DYNAMIC VERSUS DIRECT CONVERSION

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ABSTRACT

The purpose of this paper is to compare on a lb/kw basis the performance capabilities of advanced nuclear dynamic and nuclear direct conversion space electric power plants. A dynamic conversion plant uses potassium as a working fluid at a turbine inlet temperature of 1900°F and exhaust temperature of 1300°F. The specific weight of such a plant with shielding is estimated to range from 12.5 to 8.5 lb/kw at a power level of 300 to 2,000 kw(e).

The state of the art of thermoelectric conversion is reviewed, and it is concluded that because of limited temperature potential and low efficiency, thermoelectrics are not competitive at high power levels.

The potential of thermionics with the converters located in the reactor is analyzed. In the thermionic system fuel pins are used as cathodes and the anodes are cooled by a circulating coolant flowing through the radiator. A theoretical analysis (with cathode and anode emissivity equal to 0.5) indicates that the thermionic concept is competitive with the dynamic system when cathode current densities of 10 amps/sq cm are attained. An analysis of a UC ZrC reactor (e = 0.8 from LASL experimental data) indicates that it becomes competitive with the dynamic system when a cathode power density of 30 w/sq cm. is attained. Low emissivity is necessary in the converter in order to reduce radiant heat losses and maintain good efficiency. Converter efficiency directly affects radiator size and weight.

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1. ARS Space Power Systems Conference, The Miramar Hotel, Santa Monica, California, September 27-30, 1960

2. Manager, Space Power Department

Thermionic converters mounted on the surface of a reactor with no circulating coolant result in a concept which is limited in power level by the geometry of the system. Specific performance (lb/kw(e) is also relatively poor.

No attempt is made to evaluate the feasibility, lifetime, reliability, or the development problems inherent in both dynamic and thermionic concepts.

INTRODUCTION

The growing interest in space nuclear electric power plant development and the consideration being given to dynamic and direct conversion as applied to these plants, makes it timely to analyze the performance potential of both concepts. There are doubts as to the feasibility of these concepts, but the analysis presented here assumes that such plants can be developed and evaluates only their performance potential in terms of size and weight.

DYNAMIC CONVERSION

Nuclear space power plants are now being developed for power levels ranging up to 60 kw(e). SNAP II and SNAP VIII are examples of this, in which the mercury Rankine cycle is used to convert thermal energy to electrical power. Because of the pressure-temperature characteristics of mercury (Figure 1) the cycle is limited to turbine inlet temperatures up to 1250°F (250°superheat) and exhausting at about 700°F. Waste heat can only be disposed of by direct radiation to space thus, radiator area becomes strongly dependent on $T_R{}^4$. (SNAP VIII at 30 kw(e) requires a radiator area of about 900 sq ft.) In order to build power plants at higher levels (100 kw(e)+) and keep the radiator size and weight at a reasonable level, it is necessary that turbine working fluids be employed with higher temperature potential than mercury.

A review of working fluids (Figure 1) indicates that sodium, potassium, cesium and rubidium are possible choices. Much detailed analysis has been done to evaluate the performance potential of such power plants and the writer therefore will present here only the conclusions of these studies.

Using potassium as a working fluid over-all plant efficiency can be expected to be about 15%. Operating parameters are summarized below and predicted plant performance (lb/kw(e) is shown in Figure 2.

Turbine inlet - $1900^{o}F$
Turbine exhaust - $1300^{o}F$
Turbine efficiency - 75%
Plant efficiency - 15%

A direct condensing radiator in a flat configuration was used. Tubes joined by fins were employed and massive protection against meteorite damage on each tube presumed. Radiator area required at a power level of 300 kw(e) is about 950 sq ft.

DIRECT CONVERSION

The object of this section is to review nuclear-direct conversion systems, establish the state of the art, and explore the ultimate performance potential of high power, high temperature systems. This performance potential will then be compared with dynamic (turbomachinery) systems.

During the past ten years considerable progress has been made in developing materials for thermoelectric and thermionic converters. Thermoelectric devices are now marketed commercially and the feasibility of low power nuclear auxiliary power units for space application has already been demonstrated. SNAP III and SNAP I-A are radioisotope-fueled thermoelectric auxiliary power units (APU's) which have been designed for power levels of 3 watts and 125 watts respectively. SNAP X is a reactor fueled thermoelectric APU which is designed to operate at a power level of 300 watts.

THERMOELECTRIC CONVERSION

The thermoelectric materials used in these SNAP devices are in the Teluride family. They have an upper temperature limit of 1000 to $1200^{o}F$ and when operating at a heat rejection temperature $500^{o}F$ will produce an efficiency on the order of 6%. Thus, because of temperature and efficiency limitations, this type of power conversion is restricted to low power levels where the radiator area is unimportant.

To take full advantage of the inherent reliability of a power conversion system with no moving parts the above mentioned devices have no circulating fluids and depend on direct conduction (SNAP III and SNAP X) or radiant heat transfer (SNAP I-A) from the energy source to the hot junction of the thermoelectric converter. These devices thus are also power level limited by the inherent geometry of such passive heat transfer systems. Nuclear thermoelectric APU's, based on current state of the art, are considered as interim low power units (< 1 kw(e)) primarily because of their low heat rejection temperature (500°F) and low efficiency.

High temperature materials development work is continuing in this field with the objective of extending the temperature range over which thermoelectric materials can be made to operate. But to be competitive with high temperature dynamic conversion systems, heat rejection temperatures (cold junction) must be on the order of 1200°F.

The following expression defines thermoelectric efficiency:

$$\xi = \frac{T_1 - T_2}{\frac{4}{Z} + 2\,T_1 - \frac{(T_1 - T_2)}{2}} \qquad (1)$$

where

T_1 = hot junction temperature (°K)

T_2 = cold junction temperature (°K)

Z = (figure of merit) $= \dfrac{\alpha_n - \alpha_p}{(\sqrt{K_h \rho_h} + \sqrt{K_P \rho_p})^2}$

α = mv /°K, n and p

K = w/°K cm, n and p

ρ = ohm cm, n and p

A figure of merit (Z) of 2.4×10^{-3} is required to produce an efficiency of 10% over the temperature range of interest (2000 - 1200°F). A cascaded thermoelectric design in SNAP III over a temperature range of interest (1000 - 150°F) operated with a figure of merit of approximately 0.7×10^{-3} with a corresponding device efficiency of 6%. An improvement in temperature potential of 1000°F and figure of merit by a factor of 3.4 is required before thermoelectric materials can be competitive with dynamic conversion systems in high power systems. The figure of merit tends to decrease in semiconductors with increasing temperature because they become "intrinsic"; that is, the heat input causes positive and negative charges to migrate in equal numbers toward the cold junction and no output voltage results.

Considerable development work on basic materials will be required before thermoelectric conversion can be considered for high power space systems. A significant breakthrough in materials is required to demonstrate performance potential and subsequent to this a major engineering effort is required to produce a practical long-lived device.

THERMIONIC CONVERSION

Thermionic conversion is the direct conversion scheme which appears most feasible for use in a space power unit. It is particularly interesting because of its high heat rejection temperature potential, and of course, because of its lack of moving parts.

Here we shall attempt to evaluate thermionic conversion based on theoretical predictions of performance and to determine the ultimate potential of thermionic conversion in space power plants. Much work is now being done on incorporating the cesium vapor filled thermionic converter into the core of a fast reactor so that it will produce electricity directly, and thus the discussion presented herein will center primarily around this concept and evaluate its potential.

PRINCIPLE OF OPERATION

In its simplest form a thermionic converter consists of a hot cathode from which electrons are emitted by thermal energy and a cooler anode which collects the emitted electrons (Figure 3). The potential (ϕ_c) of the cathode must be greater than that of the anode (ϕ_a) in order to drive electrons through the external circuit. The density of electron current coming off both the cathode and the anode is defined by the Dushman Equation as follows:

$$J = AT^2 E \frac{-e \phi}{KT} \qquad (2)$$

where

J = current density, amp/cm^2

$A = 120 \dfrac{\text{amp}}{\text{cm}^2 - \text{deg}^2}$

T = ^{o}K

e = electron charge, coulomb/electron

ϕ = work function, volts

K = Boltzmann constant

E = base of natural logarithm

In order for electrons to flow from cathode to anode, it can be seen from the foregoing equation that with $\phi_a < \phi_c$ it is necessary that the anode temperature be lower than the cathode temperature. Thus the thermionic converter is basically a heat engine and further analysis by Houston shows that it is subject to the limits of the Carnot cycle and the natural losses which occur in any heat engine.(1)*

SPACE CHARGE

Because electrons are charged particles, the cloud of electrons between the cathode and the anode forms a space charge barrier. If not provided for, space charge limits current output so markedly that output and efficiency drop drastically.

There are several ways of coping with this problem but only two are considered here, that is close spaced diodes and surface contact ionization.

It can be shown that the effect of space charge can be minimized by spacing the anode and cathode close together. But to be effective, a spacing in the order of .0004 in. or less, is necessary. A second way of overcoming the space charge barrier which is still passive, is to neutralize the effect of the negative electron charge with positive ions. A converter filled with cesium vapor is commonly used for this purpose. Cesium neutralizes the space charge and may adjust the work function of both the anode and the cathode. Thus, the same material may be used for both cathode and anode surfaces and this will help to prolong the life of the device.

When considering these two techniques in connection with nuclear power in space one must consider the state of the art in reactor technology as it applies to temperatures attainable in reactors. Liquid-metal-cooled reactors are temperature limited by materials corrosion considerations. Gas-cooled reactors have higher temperature potential but are unattractive because of their much lower power density. Because a cathode temperature capability of 2000°K appears necessary in order to make thermionic conversion competitive with dynamic methods,

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* Reference numbers are shown in parentheses and are listed at the end of the paper.

the cathode must be an integral part of the fuel element where, insulated from the liquid metal coolant by the anode, high temperatures are possible. Fabrication problems combined with thermal expansion eliminate further serious consideration of the close spaced diode. One need only consider then the gas filled converter.

EFFICIENCY

Efficiency is power out divided by the energy in and Houston writes the equation as follows:

$$\xi = \frac{(V_c - V_a)(J_c - J_a) - R(J_c - J_a)^2}{J_c \, V_c + \frac{2KT_c}{e} - J_a \, V_a + \frac{2KT_a}{e} + K + R + I} \qquad (3)$$

The numerator is made up of power output minus the losses in electrodes and leads. The denominator is made up as follows; the first term is the energy required to evaporate electrons from the cathode and overcome the space charge barrier, the second term gives the amount of energy returned to the cathode by the bucking current of the anode, the third and fourth terms represent conduction and radiation losses, and the fifth term the amount of energy required to ionize cesium if this is the medium employed to overcome space charge. The influence of cathode current density J_c can be seen by examining Figure 4. This figure illustrates increasing converter efficiency with increasing current densities ranging from 1 to 10 amperes per sq cm with an anode work function (ϕ_a) of one volt. The marked effect on efficiency of ϕ_a is also shown in Figure 4, which is a plot of these same current densities with ϕ_a equal to 2 volts. It is obvious on examining Figure 5, which is a plot of energy distribution versus temperature, why these effects take place. High cathode current densities override radiant heat losses and thus improve efficiency. Increasing ϕ_a directly reduces output by reducing the potential difference between cathode and anode for the same current density.

THERMIONIC CONVERTER IN REACTOR CORE WITH A CIRCULATING COOLANT

In order to extend the power level of nuclear thermionic systems a circulating coolant between the reactor and the radiator is necessary. A choice must be made between locating the converter in the radiator and thus having the reactor coolant at cathode temperature (2000°K+) or locating the thermionic converter in the core and cooling the anode (1000 to 1100°K). The second approach appears more desirable because materials technology is better developed at the lower temperature. It may be possible to use an E.M. pump and sodium or NaK as a coolant. Research work has been under way at LASL on this concept, and private industry has also shown an interest in the approach.

The core configuration might typically be made up of fuel rods whose surface would be the cathode. Individual fuel rods would be surrounded by concentric cylinders (anodes) which are cooled by a circulating liquid metal. (Figure 6.) The outside surface of the anode cylinder could be covered by a thin electrical insulation layer. By properly insulating and spacing the cathodes and anodes a series, parallel array can be arranged to improve output voltage characteristics.

In any high power nuclear space power plant, the radiator is a component of prime importance. Radiator area is extremely sensitive to rejection temperature and here the thermionic device appears to have an advantage. A close look at anode conditions shows however that there is an upper limit to anode temperature which is related to anode work function. Houston(1) shows that device efficiency is sensitive to anode temperature and work function and thus cannot be ignored, that is, for an anode work function of one volt the maximum permissible temperature is 640°K (690°F). At higher anode temperatures, the efficiency decreases rapidly due to heavy back emission. If one uses an anode work function of 1.7 volts, the allowable anode temperature becomes 1050°K (1400°F) with a corresponding back emission of one ampere. Assuming a coolant temperature drop of 100°F and a thermal gradient of 50°F from anode surface to coolant we can thus expect the radiator temperature to be an average of 1300°F. This compares directly with radiator temperature for Rankine cycles using potassium as a working fluid, (turbine inlet = 1900°F, turbine exhaust = 1300°F).

If one assumes the same meteorite protection, radiator areas and weights are equal on strictly a temperature basis. We must then look at system efficiency as it affects radiator size and weight.

Cathode current densities of 3 amps/sq cm are obtainable and J_c of 10-20 amps/sq cm are reported in laboratory experiments. Figure 7 is a plot of calculated device efficiencies with $\phi_a = 1.7$. This plot is similar to Houston's analysis except that back emission from the anode, re-radiation of thermal energy ($E = 0.5$) back to the cathode, and I^2R losses were considered. These losses are summarized in Figure 8. It is now meaningful to establish reactor power density and from this to determine reactor core size. If a typical geometry is laid out using 1/2 in. diameter cathodes on 3/4 in. centers we find that it is possible to have 30,000 sq cm of cathode surface per cubic foot of core. Fuel occupies 35% of the core volume and with UC as a fuel material the critical volume becomes 1.04 cu ft in a cylindrical geometry (L/D = 1) with a 4 cm BeO reflector (m_c = 132 Kg U-235). Figure 9 illustrates over-all reactor geometry.

The core geometry was selected on considerations of power density and criticality requirements. Spacing between fuel pin surfaces was determined by estimating required cladding -30 mils, gap -20 mils, anode thickness -60 mils, and separation -30 mils. Spacing between fuel surfaces is thus .25 inches. It can be shown that cathode surface is greatest when fuel pin diameter also equals .25 inches. This means however that the fuel (UC) would only occupy 10% of the core volume and as is shown in Figure 10 criticality is difficult to obtain. Using a fuel pin diameter of one half inch reduces cathode surface by only 11% and raises fuel volume in the core to 35%.

The thermionic reactor described with a cathode current density of 3 amps/sq cm has a corresponding thermionic power density of 62.4 kw(e)/cu ft. This core with J = 10 amps. sq cm has a thermionic power density of 337 kw(e)/cu ft. The power density attainable in a liquid metal cooled core (30 Mw_{th}/ cu ft) combined with a Rankine cycle (ξ = 15%) is 4,500 kw(e) cu ft. In order to compare the two system concepts fully however, it is necessary to evaluate the effect of reactor weight, shield weight and radiator size and weight.

An estimate has been made of power plant specific weight (lb/kw(e)) by scaling this same thermionic geometry over a range of size and power. The results are shown in Figures 11 and 12. A comparison to the specific weight of a dynamic conversion plant is shown in Figure 13.

The shadow shield weight was calculated based on shielding a 10^1 compartment with a separation distance of 50^1. Radiator weight was based on using massive protection against meteorites and was adjusted on a lb/kw basis by system efficiency. No attempt was made to adjust reactor L/D ratio. Power density in the thermionic core is considered optimistic because no allowance was made for leads, insulating spacers and power and temperature variation with flux density and reactor life.

Locating thermionic converters directly in the core has the effect of reducing fuel density. In order to go critical it is thus necessary to make the core larger and increase fuel inventory. Figure 14 illustrates the difference in fuel inventory required for a fast reactor (65% fuel volume) and a thermionic reactor (35% fuel volume). The fuel inventory in the thermionic reactor is significantly greater.

The writer has been informed that recent experiments have been performed, using UC ZrC as a cathode material, which resulted in a cathode power density of 18 watts/sq cm.(2) Cathode temperature was estimated to be 2100°C. Emissivity has been measured at 0.8 on this compound by LASL. (Note that the foregoing theoretical analysis assumed E = 0.5.) Eventual cathode power densities of 20 to 30 watts at this same temperature (2100°C) are predicted.

Efficiency at the conditions stated above are calculated to be 9% and 11.7% at 20 and 30 watts per sq cm respectively. Lowered efficiency as compared to previously calculated cases is due primarily to the high cathode anode emissivity (0.8).

The power plant specific performance at these high cathode power densities is plotted in Figure 15. Note the overriding effect of radiator weight as it is influenced by efficiency. Development work has been initiated to include radiation baffles between cathode and anode to reduce thermal radiation losses and thus improve efficiency. The thermionic system without radiation baffles is again seen to be comparable in performance potential to the dynamic power plant.

COMPLETELY STATIC NUCLEAR THERMIONIC CONVERTER

A completely static, nuclear, thermionic, space power plant can be visualized which employs no circulating fluids and thus enhances reliability. This can be done by utilizing a fast uranium carbide fueled reactor with a high temperature capability. The surface of the reactor could be the cathode and the anode would be made up of a shell around the reactor with the void volume between filled with cesium vapor. The anode could be cooled by radiation directly to space and the reactor reflector controlled. An appropriate high temperature material such as tungsten, might be used for cathode and anode surfaces.

Such a plant with the core diluted with carbon to increase surface area would be a cylinder approximately two feet in diameter by two feet in length. Its power rating would range from 16 to 32 kw(e) at J_c = 3 and J_c = 10 respectively, and its unshielded weight would be approximately 1500 pounds. This type of plant is power level limited by geometry and shows relatively poor potential on a lb/kw_e basis.

REFERENCES

1. J. M. Houston, "Theoretical Efficiency of the Thermionic Converter," Journal of Applied Physics, Vol. 30, No. 4, April, 1959

2. Dr. G. Grover, LASL, Telecon, 7 Sept. 1960

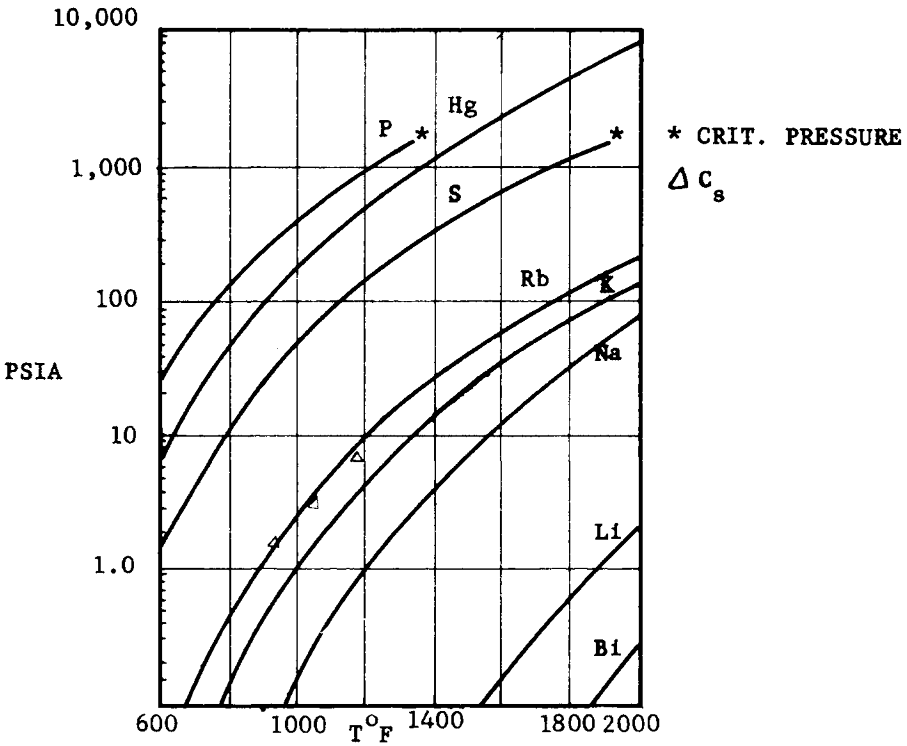


Fig. 1. Vapor Pressure of Possible Working Fluids

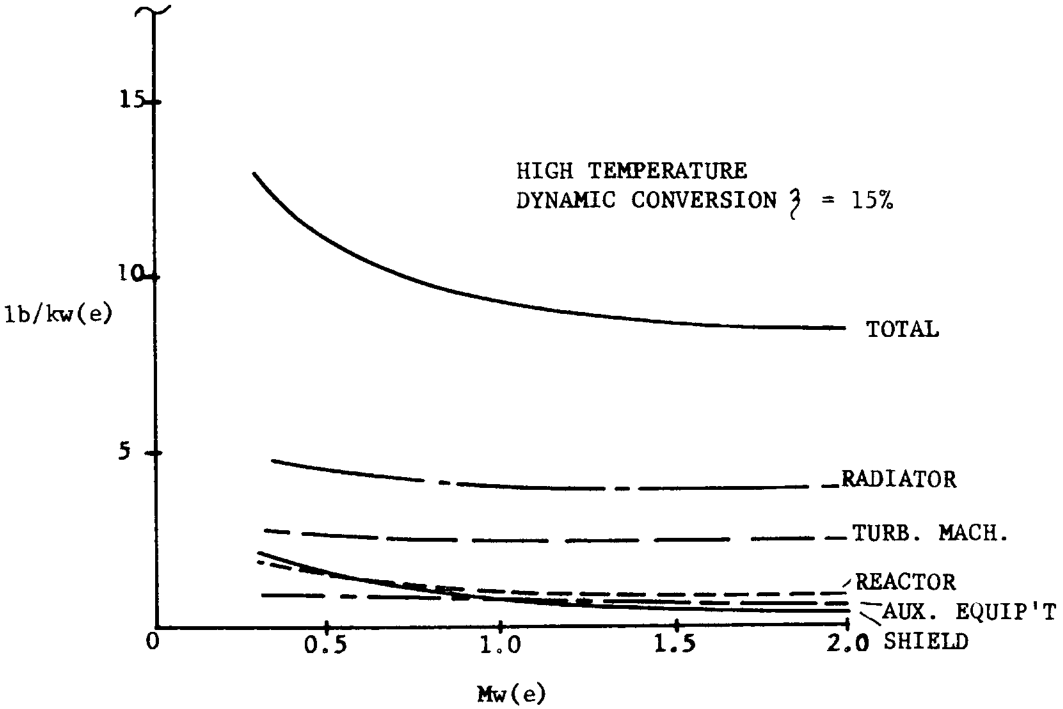


Fig. 2. Specific Performance, Lb/Kw(E) Dynamic System

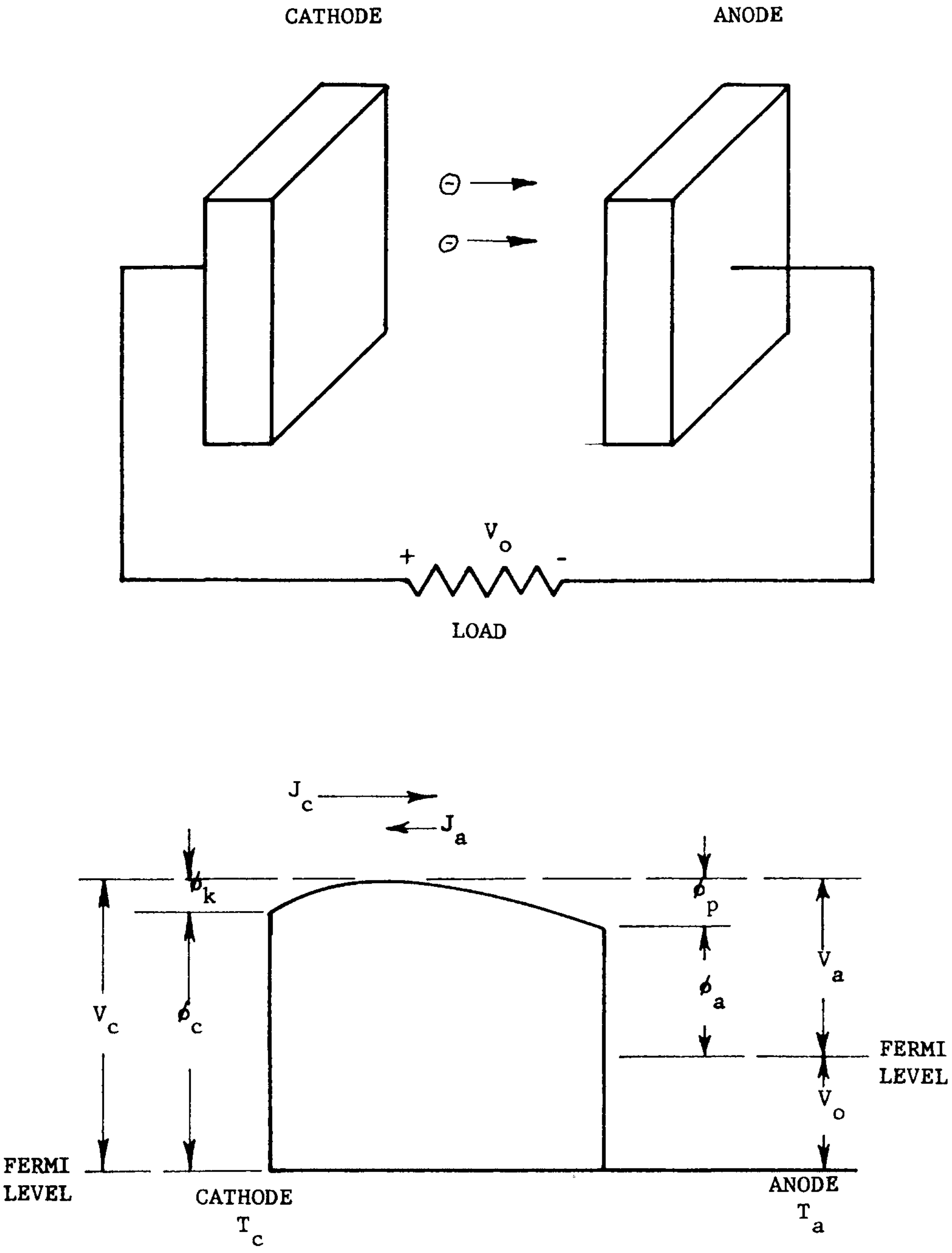


Fig. 3. Thermionic Conversion

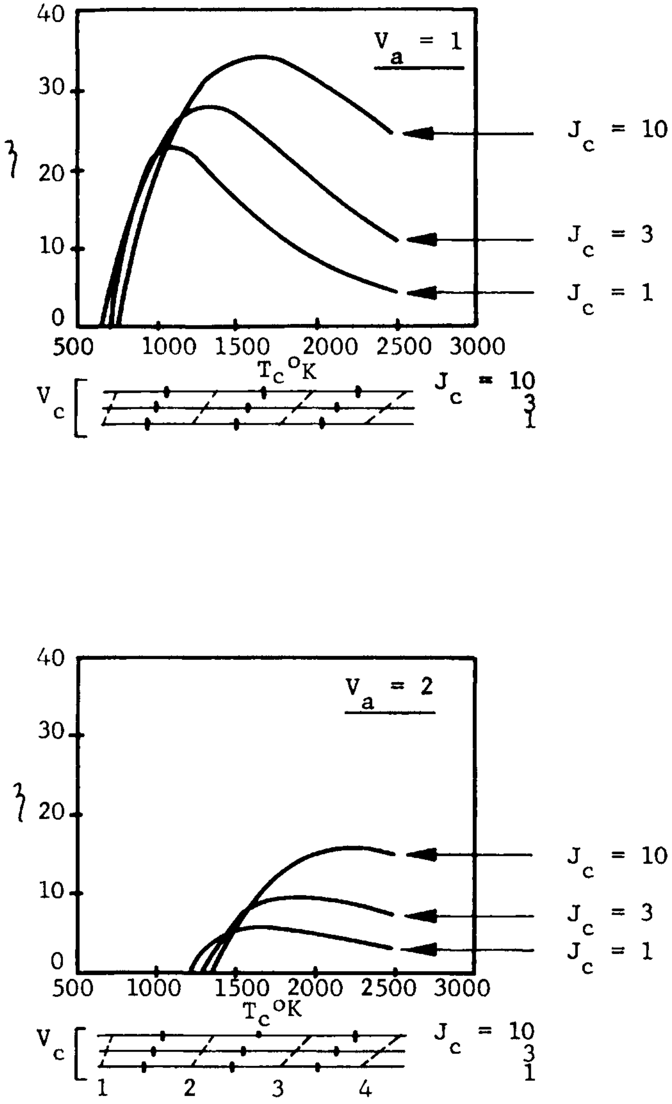


Fig. 4. Cathode Temperature Vs Efficiency

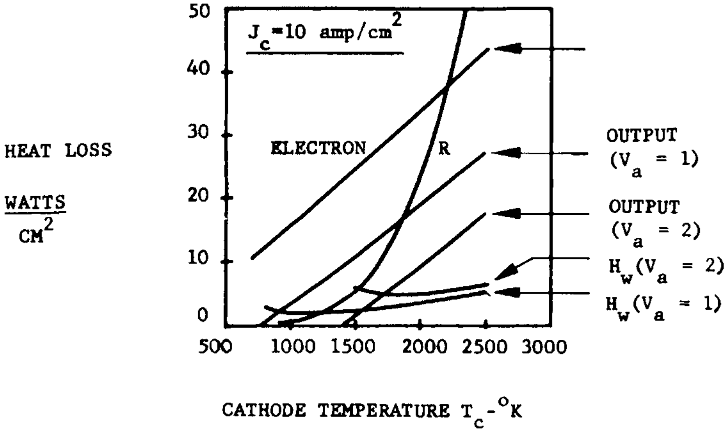


Fig. 5. Cathode Energy Distribution

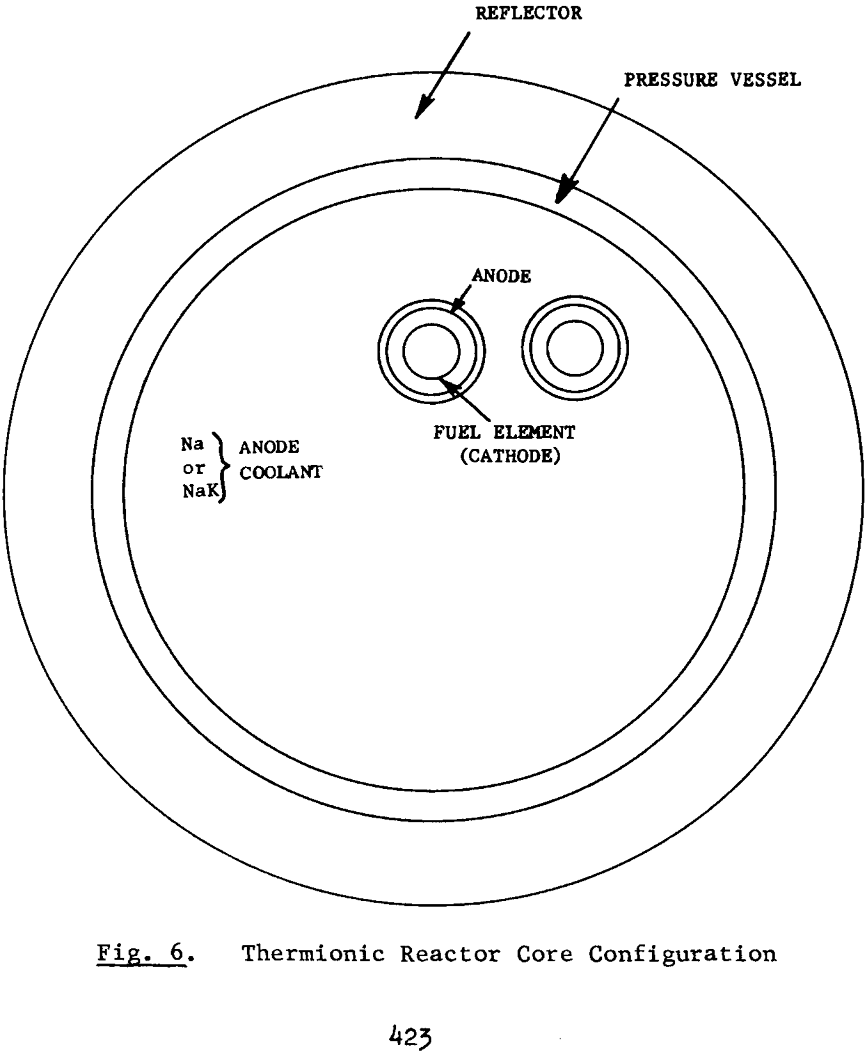


Fig. 6. Thermionic Reactor Core Configuration

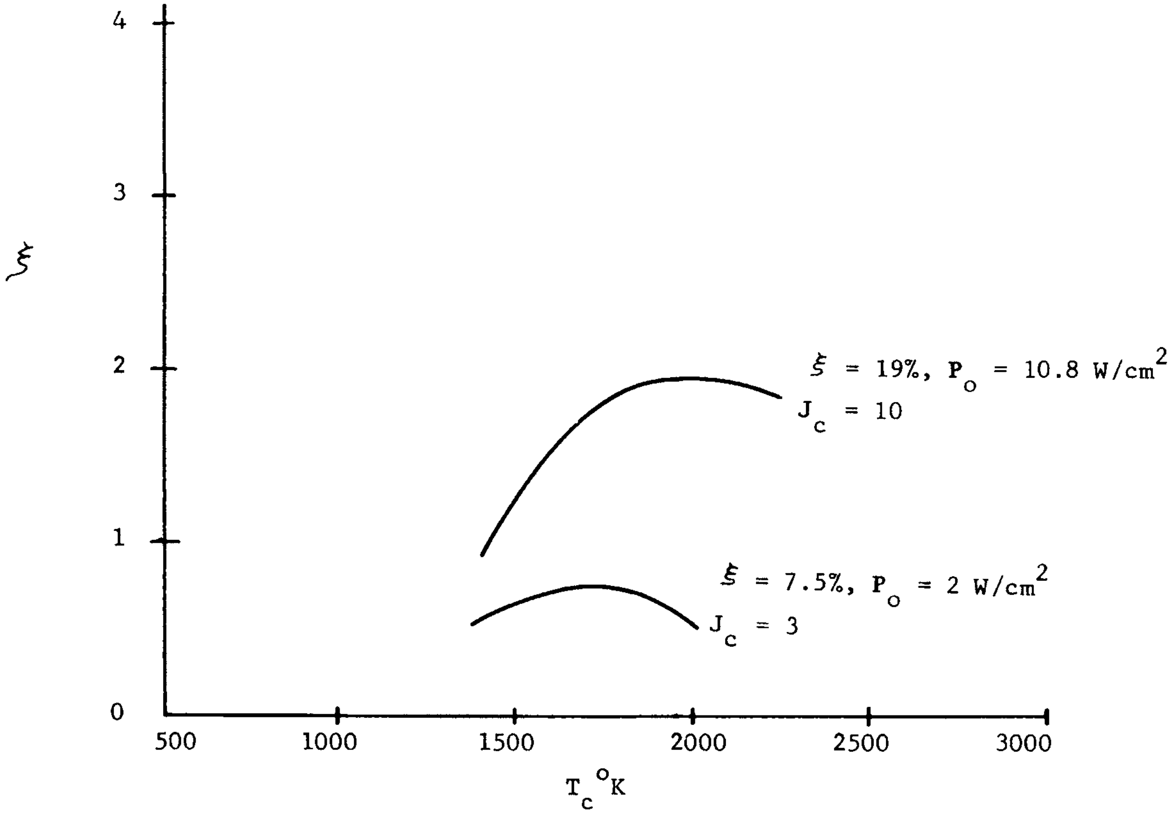


Fig. 7. Thermionic Converter Efficiency
$\phi_a = 1.7$, $J_a = 1.0$

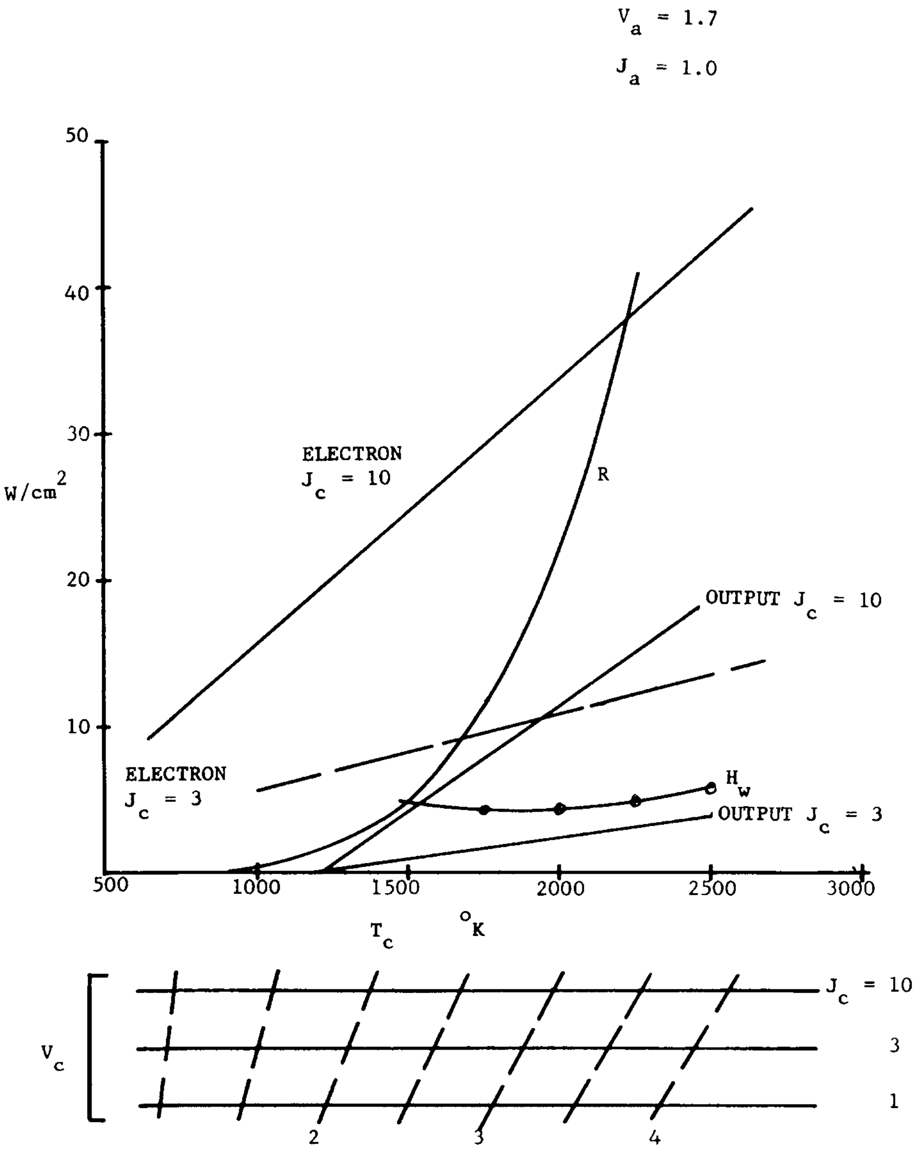


Fig. 8. Thermionic Converter Energy Distribution

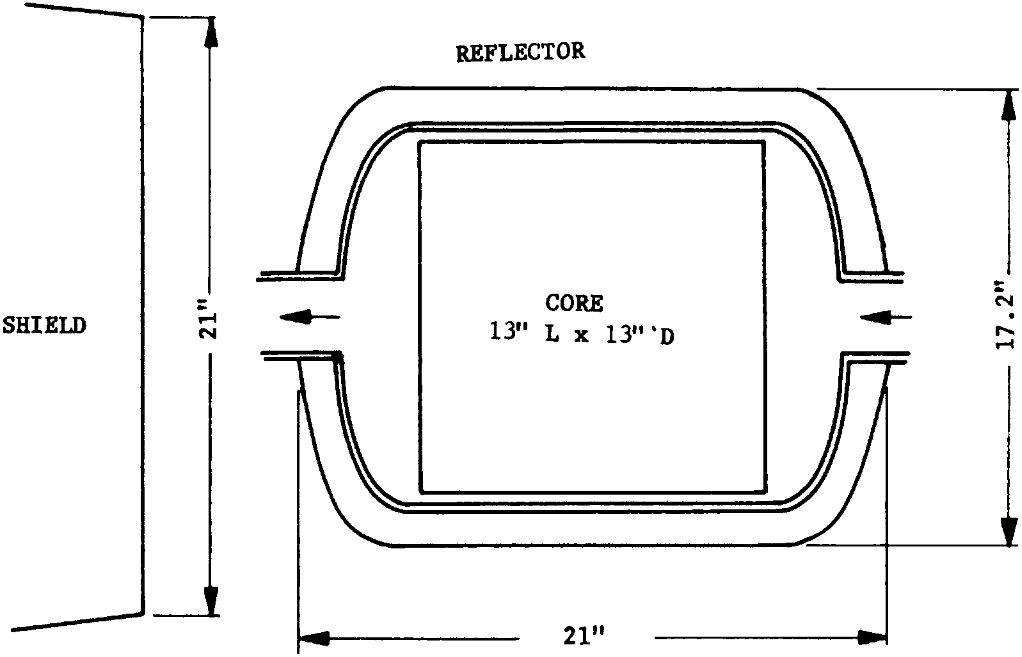


Fig. 9. Thermionic Reactor Minimum Critical

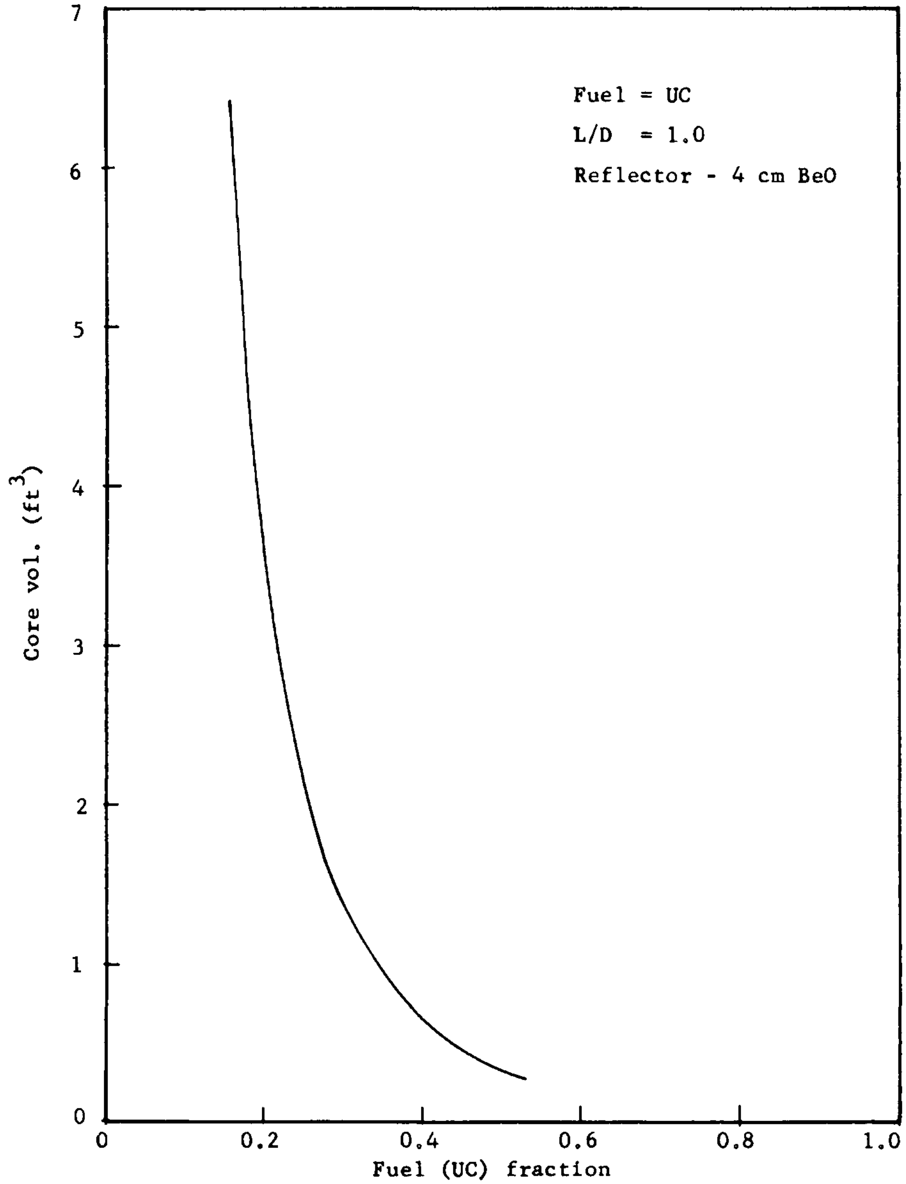


Fig. 10. Effect of Fuel Concentration on Core Size

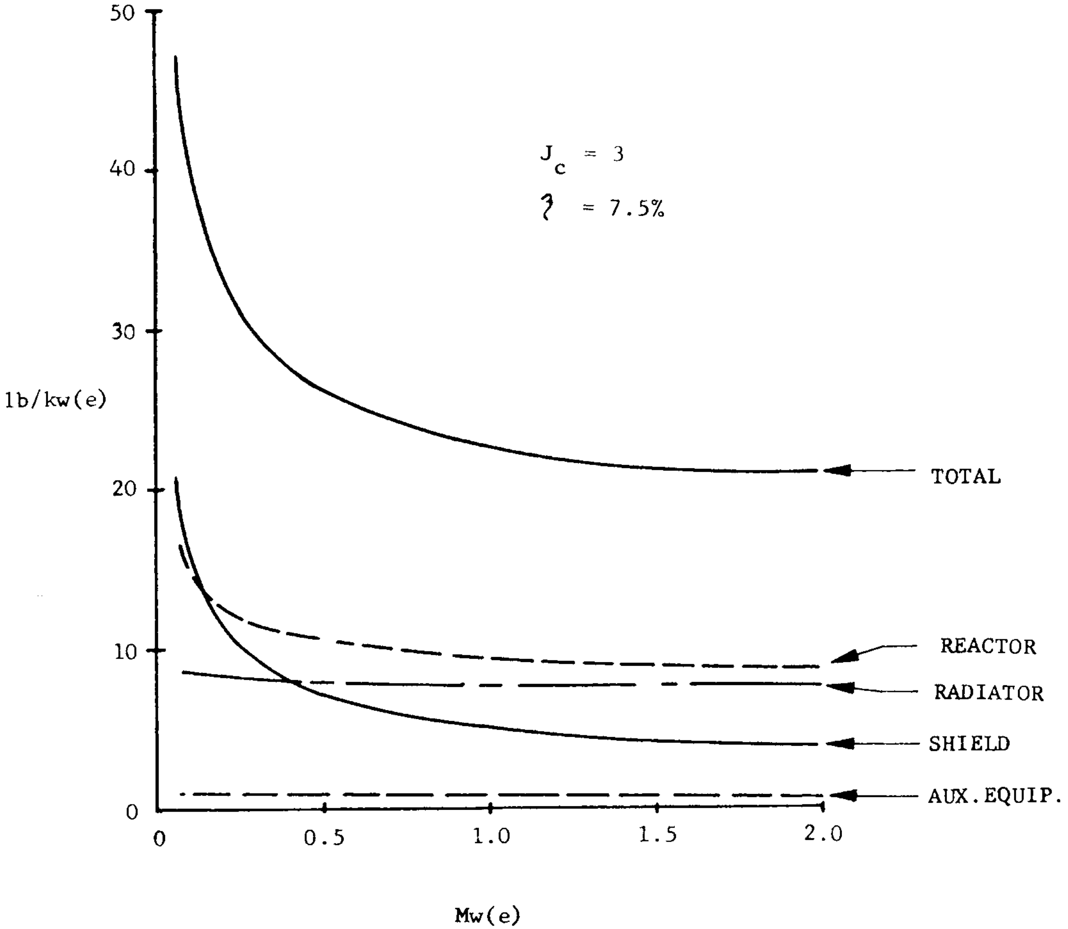
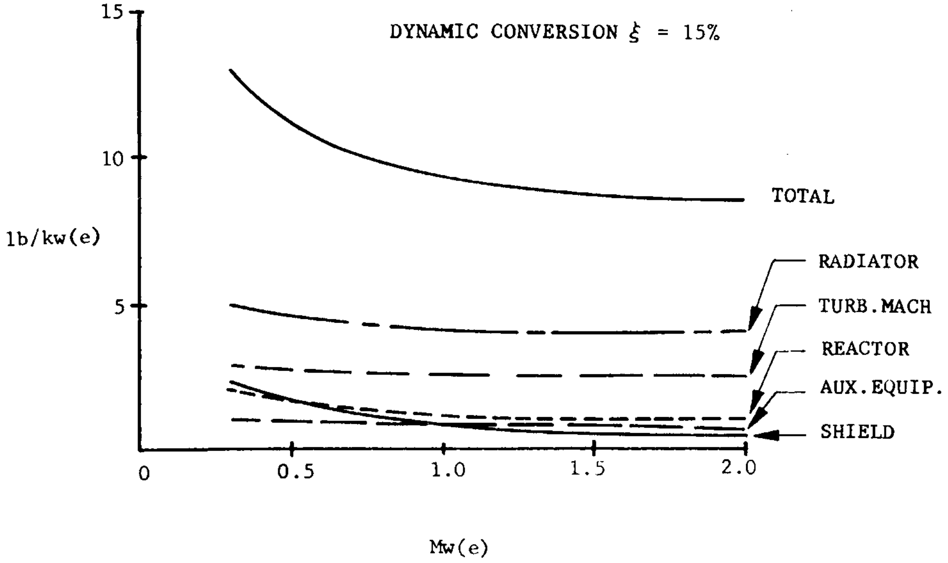


Fig. 11. Specific Performance Thermionic System J_c = 3



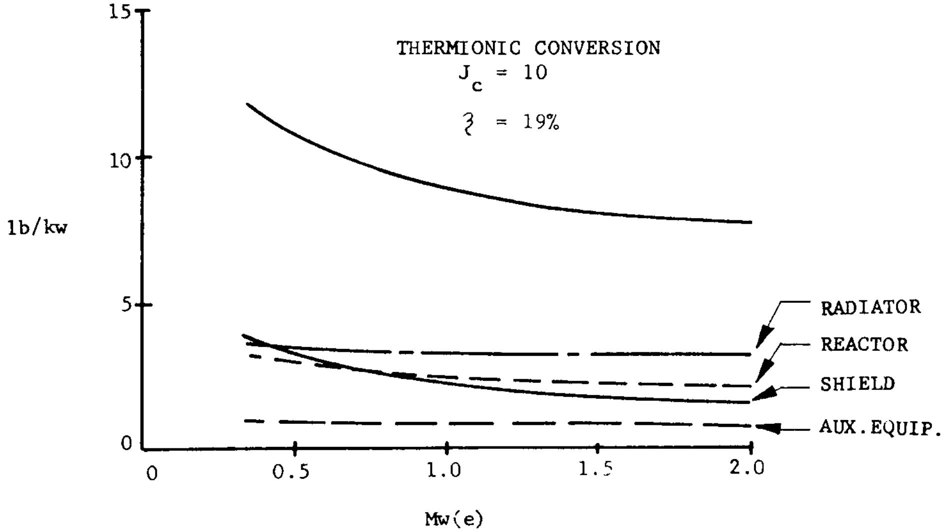


Fig. 12. Performance Comparison of Dynamic and Thermionic Systems

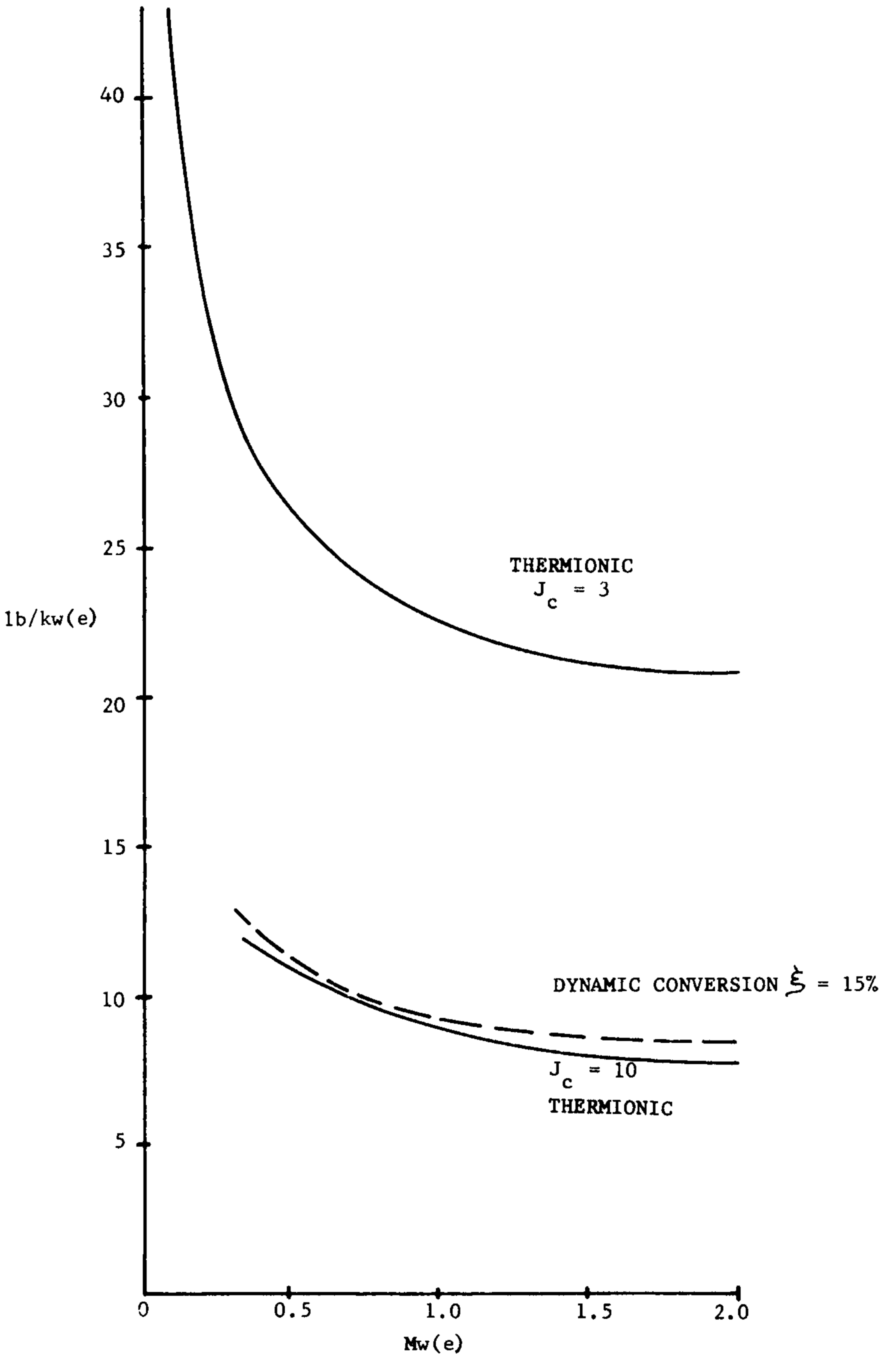


Fig. 13. Specific Performance (lb/kw) Thermionic System $J_c = 3$, $J_c = 10$

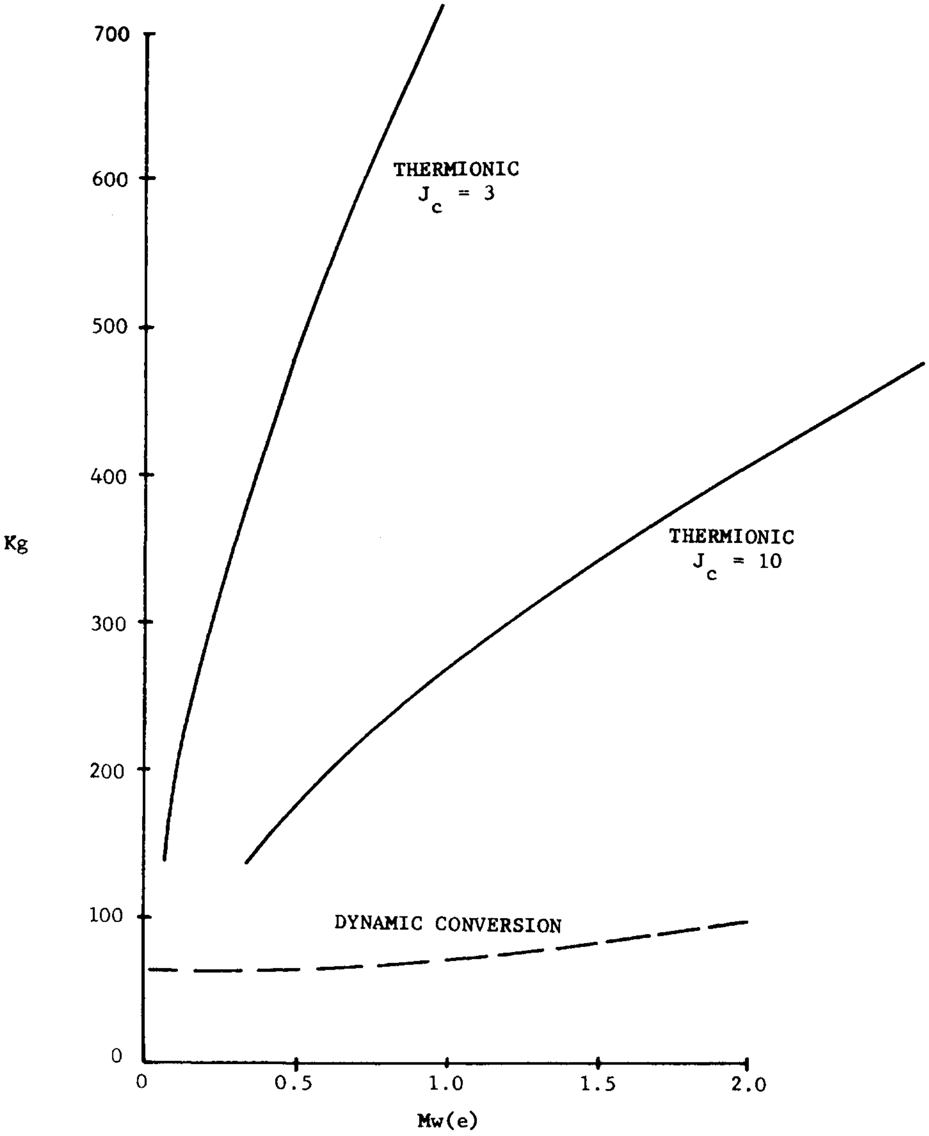


Fig. 14. Fuel Inventory U -235

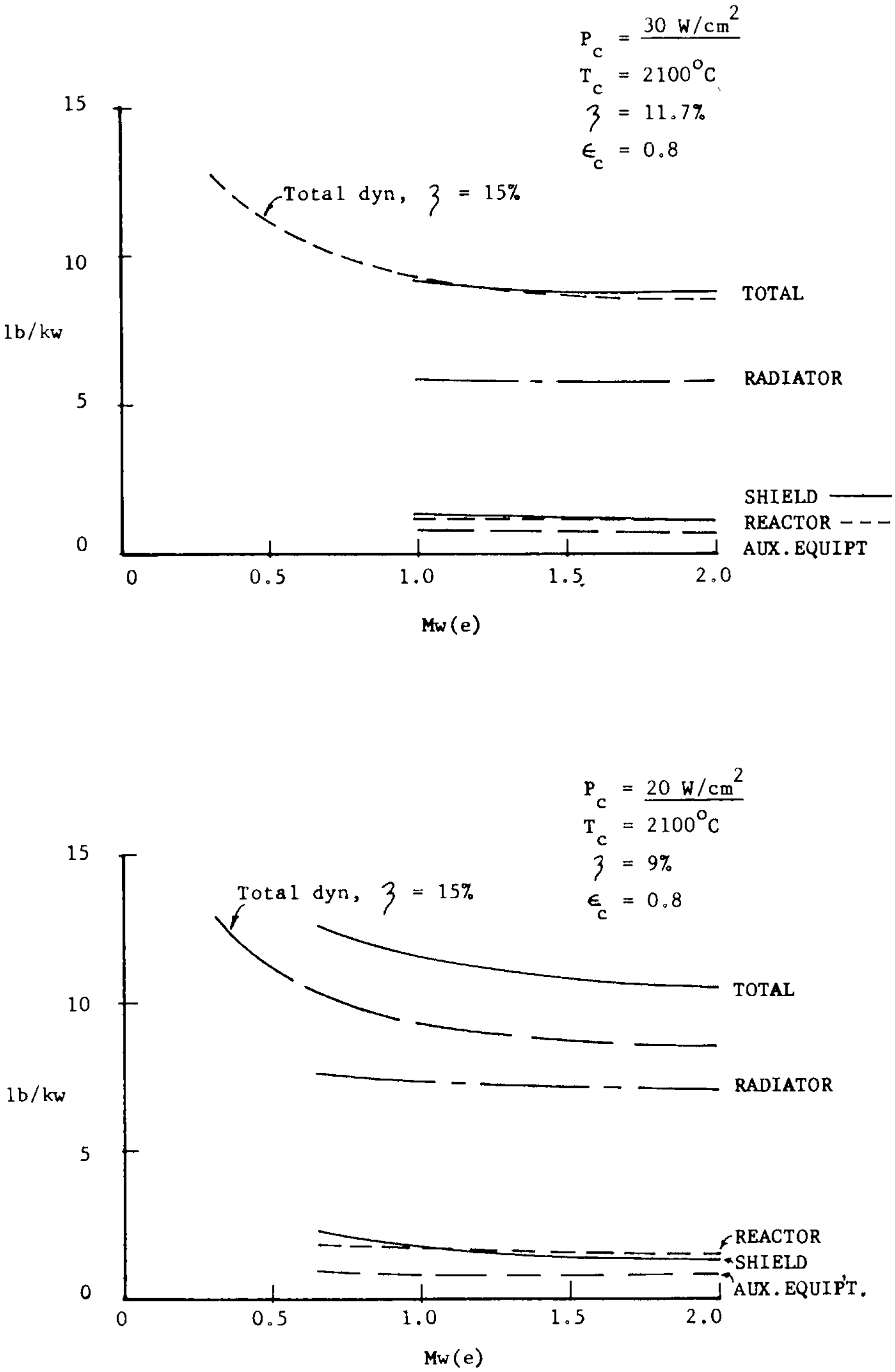


Fig. 15. Specific Performance Lb/Kw UC ZrC