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AN OUT-OF-CORE THERMIONIC-CONVERTER SYSTEM FOR NUCLEAR SPACE POWER

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ABSTRACT

Designs of nuclear thermionic space power systems with the converter outside the reactor have been re-examined in the perspective of recent advances in heat-transfer methods, materials, converter performance, and radiator design. The 40- to 70-kW(e) power range is treated.

The configuration 1) meets the constraints of readily available launch vehicles; 2) allows for off-design operation including startup, shutdown, and possible emergency conditions; 3) provides tolerance of failure by extensive use of modular, redundant elements; 4) incorporates and uses heat pipes in a fashion that reduces the need for extensive in-pile testing of system components; and 5) uses thermionic converters, nuclear fuel elements, and heat-transfer devices in a geometrical form adapted from existing in-core thermionic system designs. This approach contributes to a cohesive research and development program for in- and out-of-core thermionic systems at a broad range of powers.

Designs and in some cases performance data for elements and groups of the elements of the system are included. They are novel heat-pipes that extract heat from the reactor and form part of a modular cross flow heat exchanger, long heat pipes that provide electrical isolation of the individual thermionic converters, and thermionic converters that include space radiators that then compose a converter-radiator module. As a part of the presentation of the design and performance, benefits of the highly modular system approach to reliability, safety, economy of development, and flexibility are discussed.

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I. INTRODUCTION

Development of space-nuclear-thermionic energy conversion in the United States is almost completely focused on the use of converters located in the core of the reactor. The Lewis Research Center of the NASA is providing technological support to this activity. As a part of the program a small amount of effort is being invested in examining alternate approaches in nuclear thermionic designs. Out-of-core thermionic systems studies for the 150 and 350 kW(e) power level, references [1 and 2], are examples of this effort. Since these studies there has been a stronger alignment of our laboratory's effort with the in-core thermionic reactor program. As a result the out-of-core development work has been restricted to designs that are based on the use of fuel elements and thermionic converters that are geometrically consistent with the Gulf General Atomic in-core system, reference [3]. The desirability of this approach is obvious: The development of dimensionally stable, high performance thermionic fuel elements involves a complex and costly program that as yet does not provide adaptable thermionic fuel elements. Therefore consistency in dimensions, geometry, materials, fabrication procedures, and operating conditions for the in-core and possible out-of-core designs must be maintained.

Several recent technological advances have provided the opportunity of transposing the developments of in-core thermionic system to out-of-core designs. They are improved thermionic converter performance at low emitter temperatures; development of high-strength, corrosion-resistant, ductile, refractory metal alloys, references [4 and 5]; refractory metal fabrication by chemical vapor deposition; new compact-reactor design concepts, references [6 and 7]; demonstration of high temperature, high throughput heat-pipes, reference [8]; and the utilization of such heat pipes as a means of achieving electrical isolation of the thermionic converter emitter from the heat source, reference [9].

The heat pipe provides an extremely high thermal flux in a configuration that has a relatively large electrical impedance. The vapor-filled, thin walled pipes can be used to connect the heat source directly to the converters. This eliminates temperature drops associated with out-of-core thermionic systems that use radiant heat transfer and precludes the problem of high-temperature chemical interactions encountered with metallic oxide insulated emitters. The use of heat pipes for electrical isolation is one of the main distinctions between this and other out-of-core designs such as reference [10].

Since the publication of the previous reports on out-of-core thermionics the possible uses of nuclear thermionics in the space power field are better defined. There is an increasing number of possibilities for these power sources in communications and applications technology satellites and for solar system exploration.

The projected use of thermionics in solar system exploration is, of course, for nuclear electric propulsion. As the nuclear electric propulsion has approached the design stage several new considerations have entered. The general characteristics of the launch vehicles that will be available in the next two decades are now specified, a variety of planetary missions are projected, and payload requirements are identified. From this information mission analyses have established trip times, thrust schedules, propulsion-system specific mass, and first order estimates of scientific payloads and their required vehicle configurations. An interesting result of the nuclear electric propulsion (NEP) studies is that many of the space exploration missions based on a two stage chemical launch can be achieved at relatively low electrical power. A dominant power plant characteristic in establishing mission feasibility is specific mass: propulsion system mass per unit electrical power, α, Kg/kW(e). The propulsion system mass and trip times for two NEP missions are shown in figure 1a and 1b. (These data are extracted from reference [11].) Note that at lower values of electrical power higher values of α are allowed for both Titan, Centaur and Shuttle, Centaur launches. This is a consequence of the greater escape velocities that are attained with lighter, lower power vehicles. The general trend is the lower the energy requirements (the less ambitious missions) the larger the α allowed at low power levels. Also, relatively small increases in trip times provide for further relaxation of the α required at low powers.

These characteristics are brought forth because the results suggest that the separation between the so-called auxiliary power requirements and those of NEP is not as great as previously assumed if α is reasonable at low powers. Thus the extremely attractive possibility exists that a single nuclear power plant can meet the needs of both classes of missions.

Also, as nuclear thermionics approaches the application stage of NEP and auxiliary power other requirements emerge: lower developmental and recurring costs (the multiple applications suggested in the previous paragraph will of course increase economy); greater reliability, and more ease and assurance in testing of the elements and the complete system. There is yet considerable debate on what constitutes satisfactory preflight acceptance tests. In any event the power plant that demonstrates the best reliability will receive wider acceptance.

The system described in this paper is highly modularized to ease testing and to provide for redundant elements needed for reliability. Also, through this modularity, easy scaling over a wide power range is available. As stated previously the present technology in the in-core TFE development [3] is retained. The fuel and fuel-clad materials and diameters are the same as in the G.G.A., AEC, NASA in-core development. The converters also retain the diametrical consistency with the major difference being that the six cell units are located out-of-core on heat pipes. The thruster power range examined is 30 to 60 kW(e), but scaling characteristics to lower powers are indicated. The 30 to 60 kW(e) capability was selected since this meets many of the NEP missions and constitutes the greatest design challenge in obtaining the low α's required for NEP. If satisfactory α's can be achieved for 30 to 60 kW(e), the small lightweight power plants can be simply derated to provide many auxiliary power needs. Alternately the external modular elements can be reduced in number. But in either approach the system does not require any significant reengineering for the lower powers.

II. SYSTEM DESCRIPTION

The NEP spacecraft configuration selected is shown in figure 2. Out-of-core thermionic power plants adapt to other configurations, but for the sake of consistency with several recent studies the side thrust spacecraft was chosen. The high-temperature radiator is 1 meter in diameter, and the length varies from 3.4 to 5.6 meters in the 40 to 70 kW(e) (unconditioned power) range. A compact heat-pipe-cooled reactor is located at the rear of the high-temperature radiator, and since the reactor is designed on the basis of criticality, its size is constant over the power range. High-temperature heat pipes connect the reactor to the bank of converters. An intermediate heat exchange in the reactor area is used for power smoothing and increased reliability. The reactor heat-exchanger and the converter are separated by 68.4 cm heat pipes for all powers. This provides adequate electrical isolation from the reactor for the low output voltage converter banks. The heat from the diode collectors is extracted by ferrous-alloy heat pipes that also form the surfaces of the high-temperature radiator. Twenty electrically independent sections of the radiators are used to eliminate usual insulating collector trilayers.

The electrical output from the converters is carried to the rear of the spacecraft by paralleled low-voltage leads.

The reduction of radiation exposure of the payload and the power conditioning is achieved by the use of lithium hydride to reduce neutron damage; the mercury propellant decreases the effect of gamma radiation.

The general shielding arrangement is similar to previous in-core, NEP studies except that the smaller reactor, the lower thermal power levels, and less dense radiator provide the opportunity for reducing the shield thickness and for shaping of the shield.

Twelve 3 to 5 kW(e) thrusters are located centrally, followed by the power conditioning section containing heat-pipe cooled power transistors located 5 meters from the center of the reactor. Two transistors are separately coupled to a toroidal transformer and thus form a compact low voltage switching segment. A shaped shield around the low voltage components provides additional radiation protection. The heat-pipes coupled to the transistors fan out to become a flat low temperature radiator. The high voltage region of the power conditioning is located behind the low-temperature radiator. The scientific payload and antennas compose the final section of the spacecraft.

Because of the relatively short length of this spacecraft, part of the scientific payload and antennas would probably be mounted on an extendable boom to provide for additional separation distance from the reactor and the thrusters. These details have not been examined.

III. THE REACTOR, AND MODULAR CROSS FLOW HEAT EXCHANGERS

The heat-pipe cooled, vented, fast-neutron reactor shown schematically in figure 3 was selected for this study. Heat-pipe cooling was chosen for the following reasons.

The large number of independent sealed elements provides redundancy and eliminates the single-point failure mode of liquid-metal-cooled reactors. The many separate heat-transfer paths also allow a relatively inexpensive statistical evaluation of the reliability of the reactor coolant system.

Heat pipes also eliminate the usual electromagnetic (EM) pumps. This saves the electrical power required to operate inefficient EM pumps and eliminates shielded volumes required to house the pumps. Furthermore heat pipes maintain a nearly constant temperature core, greatly simplify part-power operation, and in event of the requirement of reactor shutdown provide cooling independent of other auxiliary electrical power requirements.

The reactor core is an assembly of two elements, tungsten encapsulated fuel rods and reactor heat pipes. These heat pipes also form two heat exchangers at the ends of the reactor (figure 3a and 3b). Since energy is extracted from both ends the reactor, its heat pipes and fuel rods can be made symmetric about the reactor center line. Short heat pipes with low axial throughputs result. Also, the reactor can be constructed in independent halves. The isolated sections in turn reduce the electrical leakage of the heat pipe connected converter banks. This will be treated in more detail in a subsequent section. Another major advantage is that the assembly, machining, and preflight testing of the two independent sections are greatly simplified since the sections in themselves are neutronically noncritical. The electrically isolated halves then can be combined to form a critical assembly as shown in figure 3a. Control of the reactor can be established by the relative motion of the two halves as proposed in references [2 and 7] or as shown in figure 3c by a shutter-like motion of the beryllia circumferential reflector. The beryllia design is lighter than the metallic reflectors of references [2 and 7], thus is better adapted to the lower power levels of this study.

The fuel element width is 2.8 cm and is 14.25 cm long (figure 3d). The tungsten fuel clad is modified from the cylindrical shape used in in-core thermionics to stack in a square array. The end of the fuel clad at the reactor center line is increased in thickness to .254 cm and in the stacked array provides a modular center plate. The end section is thicker than its equivalent in in-core thermionics. At the outer ends of the fuel element the last 5 cm of the fuel element contains either 3 cm of unenriched uranium carbide followed by 2 cm of tungsten or 5 cm of molybdenum. These inserts are the axial neutron reflectors for the reactor. The metallic end sections are cross linked with tie rods to provide an articulated, yet firmly locked reactor structure.

The tungsten reactor heat pipes are cylindrical in the fueled section and transform into a rectangular cross section to form the surfaces of a flat-plate cross-flow heat exchanger. The chemical vapor deposition process permits the easy fabrication of this somewhat unusual shape. A photograph of this type of heat pipe in operation is shown in figure 4.

The fuel elements and reactor heat pipes are nested together and are constrained radially by a tungsten housing consisting of stacks of carefully machined washer-like pieces. The laminated tungsten discs may be separated to provide stronger nucleonic coupling of the beryllia reflector with the core. The thickness of the laminated tungsten housing provides a hoop stress consistent with the hoop stress that has been found to give diametrical stability of the various uranium-carbide, tungsten fuel-pin tests.

The assembled core is then enclosed with thin tantalum that forms a fission gas containment vessel. The beryllia reflector pieces are outside the can. It is difficult to visualize how the assembly and encapsulation of this type of reactor is achieved; so a series of photographs (figure 5a, b, and c) is shown illustrating assembly of a model of the heat-pipe-cooled reactor proposed in references [2 and 7]. The photographs also indicate how the modular reactor heat pipes can form series of slab-like, encapsulated heat exchanging surfaces that in turn can accept the flattened ends of heat pipes that lead to the converter bank. Since the reactor shown is for a higher power, the number of fuel elements and heat pipes is considerably greater than that for the reactor proposed for 40 to 70 kW(e). The lower power reactor uses 82 fuel elements and 89 reactor heat pipes in contrast to the 162 fuel elements and 185 heat pipes used in each reactor half as shown in the photographs. As stated earlier the lower power reactor uses a beryllia shutter-like reflector instead of the fixed metallic reflector that is simulated in the model in figure 5.

The thermal transfer from the fuel elements to the reactor heat pipes and to the converter heat pipes relies on pressure contact between the surfaces. This, of course, requires careful machining of the mating surfaces. The more challenging fabrication problem is mating the cylindrical heat pipes to the fuel elements. But this appears to be relatively easily accomplished by machining the final dimensions of the cylindrical corners of the fuel element in the assembled noncritical core half. From the results of small scale studies the use of thin layers of tantalum or niobium between the tungsten surfaces appears to be required if a good thermal bond is to be established at reasonable unit pressures and temperatures. Thus this study assumes the use of tantalum or niobium plated heat pipes in the reactor core.

The reactor core is nominally 28.5 cm in diameter and 29.0 cm long. A maximum uranium loading of 165 kg based on fully dense uranium carbide is available. But for a metallic circumferential and end reflector, only 115 kgs of uranium (235) are required to provide the necessary control margin and excess reactivity for fuel burnup. A smear density of 69 percent (115/165) is therefore used in this design, with a substantial portion of the volume allocated to large central voids in the fuel element. If fabrication experience indicates the need for thicker tungsten clads this can be accomplished by simply reducing the size of the central void. The use of the beryllia reflector that is now advocated for this low power reactor will further reduce the fuel required for criticality, but this reduction has not been included since these calculations are yet incomplete. The fuel inventory based on a metallic reflector can be considered as providing a design margin.

Typical missions require the reactor to operate at the equivalent of 20,000 full power hours. At 500 kW(t) this corresponds to a fuel burnup of 1.18×10^{20} fission/cc based on fully dense fuel in 69% of the available volume.

The reactor heat-pipe diameters are 1.2 cm and at the low thermal power operate very conservatively: an axial throughput of less than 4 kW(t)/sq cm for the highest power case treated. The surface flux in the cross flow heat exchanger adjacent to the reactor is about 106 w/sq cm at 500 kW(t) and is also within acceptable heat-pipe practice. Surfaces of 1840 and 1860° K in the reactor heat pipe are used in the analysis.

The reactor heat-exchanger volume required for the transfer of the thermal output to the converter heat pipes is small; so an additional set of heat pipes is included in the cross-flow heat exchanger. This extra set of heat pipes does not leave the heat-exchanger area and is used for additional power smoothing and for parallel heat paths in event of local heat-pipe failures. The overall dimension of the resulting reactor and heat exchanger are a diameter of .42 m and a length of .54 m.

Some supporting evidence of the practicality of this reactor design is now available, even though the experimental evaluation effort is yet quite small. Three prototypic CVD-tungsten heat pipes using lithium as the working fluid have been built. One has accumulated over 4000 hours operating at about 1820° K. An axial throughput of 9.5 kW(t)/sq cm in the cylindrical section has been maintained in the life tests, reference [12]. This is over twice the flow rate required in the present study. Uranium-carbide fuel encapsulated with tungsten has also demonstrated dimensional stability at the 1.18 x 10^{20} fission/cc burnup proposed for some NEP missions. Reference [13] indicated dimensional stability of a tungsten alloy clad uranium-carbide fuel element at 1.9 x 10^{20} fission/cc. At the time this paper was submitted a burnup of over 0.6 x 10^{20} fission/cc had been achieved in a thermionic fuel element that contains several fuel pins with materials and diameters consistent with the present reactor design, reference [14].

IV. CONVERTER HEAT PIPES

The tantalum alloy heat pipes extend from each heat-exchanger to the cluster of converters. Lithium is the heat transfer fluid with argon added to ease heat-pipe startup and also to provide for a variable heated length. A separation of only 68.4 cm between the reactor and the first converter was selected in order to ease the fabrication of the converter heat pipe. The heat-pipe consists of three sections: the evaporator, the adiabatic section, and the condensor section that is used to heat the emitters of the converters. The lengths and cross sections are shown in figure 6a. Two temperatures and three thermal throughputs were analyzed for pressure loss. Adequate pumping margins could be maintained for all cases. The lithium vapor conditions are 1804° K, 2400 torr and 1824° K, 2670 torr for the two emitter temperature cases treated. The heat loss in the adiabatic section is minimized by the use of multifoil insulation. Meteoroid damage protection is provided by the high-temperature radiator and the multifoil insulation that surround the heat pipes.

Upon leaving the cross-flow heat exchanger the pipes are separated, providing electrical isolation between the converters and the heat source. The losses are proportional to the square of the voltage, thus as indicated in reference [9] it is advantageous to electrically isolate the reactor halves and use a circuit of type shown in figure 6b. An output voltage of 9.26 volts is developed with a maximum "off ground" potential of only 2.07 volts. But even at this low voltage, leakage currents exist and require a slight increase in diode current resulting in reduced voltages. The local alterations to currents and voltages for the example shown in figure 6b reduce the efficiency of the converter array to 0.935 of that of a no leakage case.

Some evidence of the feasibility of heat pipes of the dimensions, temperature, and axial throughput exists. Busse, reference [15] has successfully operated a tungsten-rhenium alloy heat pipe for over 6,000 hours at 1873° K. Some tantalum alloy heat pipes also have been tested at temperatures above 1800° K but early work indicated a tendency of the larger tantalum heat pipes to fail corrosively, reference [16]. Recently yttrium getter capsules have been introduced into tantalum alloy heat pipes operating at 1800° K and above to control the corrosion of tantalum pipes. In a comparative test at our laboratory an ungettered pipe failed at 630 hours; the gettered pipe has operated over 2000 hours with no apparent change in performance or indication of leakage. Also, as a part of our laboratory's refractory metal program, tantalum heat pipe elements have been fabricated in complex shapes by the CVD process so that a structure of the type shown in figure 6a appears quite practical.

V. THE CONVERTER CLUSTER

The converter design consistent with in-core TFE emitter and collector diameters is shown in figure 7. It is a modification of a design described in reference [17]. The primary changes are the use of lithium accumulators in the emitter heat pipe and sodium accumulators in the collector heat pipe. These accumulators provide the excess fluid needed for effective heat-pipe operation and also act as lightweight current carrying leads. The 40-70 kW(e) power range also gives lower collector temperatures and larger radiator areas per unit of power than that of reference [17]. The lower radiator temperatures permit the change from niobium alloy to stainless-steel radiators. Recent performance data, reference [18], indicates that the deleterious effect of high collector temperatures on converter efficiency may often be underestimated for high-performance converters. This tendency is an additional reason for selecting low collector temperatures.

The out-of-core design allows pretesting of the converters by electron-bombardment heating. After pretesting, six converters are shrunk onto a heat pipe. A separation of 6 cm exists between the first converter and the remaining five to provide for more effective partial power operation, discussed in more detail later.

Emitters at 1820 and 1800° K were used in estimating overall system and converter performance. The current, voltage characteristics and calculated efficiency were based on an etched-rhenium emitter and niobium collector, reference [18]. Higher converter performance have been observed, but the data of reference [18] were used because it provides a detailed evaluation of the collector temperature effect needed in this system evaluation. It should be noted that the performance characteristics used in this study are very similar to those used in the in-core TFE performance projections, reference [19], even though a different emitter material is used. In the converter optimization analysis several advantages of out-of-core heat-pipe-heated diodes became apparent. First, a performance penalty is associated with low power thermionic reactors when converters are located in the core. This results because nuclear constraints require that the converter operate at low power densities well below the peak efficiency condition. Heat-pipe-heated converters permit operation at conditions that correspond to peak system efficiency. In effect the heat pipe acts as a power transformer that adjusts the surface heat flux in the reactor to that needed for maximum performance of the thermionic-converter system. The heat pipe also provides constant temperature emitter for each converter. Further, the converter can operate at the cesium pressure that corresponds to maximum performance since the thermal runaway problem of the fuel-emitter coupled emitter cited in reference [20] is largely obviated by the out-of-core location. Also, the volumetric constraints associated with in-core thermionics are reduced. Thus large metallic cross sections in the electrodes can be used to minimize voltage drops. The use of relatively large volumes of liquid metals in the heat pipes adjacent to the electrodes, as previously mentioned, achieves these low voltage drops at low specific weights. The nuclear fuel contamination of the electrode surfaces and emitter distortion are also eliminated by the out-of-core design.

Another important advantage of the out-of-core location for the NEP missions is the high efficiency that can be maintained at part power. Typical NEP missions involve long coast times. If in-core systems are to achieve fractional power output during these coast periods, the core temperature must drop, and efficiencies fall. Liquid-metal-cooled systems degrade even more significantly since the pumps impose a very large parasitic load. The addition of an inert gas in the converter heat pipes provides a simple solution to this problem. The inert gas collects at the end of an operating heat pipe and establishes a well defined temperature front. If the gas loading and the heat pipe cross sections are properly chosen significant motion of the thermal front can be achieved in the converter zone with small vapor-temperature changes. The converter heat pipe shown in figure 6a requires an inert-gas accumulator located at the end of the pipe having a volume of only 1/3 liter. This volume provides complete activation of six converters at the design temperatures of 1800 or 1820° K; then as the lithium pressure is reduced by lowering the temperature 20° K the thermal front moves so that only a single converter (on each heat pipe) is left operating. Analytically the approximate loss in efficiency would be only 25 percent at 1/7 power. This requires a 20 percent decrease in output voltage to reduce the electrical leakage in the emitter heat.

Experimentally the use of inert gas for this variable load characteristic is in the initial test stage at our laboratory. But there is wide spread utilization of the inert-gas-loaded heat pipes in a variety of lower-temperature applications. Experimental confirmation of the exact thermionic converter configuration shown in figure 7 has not yet been established, but a diode that is geometrically similar (heat-pipe heated, heat-pipe cooled, 70 sq cm emitter area) has been successfully built and tested, reference [17]. The performance at low power densities is similar to that of reference [18], the data used in this study. As supportive evidence of the possible lifetimes it is appropriate to observe that an electrically heated out-of-core cylindrical thermionic converter has maintained constant performance for over 39,700 hours and is still on test.

VI. THERMIONIC CONVERTER RADIATOR

The thermionic converters are cooled by sodium in a stainless-steel heat pipe. One or two tubes may be connected to each diode then subsequently bonded in a series, parallel manner to similar heat pipes that form the radiator surface. Figure 8 is a schematic diagram of the heat-pipe radiator. The radiating elements are metallically connected to the thermionic converter surface so that electrical isolation must be maintained among the heat pipes that cool each string of paralleled converters.

The diagram in figure 8 is based on 20 electrically separate radiator sections each consisting of six bonded heat pipes. Reliability of the radiator, converter system is achieved by the number of diodes in parallel, and the series, parallel thermal hook-up of the panels exposed to meteoroids.

The longest heat-pipe in the array ranges from 3.4 to 5.5 meters for the various power levels treated in this study. No direct experience with these particular heat-pipe designs exists, but heat pipes of similar diameters and lengths have been evaluated at lower temperatures. These tests furnish support for the heat-transfer and fluid-flow calculations used in the radiator design.

VII. THE LOW VOLTAGE LEAD

The low voltage lead is not as long as suggested in other NEP design studies. Part of the length reduction is due to the fact the converters are located behind the reactor. The other reason for the shorter transmission lines is the decision to use heat-pipe-cooled transistors and modular toroidal transformers. The low-voltage power-conditioning elements then can be grouped in a compact package and protected from radiation by a shaped shield, which reduces the need for their extensive separation from the reactor.

Aluminum, copper, and stainless-steel-clad lithium were examined as lead materials. The lithium leads were assumed to be cooled to the solid phase by the use of heat pipes. The electrical conductivity of lithium in the solid phase is almost three times that of the liquid at the melting point. But weight penalties of the clad and the heat pipes used to cool the lithium yielded a specific weight similar to that of an aluminum conductor. The final lead chosen was a tantalum-clad heat-pipe like lithium conductor in the high-temperature converter zone and simple aluminum bars for the rest of the distance to the power conditioners.

VIII. POWER CONDITIONING

The weight and performance assessments of the power conditioning system are based on the use of heat-pipe cooled transistors. Two of these transistors are coupled directly to a small radiation-cooled toroidal transformer. Inputs to the transformers are approximately at 10 volts a.c. The outputs of 2000 volts a.c. are routed past the low temperature radiator in a series parallel arrangement to furnish 4000 volts to the high voltage portion of the power conditioning system. The toroidal transformer design and switching transistor configuration are adapted from an optimization study in reference [21]. The use of heat-pipe-cooled transistors was suggested by the high performance of a water-heat-pipe cooled silicon rectifying junction, reference [22]. The selection of individual toroidal transformers to form a modularized low-voltage stage is based on observations of the difficulty obtaining well balanced load sharing of low forward drop transistors ganged in parallel. The weight and performance assessments of the high voltage section are the result of more conventional practice and are from reference [23].

A recent article, reference [24], on power conditioning reviews some of the latest work on power conditioning, and with the exception of the approach to the low voltage stage reference [24] arrives at design approaches and estimates of feasibility that are similar to those used here.

IX. SHIELDS

The shield requirements for the power conditioning equipment and the scientific payload are very difficult to assess at the present time. Because of the many uncertainties a detailed optimization study of shield shapes and thicknesses was not attempted. The shields were scaled from those of previous studies and are arbitrary. The thicknesses were adjusted for the power level by simple attenuation relations. The vehicle diameters yielded direct geometrical corrections. A factor of .6 was introduced to account for shield shaping permitted by the small reactor and the few system components in the reactor region. Pumps, electrical leads, heat exchangers, and manifolds do not exist outside the projected area of the reactor. The radiator is the only structure that extends beyond the reactor dimensions. The reactor coolant and radiator coolant are separated; the radiator is a low-density heat-pipe structure and so should respond to shielding by a shaped shadow shield. An alternate way to reduce shield weight is to extend the high temperature radiator length to that used in previous studies, reference [23]. If this approach is used the cross sectional area and weight of the shield could be reduced significantly, although the vehicle shape is not as aesthetically pleasing.

X. SYSTEM PERFORMANCE

The power distribution and a few key component temperatures of one of the cases analyzed are shown in figure 9. The absence of pumped loops improves power utilization and temperature distribution. The power requirements for the payload, power plant-spacecraft- and reactor-control were assumed to be equal to those specified for a 120 kW(e) system. The high-voltage cable, ion engine conditioning, and thruster characteristics were assumed to be consistent with the values given in reference [23]. The other losses were calculated by the methods discussed in earlier sections. As can be seen in figure 9 an initial power of 70 kW(e) is reduced to a thruster power of 45.6 kW(e) by the various losses and load requirements.

The component masses, and where applicable sizes, and efficiencies are given in Table I for the 70 kW(e) case, other power ranges follow similar trends. The effects of the length and power density of the converters and thus system power were examined parametrically. The result in terms of specific mass, α, are shown in figure 10. Customarily, specific mass is based on the net power supplied to the power conditioning, α_1, as defined on the next page. But the subsequent conversion of low voltage power to thrust involves several losses dependent on the system design. Since the low voltages used in this study lower the efficiency of the power conditioning from that assumed in the development of figure 1, the value of α_1 in figure 10 should be increased by 5 percent if it is to be compared to the α's of figure 1. A less ambiguous parameter, α_2, based on thruster array power is included in figure 10.

$$\alpha_1 = \frac{\text{power and thrust system mass} - \begin{array}{l}\text{propellant}\\ \text{propellant tanks \& misc.}\\ \text{flight shroud penalty masses}\end{array}}{\text{unconditioned power} - \begin{array}{l}\text{payload power,}\\ \text{power plant and spacecraft power, and}\\ \text{reactor control power}\end{array}}$$

and

$$\alpha_2 = \frac{(\text{same numerator as for } \alpha_1)}{\text{thruster array power (see figure 9)}}$$

Specific masses consistent with the needs of NEP missions illustrated in figure 1 are predicted for the power ranges examined. The sensitivity of α to a 20° K temperature change in the emitter temperature is also indicated. Included in figure 10 are spacecraft lengths, and because of the low electrical power and reasonable component efficiencies a compact spacecraft results. These low specific masses and small sizes are based on performance characteristics that are for the most part more conservative than those used in in-core thermionics. Additional data on the high temperature parts of both systems need to be obtained before clear-cut superiority of either approach is established. But the compact low mass reactor that results from moving the converters out-of-core should reduce system masses at low power levels.

The characteristics of systems at power ranges lower than those shown in figure 10 can be estimated from Table I. The mass of the converter, radiator, and low-voltage lead scale with power. The reactor- and converter-heat-pipe masses are approximately independent of power level. The characteristics of the shield, high- and low-voltage power conditioning, and structures relate to the application, and thus can be assessed independently. As can be seen the low reactor mass should yet provide a relatively light auxiliary power plant. It should be noted that the heat pipes leading to the converter must be reduced in diameter, increased in length, and operated at lower voltages to maintain the efficiencies of the 40- to 70-kW(e) power system.

As discussed previously, should the need for variable power arise, low power also can be achieved by reducing the reactor temperature slightly and allowing the thermal front that exists at the lithium-vapor, inert gas interface to move in coordinated manner in each of the twenty heat pipes. If the output voltage is decreased 80 percent while lowering the power to 4.5 kW(e) an efficiency of 75 percent of that for 60 kW(e) is predicted.

XI. SYSTEM DEVELOPMENT

Each of the components of the system from the reactor fuel pins to the thrusters has been designed on the basis of small, easily testable elements clustered together to provide a redundant, reliable system. Most of the elements can be tested individually and in subassemblies.

If it is desired the entire system could be assembled in two independent halves and tested by electrically heating the reactor. This opportunity exists because the fuel element shown in figure 3 has a large central void, and the reactor is symmetrical about the midplane. The central void can be designed to be open at the midplane of the reactor. Then, if the reactor is separated, 82 heat pipes or electron-bombardment heaters can be introduced into the fuel voids. Thermal simulation and system checkout then can be achieved for an assembled system from fuel-element center line to radiators and thrusters. In addition to the insertion of the heaters only a few simple electrical and mechanical connections would be required for this test. Alternately, unenriched fuel could be used in the reactor, and a low-cost development program could be established, resulting in an accurate thermal, electrical, mechanical, and chemical simulation of the reactor, converters, radiators, and power conditioners in an assembled form.

XII. CONCLUDING REMARKS

A system design based on out-of-core thermionics has been presented. And an attempt has been made to illustrate how the technology developed as a part of in-core nuclear thermionics program can be applied to out-of-core thermionics. The recent developments in high-temperature heat pipes and heat-pipe materials make this possible. Also, with the converters located out-of-core a compact, low mass reactor results and provides an opportunity to develop a single power plant that meets both auxiliary and nuclear electric-propulsion requirements.

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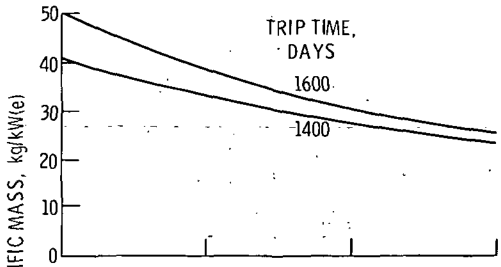
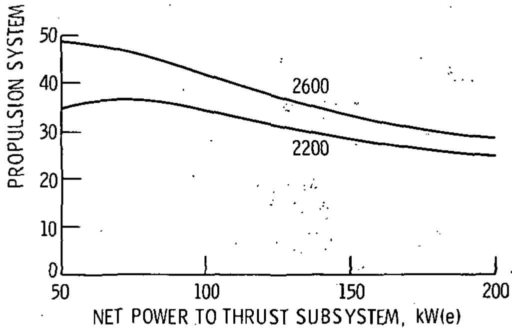
Table I - Size, Weight and Selected Efficiencies of Components of a Converter Bank Developing 70 kW(e) at the Terminals (Neglecting Heat-Pipe Leakage)

COMPONENT	SIZE, METERS	WEIGHT, KILOGRAMS	EFFICIENCY, PERCENT
Reactor	Dia. 0.418 Length 0.54	590	N/A
Converter Heat Pipe	Separation length 0.68 Total length 1.57 (abt)	37	N/A
Converters	Length 0.126 Dia. 0.054 (120 req'd)	113 (excluding input and output heat pipes)	14.23 at electrodes 11.55 at leads 10.8 including heat-pipe leakage
Radiator (high temperature)	Dia. 1.0 Length 4.77	220	N/A
Radiator Manifold	N/A	50	N/A
Low Voltage Lead	Length 3.4 (abt)	108	93.5
Power Cond.	N/A	163	(See fig. 9)
Power Cond. and Thrust Structure	N/A	39	N/A
Low Temp. Radiator	Length 3.41 to 5.63	48.8	N/A
LiH Shield	N/A	224	N/A
Power Subsystem, Structure	N/A	20	N/A
Thrust Array	Length 2.0	103	(See fig. 9)
High Voltage Cable	N/A	1.4	N/A



(a) SATURN ORBITER, 20R TITAN 3F/CENTAUR LAUNCH VEHICLE.



(b) URANUS ORBITER, 20R SHUTTLE/CENTAUR LAUNCH VEHICLE.

Figure 1. - The effect of power and trip time on power plant specific mass for two direct escape nep missions, 1000 kg payload, unconstrained thrust time.

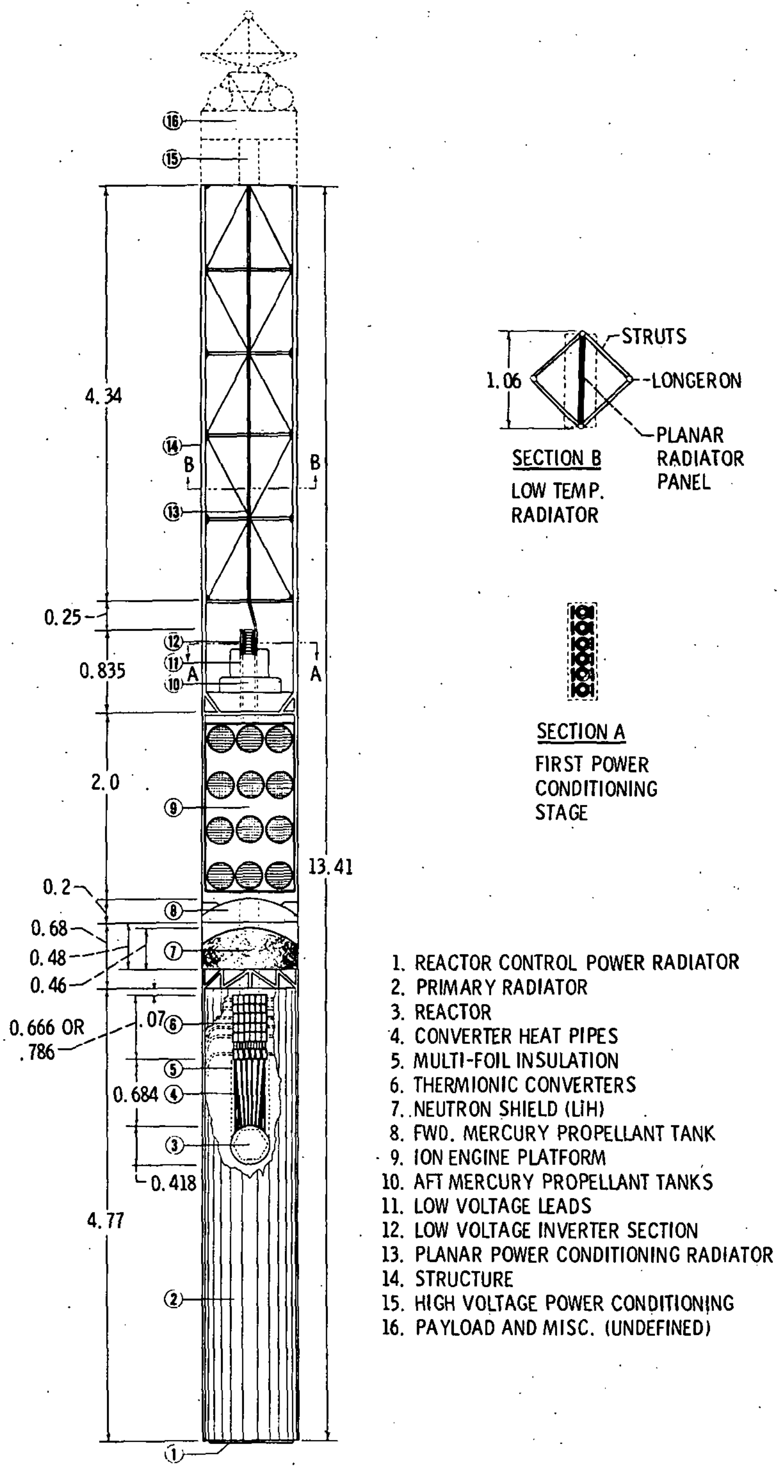
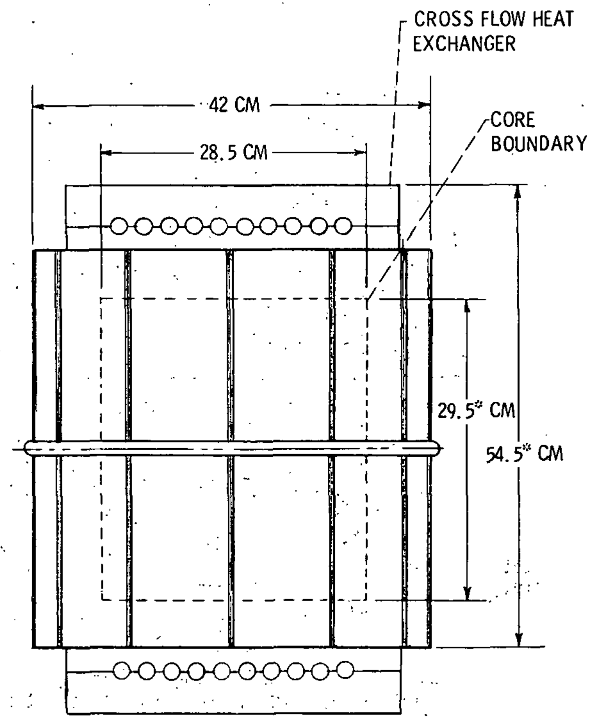
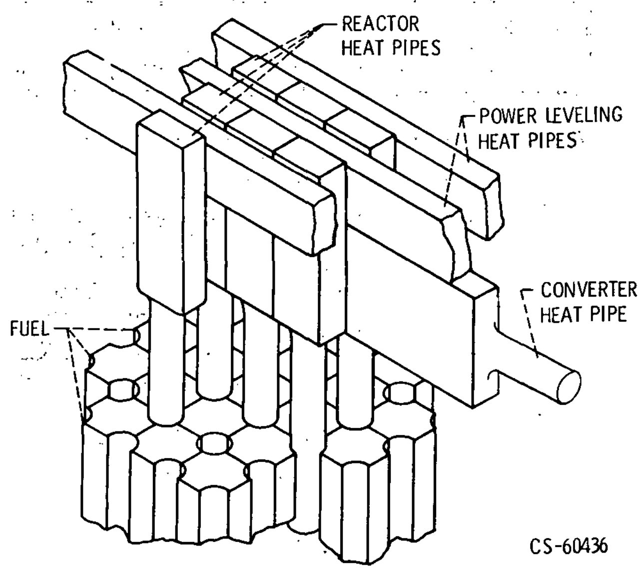


Figure 2. - NEP spacecraft configuration.



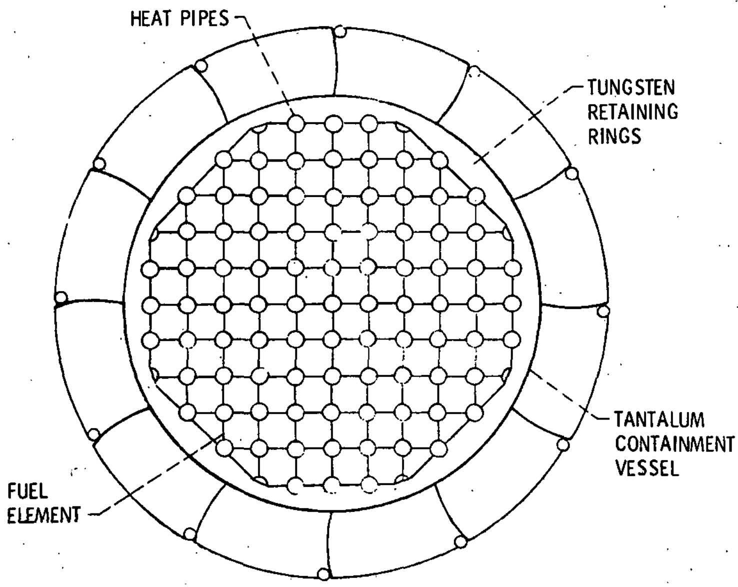
(a) EXTERNAL VIEW

*INCLUDES 0.5 CM SEPARATION.

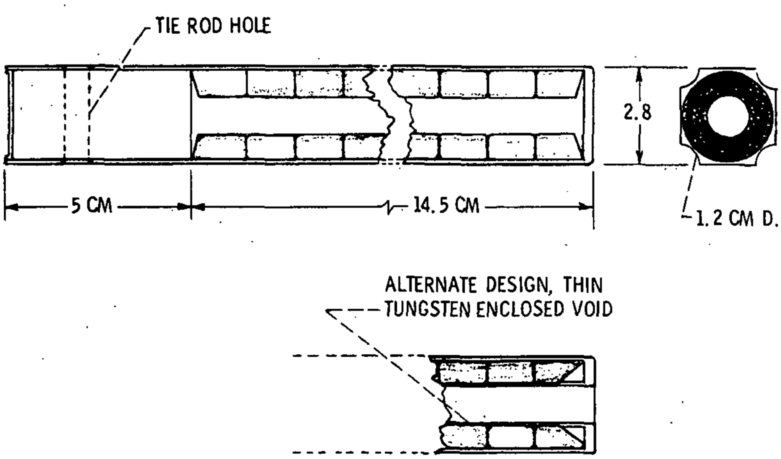


(b) SCHEMATIC DIAGRAM OF THE REACTOR CROSS-FLOW HEAT EXCHANGER; FOR CLARITY THE REACTOR HEAT PIPES ARE SHOWN PARTIALLY WITHDRAWN FROM THE CORE.

Figure 3. - Heat-pipe cooled, compact fast reactor.



(c) MIDPLANE VIEW OF THE REACTOR SHOWING FUEL, HEAT PIPES, TUNGSTEN RETAINING RINGS, AND BERYLLIA REFLECTOR.



(d) FUEL ELEMENT DESIGNS

Figure 3. - Concluded.

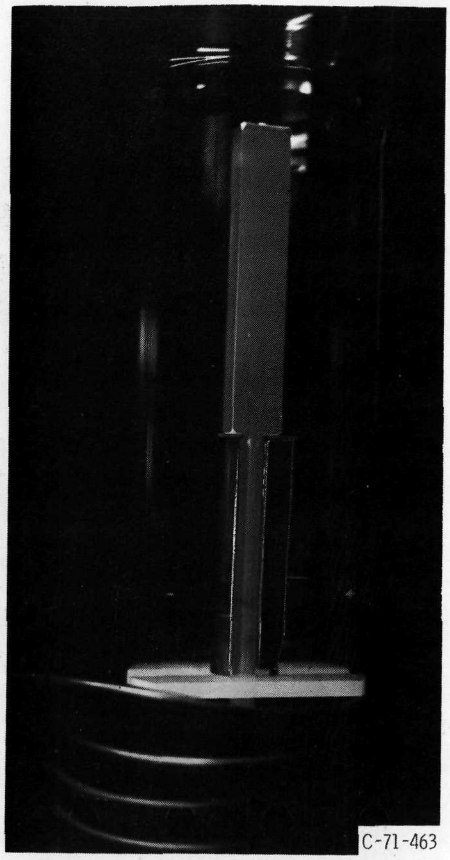


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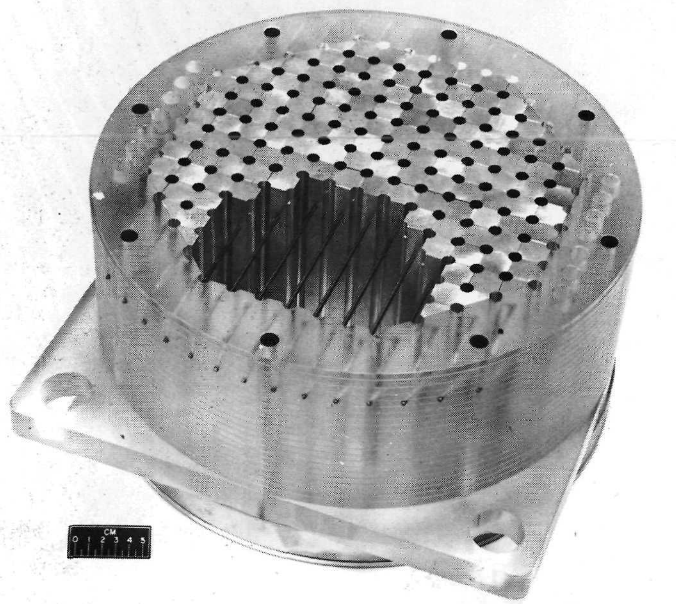
Figure 4. - Inductively heated reactor heat pipe.



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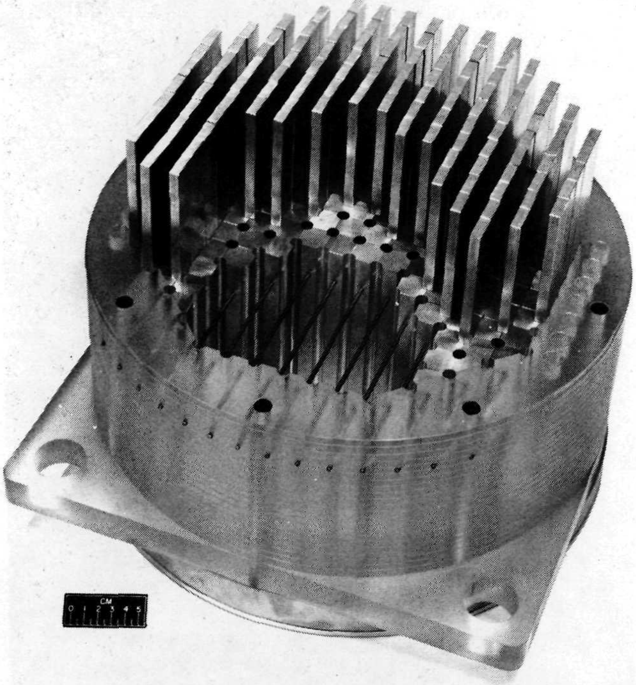
(A) PARTIALLY ASSEMBLED FUEL ELEMENTS.

Figure 5. - Assembly sequence of a typical heat pipe cooled fast reactor. (The model shown is based on 1.5 to 3 Mw(t) in contrast to 0.4 to 0.7 Mw(t) of this study.)



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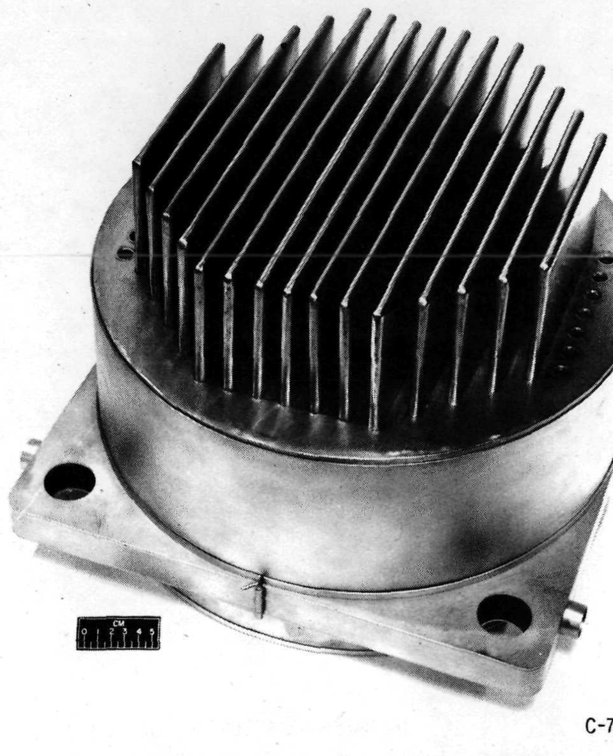
(B) PARTIALLY ASSEMBLED FUEL ELEMENTS AND HEAT PIPES.

Figure 5. - Continued.



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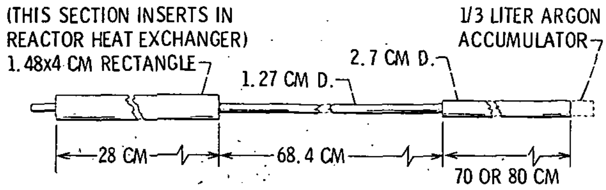
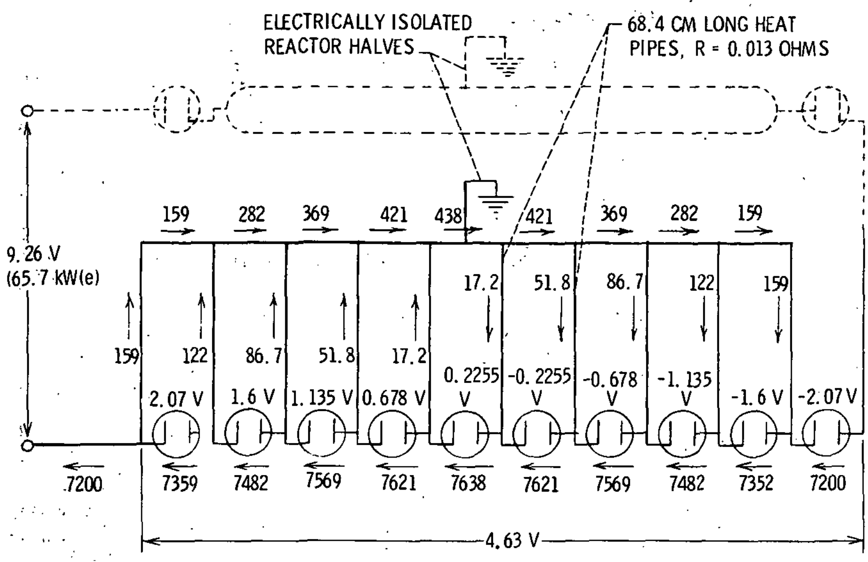
(C) ENCLOSED REACTOR HEAT PIPES FORMING PART OF FLAT-PLATE EXCHANGER. THE CONVERTER HEAT PIPES ARE INSERTED BETWEEN SURFACES SHOWN TO COMPLETE THE ASSEMBLY.

Figure 5. - Concluded.



(a) CONVERTER HEAT PIPE DIMENSIONS.



(b) THE CURRENT (NUMBERS ASSOCIATED WITH ARROWS) AND VOLTAGE OF A TYPICAL EXAMPLE OF A HEAT PIPE CONNECTED BANK OF CONVERTERS. EACH DIODE SHOWN ABOVE REPRESENTS SIX DIODES IN PARALLEL.

Figure 6. - The physical and electrical characteristics of the converter heat pipes.

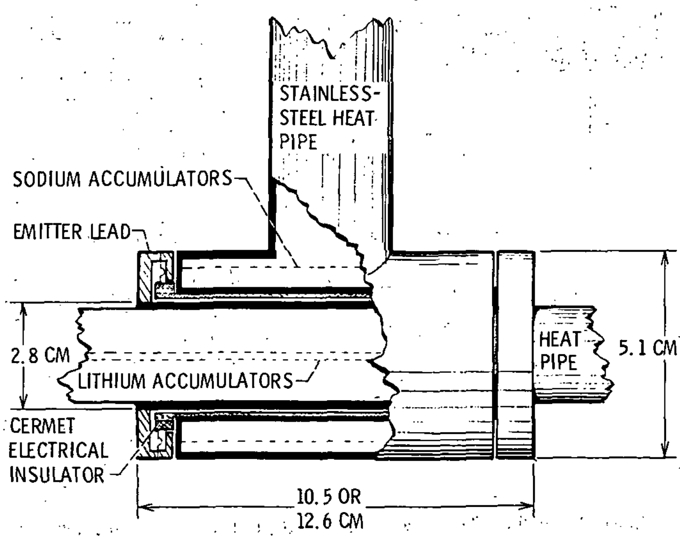


Figure 7. - Schematic diagram of the heat-pipe-heated and heat-pipe-cooled thermionic converter.

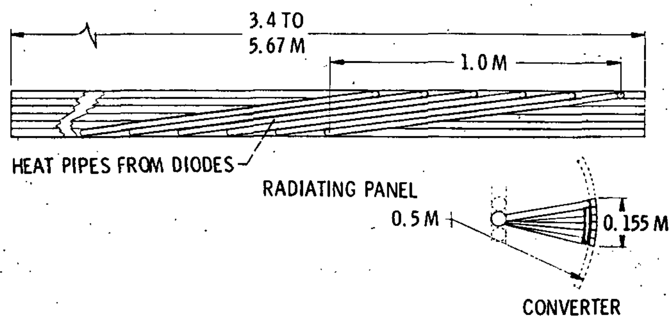


Figure 8. - Diagram of a typical radiator panel.

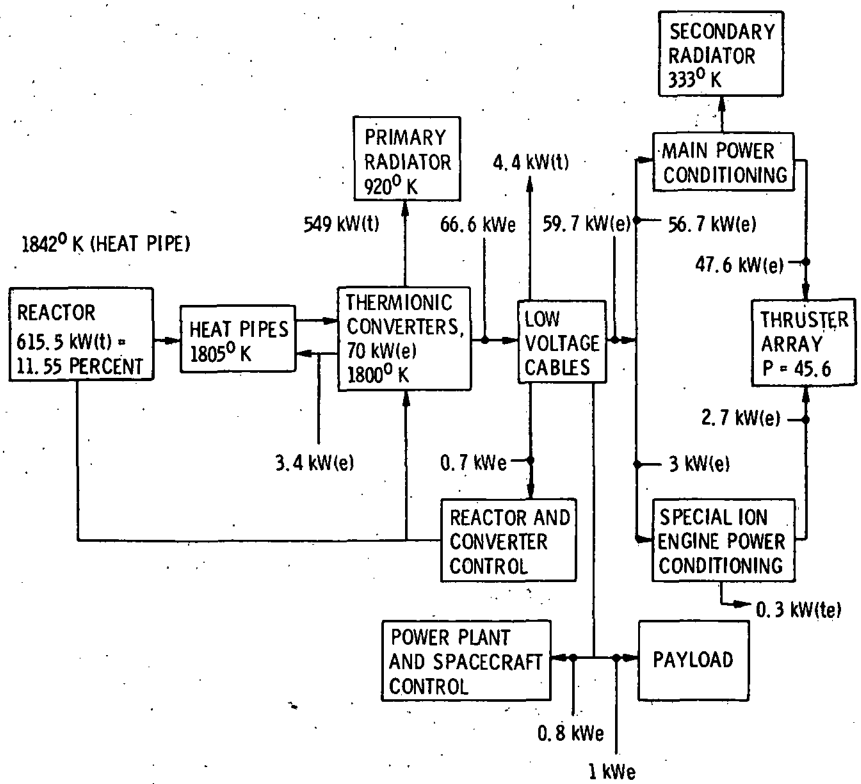


Figure 9. - Example of the power balance of a 60 kW(e) (nominal) out-of-core space power plant.

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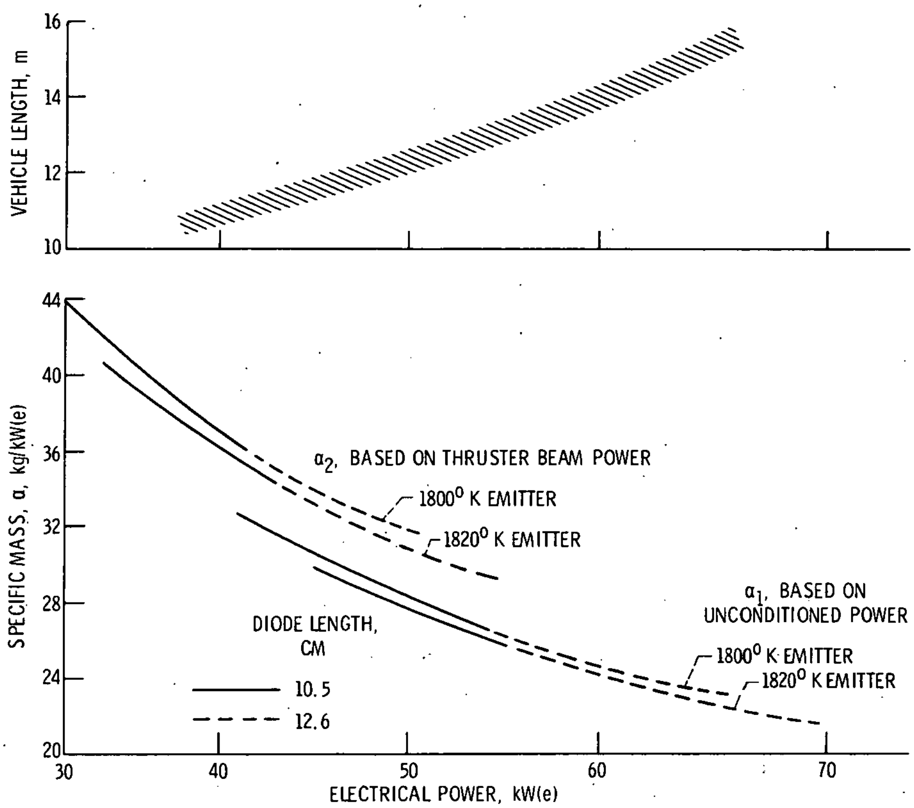

Figure 10. - The effect of electrical power on specific mass and length of an out-of-core nep spacecraft power plant.