steadily operating TFE, and the pulsing frequency would be on the order of 20 Hz at the maximum. For such low frequencies the power conditioning transformer would be relatively inefficient.

Concept 28 is the same as Concept 27 except the pulsed dc would be produced by utilizing ignition instability. The pulsing frequency could be as high as 1000 Hz with this technique. (This concept developed into Concept 16, which produces ac, and hence is not limited to half the output of this concept).

Concept 29 is to achieve higher efficiency by Rasor's method of pulsed operation and to use the higher efficiency to compensate for high voltage-induced loss (as in Concepts 18 and 19).

Concept 30 proposes more and smaller TFEs to increase the reliability against any high voltage-induced loss.

Concept 31 is to use an electrically nonconducting reactor coolant to isolate the TFEs and eliminate the common ground.

Concept 32 uses the current TFE and reactor technology with the addition of three more in-coolant TFE-to-TFE connections (for a total of five per string) so that only the last two TFEs penetrate the vessel. The string of six TFEs would be isolated from the coolant ground as in Concept 2. The string would have just two cesium reservoirs, or sorption reservoirs would be required (since they can reject heat to the coolant temperature).

Concept 33 increases the reliability against the leaking of cesium into the fission product space by using two insulator-seals in each converter. Losses due to arcs to ground are diminished with low probability that interelectrode cesium will enter the space.

Concept 34 proposes redesign of insulator-seals and welds to the most leakproof technology for increased reliability against cesium leaks, as discussed for Concept 33.

Concept 35 involves the attachment of six heat pipes shaped as trisected sections of a tricusp bonded or fabricated integrally to the TFE sheath. The resulting fuel element configuration is a hexagonal prismatic block. This design is a cross between Concept 3, in which all of the TFEs and tricusped heat pipes are brazed solidly, and Concept 6, in which the TFEs and integral heat pipes are modular but there are only two (in that case lenticular) heat pipes for each TFE.

Concept 36 is to generally redesign the intercell and TFE end configurations to avoid high-voltage differences in close proximity. Concept 10 is a case of this general proposed solution.

Concept 37 is to employ "thin film thermionics." This concept was not defined any further, and hence cannot be presented.

Concept 38 is to use the "pancake" design with mixed cesium and fission products. This was discussed as an option to Concept 13.

Concept 39 proposed a reactor be designed based on the extinguished mode of converter operation. It is not clear how this would result in a power plant capable of higher output voltage.

Concept 40 is to use a cesium thyratron in each TFE to produce pulsed dc, or ac, output. This is similar to Concept 16.

Table B-1

Coolant Reliability

High Voltage Concept No.	Greater Inherent Reliability?	If not, is it Compatible with Another Method?
1	No	Yes
2	Yes	
3	Yes	
4	Yes	
5	Yes	
6	Yes	
7	Yes	
8	Yes	
9	No	Yes
10	No	Yes
11	No	Yes
12	No	Yes
13	Yes	
14	No	Yes
15	No	Yes
16	No	Yes
17	No	Yes

Table B-2

Methods for Greater Coolant Reliability

High Voltage Concept No.	Heat Pipes	Segmented Core	Fewer Penetrations	Ribbon Ducts	Double Containment of Primary Coolant
2			x		
3	x				
4				x	
5	x	x			
6	x				
7					x
8	x				
13				x	

Table B-3

High Voltage Concept No.	Uses Current Sheath Technology?	Flexible Series/ Parallel?	Pentalayer?	Lead at Each End?
1	Yes	Yes	No	Yes
2	Yes	No	No	Yes
3	Yes	Yes	No	Yes
4	Yes	Yes	No	Yes
5	Yes	Yes	No	Yes
6	No	Yes	No	Yes
7	Yes	Yes	No	Yes
8	No	Yes	No	Yes
9	No	Yes	Yes	Yes
10	Yes	No	No	No
11	No	No	No	No
12	No	Yes	*	Yes
13	No	Yes	No	N/A
14	No	No	Yes	No
15	Yes	No	No	No
16	Yes	No	No	No
17	No	No	Yes	No

* Uses "nine-o-layer"

N/A - does not apply

Table B-4

High Voltage Concept No.	Reactor Fuel Volume Fraction Compared to Current Design
1	B
2	B
3	B
4	C
5	C
6	C
7	B
8	D
9	C
10	A
11	C
12	C
13	C
14	C
15	C
16	C
17	B

A - Better than current design*
B - As good as current design
C - Somewhat worse than current design
D - Much worse than current design

*Current design is converters in a close-packed (triangular) array.

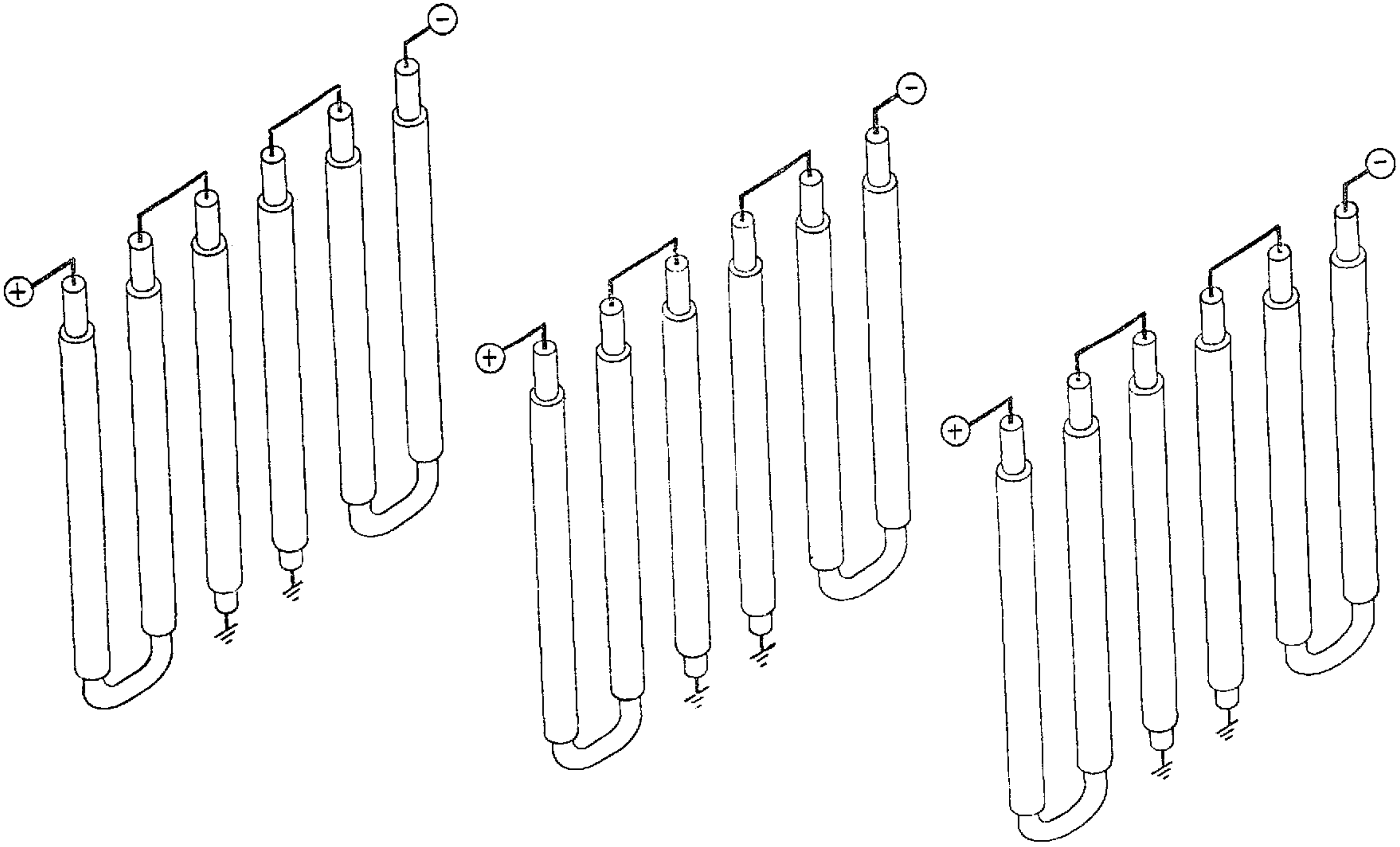


Figure B-1. Current design – TFEs in groups of six

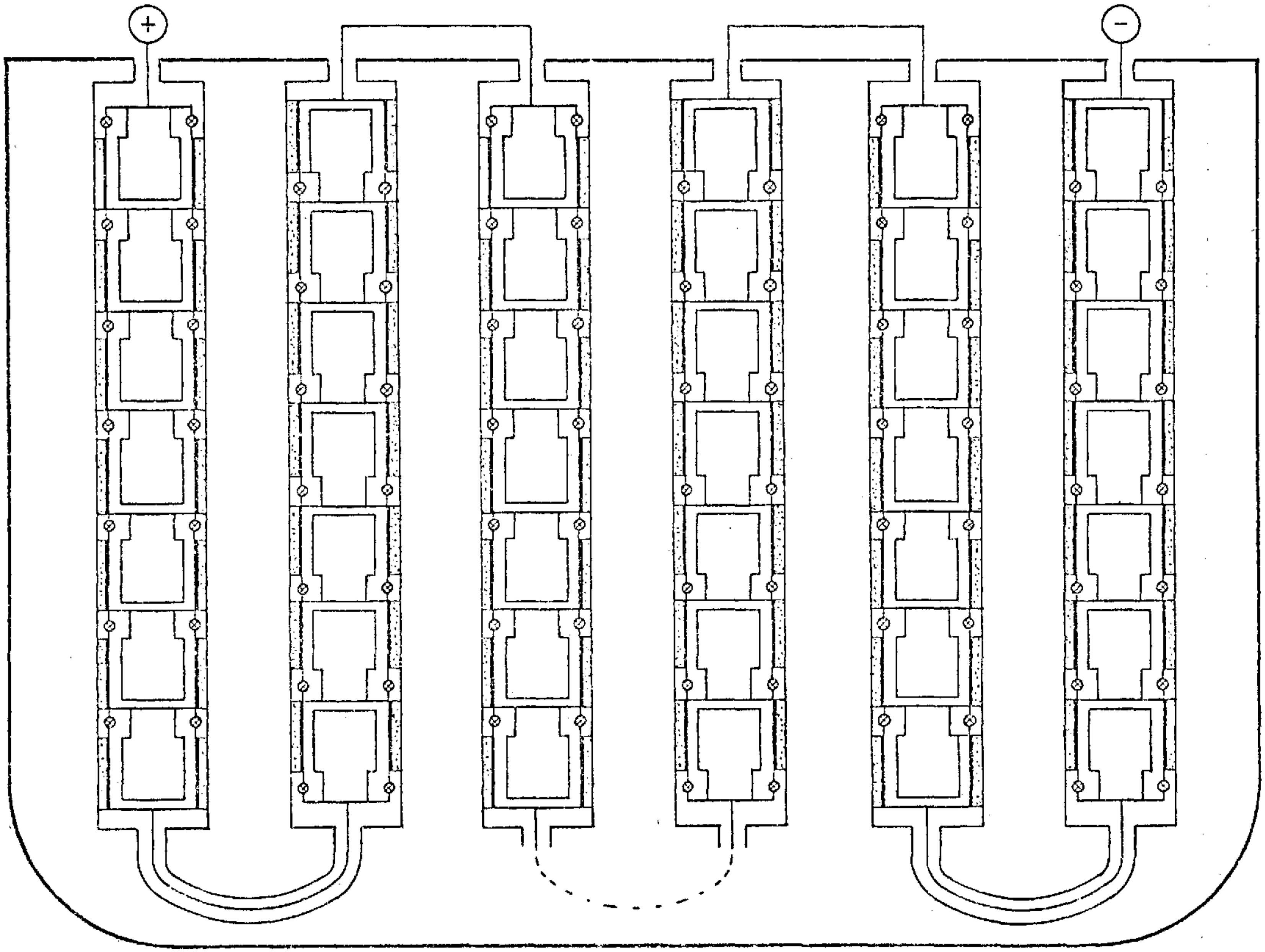


Figure B-2. Current design – connection of six TFEs

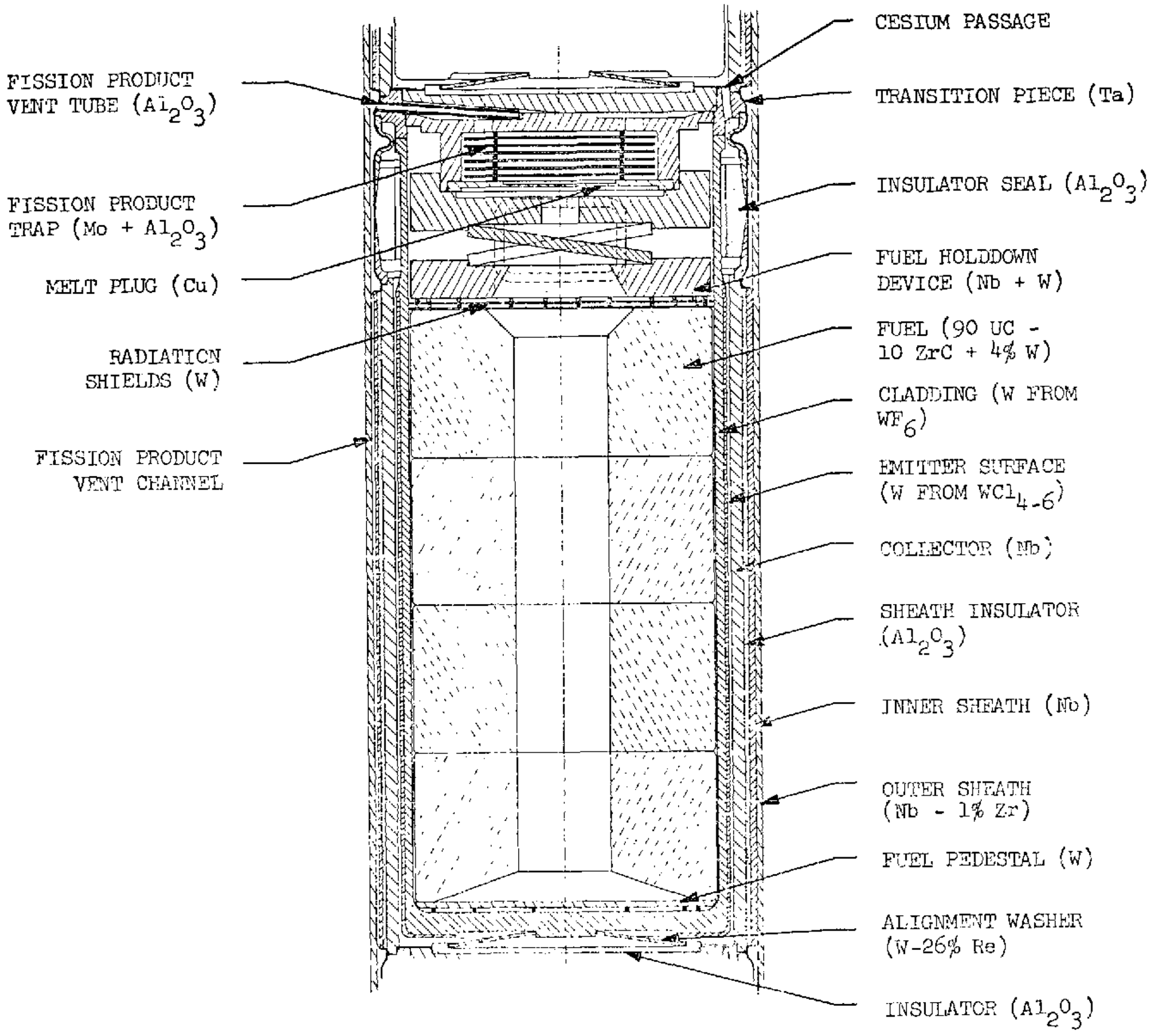


Figure B-3. Current design — converter detail

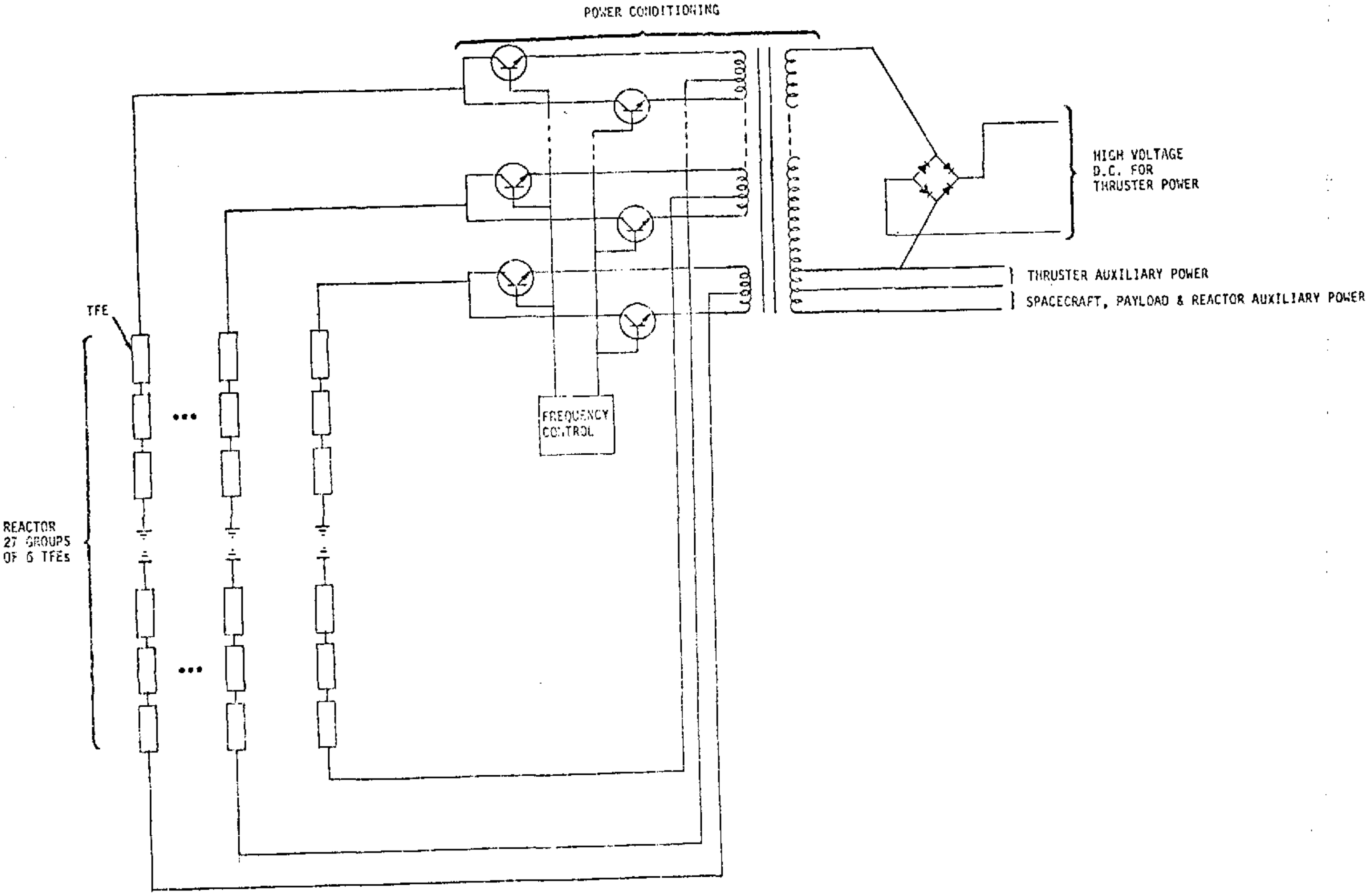
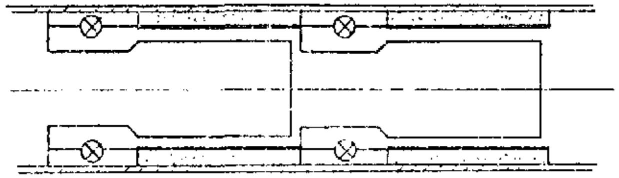
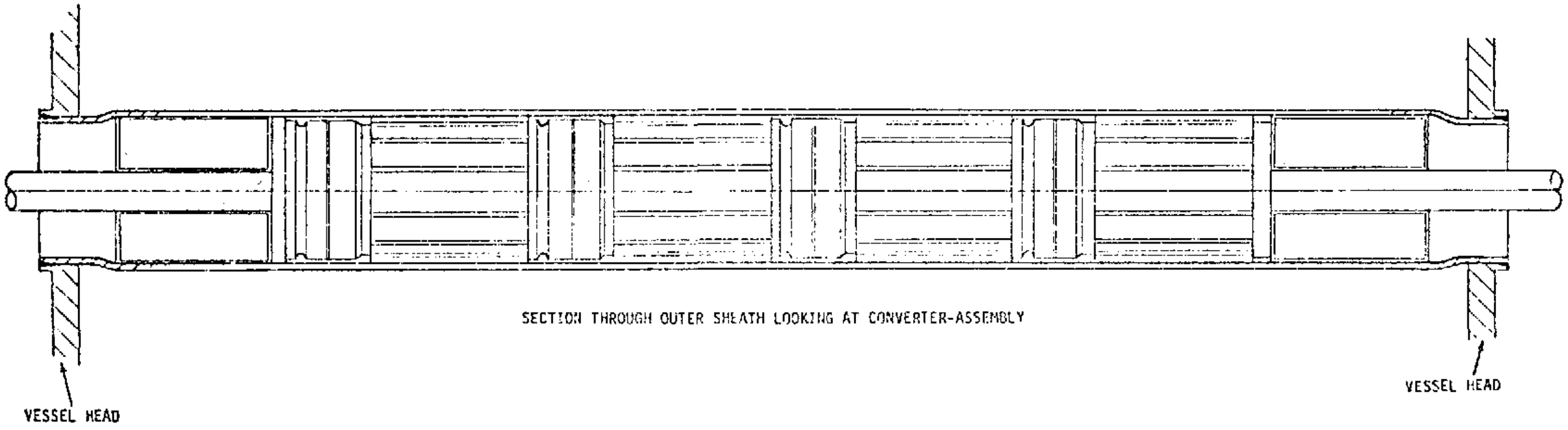


Figure B-4. Current design – power conditioning and distribution

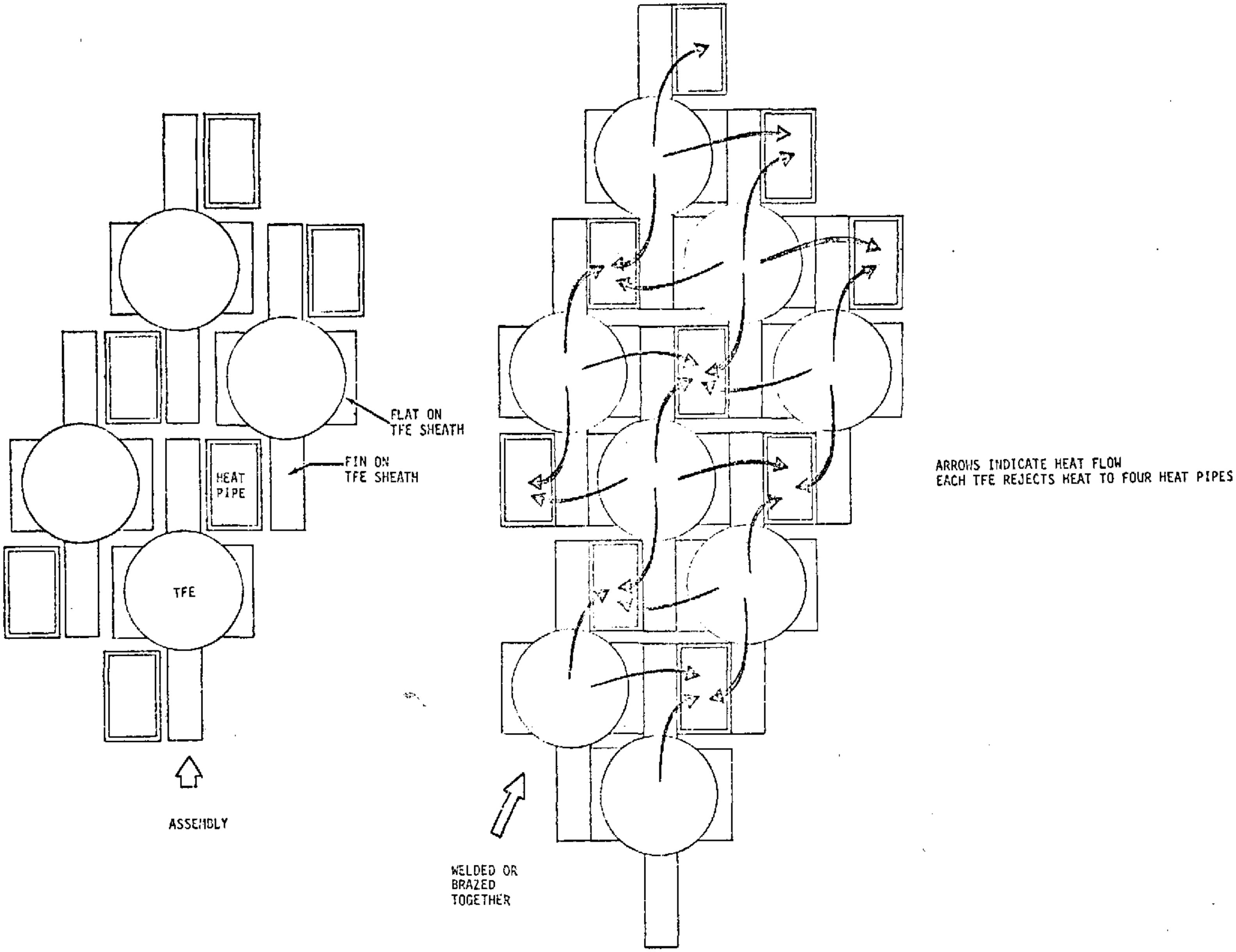


SCHEMATIC OF CONNECTION



SECTION THROUGH OUTER SHEATH LOOKING AT CONVERTER-ASSEMBLY

Figure B-5. Concept 1



ARROWS INDICATE HEAT FLOW
EACH TFE REJECTS HEAT TO FOUR HEAT PIPES

Figure B-6. Concept 8

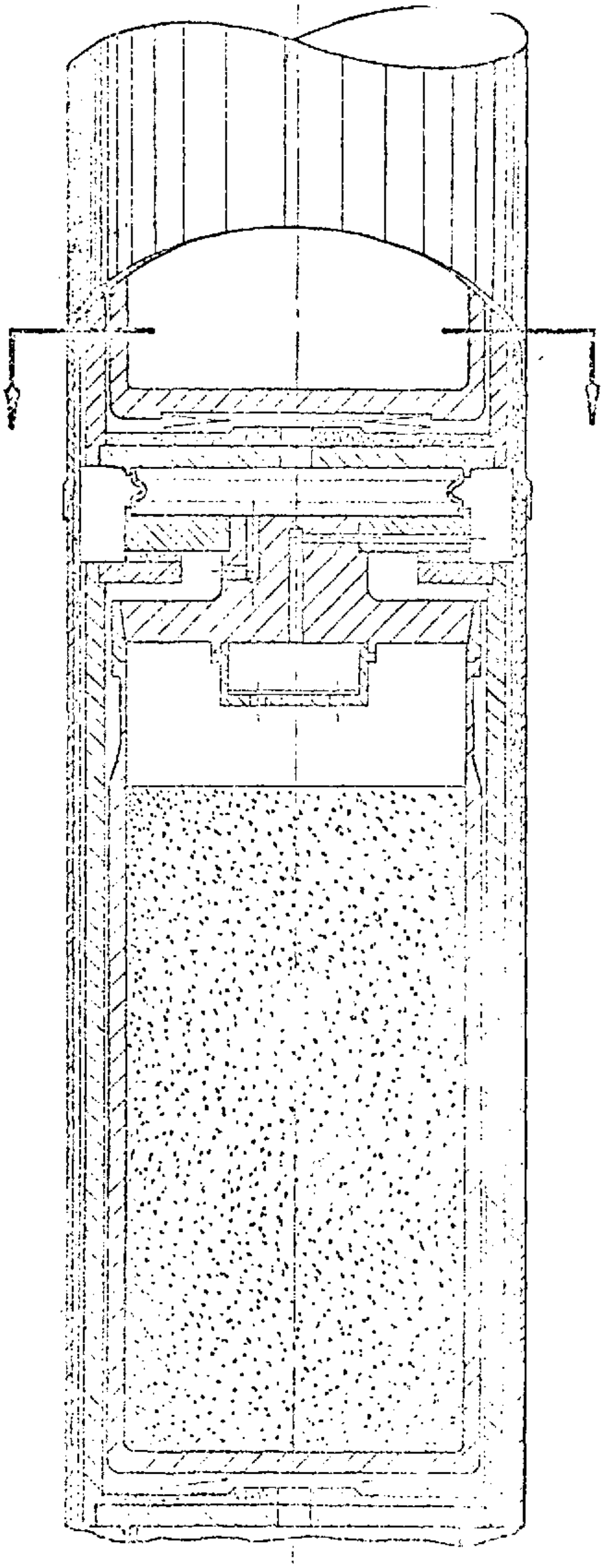


Figure B-7. Concept 10

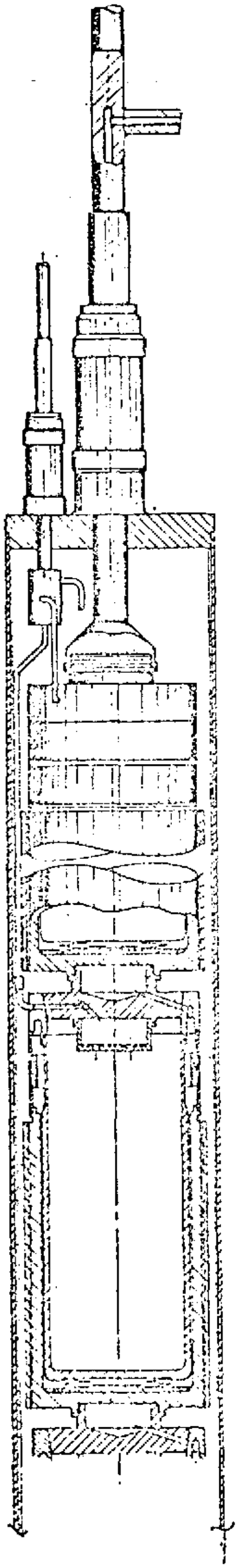


Figure B-8. Concept 11

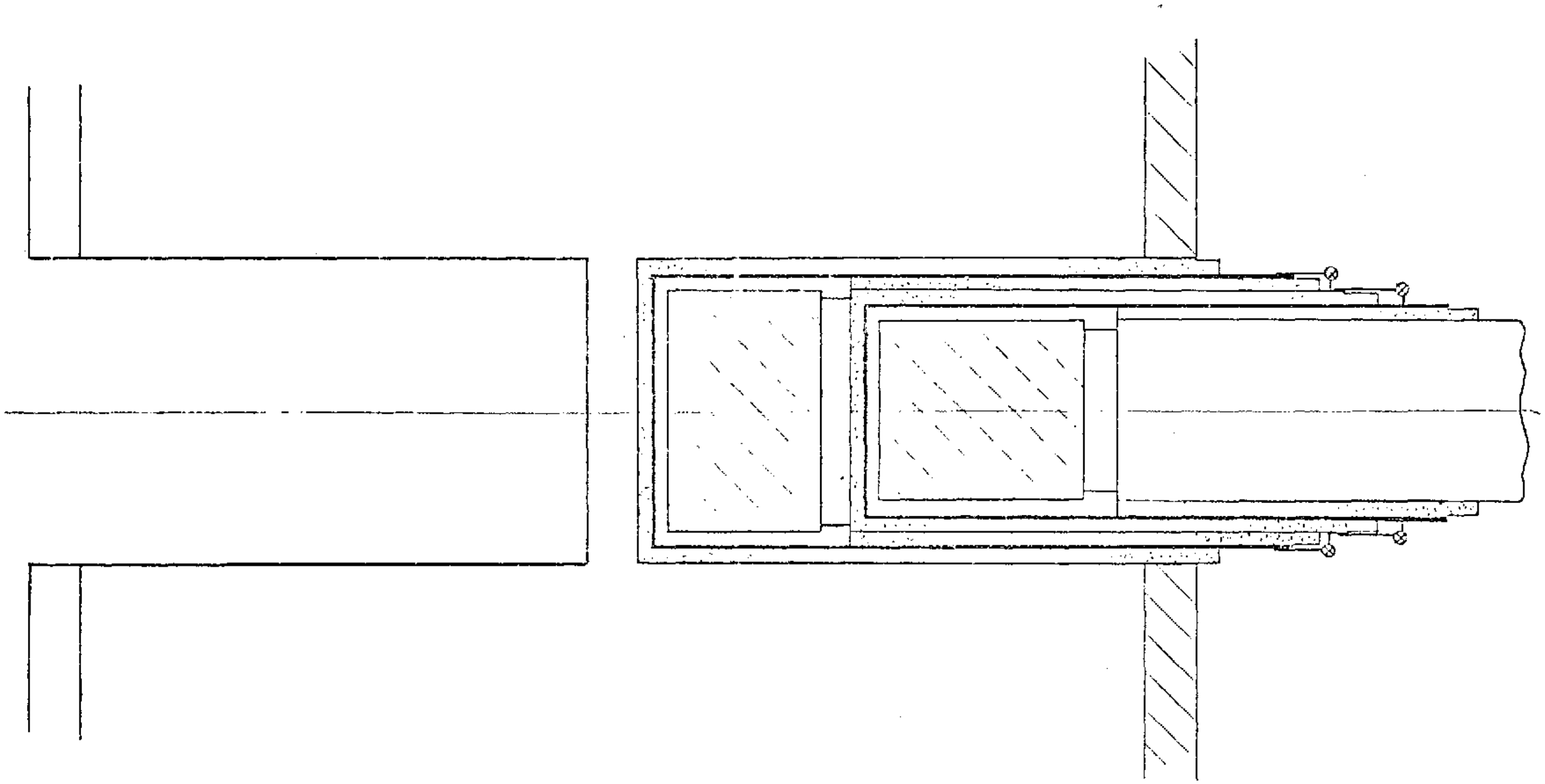


Figure B-9. Concept 12

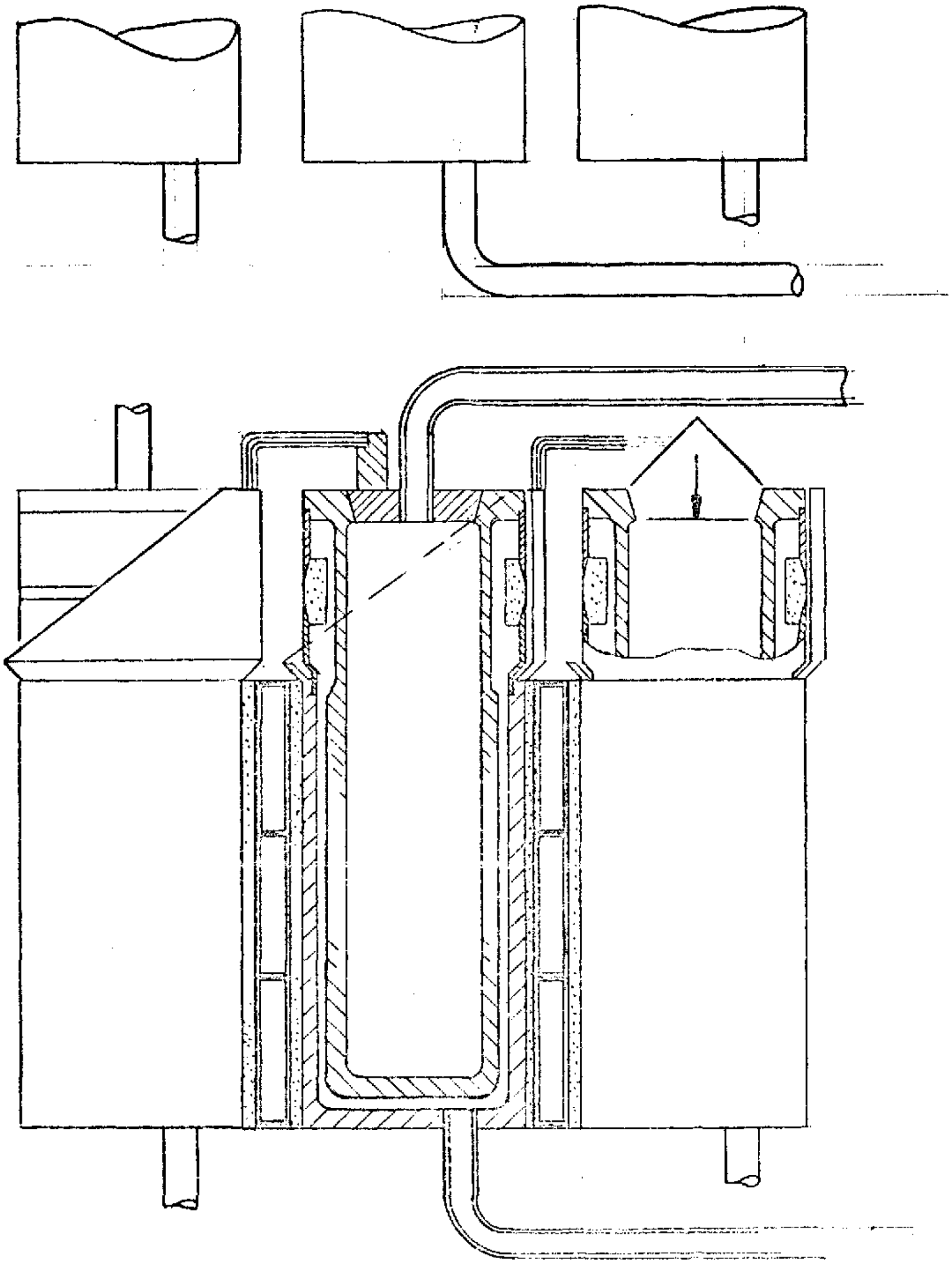
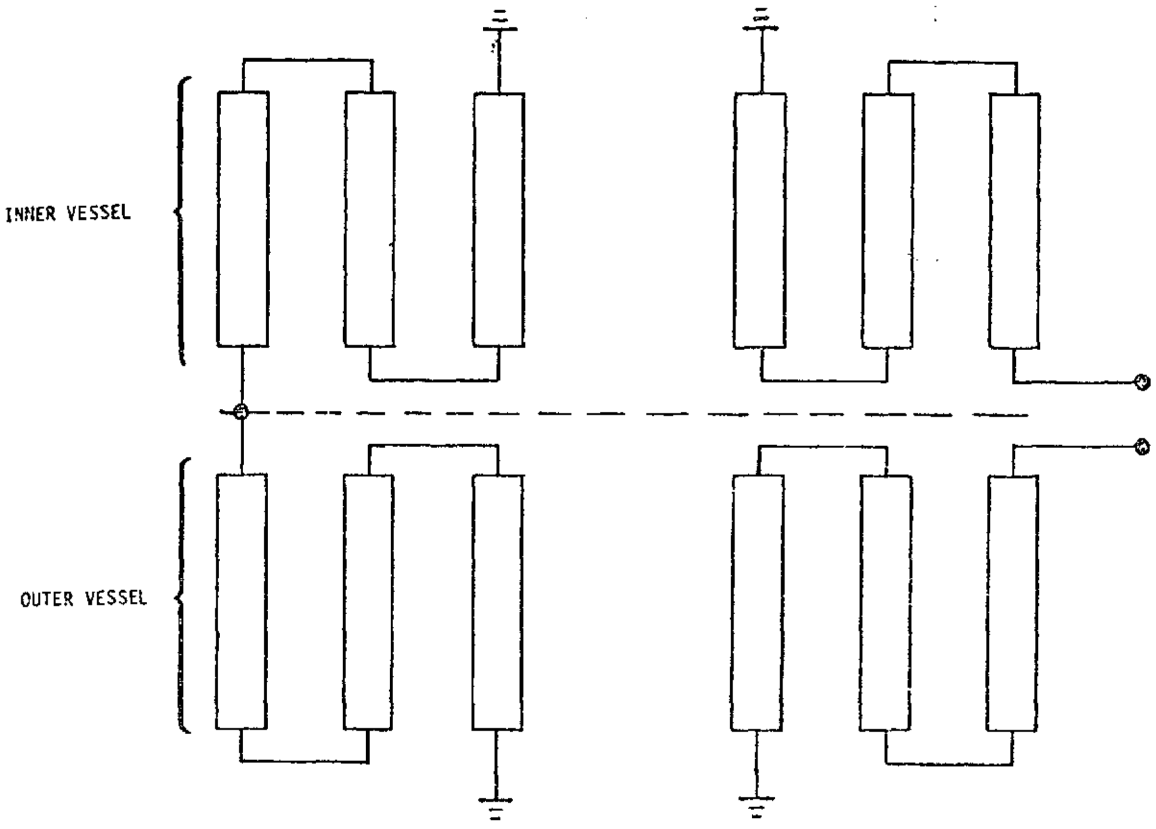
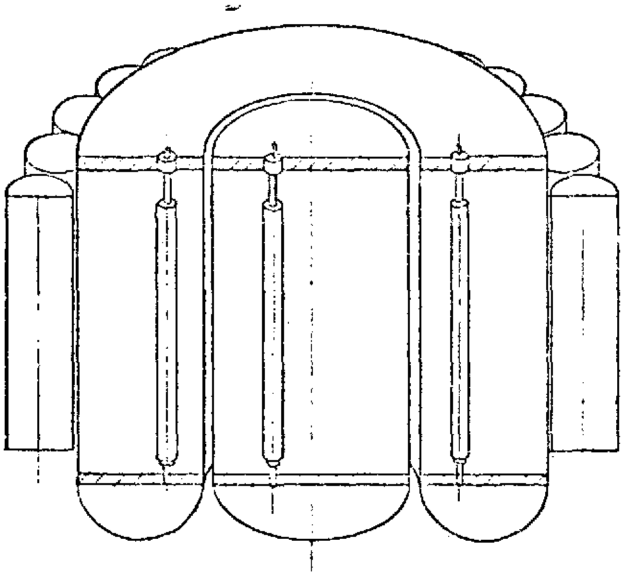


Figure B-10. Concept 13



TFE CONNECTION SCHEMATIC



REACTOR CROSS SECTION

Figure B-11. Concept 15

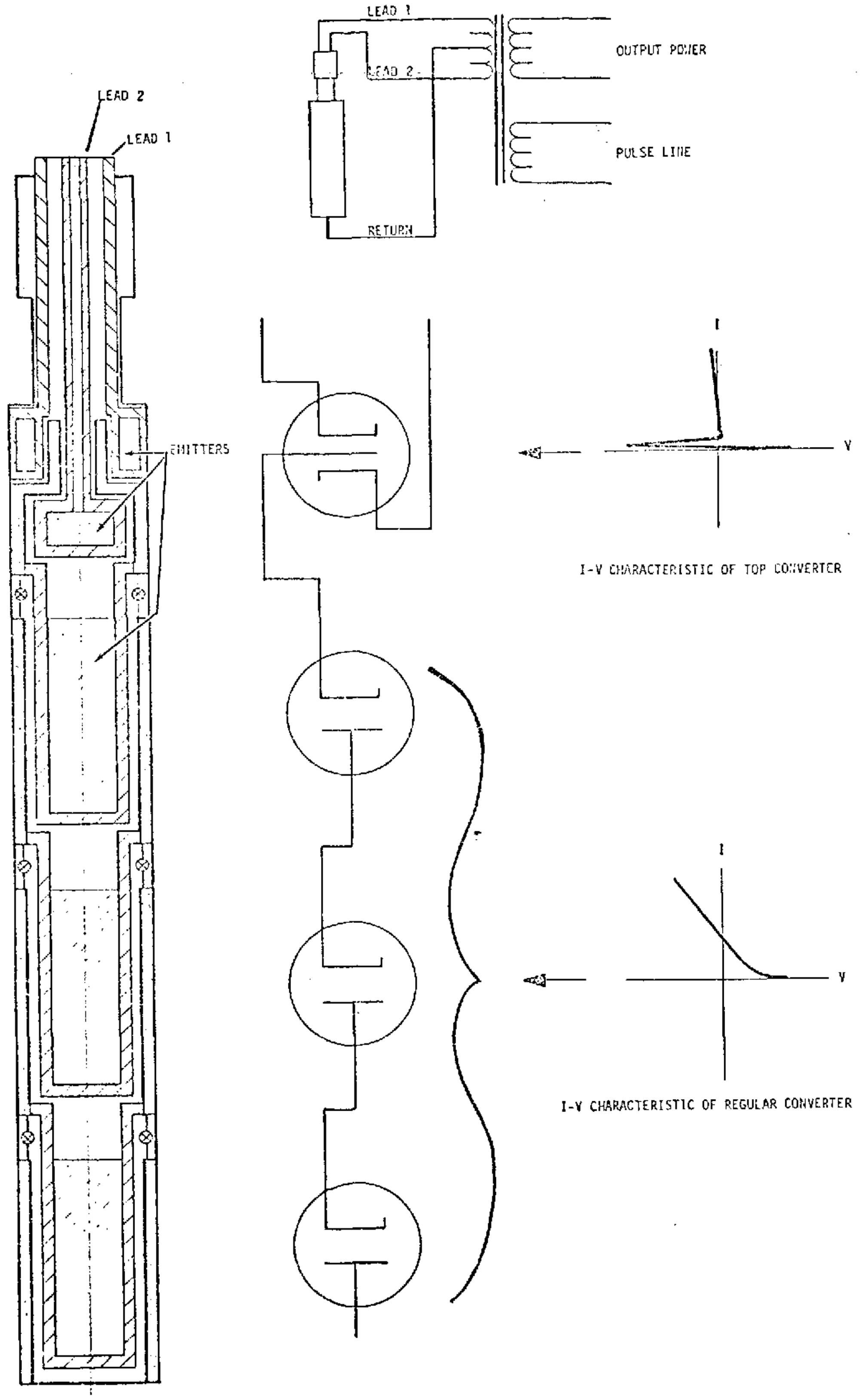


Figure B-12. Concept 16

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