ELIAS P. GYFTOPOULOS, GEORGE N. HATSOPOULOS

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Thermionic nuclear reactors

A unique power system for space, submarine propulsion, and applications in remote areas should result from the successful coupling of nuclear reactors with thermionic converters. Three conceptual designs of thermionic nuclear reactors are reviewed to establish requirements for performance characteristics and materials and to pinpoint some of the problem areas

Since the inception of controlled nuclear reactions as a source of energy, scientists and engineers have been fascinated by the idea of extracting this energy directly in the form of electricity. The idea has not yet been implemented. No practical scheme has been developed to use the electrically charged fissides to produce electric power.

An alternative approach to the problem of direct conversion of energy released in controlled nuclear reactions is the coupling of the reactor with direct energy conversion devices, such as thermoelectric or thermionic converters. These converters transform nuclear heat directly into electricity without the intermediate step of conversion into mechanical energy.

The present and anticipated technological advances in high-temperature nuclear fuels and thermionic converters indicate that the marriage of the two into a nuclear thermionic reactor has a series of unique features for several special applications. First, a thermionic nuclear reactor is characterized by completely silent operation. Therefore, a compact and efficient thermionic nuclear power plant may be of great import to submarine propulsion. Second, heat may be rejected from a thermionic nuclear reactor at the relatively high temperature level of 1,000 degrees K. This feature is very attractive in space applications because it results in appreciable savings in the weight and surface area of the radiator. Third, a thermionic nuclear reactor may operate practically maintenance-free for long periods because it involves no moving parts. This requirement is essential for applications in space and in remote areas.

THERMIONIC CONVERTERS

General Principles • A thermionic converter is a device that accepts heat at a high temperature T_e, rejects heat at a lower temperature T_c, and generates electric energy. It consists of two electrodes (Fig. 1)—the emitter and the collector. The emitter receives heat q_e and delivers electrons. The emitted electrons are transported through the interelectrode spacing y and are collected at the collector, which is also a sink for the rejected heat q_c. The collected electrons return to the emitter via the external electric load.

The electrons in transit in the interelectrode space result in a negative-space-charge barrier. This barrier may cause a decrease of the output electric power by many orders of magnitude and thus render the

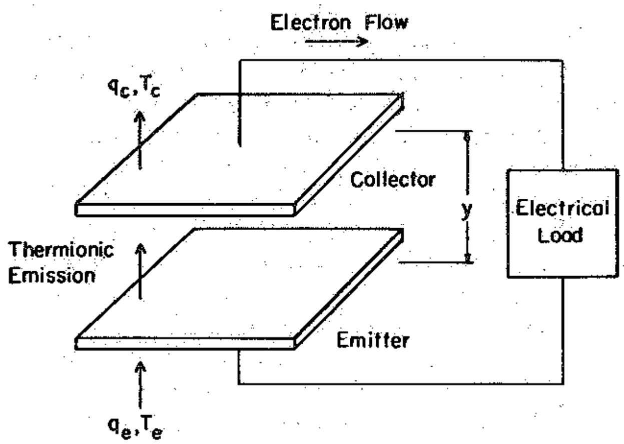

Fig. 1. Schematic diagram of a thermionic converter

converter impractical. However, the formation of the barrier can be prevented by at least two methods—the reduction of the interelectrode spacing to a few microns and the introduction of positive ions. Both methods have been used in practice. The former resulted in the development of the close-spaced vacuum converter, and the latter in the development of the cesium thermionic converter.

Thermionic conversion is, in effect, the use of the kinetic energy associated with electrons thermionically emitted from metals at high temperatures—a phenomenon known as the Edison effect. The use of this effect to convert heat into electricity was first

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Elias P. Gyftopoulos and George N. Hatsopoulos are with the Massachusetts Institute of Technology, Cambridge, Mass.

suggested by Schlichter in 1915 and has since been studied by others.[1-10]

Performance Characteristics • The current and voltage outputs of a thermionic converter operating at constant emitter and collector temperatures depend on the impedance of the load across the converter. There is a particular combination of current and voltage output for which the efficiency of conversion is maximum.

The maximum of the maximum efficiency values and the corresponding electric power density of any converter operating at given source and sink temperatures are limited by upper bound values resulting from the physics of the phenomena involved. These values are independent of the configuration and the materials used and provide an upper limit of what can be expected from any future developments.

Ideal Converters • A converter operating at fixed electrode temperatures and work functions attains its maximum efficiency in the absence of transport effects in the interelectrode space. The transport effects result from collisions between electrons and cesium atoms or ions, or from negative space charge potential barriers, or both. A converter operating in the absence of transport effects is referred to as an ideal converter.

Complete space-charge neutralization is achieved when the ratio of the ion current to the electron current equals the square root of the ratio of the mass of the electrons to the mass of the cesium ions. This ratio is equal to 1/500. On the other hand, the number of collisions between electrons and cesium atoms or ions is determined by the ratio of the interelectrode spacing y to the mean free path of electrons λ. Consequently, to achieve the ideal mode of operation in practice, the cesium pressure must be sufficiently high to result in an ion current greater than 1/500 of the electron current, and the interelectrode spacing must be sufficiently small that collisions are negligible.

A typical voltage–current characteristic of an ideal converter is shown by the dashed line of Fig. 2. The maximum power output is obtained when the output voltage is equal to the difference $\Delta\phi$ between the emitter work function ϕ_e and the collector work function ϕ_c. For output voltages greater than $\Delta\phi$ the output current decreases exponentially with $(V-\Delta\phi)/kT_e$, where k is the Boltzmann constant.

The output voltage for maximum efficiency of an ideal converter is in general greater than the output voltage for maximum power. This fact can be easily established by inspection of the efficiency expression

$$\eta = \frac{IV}{I(\phi_c + V + 2kT_e) + Q} = \frac{V}{\phi_c + V + 2kT_e + Q/I} \quad (1)$$

where $I(\phi_c + V + 2kT_e)$ is the heat rate necessary to evaporate a current I, and Q is the sum of the heat losses consisting of radiation between the electrodes, conduction through the supporting structure and the output leads, and conduction through the cesium vapor.

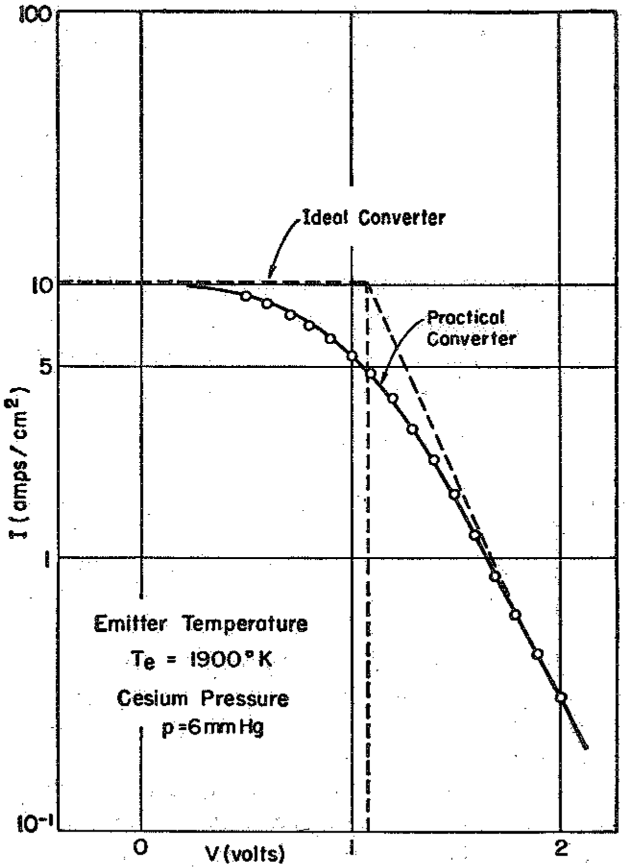

Fig. 2. Typical current–voltage characteristics of ideal and practical converters

The exponential part of the voltage–current characteristic is fixed by the collector work function and the emitter temperature and is independent of the emitter work function:

$$I = I_s \exp[-(V - \Delta\phi)/kT_e] = 120T_e^2 \exp[-(V + \phi_c)/kT_e] \quad (2)$$

where I_s is the saturation current of the emitter. Consequently, the optimum voltage V_m for maximum efficiency is fixed by ϕ_c and T_e. All ideal converters, having an emitter work function below $\phi_c + V_m$, give the same efficiency. However, it is advantageous to use the emitter with a high work function because the higher the emitter work function the greater is the ionization probability of cesium atoms and, therefore, the smaller is the cesium pressure for a required ion current. This statement implies that for an ideal converter, operating at a given emitter temperature and collector work function, there exists an optimum emitter work function.

It should be noted that in the preceding analysis back emission from the collector was assumed to be zero. The assumption is valid provided that the collector is at a sufficiently low temperature in relation to ϕ_c. For given emitter and collector temperatures,

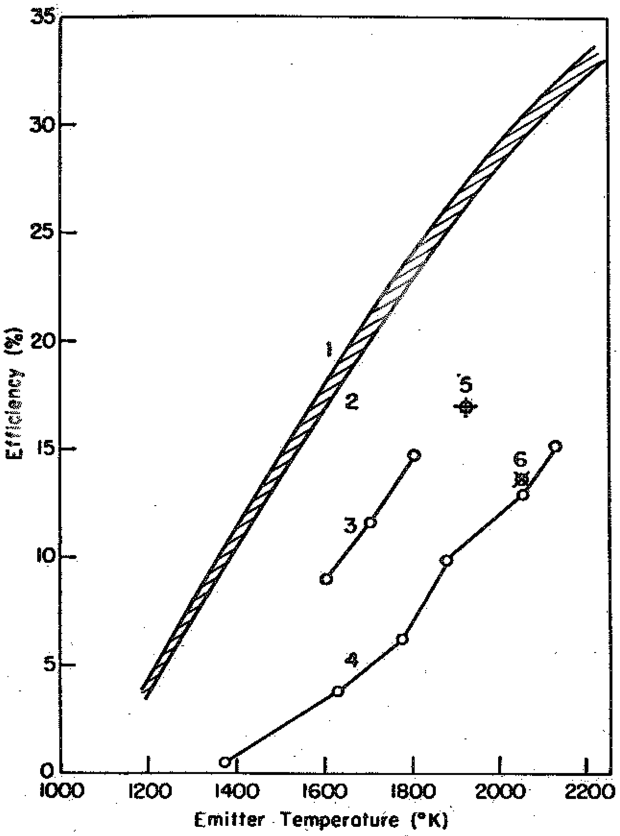

Fig. 3. Thermal efficiency of thermionic converters. Upper curves: *Efficiency of ideal converter, including only radiation losses, with emissivity of (1) 0.25 and (2) 0.33.* Lower curves: *Calculated efficiency of (3) molybdenum and (4) tungsten emitter converter, not including radiation from back of emitter.* Points: *Measured efficiency of (5) molybdenum and (6) tantalum emitter converter*

an increase of both the electric power output and the thermal efficiency can be achieved by means of a decrease of ϕ_c up to the point where back emission becomes appreciable. In other words, the optimum ϕ_c is a unique function of the emitter and collector temperatures.

The maximum of the maximum efficiencies of ideal converters as a function of the emitter temperature is shown in Fig. 3. The collector temperature is assumed to be 900 degrees K. This value is chosen because many important applications require high temperatures for heat rejection. Only radiation losses are considered in the calculation. The boundaries of the dashed area in the figure correspond to thermal emissivities of the electrodes of 0.25 and 0.33.

Practical Converters and Transport Effects • As already indicated, the presence of cesium in the interelectrode space can eliminate the negative space charge. Furthermore, it has been shown that the presence of the cesium vapor may lower the effective work function of metals by a substantial percentage.[11, 12] These facts often make desirable the operation of converters under relatively high cesium pressures. Since manufactural requirements limit the interelectrode spacing to a few thousandths of an inch, collisions between electrons and cesium atoms or ions are unavoidable.

In the presence of collisions, the voltage–current characteristic is different from that of the ideal converter. A typical experimental characteristic is shown in Fig. 2.

At emitter temperatures below 1,800 degrees K, ϕ_e must be reduced to such low values for adequate electron emission that surface ionization becomes inefficient. Thus, the electron space charge may not be neutralized by cesium ions produced at the emitter surface. However, if the cesium pressure is high, and under certain operating conditions, cesium may be excited and ionized by energetic electrons and photons throughout the interelectrode space and sufficient ions may be produced to override the negative space charge. The necessary energetic electrons may result from acceleration by a positive emitter sheath.

Such processes are evidenced by many experimental observations, as illustrated by the voltage–current characteristic shown in Fig. 4. Note that the characteristic exhibits a hysteresis loop in which the output current attains two substantially different values over a broad range of values of the output voltage. The lower curve of the figure may be interpreted as representing an operation under electron space charge limitations, whereas the upper curve may be interpreted as an operation under ion-rich conditions resulting from volume ionization. These two types of operation may be classified as the extinguished and ignited modes, respectively.

It is apparent that for the ignited mode to be established, a large number of collisions between electrons and cesium atoms is necessary. On the other hand, an excessive number of collisions reduces the output current for a given output voltage. Therefore, for given electrode materials and temperatures, there is an optimum spacing that yields maximum power output.

In the light of the preceding discussion, in general, for any type of operation of practical converters the interelectrode spacing is a controlling factor of the efficiency of conversion and the electric power output.

Variations in the optimum electric power density as a function of the interelectrode spacing and the emitter temperature, for a converter having a niobium emitter and a molybdenum collector, are shown in Fig. 5.

The measured thermal efficiency of a few converters, which may be considered representative of the state of the art, is shown in Fig. 3. Comparison of the calculated upper bound curves and the measured data clearly indicates that there is an appreciable range for improvement of the efficiency of thermionic converters.

Effect of Materials on Performance • The output current of a practical converter is predominantly controlled by the transport mechanisms in the interelec-

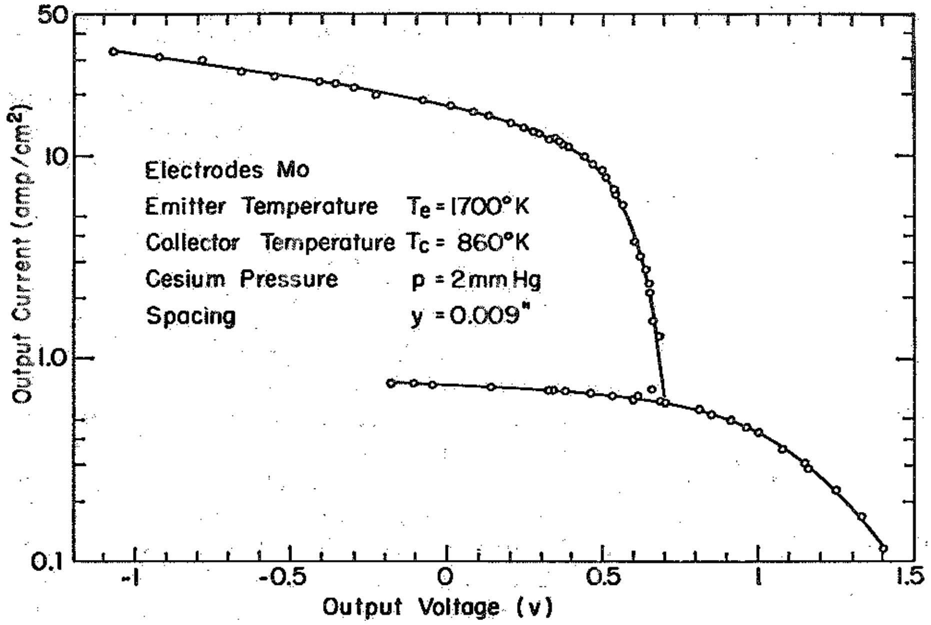

Fig. 4. Extinguished and ignited mode current-voltage characteristics of a cesium thermionic converter

trode space and the work function and temperature of the emitter. The output voltage also depends on the transport mechanisms and, in addition, on the work function of the collector. For high power output and efficiency, the emitter must be operated at a high temperature and yet have a low work function; the collector must have as low a work function as is consistent with the collector temperature.

Composite surfaces of mixtures of oxides—such as barium oxide, strontium oxide, etc.—may be stably operated at temperatures of about 1,500 degrees K and they have sufficiently low work functions at this temperature to emit currents of approximately 5 amp per cm². On the other hand, pure refractory metals—such as tungsten, tantalum, and molybdenum—can be operated at temperatures in excess of 2,000 degrees K but have a work function too high to yield a satisfactory current density. However, in the presence of a sufficiently high concentration of cesium vapor, the effective work function of these metals is lower and the emitter current may be in excess of 100 amp per cm². For example, the work function of tungsten is 4.5 ev (electron volts) and the saturation current in the temperature range of 1,900 to 2,200 degrees K is only 0.5 to 26 milliamperes per cm². In the presence of cesium at a pressure of about 1 mm Hg, the tungsten surface is partially coated with cesium atoms, the work function is reduced and the saturation current is 10 to 20 amp per cm² for the same emitter temperature range.

For converters operating at emitter temperatures above 1,800 degrees K it is advantageous to minimize the transport effects. Thus, emitter materials requiring small cesium pressures to attain a given work function are more practical than those requiring larger pressures. In this respect, tungsten is better than molybdenum, and molybdenum is better than tantalum. It appears that the higher the work function of the metal, the greater the affinity for cesium. Consequently, out of the refractory metals, irridium would require the least cesium pressure to attain a given cesium coverage and hence a given work function.

Refractory metals can also be used as collectors. Their work function is readily reduced to the level of approximately 1.7 ev by a partial coverage by cesium of the order of 70 per cent. Such a coverage can be achieved at collector temperatures lower than 1,000 degrees K and cesium pressures greater than 0.2 mm Hg. Actually it is shown that the best sub-

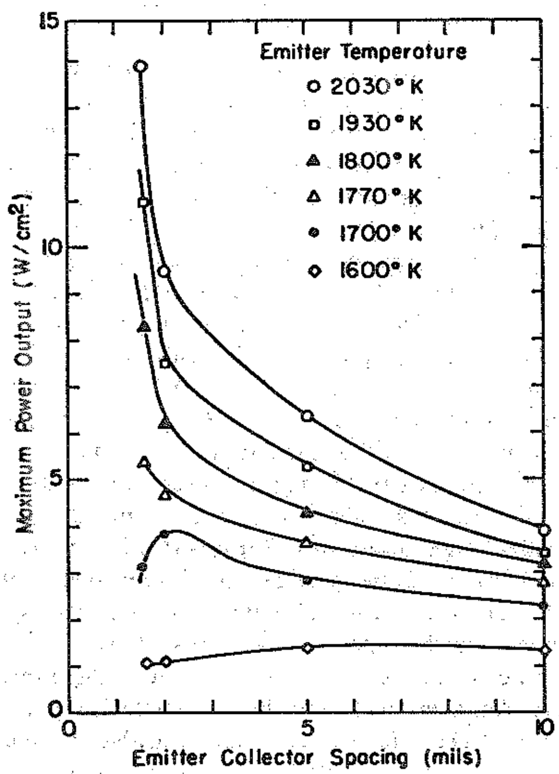

Fig. 5 Optimum electric power density as a function of interelectrode spacing and emitter temperature

strate material for a collector of a cesium thermionic converter is one with a very high work function (> 10 ev) because then the minimum work function reached in the presence of cesium vapor can be as low as 1 ev.[12]

Life of Thermionic Converters • The longest measured life of practical thermionic converters tested so far is of the order of a few thousand hours. The relatively short lives observed are primarily attributable to structural failures. With the present rate of progress, it is expected that the structural problems will be eliminated in the very near future. Eventually, the life of converters will be limited by the corrosive effects of cesium and the evaporation of the emitter.

Structural materials readily attacked by cesium have already been eliminated from present converter designs. However, the effect of cesium on the remaining materials, over long periods, cannot be estimated because of lack of experimental data.

For the same reason, it is hard to assert the effects of emitter evaporation. From vapor pressure data, it appears that the evaporation of some refractory metals—such as tungsten, operating at 2,000 degrees K—is so low that converters could last up to several years. However, it is suspected that high emission-current densities and the presence of the cesium vapor might increase the rate of evaporation. The extent of such an increase is not yet known.

Future Developments • The improvement of performance and the achievement of long-lived thermionic converters depend, in the final analysis, on the development of suitable emitter and collector materials.

The most suitable collector is one that has a low effective work function when partially coated with cesium. The exact value of the work function desired depends on the collector temperature, so there is no appreciable back emission.

Analysis shows that the higher the work function of a material without cesium coverage, the lower the effective work function achieved with a partial cesium coverage.[12] In this sense then, the material that must be used for collectors is one with a very high work function. The only possibility is to develop a stable compound of a metal and an electronegative substance, such as a halogen, that will have a great affinity for cesium.

The requirements for the most suitable emitter are not completely understood. Of course, the best emitter is one that can be operated at very high temperatures with an emission of several tens of amperes per centimeter square and with no appreciable evaporation in the presence of cesium vapor, over periods of several years. However, the value of the emitter work function that is sought is ambiguous. The reason for this ambiguity is that whether it is advantageous to neutralize the electron space charge by ions produced by surface or volume ionization is not yet clear.

Several other methods for production of cesium ions are being studied. These methods utilize electrodes other than the emitter and collector to supply ions either by surface or discharge ionization. Even though these methods may result in the development of efficient thermionic converters, their practicability may be limited by the added complication of the additional electrodes and auxiliary voltage supplies.

In addition, a compound or mixture of vapors may be found which ionizes more readily than cesium atoms. Such a vapor will change all the specifications for future developments. Similarly, the idea of a liquid collector separated from the emitter by a boiling film may prove practical and again change the entire outlook toward thermionic conversion.

THERMIONIC NUCLEAR REACTORS

The preceding discussion indicates that the critical parameters of a thermionic converter are the emitter and collector materials and spacing, the cesium pressure, and the temperatures of operation. It is also evident that thermionic converters are inherently low-voltage devices and, therefore, any large power unit must incorporate many converters in series.

The effect of these parameters on the performance of thermionic converters limits the choice of methods of coupling of a nuclear reactor with converters.[13] For example, the intriguing idea of using a nuclear fuel both as a heat source and as an emitter cannot be implemented at present because the available high-temperature fuels do not absorb cesium and do not exhibit the surface stability required by the relatively small converter spacings. Because these materials do not absorb cesium there is a substantial loss of converter efficiency; the fuel material evaporates and deposits on the collector and prevents the reduction of the collector work function by cesium coverage. Moreover, flaking and swelling of the fuel limit the life of the converter to impractical periods of time. Consequently, the functions of the nuclear fuel and the emitter must be performed by different materials.

The separation of the functions of fuel and emitter leads to two possible methods of coupling thermionic converters with a nuclear heat source. The first is to arrange the converters in a heat exchanger structure external to the reactor. Heat is conveyed to the emitters by means of a high-temperature-coolant loop. The second is to incorporate into each converter a slug of nuclear fuel and arrange the fueled converters into a critical assembly. Each fuel slug constitutes the heat source for one converter. The latter method can be realized by means of two designs. In the first, the fueled converters are arranged so that all the converters are on the outer surface of the resulting critical core. In the second, several fuel-converter units are assembled into a cylindrical fuel element and a large number of fuel elements are arranged to form a critical core.

Each method has its own advantages, problems,

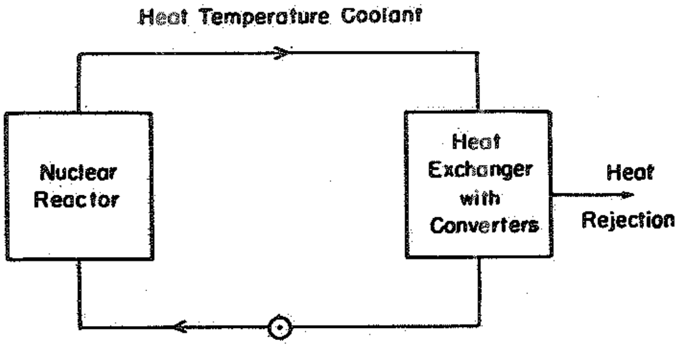

Fig. 6. Thermionic nuclear reactor with converters separate from reactor core

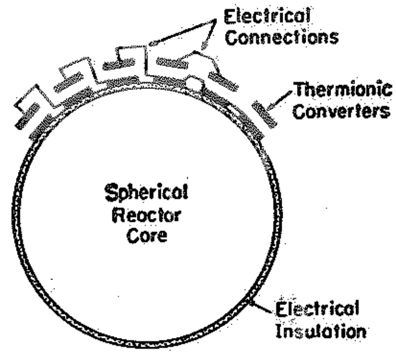

Fig. 7. Thermionic nuclear reactor with converters to outer surface of reactor core

and limitations. The choice of a particular concept depends on the over-all system power rating or power density of the converters, or both, the temperatures of operation, the availability of high-temperature liquid-metal coolants and electrical insulation, the specific weight and volume requirements, and the type of application. The influence of these factors on the selection of a design is described in detail in the following sections.

Conversion System Separate from the Reactor • Fig. 6 is a schematic diagram of the concept of a conversion system separate from the nuclear reactor. The thermionic converters are either of planar or cylindrical geometry and are electrically connected in parallel-series combinations. They are arranged to form a heat exchanger structure. The primary side of the heat exchanger structure is formed by the non-emitting surface of the emitters. The secondary side consists of the outer surface of the collectors. Heat is conveyed to the emitters from the reactor by a primary coolant loop and rejected either by a secondary coolant or by direct radiation into free space.

From the previous discussion it is apparent that in order for a converter to have a reasonable efficiency and surface power density, the emitter temperature should be at least 1,500 degrees K. The implication of this statement is that the primary coolant must be a high-temperature liquid metal, such as lithium. On the other hand, because in this design the primary coolant is in contact with the emitters and because the converters must be connected electrically in series, the emitters must be isolated electrically from the liquid-metal coolant. Hence, this design requires the use of electrical insulation at temperatures higher than 1,500 degrees K. The insulation must also be a good heat conductor, so that heat is transferred to the emitters without an appreciable temperature drop.

The performance of the converters can be improved by increasing the surface power density and efficiency. These in turn can be increased by raising the emitter temperature and lowering the effective collector work function. Unfortunately, such changes are not advantageous, for space applications, to a thermionic nuclear reactor with a separate conversion system for the following reasons. First, the emitter temperature is limited by the availability of high-temperature liquid-metal coolants. More precisely, if the power plant is to have no moving parts, the coolant must be circulated by an electromagnetic pump and not be allowed to vaporize. The best liquid metal available, as already indicated, is lithium. The boiling point of lithium is 1,610 degrees K. Hence, assuming that the temperature drop across the electrical insulation is about 100 degrees K, the emitter temperature cannot be raised above 1,500 degrees K without pressurization of the primary loop and the consequent increase in weight and complexity. Second, lowering of the collector work function does not affect the overall weight of the system. Specifically, the available collector materials, when optimally coated by cesium, have an effective work function of 1.7 ev and can be operated at a temperature of 950 degrees K without appreciable back emission. If a new collector material were found with an optimum work function of 1 ev, it would have to be operated at 700 degrees K for the same reason. Consequently, even though the efficiency may go up by a factor of 2, the black-body radiation decreases by a factor of $(950/700)^4 \approx 2$, and the radiator area remains practically the same. Third, no substantial gains are expected from the reactor, since calculations indicate that the reactor weight is only a small fraction of the specific weight of the system. This is because the core design is not affected here by the materials of the converters and because liquid-metal-cooled reactors are very compact.

For these reasons, it is believed that the concept of a conversion system separate from the reactor is not amenable to substantial improvements by technological developments in the fields of high-temperature nuclear fuels and efficient operation of thermionic converters. Consequently, a system of this type has limited growth potential.

In fact, the entire concept of a conversion system separate from the reactor hinges on the availability of a high-temperature electrical insulator that is also a good heat conductor and can be metallurgically bonded to the emitters. Such a material is not available at the present stage of technological development. Preliminary calculations indicate that for a 30-kwe system in which heat is rejected by direct radiation into free space, the over-all specific weight is 35 pounds per kwe.

Conversion System Attached to Outer Surface of Reactor • Fig. 7 shows schematically the concept of thermionic converters attached to the outer surface of a spherical nuclear reactor core.

The converters are of a planar geometry and are electrically connected in parallel-series combinations. The nonemitting side of the emitters is attached to the core. Heat is carried to the emitters by conduction through the core, and is rejected from the collectors either by radiation into free space or by convection by means of a coolant loop.

The reactor core design in this case is greatly affected by the characteristic parameters of the converters. To see this clearly, consider first the requirement of electrical insulation between the emitters and the core. If high-temperature insulation were available, it would be possible to have a solid core and attach the emitters directly to it. However, as already indicated, such insulation is not available; hence, the core must be sectionalized. To this effect, a fuel slug is attached to a single converter and many converter fuel-slug units are combined into a spherical critical assembly. Fig. 8 shows in schematic form two typical converter fuel-slug units cooled by a liquid-metal coolant. Note that by proper extension of the emitter support, all electrical insulators are on the low-temperature side of the converter.

Second, consider the question of the size and the geometry of the spherical core. For a given electric power rating, the outer surface area of the nuclear core must be inversely proportional to the electrical surface power density of the converters. Furthermore, since heat is carried through the core by conduction, the core should be a spherical shell so that the temperature drop along the fuel will be minimized and the maximum fuel temperature will be made tolerable. The thickness of the spherical shell is proportional to the converter efficiency. For power densities in the range of about 10 to 50 watts per cm^2 and over-all power ratings of about 50 kwe and higher, the radius of the core is such that a spherical shell can become critical with a practical enrichment.

Third, consider the problem of emitter distortion resulting from changes in fuel size induced by irradiation. The small spacings, necessary for optimum converter performance, require that the emitter not be distorted by fuel swelling. To achieve this, the fuel slug must be loosely encased, with a few mils' clearance, inside the emitter extension. The lack of metallurgical bonding between the emitter and the fuel results in radiative heat transfer between these two bodies and, consequently, higher fuel temperatures. Gaseous fissides do not affect converter performance in this design because any fissides that diffuse out of the fuel leak into the central region of the core. In the light of the preceding arguments, it should be apparent that the concept of a conversion system attached to the outer surface of a nuclear reactor core has limited capabilities. First, even if converters with the most optimistic electrical surface power density were available, the over-all power rating of the system could not exceed a few hundred kwe without the use of an extremely large core. Second, a spherical-shell core leads to a poor use of the nuclear fuel. Third, the seemingly advantageous feature of having the converters outside the fuel region is effectively lost

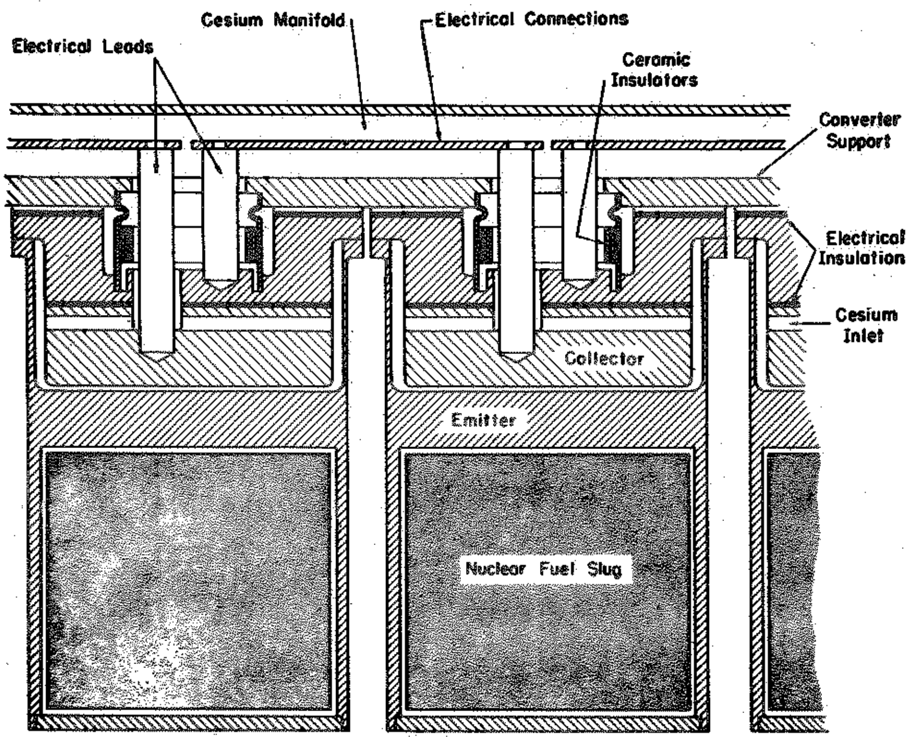

Fig. 8. Converter fuel-slug units

because of the lack of high-temperature electrical insulation compatible with the emitters. Fourth, all materials used in this design are operated at their limit temperatures and yet the over-all performance is poorer than that which could be achieved under similar conditions with a different arrangement. Such an arrangement is discussed in the next section.

Calculations indicate that for a 30-kwe space system of this type the over-all weight is 58 pounds per kwe when the heat is radiated directly into free space from finned collectors, or 51 pounds per kwe when a separate radiator is used.

Conversion System Integrated into the Nuclear Reactor Core • In still another type of thermionic nuclear reactor, the converters are an integral part of the fuel elements. The design resembles an ordinary nuclear reactor core with cylindrical fuel elements. However, each fuel element consists of several individually fueled converters connected electrically in series. The fuel elements in the reactor are electrically connected in parallel-series combinations. The reactor is cooled either by means of a liquid-metal loop if the system is designed for space or a submarine, or by any other coolant if the application does not require a high temperature for heat rejection or an electromagnetic pump for silent and maintenance-free operation.

The converters are contained inside a thin-walled tube and are electrically insulated from it by a thin layer of insulation sprayed on the outer surface of the cylindrical collectors (Fig. 9). The thin-walled tube provides the structural rigidity of the fuel element. Each converter consists of a fuel slug, loosely enclosed in a cylindrical casing that serves as the emitter. Surrounding the emitter are the concentric annular regions of the cesium vapor, the collector, the insulation, and the supporting tube. The emitter of each converter is electrically connected and mechanically cantilevered from the collector of the next converter. All converters in a fuel element are in vapor communication. Note also that all electrical insulators in this design are on the collector side—that is, the low-temperature side—of the converters.

The reactor power density and volume are respectively proportional and inversely proportional to the surface power density of the converters. The critical enrichment depends on the converter materials.

Integration of the conversion system into the nuclear reactor core is the most effective way of coupling thermionic converters with a nuclear heat source for several reasons. First, thermionic conversion is essentially a surface phenomenon, while a nuclear reaction is a volume phenomenon. Consequently, by direct analogy between heat transfer at an interface of volume distributed heat sources, it is evident that the most effective use of a given critical volume is achieved when the conversion surface is disperson so that a large surface-to-volume ratio is reached.

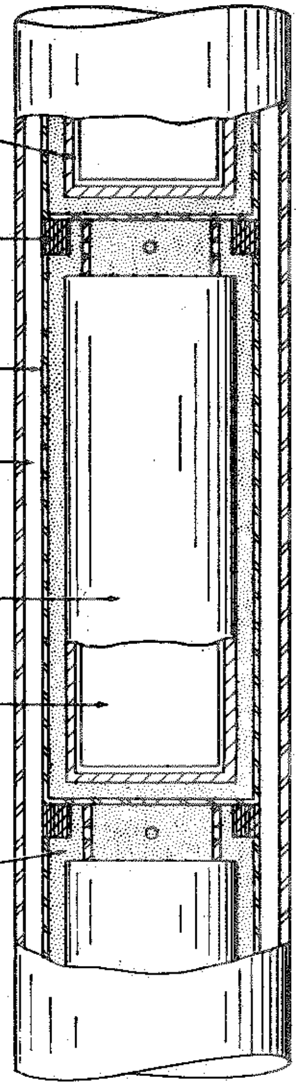

Fig. 10. Converter integrated into the fuel element

Second, the same analogy between thermionic conversion and heat transfer clearly indicates that for a given temperature at the interface, the maximum fuel temperature is lower when the surface to volume ratio is large than when it is small. In other words, given an upper fuel-temperature limit, the emitters can be operated at a much higher temperature level when they are dispersed through the fuel than in any other case. Hence, the converters are more efficient.

Third, there is not as severe a limitation imposed by the availability of high-temperature electrical insulation as in the previous designs because all insulators are on the low-temperature side of the converters.

Fourth, any improvements in the performance of thermionic converters are directly reflected on the over-all system because the reactor weight is inversely proportional to the performance of the converters and it is a substantial fraction of the over-all weight of the system.

Finally, it turns out that the specific weight of this system is at least one order of magnitude lower than the previous two designs under similar maximum fuel temperature limitations.

Admittedly, the integration of the conversion system into the nuclear reactor core presents more technical problems. For example, fissides that diffuse out of the fuel may leak into the cesium-vapor space, the emitter material must be made compatible with the nuclear fuel under high-temperature and high-irradiating-field conditions, the fuel element design is complex, and the fuel inventory is increased by the presence of the converter materials in the core. However, all of these problems are not of a basic nature and since the concept is so superior to the others, it is recommended that it should be most actively pursued and developed. Preliminary calculations indicate that the specific weight of a 1-Mwe system is 3.9 pounds per kwe.

Problem Areas of Thermionic Nuclear Reactors • On the basis of the discussion and preliminary results presented in the preceding sections, it appears that the most promising method of coupling thermionic converters with a nuclear reactor is to distribute the converters throughout the reactor core.

The development of a thermionic nuclear reactor of this type presumes the successful solution of a series of technical problems, some of which are already under investigation. These problems arise from the special operational requirements of the converters and may be summarized as follows:

1. Nuclear fuel elements capable of operating at high temperatures at both the center and the surface of the element must be developed. Even though fuels have been operated at high center temperatures, there is no similar experience with fuels operating at high surface temperatures.
2. The behavior of high-temperature nuclear fuels freely encased in a cladding material must be examined. It is important to establish the appropriate gap size to achieve a distortion-free emitter casing as required for a thermionic nuclear reactor.
3. The metallurgical compatibility of emitter and nuclear fuel materials must be thoroughly investigated to develop suitable emitter-fuel material combinations, capable of stable operation at high temperature levels.
4. The diffusion of gaseous fissides through the emitter casing and the effect of the former on the performance of the converter must be studied. If fissides prove to be deleterious to the converter performance, either proper diffusion barriers must be sprayed on the nonemitting surface of the emitter or means must be developed for the continuous recirculation and purification of the cesium vapor through all of the fuel elements.
5. The diffusion of fuel and nongaseous fissides through various emitter materials must also be studied and appropriate diffusion barriers be developed if it proves to be substantial.
6. High-temperature electrical insulation, metallurgically bondable to collector and structural materials over relatively large areas and with good heat conductivity, must be developed.

Other areas that must be examined are pertinent to high-temperature liquid-metal coolants and structural materials, welding and assembly procedures, temperature uniformity throughout the nuclear core, and a series of problems common to any reactor design.

CONCLUSIONS

It has been found that the best performance of cesium thermionic converters is achieved when the emitter temperature is high and the collector work function low. When the emitter temperature is above 1,800 degrees K, the smaller the interelectrode spacing, the higher the thermal efficiency and electrical power output of the converter. On the other hand, when the emitter temperature is below 1,800 degrees K, there is an optimum spacing of a few mils at which the best performance is achieved.

For the conversion of nuclear heat into electricity by means of thermionic converters, it is concluded that the best method of coupling a nuclear reactor core with converters is by the incorporation of the converters into the fuel elements. This method leads to an efficient and compact design with a very good growth potential.

Several problem areas are indicated in which further development work needs to be intensified or initiated before the design and construction of the first thermionic nuclear reactor may be achieved.

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