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**A 1.5 MWE THERMIONIC REACTOR
SPACE POWER SYSTEM***

C. K. Smith and R. Y. Parkinson
Atomics International
A Division of North American Aviation, Inc.
Canoga Park, California

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A 1.5 MWE THERMIONIC REACTOR SPACE POWER SYSTEM

C. K. Smith and R. Y. Parkinson
Atomics International
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Canoga Park, California

The objective of this paper is to indicate the performance potential of nuclear reactor space power system concepts employing direct-nuclear-heated thermionic converters within the reactor fuel elements. Such systems possess relatively fixed characteristics over the range from several hundred kilowatts to several megawatts electric output; the 1.5 Mwe system characteristics described here are typical.

As an introduction for those not familiar with the thermionic means of direct energy conversion, Figure 1 is a schematic showing the essential components of the cesium vapor diode converter.

The thermionic converter is a device in which heat is converted to electrical energy by direct thermal excitation of charged particles at the surface of an electrode. Energy conversion occurs by vaporization of electrons from a hot electron reservoir, called the cathode or emitter electrode, and subsequent condensation of those electrons into a colder electrode at higher potential, called the anode or collector electrode. The thermionic conversion process thus resembles that in a vapor cycle heat engine, with electrons as the working fluid.

Provision must be made to neutralize the negatively charged electron gas, otherwise its presence in the interelectrode space will inhibit further electron emission. In the cesium vapor converter, positive ions are generated for this purpose by thermal

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Figure 1. Schematic Showing Essential Components of the Cesium Vapor Thermionic Converter

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ionization of the cesium vapor in which the electrodes are immersed. Without the neutralizing ions, i. e., in the vacuum diode, the interelectrode spacing must be extremely small (about 0.0001 inch) to obtain emission currents large enough for the present application. In view of the extreme difficulty in maintaining this spacing in an engineering design, only the cesium vapor converter will be considered here; spacings on the order of tens of mils are practical in the latter type of converter.

Figure 2 presents a schematic of the complete system. Unlike other system concepts, the reactor coolant is circulated at the heat rejection temperature, because power conversion occurs within the fuel element itself. Heat rejection temperatures of interest from both the conversion and space radiator design viewpoints are on the order of 1500°F maximum; therefore, an electromagnetic pump can be used and operation is static. In addition, many reactor components developed to operate near this temperature for SNAP 8 can be adapted very readily. The primary development area is then associated with the converter-fuel element.

Figure 3 shows a cutaway through a converter-fuel element. A number of these converter cells with direct-nuclear-heated emitters are stacked and connected in electrical series within the element. It is anticipated that provision will have to be made for bleeding of cesium vapor axially through the cells, so that a low equilibrium concentration of fission products in the interelectrode space will be established. It is toward a design of this general type that work is directed.

A cross-sectional view of the thermionic reactor concept is shown in Figure 4. As is illustrated, the small core size permits simplified reactor control by means of rotatable sections of the

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Figure 2. Schematic of Convection In-Core Concept

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Figure 3. Typical Converter Section

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Figure 4. Cross-Section of Thermionic Reactor Concept

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radial neutron reflector; resulting power perturbations within the core are much less severe than if control rods were used. Except for the interior of the converter-fuel element, reactor hardware requirements and operating conditions are similar to those of SNAP 8.

Figure 5 compares the actual design values of diode power density, diode efficiency, and collector temperature with the theoretically ideal values for the design emitter temperature of 2073°K. The maximum collector temperature of 1090°K was fixed by the maximum allowable radiator temperature of 1500°F as discussed in a following section. The collector temperature range of 140°C (250°F) was determined by an analysis of the entire coolant system to determine the optimum ΔT through the reactor and radiator. The design range of collector temperature brackets the optimum, ideal device temperature; optimum collector temperatures measured experimentally are very near the predicted values shown.

Carnot efficiency is shown vs emitter temperature for the ideal device collector temperature. Maximum, ideal device efficiency is shown for an effective emitter-collector emissivity of 0.2 and a collector work function of 1.7 ev. An average efficiency of 18.7% was selected for the reference design emitter temperature of 2073°K. For comparison, Carnot efficiency at this temperature is 49%, and ideal device efficiency is 29%.

Carnot, and ideal device power density are shown vs emitter temperature. An average power density of 17.0 watts/cm² was selected for the reference design. Design power density and design efficiency are both somewhat above current state-of-the-art for laboratory devices but are seen to be well below ideal device performance. It is expected that reproducible design point performance

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Figure 5. Comparison of 1.5 Mwe System Design Points with Ideal Performance

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will be reached within a few years with a vigorous research and development program.

In Figure 6, work function limits for neutralized, optimum emitter currents are shown as a function of emitter temperature. The acceptability of materials as converter emitters (at practical temperatures and pressures) can be judged according to their bare work functions by recognition of these different but overlapping groups:

- 1) Materials giving both adequate ion and electron emissions (i. e., potentially best suited for diode operation), having $2.6 < \phi_{eo} < 3.2$ ev or $\phi_{eo} > 4.2$ ev.
- 2) Materials giving adequate electron emission only (i. e., requiring other sources of ions, as in triode operation), having $4.2 > \phi_{eo} > 4.0$ ev or $\phi_{eo} < 2.6$ ev.
- 3) Materials giving neither adequate ion emission nor adequate electron emission, except at unattractively high temperatures or pressures (i. e., unacceptable for any type of converter), having $3.2 < \phi_{eo} < 4.0$ ev.

In addition to the acceptability of the work function of a material, its ability to operate for an acceptably long time as an efficient converter emitter must be considered. For low work function materials that are not wetted by the cesium vapor, there is a fundamental correlation between the vaporization and emission processes, such that a high rate of vaporization tends to accompany large electron emission currents. For the high work function emitters, which are wetted by the cesium vapor, this obstacle is circumvented by renewing the surface (film) from a reservoir, as it evaporates, and by greatly decreasing the temperature required for adequate electron emission. Thus the high work function "wetted" emitters are superior in lifetime to the low work function "dry" emitters.

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Figure 6. Regions of Acceptable Work Functions

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The foregoing considerations strongly suggest that the high-work-function refractory metals (such as Ta, Mo, W, Re, and Ir) are the best known materials for emitters in thermionic converters, in that:

- 1) The ion and electron emission requirements can be satisfied over a wide range of attractive temperatures and pressures by choosing appropriately among them.
- 2) They have extremely great potential lifetime and stability, with continuous and perpetual renewal of the emitting surface by cesium vapor.
- 3) Their vaporization products are compatible with a low collector work function and low thermal emissivity.

Table I describes the more important factors involved in selection of fueled converter component materials and lists some of the best materials candidates for use in a high output system. Final selection of materials combinations will be governed to a large extent by the rates of materials interactions at contact boundaries, by the sensitivity of converter performance to such interactions, by the probability of achieving successful bonds between materials at critical locations, and by the environmental effects (including irradiation) on physical properties. Much information is yet to be gained in these areas.

Table II is a summary of the 1.5 Mwe design resulting from this study. For design purposes, a rhenium emitter surface and a molybdenum collector were selected. Rhenium possesses excellent emission and high temperature characteristics and will not react chemically with carbon from the fuel. Molybdenum has the lowest electrical resistivity of the refractory metals and yields low I^2R loss in the collector.

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TABLE I
FUELED CONVERTER MATERIALS

Component	Desired Materials Characteristics	Best Candidates
Fueled emitter	High electrical and thermal conductivities High uranium density Radiation stability Melting point $>2800^{\circ}\text{K}$ Low thermal emissivity	Carbides with refractory metal claddings, cermets
Current leads	High electrical conductivity Low thermal conductivity High strength Melting point $>2800^{\circ}\text{K}$	Refractory metals
Emitter insulation	High electrical resistivity Low thermal conductivity Radiation stability Melting point $>2200^{\circ}\text{K}^*$	Alumina
Collector	High electrical and thermal conductivities Melting point $>1200^{\circ}\text{K}$ Low thermal emissivity	(Many)
Collector insulator	High electrical resistivity and dielectric strength High thermal conductivity Radiation stability Melting point $>1200^{\circ}\text{K}$	Beryllia
Outer envelope	High thermal conductivity Compatible with coolant at $\sim 1000^{\circ}\text{K}$	Niobium
Coolant	High specific heat Low density and viscosity Low induced radioactivity level	Lithium-7

*Emitter insulation can be positioned to operate several hundred degrees cooler than emitter.

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TABLE II
1.50 NET MWE THERMIONIC REACTOR
PLANT SUMMARY

Reactor	
Output	2500 v d-c - 600 amps (200 amps from each of 3 sections)
Fuel material	UC
Core Volume	2 ft ³
Coolant	Lithium-7
Maximum coolant temperature	1500°F
In-Core Converters	
Type	Cesium diode, cylindrical, fueled emitter
Average emitter power density	17 watts/cm ²
Emitter surface temperature	1800°C
Radiator (Cylindrical Design)	
Size	37.6 ft x 15 ft OD = 1770 ft ²
Effective temperature	1385°F
Pump	
Type	Single phase annular induction
Power input	0.3 Mwe at 2500 vac
Component Weights (With Li Inventory)	
Reactor	1600 lb
Radiator with Li inventory	3260
Pump	470
Piping and manifolding with Li inventory	615
Auxiliaries (transmission, startup, etc.)	235
Radiator insulation for startup preheat	400
	6580 lb

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The total system weight includes 400 pounds of radiator insulation for startup preheat. If the unit is operating during launch, this insulation will not be required.

This design is based on converter performance which is expected to be attained within the next few years. The effects of lesser performance are discussed later.

Since the space radiator required for heat rejection will be one of the heavier system components, careful selection of radiator material and operating temperature are particularly important. Figure 7 presents normalized radiator weights as a function of radiator material and maximum radiator temperature. Weights are normalized to the weight of an all-beryllium radiator operating at a maximum temperature of 1500°F. In performing the calculations leading to the curves of Figure 6, radiator thickness is proportional to radiator area to the 0.3 power, and radiator weight per unit area and thickness varies as $\rho^{5/6}/E_T^{1/6}$, where ρ = density and E_T = the modulus of elasticity. It is seen that beryllium, with a density of only 1.8 gm/cc, and with the very high modulus of elasticity of 38.5 pounds per square inch at 1500°F, provides by far the lightest radiator at reference design temperatures. Niobium, the lightest of the refractory metals, is included for comparison. It is seen that a niobium radiator would have to be operated above 2200°F to compare favorably with a beryllium radiator at 1500°F. Unfortunately, 2200°F is well above the optimum collector temperature and would result in a serious degradation in diode performance. In addition, a second coolant loop with its own electromagnetic pump would have to be added to cool the primary EM pump magnets if the system were to operate statically because the 2200°F primary coolant temperature is above the curie point of useful magnet materials (2050°F for cobalt).

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Figure 7. Normalized Radiator Weights

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Figure 8. Coolant System Weight vs Radiator Temperature and Pressure Drop

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Figure 9. Core, Pump, and Radiator Weight vs Emitter Diameter

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high that resistance losses result in excessively heavy pump and radiator weights. As the number of cells is increased, resistance losses and system weight decrease. Eventually, resistance losses are small enough that a further increase in the total number of cells does not result in a substantial decrease in system weight. In the present reference design a total of 7500 cells with 1/2-inch emitter diameter was selected. The small potential savings in weight in going to 10,000 cells is believed to be not worth the added complexity of 2500 additional cells. The optimum emitter diameter utilizing 7500 cells is seen to be about 0.5 inch.

The very high temperatures and numerous dissimilar material contacts, combined with the reactor environment furnishes the possibility of numerous materials reactions and interactions. Figure 10 presents a schematic of the fuel element structure indicating the particular dissimilar material contacts in the reference design, the magnitude of the design temperatures, and the variety of reactions possible. The ultimate criterion in judging the severity of each of these reactions is not what is the extent of the reaction, but rather what is the effect of this reaction upon converter performance. As an example, consider the effect of the evaporation of the emitter material into the cesium gap. Severe evaporation could restrict design lifetime by removing the emitter material and exposing a surface with an unacceptable work function. The evaporated material could preferentially deposit on a limited site, changing the diode gap and eventually shorting out the cell; the evaporated material could uniformly deposit on the collector and furnish a surface with an unacceptable emissivity which would drastically alter diode efficiency and power density. Finally, the evaporated material could plate over the intercell insulation, shorting out several cells.

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Figure 10. Potential Materials Interactions in Fueled Diode
Using Selected Materials

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The reactor environment imposes three additional effects upon the operation of a cesium diode:

- 1) The effect of fission products trapped in the fueled emitter
- 2) The effect of fission products released into the cesium gap
- 3) The effect of the neutron and gamma ray flux fields upon all diode components.

A summary of the possible effects is given in Table III. The effect of escaping fission products is analyzed in greater detail in the following section. Trapped fission products will lead to a gradual fuel growth and the possibility of fuel swelling. Little is known of the performance of nuclear fuels at temperatures in the region of the reference design. Recent experiments indicate, however, that, at very high temperatures, the fuel experiences a considerable annealing effect and, therefore, material property changes may not be as great as at lower, more conventional, temperatures. Much additional experimental work remains to be done in the study of high temperature fuel stability, however, and satisfactory fuel stability is expected to be the major criteria in selection of potential fuel materials. The radiation field will effect all diode materials, but here again the high operating temperatures are expected to have an annealing effect.

At the reference design fuel temperature, bulk diffusion of fission products will be quite significant. Any transient analysis of the diffusion mechanism is complicated by the fact that over 90% of the fission nuclides undergo a series of beta decay, changing their element identity several times before coming stable. However, over 90% of these fission products decay into stable end products within one hour from their time of birth. Therefore,

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TABLE III

POTENTIAL EFFECTS OF REACTOR ENVIRONMENT

Nuclear Phenomena	Possible Effects
Escaping fission products	
Contamination of emitter surface	Variation of work function
Contamination of cesium vapor	Variation of plasma resistivity and of emitter and collector work functions
Contamination of collector surface	Variation of work function
Trapped fission products	
Fuel swelling	Varying performance Short circuit Surface rupture Loss of fuel-clad bond Cracking of fuel
Fission product and nuclear radiation damage	
Alteration of physical properties	Increase yield strength Increase electrical resistivity Decrease thermal conductivity
Transient effects on cesium plasma	Negligible

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a steady-state analysis need concern only the stable end products. Those fission products that have a significant vapor pressure at 1800°C and migrate to the emitter surface will evaporate at a rate proportional to their vapor pressure and surface concentration. Of the elements that do evaporate into the cesium gap, those that have a boiling point greater than 850°C will condense on the collector and in the cesium reservoir as solids or liquids. Those that have a boiling point between 350° and 850°C will condense in the cesium reservoir only. Those that have a boiling point below 350°C will remain in the gap as a gas.

A small amount of solid or liquid deposition on the collector will not be particularly harmful, since experiments have shown that at design temperature the work function of the collector approaches that of cesium regardless of the collector material. A large amount of deposition would decrease the gap size, causing a significant change in converter performance and possibly eventually shorting out of the cell. Any significant amount of fission gas in the diode gap may change the work function of the emitter and collector, and change the space charge neutralization properties in the diode. This could result in drastic changes in converter performance.

The probable disposition of the major fission products is shown in Table IV. The following conclusions may be drawn:

- 1) Solid product deposition on the collector should be slight. Those elements that have a melting point above 850°C also have a boiling point above 1900°C and will therefore not be released from the fuel in any great amount.
- 2) The elements strontium and barium will condense on the collector as liquids.

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TABLE IV
PROBABLE DISPOSITION OF FISSION PRODUCTS HAVING A
YIELD GREATER THAN 0.5 GM-ATOM/10,000 HOURS

Element	Yield (gm-atoms/10,000 hours)	Most Probable Final Status
Inert gas		Remain as gas, will escape from unobstructed system
Xe	2.4	
Kr	0.54	
Alkali metal		Condense in Cs reservoir with subsequent high vapor pressure
Rb	0.52	
Alkali earth		Condense on collectors as liquids
Sr	1.15	
Ba	0.77	
Rare earth		Slightly volatile; majority remain in fuel as free elements, alloys, and carbides
Nd	2.46	
Ce	2.03	
La	0.80	
Pr	0.80	
Refractory metals		Nonvolatile; remain in fuel as carbides
Mo	3.27	
Zr	4.11	
Platinum group		Nonvolatile; remain in fuel as carbides
Ru	1.52	

Assumptions: 1800°C emitter temperature
800°C collector temperature
300°C cesium reservoir temperature
Carbide fuel

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- 3) The elements rubidium and tellurium will condense in the cesium reservoir.
- 4) The elements krypton, xenon, and iodine will remain in the diode gap as gases; it is anticipated that cesium gas must be swept through the reactor core and dumped during design lifetime in order to maintain the concentration of these elements at an acceptably low level.

Experiments to determine the need for reactor power flattening have been initiated during the past year. These are described in a paper being presented in Session F by J. W. Holland of Atomics International. Preliminary results indicate it will be necessary to employ power flattening means such as varying nuclear fuel concentration in several regions of the core.

To illustrate the possible growth toward such a high-performance system as has been described, calculations of system specific weights at lower outputs were made by simply assuming the exact same components and, therefore, size and total weight as in the system resulting from this study and considering lesser converter performances. The results, presented in Figure 11, indicate that it is only necessary to achieve overall conversion efficiencies greater than 10%, with corresponding average power densities greater than 8 watts/cm^2 , to meet the 10 lb/kwe goal of other advanced space systems. Higher converter performance levels have already been observed reproducibly in the laboratory at interelectrode spacings up to about 8 mils. Future work must then be devoted to further improvement of performance with a concurrent major effort devoted to achievement of the long life and high reliability needed for a successful space system.

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Figure 11. Variation in System Weight with Converter Performance

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CONCLUSION

In conclusion, a large portion of the future effort relative to this system concept must be devoted to achievement of adequate converter lifetime and reliability, particularly in regard to interactions of materials and the sensitivity of converter performance to possible fuel component and fission product material contaminants. Additional work is needed to firmly establish the required degree of reactor power flattening. Even at current converter performance levels, systems weighing less than about 10 lb/kwe unshielded would be possible if adequate lifetime and reliability were achieved. As converter performance is further improved and as methods for control of life-limiting factors are developed, the in-core thermionic reactor system possesses the potential for achievement of complete system specific weights of 4 to 5-lb/kwe unshielded, as compared to the 10-lb/kwe unshielded goal of other advanced space system concepts now being studied.