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SYNTHESIS OF THERMIONIC POWER CONVERSION
TO NUCLEAR REACTORS
FOR SPACE POWER APPLICATIONS

by

L. W. Perry and W. G. Homeyer

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SYNTHESIS OF THERMIONIC POWER CONVERSION TO NUCLEAR REACTORS FOR SPACE POWER APPLICATIONS*

L. W. Perry and W. G. Homeyer

This paper briefly compares the three general concepts for combining thermionic cells in a reactor in terms of the individual thermionic cell performance. The in-core cell concept, which has the greatest performance potential, is discussed in more detail, and two arrangements of fuel and coolant are compared. Of these, the internal fuel configuration is shown to allow higher power densities over a broad range of cell diameters. This concept is studied more fully and the interrelated thermal, thermionic, and nuclear considerations of a thermionic reactor are discussed in light of the basic thermionic cell parameters.

Comparison of Three General Cell-Reactor Concepts. The performance of nuclear thermionic reactors in terms of specific power (weight-to-power ratio) can be evaluated by the performance of the individual thermionic cell-fuel element employed. One concept of thermionic reactors (in-core cells) employs the nuclear fuel-thermionic cells internal to the core with the emitter directly heated by fissioning within the cell. A cylindrical thermionic cell containing the nuclear fuel within the emitter is assumed. The cylindrical surface area of such a cell, $\pi D_e l$, is used as the power producing area. The net power of the cell would be $P = \pi D_e l \sigma$ (watts) where σ is the average thermionic power density. The weight of the fuel-emitter is $W = \frac{\pi}{4} D_e^2 l \rho$ (gms) where ρ is the average material density. Then the weight-to-power ratio of the fuel-emitter is $\frac{\pi}{4} D_e^2 l \rho / \pi D_e l \sigma$ or $D_e \rho / 4 \sigma$ (gms/watt). Weights of other major reactor components are not included, such as the collector, insulators, leads, structure, coolant, and reflector. These values, although important to reactor weight, are to a first order comparable for different concepts and may be neglected for relative comparisons. The importance of cell radius, material density, and thermionic power density can be readily seen.

In the three general concepts considered here, thermionic cells are placed--internal to the core, on the surface of the core where they are heated by conduction from the reactor, and external to the core where they are heated by a liquid metal coolant loop, or by heat pipes. In the concept with cells on the surface of a compact reactor, heating of the cells is by contact with the reactor surface and the waste heat is directly rejected from the thermionic collector to space. For this case, the effective cell radius is equal to the reactor radius. In comparing this case to the in-pile cell case, the material density and thermionic power density are comparable. However,

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as the cell radius is now much larger (equal to reactor radius), the weight-to-power ratio is greater than that of the cell internal concept.

The third general concept is that employing a coolant loop or heat pipes to transport the heat from the nuclear fuel to thermionic cells external to the reactor. In this case the emitter coolant loop interposes a thermal barrier between the nuclear fuel and the emitter, lowering the emitter temperature. The lower emitter temperature will result in a lower thermionic power density than for the in-core cell case where the emitter and fuel are in contact. Since the power produced by a diode of given weight will be less, the external cell concept will result in a higher weight-to-power ratio than the in-pile cell reactor concept.

Comparison of Two In-Core Cell Concepts. In addition to the cylindrical internal fuel in-core concept another in-core geometry may be considered, the external fuel in-core concept, i.e., where the coolant channel is in the center of the cell and the electrodes and fuel concentric about it. Figure 1 schematically illustrates the two in-pile concepts.

In order to compare the two in-pile cases, several different cell diameters are considered. Comparable cell parameters, such as emitter clad, thermionic power density, coolant volume fraction, etc., are held constant in both cases. To make the geometry comparable the fuel external cell whose outer form is hexagonal is given an outer diameter 5% larger than the diameter of an equivalent cylinder. The output power per unit length of cell and the fuel volume fraction are listed below for cells of several diameters.

TABLE I
In-Core Thermionic Cells
($\sigma = 5 \text{ watt/cm}^2$)

Fuel-Internal			Fuel-External		
Cell Dia.	Watts/Cm	Fuel Vol. Fraction	Cell Dia.	Watts/Cm	Fuel Vol. Fraction
3.15 in.	120	77%	3.30 in.	46	80%
1.58 in.	56	65%	1.65 in.	26	68%
0.78 in.	25	44%	0.83 in.	16	43%
0.59 in.	17	32%	0.61 in.	13	26%

RADIAL-INTERNAL FUEL

D_e (DIAMETER OF EMITTER)
 t_c (EMITTER CLAD THICKNESS)
 t (SHROUD THICKNESS
 (COLLECTOR + CESIUM GAP +
 INSULATOR + CLAD))
 U (CELL CENTER SPACING)

RADIAL-EXTERNAL FUEL

l (EMITTER LENGTH)
 s (INTERNAL ELECTRODE SPACING)

AXIAL-INTERNAL AND EXTERNAL FUEL

Figure 1--In-Core Thermionic Cell Arrangements.

The results can be evaluated in terms of the ability of the cell geometry to generate electrical power in a given fuel volume. The difference in the electrical output and the fuel volume fraction is attributable to a geometric effect which favors (i.e., higher electrical power/volume of fuel) the internal fuel cell. The difference between the two types increases with increasing cell diameter and for the two cases studied (cell diameters >0.5 in.) the internal fuel in-core cell concept can be expected to produce a higher electrical power output for a given fuel fraction (or reactor volume).

In-Core Thermionic Reactor Concept. The incorporation of thermionic cells into a nuclear reactor requires consideration of the interrelated constraints imposed by the thermionic cells, the waste heat coolant, and the reactor neutronic criticality. The reactor type considered most applicable to in-pile thermionics is a compact fast reactor. In a fast reactor, the thermionic cells can be operated with a coolant (collector) temperature (700°C to 1000°C) much above the material temperature limits (500°C to 700°C) imposed by efficient moderators (high H content) necessary for compact thermal reactors. In addition, refractory metals may be used without severe neutron resonance absorption. With the fast compact reactor the critical core diameter depends primarily on the atomic density of the fissionable nuclides, with other materials in the core having only relatively minor effects. Table II lists the critical reactor diameters for several fuel materials.

TABLE II
Approximate Fast Reactor Critical Diameters
(3 In. Be Reflector) (~ 25% Fuel Volume Fraction) (L/D = 2)

<u>Fuel Material</u>	<u>Fissile Atom Density</u>	<u>Reactor Core Diameter</u>
UC	7.1×10^{21} atoms/cm ³	19.3 in.
UO ₂	5.6×10^{21} atoms/cm ³	22.8 in.
UO ₂ -W (60:40)	3.4×10^{21} atoms/cm ³	25.0 in.

To illustrate the interrelationship of the thermionic, thermal, and neutronic considerations for in-core thermionic reactors, relations can be derived for a simple model of the internal fuel in-core concept which relates the nuclear fuel volume fraction (fissile atom density) required to obtain nuclear criticality to the thermionic cell and reactor parameters. The basic thermionic cell and reactor parameters are schematically represented in Figure 1. The volume fraction of the nuclear fuel is given by

$$V_f = \left[\frac{D_e - 2t_c}{D_e + 2t} \right]^2 (1 - V_c) \left[\frac{l}{s + l} \right]$$

where V_c is the coolant dilution factor defined as

$$V_c = 1 - \frac{\pi}{2\sqrt{3}} \left[\frac{D_e + 2t}{U} \right]^2$$

If D is the critical reactor diameter and R the reactor length-to-diameter ratio, the total electrical power of the reactor is then

$$P = \frac{\pi D_e \sigma}{(D_e + 2t)^2} (1 - V_c) \left[\frac{\ell}{s + \ell} \right] R D^3 \text{ (watts)}$$

where σ is again the net average cell thermionic power density.

Estimates of the effects of various thermionic cell parameters on the reactor performance can be made based on this simplified model by selecting representative parameters. First it must be noted that within a cell the thermionic power density, the emitter length, and the material and thickness of the clad are closely related by the joule electrical losses. For example, with a thermionic power density of 10 watts/cm² (13 amps/cm² at 0.77v) and a tungsten clad, the clad thicknesses required to hold the electrical loss within the emitter to ~10% for several emitter lengths are:

Clad thickness	0.02 in.	0.04 in.	0.06 in.	0.08 in.
Emitter length	1.70 in.	2.20 in.	2.70 in.	3.00 in.

It is seen that beyond ~2.5 inches the emitter length increases only slightly with increasing clad thickness. Further increasing the emitter thickness would dilute the fuel loading in the reactor and increase the emitter weight so that in practical cases a balance must be found between cell length and clad thickness.

In the following table parameters are selected to permit estimation of thermionic reactor performance. These parameters are representative of those currently being used in thermionic cell experiments. No attempt to determine optimum parameters is made. The representative values are used to show the general range of thermionic reactor performance and the effects of changing some of the major parameters.

TABLE III
Typical Thermionic Cell Parameters

Thermionic power density (σ) = 5 watts/cm²

Cell length (ℓ) = 2.5 in.

Emitter clad thickness (t_c) = 0.05 in.

Cell axial spacing (s) = 1.0 in.

Collector - shroud thickness (t) = 0.07 in. (0.01 Cs gap + 0.03 in. collector + 0.03 in. shroud)

Coolant dilution factor (V_c) = 0.25

The power output of a thermionic reactor employing these parameters is given as a function of the thermionic cell diameter in Table IV. The reactor is assumed to use a fuel with a U-235 density of 2.3×10^{22} atoms/in³, a 3 in. Be reflector, and a cylindrical core with length and diameter equal. As noted before, the specific weight of the basic thermionic cell increases with increasing diameter. This is shown in Table V. Finally, estimates of the specific weight of thermionic reactors (cells + coolant + reflector) are given as a function of electrical power output in Table VI.

To increase the power output or decrease the specific weight the basic parameters of the thermionic cell must be changed. For example, increasing the average net thermionic power density beyond the 5 watts/cm² value would make the following changes in a reactor with 2.0 inch diameter cells:

Power Density (Watts/cm ²)	Specific Weight (lb/kw)	Total Power (kw)
5	7.1	66
7	5.1	92
10	3.5	132

Changes in cell or reactor parameters which reduce the fuel volume fraction, such as increases in coolant dilution factor or axial emitter spacing, require that a larger core diameter be used in order to regain nuclear criticality. The larger core diameter could be obtained by adding more thermionic cells of the same diameter, but this would make a large increase in the size of the reactor and provide more power than required. If, instead, the reactor is to be made as small as possible, the cell diameter should be increased sufficiently to meet the criticality requirement while providing exactly the power output required. The effect of changes in the coolant dilution factor can be seen in the following example:

V_c	Power at $D_e = 1$ inch (kw) ^e	D_e for 128 kw (in)	Specific Weight (lb/ekw)
0.25	128	1.0	4.4
0.35	142	1.1	4.7
0.50	211	1.4	5.5

In summary, the in-core cell reactor with fuel internal to the emitter has the potential of giving light compact thermionic reactor systems. The performance of this type of reactor can be improved significantly by the use of fuels with increased fissile atomic density, by increased thermionic power density, and by increased compaction of the cells. Thermionic cell length is fixed within a narrow range by electrical losses. Cell diameter, on the other hand, is an important parameter, which must be selected with care to meet requirements for power output and nuclear criticality. Finally, estimates obtained from representative cell and reactor parameters indicate that present thermionic performance appears adequate for compact, lightweight thermionic reactors.

TABLE IV
Reactor Electrical Power Output
for
Different Emitter Diameters

Emitter Diameter (in.)	0.5	1.0	1.5	2.0
Reactor Power (ekw)	400	130	87	66

TABLE V
Specific Weight of Thermionic Cells
for
Different Emitter Diameters

Emitter Diameter (in.)	0.5	1.0	1.5	2.0
Specific Weight of Cells (lbs/ekw)	3	4.4	5.7	7.1

TABLE VI
Specific Weight of Thermionic Reactor
vs
Electrical Power

Reactor Electrical Power (ekw)	75	100	200	300
Reactor Specific Weight (lbs/ekw)	26	20	12	10