Thermionic Nuclear Reactors

E. P. GYFTOPOULOS G. N. HATSOPOULOS

Summary: The coupling of nuclear reactors with thermionic converters is reviewed.

First, the paper discusses principles of operation of thermionic converters, together with present and anticipated advancements. Particular emphasis is given to parameters that influence optimum performance and life of converters; namely, work function of emitter and collector, spacing between the same, temperatures of operation, cesium vapor pressure, and materials. The discussion is illustrated by a series of experimental results and amplified by theoretical analysis.

Next, three conceptual designs of thermionic nuclear reactors are reviewed and presented as reference points to establish performance characteristics and materials requirements, as well as problem areas that result from the marriage of nuclear reactors and thermionic converters.

Chief conclusions are: (1) The most efficient way of coupling thermionic converters with a reactor is by dispersing the former throughout the volume of the nuclear core, and (2) thermionic nuclear reactors have several unique features for space, submarine propulsion, and applications in remote areas.

SINCE THE INCEPTION of controlled nuclear reactions as a source of energy, scientists and engineers have been intrigued 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 which uses the electrically charged fissides to produce electric power.

An alternate approach to the problem of direct conversion of energy released in controlled nuclear reactions is to couple 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.

A nuclear thermionic reactor has a series of unique features for several special applications. First, it is completely silent in 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 (Kelvin)—a highly attractive feature for space applications because it results in appreciable savings in the weight and surface area of the radiator. Third, such a reactor may operate for long periods, practically maintenance-free because it does not involve any moving parts. This again is essential for space and for applications in remote areas.

The first part of the paper discusses the principles of operation of thermionic converters and the present and anticipated advancements in the state of the art of thermionic conversion. Particular emphasis is given to the parameters that influence the optimum performance and life of converters such as work-function of emitter and collector, spacing between the same, temperatures of operation, cesium vapor pressure and materials. The discussion is illustrated by a series of experimental results and amplified by theoretical analysis.

The second part of the paper reviews three conceptual designs of thermionic nuclear reactors. These designs are presented as reference points to establish the requirements on performance characteristics and materials as well as the problem areas that result from the marriage of nuclear reactors and thermionic converters. These, in turn, indicate the criteria that influence the choice of one design over the other, depending on the particular application.

Thermionic Converters

General Principles

A thermionic converter is a device which accepts heat at a high temperature T_e, rejects heat at a lower temperature T_c, and generates electric energy. The converter consists of two electrodes shown in 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 to 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.

Electrons in transit in the interelectrode space result in a negative space charge barrier. This barrier may cause

Paper 62-1429, recommended by the AIEE Nucleonics Committee and approved by the AIEE Technical Operations Department for presentation at the AIEE Fall General Meeting, Chicago, Ill., October 7–12, 1962. Manuscript submitted June 1, 1962; made available for printing August 8, 1962.

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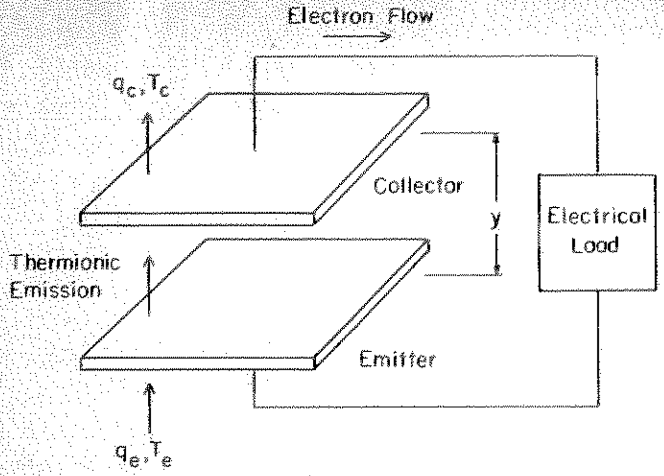


Fig. 1. Schematic of thermionic converter

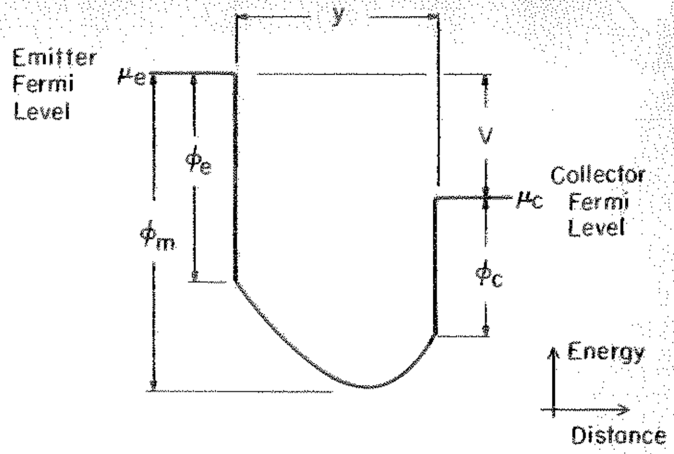


Fig. 2. Potential distribution in a vacuum thermionic converter

a decrease of output electric power by many orders of magnitude and thus render the converter impractical. However, the formation of the barrier can be prevented by at least two methods—by reducing the interelectrode spacing to a few microns and by 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 effectively the use of the kinetic energy associated with electrons thermionically emitted from metals at high temperatures. This phenomenon is known as the Edison effect, the use of which to convert heat into electricity was first suggested by Schlichter in 1915.[1] Subsequently, Champeix in 1951 gave a qualitative discussion of the process, concluding it was impractical.[2] In 1956, one of the collaborators on the present paper gave a detailed thermionic and thermodynamic analysis of the subject and proposed close spacings and crossed electric and magnetic fields to control the effects of space charge.[3] Since then, several authors have published analytical and experimental studies of both vacuum and cesium thermionic converters.[4–10]

Further discussion herein centers around the characteristic parameters of cesium thermionic converters, referred to simply as converters or thermionic converters unless otherwise stated.

Potential Distribution in a Thermionic Converter

Two parallel plates of electron emissive materials, when placed in vacuum as shown in Fig. 1, are considered. The emitter and collector are held at constant temperatures T_e and T_c, respectively. Furthermore, the Fermi level of the collector μ_c is held negative with respect to the Fermi level μ_e of the emitter. Under these conditions, the potential distribution from the emitter surface to the collector surface has the form shown in Fig. 2.[11,12]

The meaning of this potential diagram is: First, electrons are prevented from escaping out of the emitter surface into the evacuated interelectrode space by the emitter surface potential barrier ϕ_e. This is the emitter effective work-function. A similar effect occurs at the collector, whose effective work-function is ϕ_c. Second, if the emitter is at a sufficiently high temperature, electrons acquire enough energy to overcome barrier ϕ_e and are emitted into the evacuated space. Those electrons, having energies below the space charge potential minimum ϕ_m, reach the collector while electrons in energy levels between ϕ_e and ϕ_m are returned to the emitter and do not contribute to the output current.

For a given potential difference $V+\phi_c$ between the electrochemical potential μ_e of the emitter and the potential outside the collector, it is theoretically possible to avoid completely the space charge effects by reducing the distance between the electrodes.[3] However, this method is not too practical because of the small spacing required for useful current output.

Another way to achieve space charge neutralization is by introduction of cesium vapor in the interelectrode space. The cesium atoms collide with the hot emitter surface and are ionized. The ions are trapped in the negative potential well, shown in Fig. 2, and reduce the space charge minimum. When a sufficient number of ions is produced to neutralize the space charge at the emitter surface, the potential distribution takes the form indicated in Fig. 3. However, this potential distribution is unstable. The slightest excess of positive ions at the emitter surface results in further reduction of the negative space charge because the velocity of the electrons is increased. Production of ions higher than that required for space charge neutralization at the emitter leads to formation of positive sheaths as illustrated in Fig. 4.

Performance Characteristics of Thermionic Converters

The current and voltage output of a thermionic converter, operating at constant emitter and collector temperatures, depend on 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 efficiency 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 materials used and provide an upper limit of what can be expected from any future developments. The subject is discussed in the subsequent section.

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. Transport effects result from collisions between electrons and cesium atoms or ions and/or negative space charge potential barriers. A converter operating in the absence of transport effects is referred to as an ideal converter.

Complete space charge neutralization is

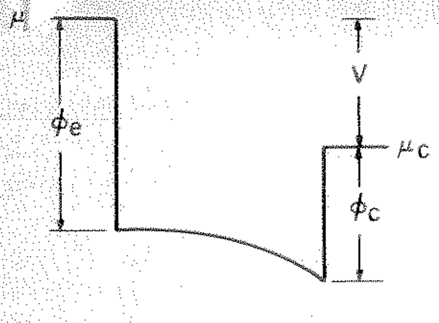


Fig. 3. Unstable potential distribution in a cesium thermionic converter

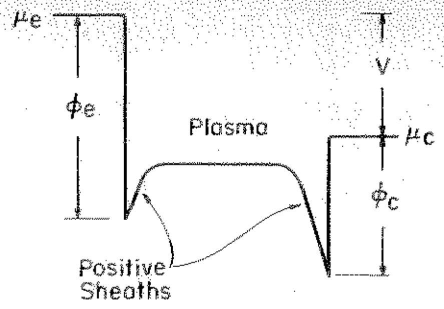


Fig. 4. Potential distribution in a cesium thermionic converter with an ion current greater than 1/500 of electron current

achieved when the ratio of the ion current to the electron current equals the square root of the ratio of the electrons mass to the cesium ions mass. 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, in order 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 so that collisions are negligible.

A typical voltage-current characteristic of an ideal converter is shown by the dashed line in Fig. 5. 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 seen from the following analysis. Thermal efficiency η is given by the 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 and conduction through the supporting structure, through output leads, and through the cesium vapor. Efficiency is zero for a zero value of output voltage V (short-circuit condition) or for a zero value of output current I (open-circuit condition). Therefore, it is evident that the efficiency reaches a maximum for a specific value of the voltage between short- and open-circuit conditions. The optimum value of voltage V_m depends strongly on the heat losses Q. As Q approaches zero, V_m can never be smaller than $\Delta\phi$. For, if $V<\Delta\phi$, I remains constant and η decreases with V as seen in equation 1.

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

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

where I_s is the saturation current of the emitter. Consequently, the optimum voltage V_m for maximum efficiency is fixed by the collector work-function ϕ_c and the emitter temperature T_e. All ideal converters, having an emitter work-function below ϕ_c+V_m, give the same efficiency. However, it is advantageous to use the emitter with a high work-function, because the greater this 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 implies that, for an ideal converter operating at a given emitter temperature and collector work-function, there exists an optimum emitter work-function.

In the preceding analysis, back-emission from the collector has been assumed zero, which assumption is valid provided the collector is at a sufficiently low temperature in relation to the work-function ϕ_c. For given emitter and collector temperatures, an increase of both electric power output and thermal efficiency can be achieved by decreasing the collector work-function to the point where back-emission becomes appreciable. In other words, the optimum collector work-function is a unique function of the emitter and collector temperatures.

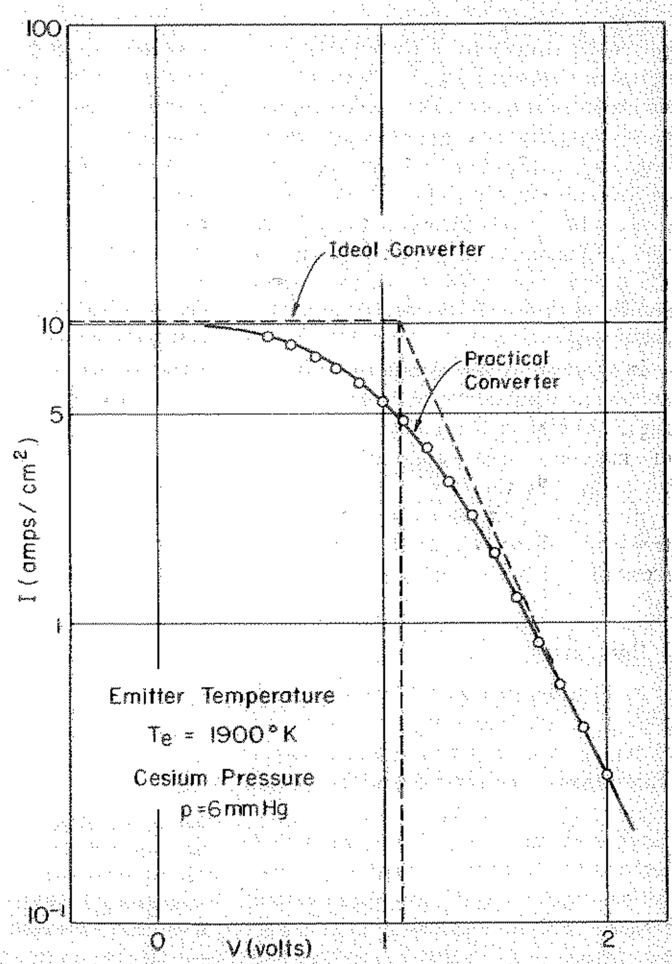


Fig. 5. Typical current-voltage characteristics of ideal and practical converters

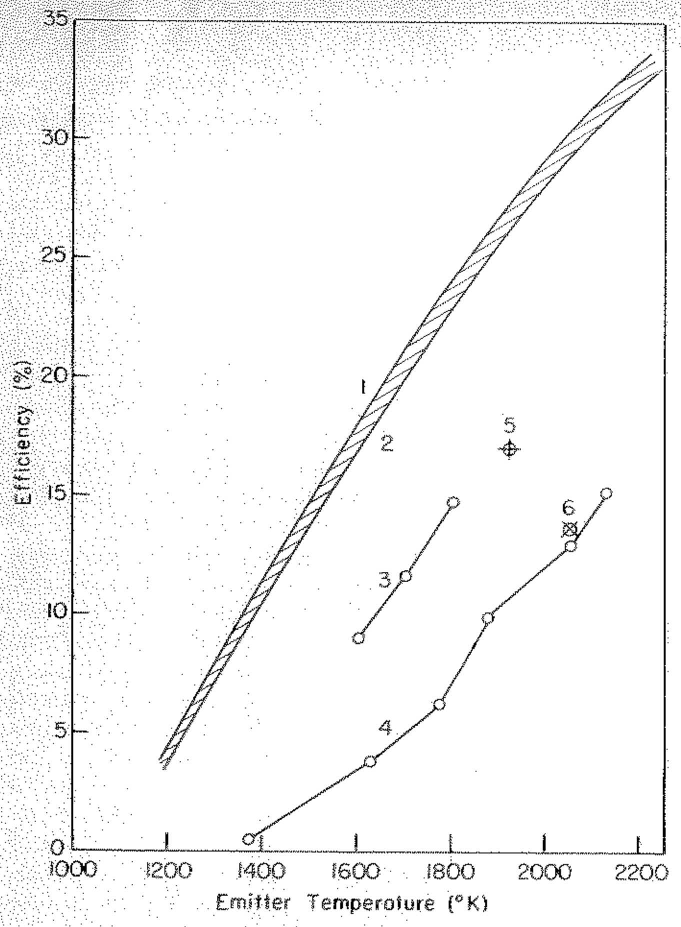


Fig. 6. Thermal efficiency of thermionic converters

1—Efficiency of ideal converter including only radiation losses, emissivity 0.25

2—Efficiency of ideal converter including only radiation losses, emissivity 0.33

3—Calculated efficiency of molybdenum emitter converter, not including radiation from back of emitter—Thermo Electron Engineering Corporation, private communication

4—Calculated efficiency of tungsten emitter converter, not including radiation from back of emitter—V. C. Wilson and J. Lawrence, General Electric Company Scientific Report No. 3, Contract AF 19-(694)-5472, August 1960

5—Measured efficiency of molybdenum emitter converter—N. S. Rasor, Indicated Air Speed Paper No. 61–72, January 1961

6—Measured efficiency of tantalum emitter converter—Thermo Electron Engineering Corporation, private communication

The maximum efficiency of ideal converters as a function of the emitter temperature is shown in Fig. 6. 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. Boundaries of the dashed area in the figure correspond to thermal emissivities of the electrodes of 0.25 and 0.33, respectively.

In practice, it is difficult to construct and use an ideal converter because of the required small spacing and/or the lack of materials with appropriate work-functions. Furthermore, practical converters are influenced appreciably by transport effects, discussed in the next section.

Practical Converters—Transport Effects

As already indicated, the presence of cesium in the interelectrode space can eliminate the negative space charge. Furthermore, the presence of the cesium vapor may lower the effective work-function of metals by a substantial percentage.[13,14] Hence, operation of converters under relatively high cesium pressure is often desirable. Since manufacturing requirements limit the interelectrode spacing to above 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. 5, where, as the voltage is decreased, the current tends asymptotically to the saturation current of the emitter. Moreover, at any given voltage, the current is considerably less than it would be for the collision-free case, with the same value of saturation current. The reason for this reduction is that electrons collide with cesium and are returned to the emitter. The experimental results shown in Fig. 5 can be theoretically correlated by considering the converter as a double probe.[15]

At emitter temperatures below 1,800 degrees K, the emitter work-function 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 as shown in Fig. 4.

Indeed, such processes are evidenced by many experimental observations as illustrated by the voltage-current characteristic shown in Fig. 7. This 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.

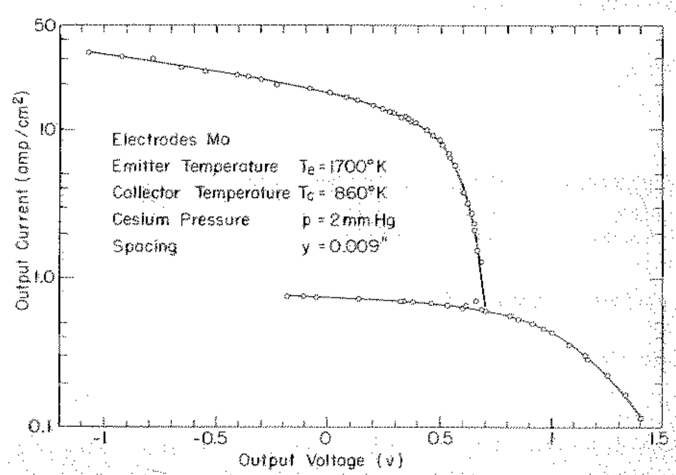


Fig. 7. Extinguished and ignited mode current-voltage characteristics of a cesium thermionic converter

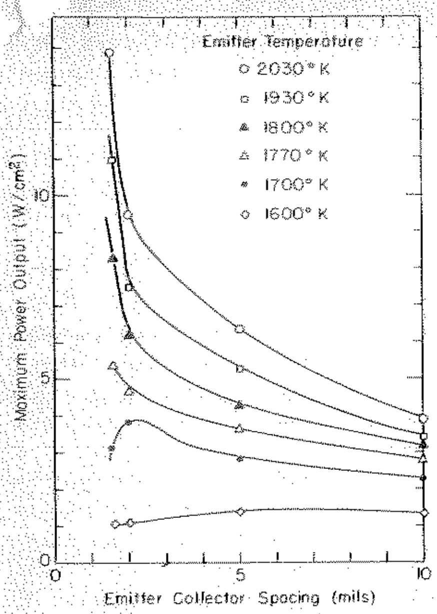


Fig. 8. Optimum electric power density as a function of interelectrode spacing and emitter temperature

The lower curve of the figure may be interpreted as representing an operation under electron space charge limitations, while 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.

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 exists an optimum spacing which yields maximum power output.

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

Variations in optimum electric power density as a function of the interelectrode spacing and the emitter temperature are shown in Fig. 8 for a converter having a niobium emitter and a molybdenum collector. Note that an optimum spacing for maximum power output is observed only at temperatures below 1,800 degrees K. At higher temperatures, adequate surface ionization occurs to neutralize the electron space charge so that ionizing collisions are not necessary. Under these conditions, the optimum output power density increases with decreasing interelectrode spacing.

The measured thermal efficiency of a few converters, representative of the state of the art, is shown in Fig. 6. Comparison of the calculated upper bound curves and the measured data clearly indicates that there is an appreciable range for improving the efficiency of thermionic converters.

Effect of Materials on Performance of Thermionic Converters

The output current of a practical converter is predominantly controlled by the transport mechanisms in the interelectrode space and the work-function and temperature of the emitter. 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 consistent with the collector temperature.

Composite surfaces of mixtures of oxides—such as barium or strontium oxide—may be stably operated at temperatures of about 1,500 degrees K and they have sufficiently low work-functions at this temperature so as to emit currents of the order of 5 amp/cm² (amperes per square centimeter). 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 their work-function is 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/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 degrees to 2,200 degrees K is only 0.5 to 26 ma (milliamperes)/cm². In the presence of cesium at a pressure of the order 1 mm (millimeter) Hg (mercury), the tungsten surface is partially coated with cesium atoms, the work-function is reduced, and the saturation current is 10 to 20 amp/cm² for the same emitter temperature range.

For converters operating at emitter temperatures greater than 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 is the affinity for cesium. Consequently, out of the refractory metals, iridium would require the least cesium pressure to attain a given cesium coverage and, hence, a given work-function.

But, if the work-function of an emitter is lowered too much in the presence of cesium at a given pressure, the surface loses its ability to ionize cesium and, therefore, it is no longer useful as an emitter.

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%. Such coverage can be achieved at collector temperatures lower than 1,000 degrees K and cesium pressures greater than 0.2 mm Hg. Actually, the best substrate 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.[14]

Several high-melting-point materials are usable for emitters—uranium carbide, zirconium carbide, and the like. Some of these carbides have work-functions of the order of 3 ev, and emit high currents at temperatures of the order of 2,200 degrees K. Unfortunately, these materials are not coated by cesium. When used as emitters, they evaporate and condense on the collector after some hours of operation. Thus, the collector work-function is raised to about 3 ev, and the converter output is reduced by more than an order of magnitude. Converters utilizing a mixture of carbides as emitters, built

Table 1. Measured Performance of Some Practical Converters for Space Applications*

Converter No.	Life, Hours	Thermal Cycles	Remarks
1	839	3	Still Operative
2	327	20	Still Operative
3	938	57	Failure Due to Impurities in Vacuum System
4	425	116	Failure Due to Emitter Support Cracking
5	868	10	Failure Due to Emitter Support Cracking
6	89	3	Failure Due to Emitter Support Cracking

* Courtesy Thermo Electron Engineering Corporation, August 1961.

Emitter Material:	Tantalum
Emitter Temperature:	2,000 degrees K
Collector Temperature:	900 degrees K
Power Density:	10 watts/cm²
Efficiency:	10 to 12%

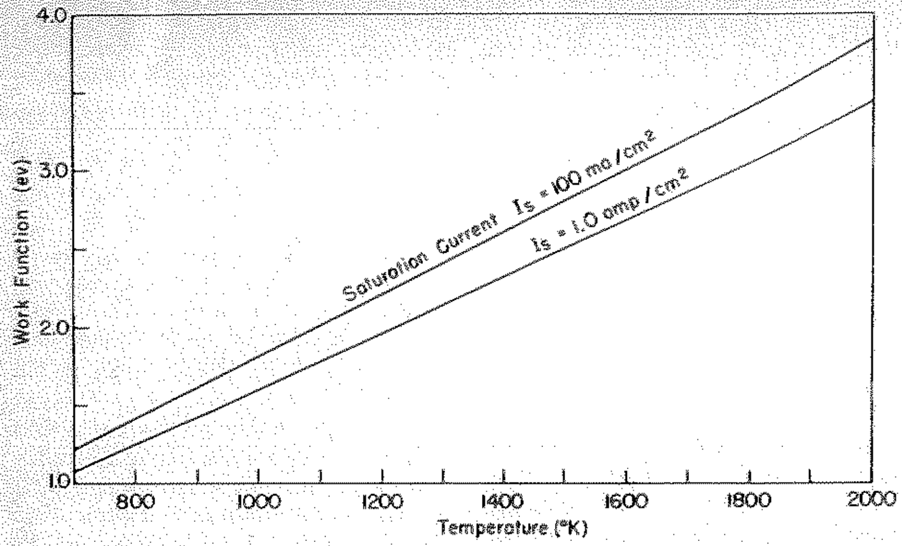


Fig. 9. Collector work-function versus collector temperature for negligible back-emission

to date, have failed in this fashion after a few tens of hours' operation.

LIFE OF THERMIONIC CONVERTERS

The longest measured life of practical thermionic converters tested, as listed in Table I, is about 1,000 hours. However, lives of up to 3,000 hours have been achieved according to a private communication from Dr. V. C. Wilson of the General Electric Research Laboratories.

Reasons for relatively short lives are primarily structural failures. At the present rate of progress, structural problems should be eliminated in the 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 of time, 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 cesium vapor might increase the evaporation rate. The extent of such an increase is not yet known.

FUTURE DEVELOPMENTS IN THERMIONIC CONVERTERS

Improved performance as well as long life for thermionic converters depends, in the final analysis, on the development of suitable emitter and collector materials.

The most suitable collector is one which has a low effective work-function when partially coated with cesium. The exact value desired for this function depends on the collector temperature so that there is no appreciable back-emission. Fig. 9 is a plot of work-function versus temperature, with small saturation currents as a parameter.

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.[14] 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, which will have a great affinity for cesium.

Requirements on 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 amp/cm² 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 being that, as yet, it is not clear which offers greater advantage, surface or volume ionization.

If surface ionization is adopted, then the emitter should be an efficient ionizer of cesium, having a high work-function so that the cesium pressure is low and the converter spacing is more than a few mils without appreciable losses in the interelectrode space. On the other hand, if volume ionization proves to be a better mode of converter operation, then lower work-functions would be required. For, given an emitter temperature, the smaller the work-function, the larger the saturation current.

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 the auxiliary voltage supplies.

The preceding arguments are based on the assumption that cesium vapor is the only means for space charge neutralization. Evidently, there are other possibilities. 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. Such a collector was described during a meeting of the Joint Technical Society, Department of Defense Symposium on Thermionic Power Conversion, Colorado Springs, Colo., May 14–17, 1962, in a paper presented by P. Brosens and G. N. Hatsopoulos under the title, "Thermionic Energy Converter with a Liquid Collector."

Thermionic Nuclear Reactors

GENERAL REMARKS

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. Moreover, thermionic converters are inherently low-voltage devices; therefore, any large power unit must incorporate many converters in series.

The effect of these parameters on converter performance limits the choice on ways to couple a nulcear reactor with converters.[16] For example, the intriguing idea of using a nuclear fuel both as a heat source and as an emitter cannot be implemented at the present time because the available high-temperature fuels do not adsorb cesium and do not exhibit the surface stability required by the relatively small converter spacings.

The nonadsorption of cesium results in a substantial loss of converter efficiency because the fuel material evaporates and

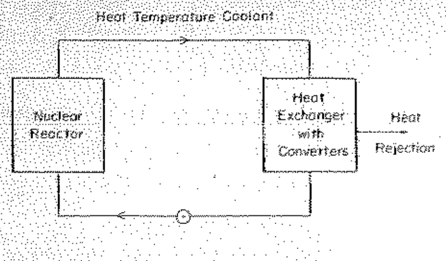


Fig. 10. Schematic of thermionic nuclear reactor with converters separate from the reactor core

deposits a coating on the collector, thereby preventing reduction of the collector work-function. Furthermore, flaking and swelling of the fuel can 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.

These separate functions of fuel and emitter suggest two possible methods of coupling thermionic converters with a nuclear heat source. The first is to arrange converters in a heat exchanger structure external to the reactor, and have heat conveyed to the emitters by a high-temperature coolant loop. The second method 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 the following designs: (1) arranging the fueled converters so that all of them are on the outer surface of the resulting critical core, and (2) assembling several fuel-converter units into a cylindrical fuel element and arranging a large number of fuel elements to form a critical core.

Each method has its own advantages, problems, and limitations. Choice of a particular concept depends on over-all system power rating and/or power density of the converters, temperatures of operation, availability of high-temperature metal coolants and electrical insulation, specific weight and volume requirements, and type of application. The influence of these factors on the selection of a design is described in detail in succeeding sections.

Conversion System Separate from Nuclear Reactor

Fig. 10 schematically illustrates the concept of a conversion system separate from the nuclear reactor.

The thermionic converters may be of either planar or cylindrical geometry and are electrically connected in parallel-series combinations, so arranged as to form a heat-exchanger structure. The primary side of this structure is formed by the non-emitting surface of the emitters, while 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.

The discussion throughout the previous main section of this paper makes it apparent that, in order to have a converter with a reasonable efficiency and surface power density, the emitter temperature should be 1,500 degrees K or higher. This implies that the primary coolant must be a high-temperature liquid metal such as lithium.

On the other hand, in view of the facts that in this design the primary coolant is in contact with the emitters and that the converters must be connected electrically in series, the emitters must be isolated electrically from the liquid metal coolant. Hence, this design requires using electrical insulation, which stands temperatures higher than 1,500 degrees K, and which must also be a good heat conductor so that heat is transferred to the emitters without an appreciable temperature drop.

The size of the heat-exchanger structure, for a system cooled by a secondary loop, is inversely proportional to the electrical surface power density of the converters while, for a system radiating into free space, it is defined by the efficiency of the converters. The relation between radiating area and converter efficiency is

$$\text{Area} \propto \frac{1}{(\text{efficiency})} - 1 \qquad (3)$$

The nuclear reactor size is inversely proportional to the efficiency of the converters. The liquid metal temperature is determined by the emitter temperature and the temperature drop across the electrical insulation. The critical mass and volume power density of the reactor, however, are not affected by the converter characteristics. The volume power density, can be as high as is compatible with a liquid metal cooled core ($\sim$2,000 kw/l).

Implications of the foregoing general remarks as applied to a power plant designed for space are examined next; particularly the effect that future improvements in thermionic converter performance will have on the specific volume and weight of the plant. This improved performance is attainable through increased surface power density and efficiency, accomplished by raising the emitter temperature and lowering the effective collector work-function.

Such changes, unfortunately, are not advantageous to a thermionic nuclear reactor designed for space with a separate conversion system. The reasons are:

1. The emitter temperature is limited by the availability of high-temperature liquid metal coolants. More precisely, in order to have a power plant without 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 which is 1,610 degrees K. Hence, assuming that the temperature drop across the electrical insulation is of the order of 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.

2. Lowering of the collector work-function does not affect the over-all 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 might go up by a factor of 2, the black body radiation decreases by a factor of $(950/700)^4 \sim 2$ and the radiator area remains practically the same.

3. No substantial gains are expected from the reactor because calculations indicate the reactor weight is only a small fraction of the system's specific weight, since the core design is unaffected by the converter materials and since liquid metal cooled reactors are very compact.

The concept of a conversion system separate from the reactor, therefore, is not amenable to substantial improvements by technological developments of high-temperature nuclear fuels and efficient operation of thermionic converters; consequently, it has limited growth potential. Actually, this entire separa-

Table II. List of Major Parameters of Design with Conversion System Separate from Nuclear Reactor; See Fig. 10

Electrical Output, Net	30 kwe
Reactor Power	500 kwt (thermal kilowatts)
Core Geometry	Cylindrical
Core Diameter	25 cm
Core Height	20 cm
Uranium Loading	154 lbs
Coolant Inlet Temperature	1,450 degrees K
Coolant Outlet Temperature	1,550 degrees K
Converter Efficiency	6%
Converter Power Density	3 watts/cm²
Weight Breakdown	
Reactor	510 lbs
Heat Exchanger-Radiator	450 lbs
Pump and Main Piping	70 lbs
Total	1030 lbs
Specific Weight	35 lbs/kwe
Reactor Specific Weight	17 lbs/kwe

Note: The same reactor could be used for a much higher power. Then the reactor specific weight would be much smaller.

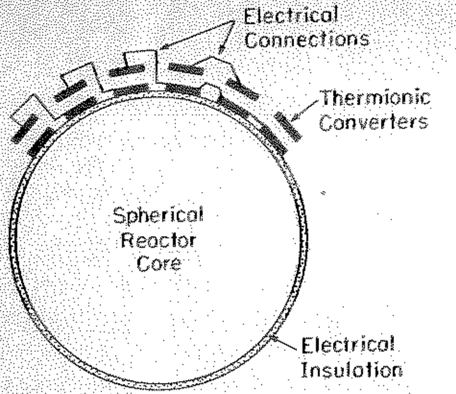


Fig. 11. Schematic of thermionic nuclear reactor with converters attached to outer surface of reactor core

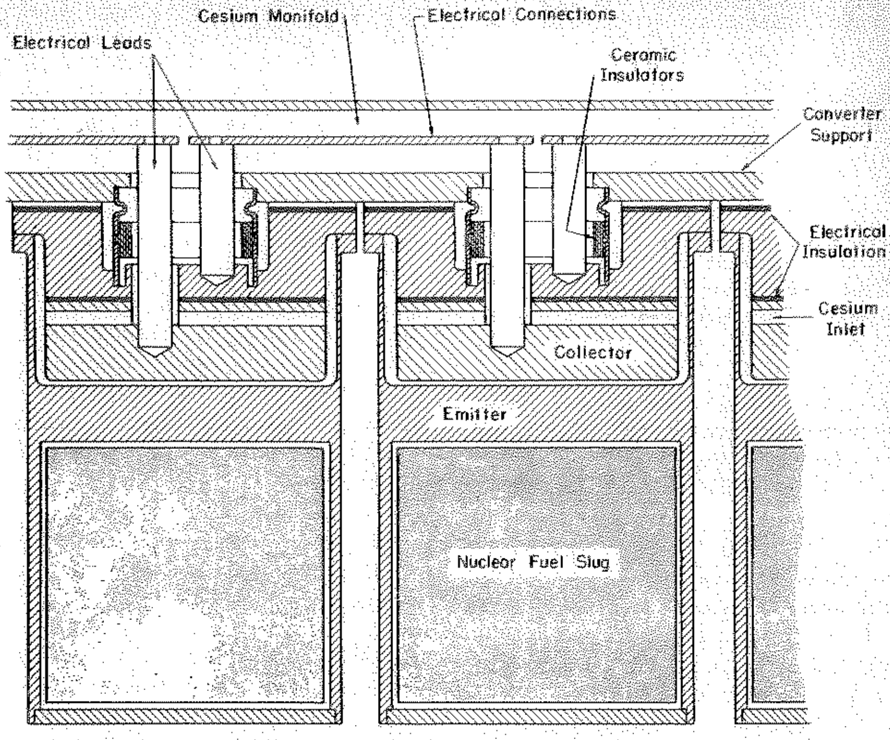


Fig. 12. Schematic of converter fuel-slug units

tion concept hinges on having a high-temperature electrical insulator which is also a good heat conductor and can be metallurgically bonded to the emitters. Such a material is not now available, even for a range of 1,400 degrees to 1,500 degrees K. This basic difficulty may be overcome by connecting all the converters in parallel, but, since each converter potential is of the order of 1 volt, the current rating of a practical power system is so high that the solution of the difficulty is valueless.

Table II summarizes the major parameters of a 30-kwe (electrical kilowatts) system in which heat is rejected by direct radiation into free space. The over-all specific weight of this system is 35 lbs (pounds)/kwe.

Conversion System Attached to Outer Surface of Nuclear Reactor

Fig. 11 schematically represents 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 them by conduction through the core and is rejected from the collectors, either by radiation into free space or by convection, using a coolant loop.

The 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 emitters and core. If high-temperature insulation were available, it would be possible to have a solid core and attach emitters directly thereto. Since such insulation is not available, 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. 12 shows in schematic form two typical converter fuel-slug units cooled by a liquid metal coolant. By properly extending the emitter support, all electrical insulators are on the low-temperature side of the converter.

Second, consider the problem of size and 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 electric surface power density of the converters. Furthermore, with heat being carried through the core by conduction, the core should be a spherical shell in order to minimize the temperature drop along the fuel and make the maximum fuel temperature tolerable. The thickness of the spherical shell is proportional to the converter efficiency. For power densities of the order of 10 to 50 watts/cm² and over-all power ratings of the order of 50 kwe and above, the core radius is such that a spherical shell can become critical with a practical enrichment.

Figs. 13 and 14 are conceptual designs of this approach, both being for space applications. One is cooled by direct radiation into free space; the other by a liquid metal loop which rejects heat through a separate radiator.

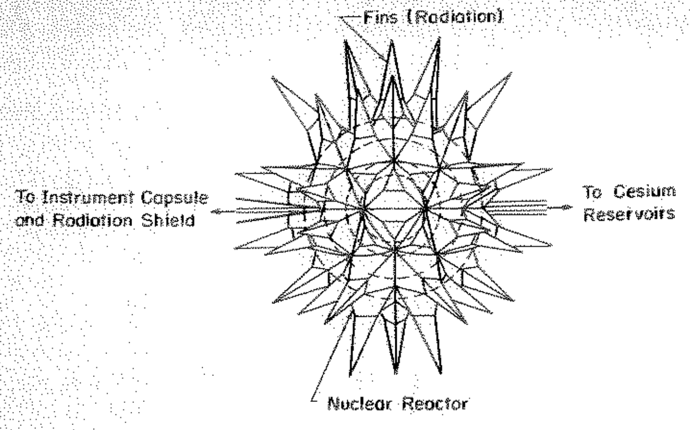
Third, consider the problem of emitter distortion due to fuel size changes induced by irradiation. The small spacings, necessary for optimum converter

Table III. List of Major Parameters of Design with Conversion System Attached to Outer Surface of Nuclear Reactor; See Fig. 13

Electrical Output, Net	30 kwe
Reactor Power	220 kwt
Core Geometry	Spherical Shell
Core Inner Radius	10.4 cm
Core Outer Radius	21 cm
Uranium Loading	242 lbs
Maximum Fuel Temperature	2,000 degrees K
Mode of Heat Rejection	Radiation from Finned Collectors
Converter Efficiency	15%
Converter Power Density	10 watts/cm²
Emitter Temperature	1,900 degrees K
Weight Breakdown	
Uranium Carbide-Graphite Fuel	340 lbs
Thermionic Converters	330 lbs
Reflectors and Radiator	860 lbs
Structural Components	200 lbs
Total	1,730 lbs
Specific Weight	58 lbs/kwe

Table IV. List of Major Parameters of Design with Conversion System Attached to Outer Surface of Nuclear Reactor; See Fig. 14

Electrical Output, Net	30 kwe
Reactor Power	220 kwt
Core Geometry	Spherical Shell
Core Inner Radius	10.4 cm
Core Outer Radius	21 cm
Uranium Loading	250 lbs
Maximum Fuel Temperature	Lithium Circulated through a Radiator
Lithium Average Temperature	1,000 degrees K
Converter Efficiency	15%
Converter Power Density	10 watts/cm¹
Emitter Temperature	1,900 degrees K
Weight Breakdown	
Uranium Carbide-Graphite Fuel	350 lbs
Thermionic Converters	350 lbs
Reflectors	350 lbs
Radiator	180 lbs
Structural Components and Coolant	300 lbs
Total	1,530 lbs
Specific Weight	51 lbs/kwe



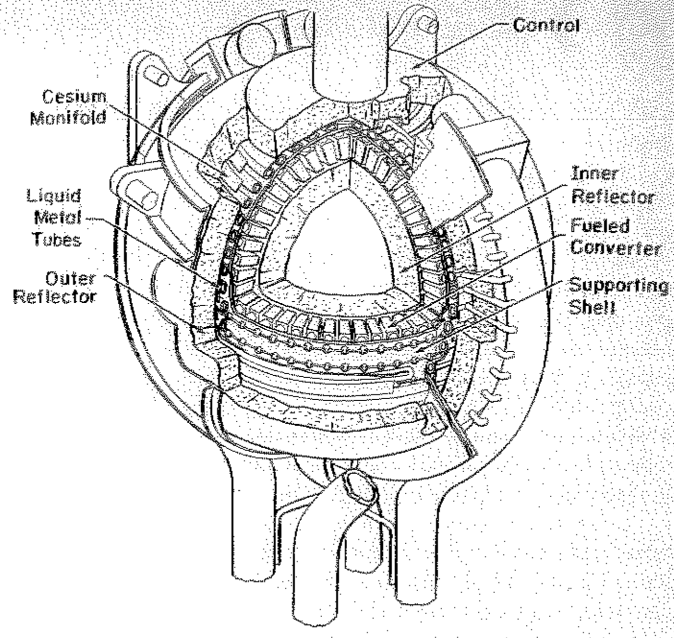


Fig. 13 (left). Schematic of thermionic nuclear reactor radiating into free space

Fig. 14 (right). Schematic of thermionic nuclear reactor cooled by means of liquid metal loop

performance, must be undistorted by fuel swelling. To achieve this, the fuel slug must be loosely encased, with a few mills clearance, inside the emitter extension. Lack of metallurgical bonding between emitter and fuel will result in radiative heat transfer between these two bodies and, consequently, higher fuel temperatures. Note that gaseous fissides do not affect the converter performance in this design because any fissides that diffuse out of the fuel will 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 because:

1. Even if converters with the most optimistic electric surface power density were available, the over-all power rating of the system could not exceed a few hundred kwe without having to cope with an extremely large core.

2. A spherical shell core leads to poor use of the nuclear fuel.

3. The seemingly advantageous feature of having the converters outside the fuel region is effectively lost because of lack of high-temperature electrical insulation compatible with the emitters.

4. All materials used in this design are operated at their limit temperatures; yet, the over-all performance is poorer than would be achievable under similar conditions with another arrangement which is discussed in the next section.

Tables III and IV list major characteristics of a 30-kwe thermionic nuclear reactor designed as shown in Figs. 13 and 14, respectively. Over-all specific weights are 58 lbs/kwe and 51 lbs/kew.

Conversion System Integrated into Nuclear Reactor Core

Fig. 15 is a schematic of a thermionic nuclear reactor in which the converters are an integral part of the fuel elements. The design resembles an ordinary nuclear reactor core with cylindrical elements. Here, however, each element consists of several individually fueled converters, connected electrically in series. The fuel elements themselves are electrically connected in parallel-series combinations. The reactor is cooled by a liquid metal loop if the system is for space or submarine ap-

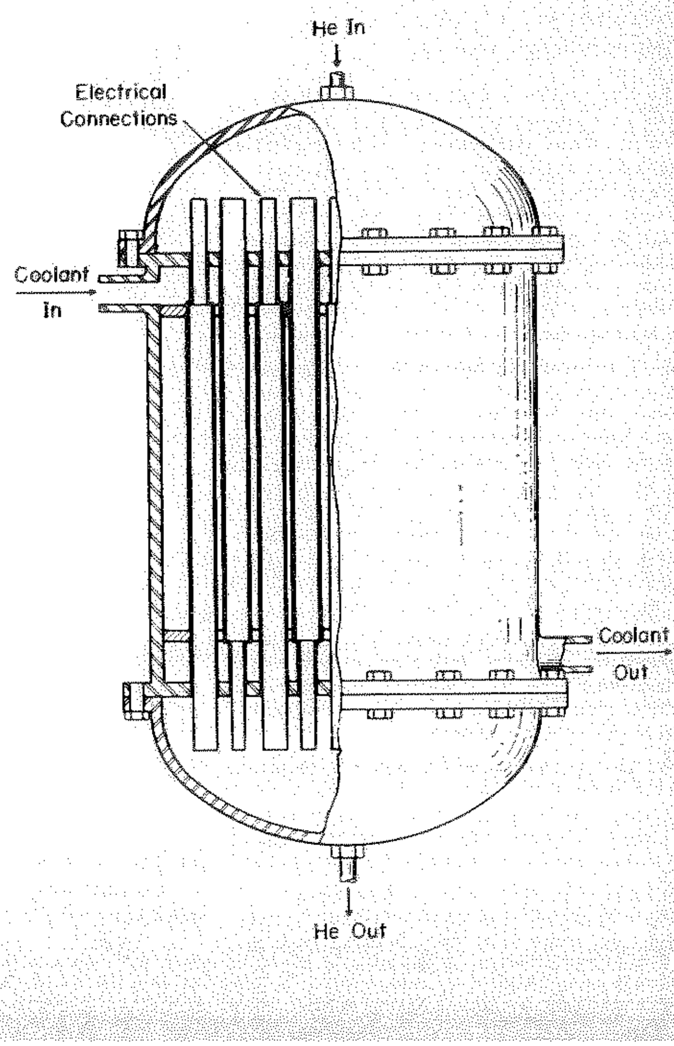


Fig. 15. Schematic of thermionic nuclear reactor with converters integrated into fuel elements

plication, or by any other coolant when neither a high temperature for heat rejection nor an electromagnetic pump for silent and maintenance-free operation is required.

The converters are contained in a thin-walled tube, and electrically insulated from it by a layer of insulation, sprayed on the outer surface of the cylindrical collectors; see Fig. 16. 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 which serves as the emitter, and surrounding it 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, and all electrical insulators in this design are on the collector or low-temperature side of the converters.

The reactor power density and volume are respectively 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 the enumerated reasons:

1. Thermionic conversion is essentially a surface phenomenon while nuclear reactions are 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 dispersed so that a large surface-to-volume ratio is reached. This is exactly the objective of the design shown in Fig. 15.

2. 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. In other words, given an upper fuel temperature limit, the emitters can be operated at a much higher temperature level than in any other case if they are dispersed through the fuel. Hence, the converters reach their highest efficiency.

3. There is not such severe limitation imposed by available high-temperature electrical insulation as in previous designs because all insulators are on the low-temperature side of the converters.

4. Any improved performance of thermionic converters is directly reflected on the overall system as the reactor weight is inversely proportional to converter performance and it is a substantial fraction of the over-all weight of the system.

5. The specific weight of this system is at least one order of magnitude lower than in the previous two designs under similar maximum fuel temperature limitations; see Table V.

Admittedly, integration of the conversion system into the nuclear reactor core has 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 enrichment is increased by the presence of converter materials in the core. However, all these problems are not of a basic nature and, since the concept is so superior to the others, it should be most actively pursued and developed. This point is well supported by the information provided in Table V. Notice that the specific weight of a 1-mwe (electrical megawatts) system is 3.9 lbs/kwe.

Problem Areas of Thermionic Nuclear Reactors

On the basis of discussions and preliminary calculations presented in pre-

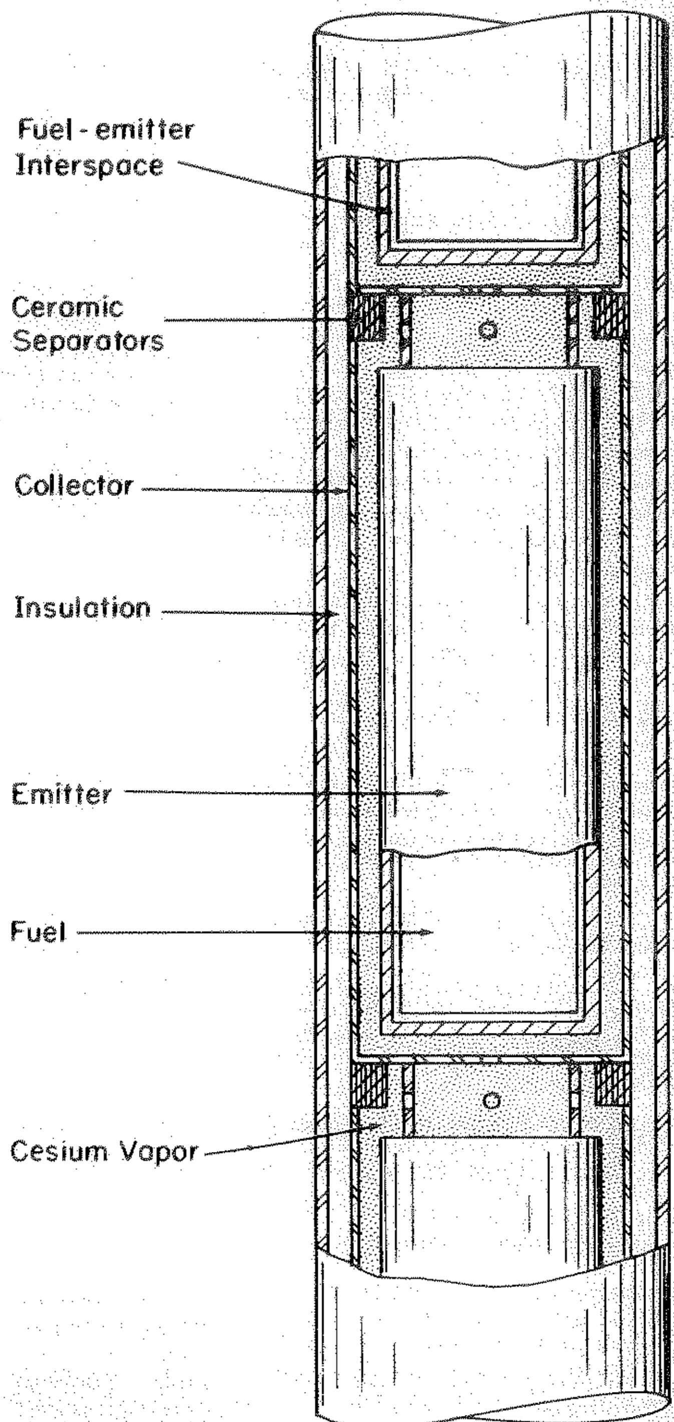


Fig. 16. Schematic of converter integrated into fuel element

Table V. List of Major Parameters of Design with Conversion System Integrated into Nuclear Reactor; See Fig. 15

Electrical Output (Net)	1 mwe
Reactor Power	5.55 mwt (thermal megawatts)
Core Geometry	Cylindrical
Core Diameter	36 cm
Core Height	70 cm
Uranium Loading	380 lbs
Maximum Fuel Temperature	2,600 degrees K
Converter Efficiency	18%
Converter Power Density	15 watts/cm²
Emitter Temperature	2,000 degrees K
Weight Breakdown	
Reactor	2,000 lbs
Primary System	200 lbs
Total	3,900 lbs
Specific Weight	3.9 lbs/kwe
Reactor Specific Weight	2.0 lbs/kwe

ceding sections, the most promising method of coupling thermionic converters with a nulcear reactor is to distribute converters throughout the reactor core.

Development of such a thermionic nuclear reactor 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 here outlined:

1. Nuclear fuel elements, capable of operating at high temperatures at both the center and 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 because establishment of the appropriate gap size is important in achieving 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 in order to develop suitable emitter-fuel material combinations, capable of stable operation at high-temperature levels.

4. Diffusion of gaseous fissides through the emitter casing and the effect of the former on converter performance must be studied. If fissides prove to be deleterious to this 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 fuel elements.

5. Diffusion of fuel and nongaseous fissides through various emitter materials must be studied, and appropriate barriers must be developed if diffusion proves 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

A review of cesium thermionic converters is given with particular emphasis on characteristic parameters that determine the performance of converters. The best performance 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 electric 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.

Regarding conversion of nuclear heat into electricity by means of thermionic converters, the conclusion is that the best method of coupling a nuclear reactor core with converters is by incorporating the latter into the fuel elements. This method leads to an efficient and compact design with good growth potential.

Several problems are posed where further development work needs to be intesnified or initiated in order to arrive at the design and construction of the first thermionic nuclear reactor.

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A reprint from **COMMUNICATION AND ELECTRONICS**, published by The Institute of Electrical and Electronics Engineers, Inc.

March 1963 issue