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THE PERFORMANCE OF THERMIONIC REACTORS
FOR 50 to 100 kWe*

by

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ABSTRACT

Four types of thermionic reactors for the 50 to 100 kWe power range were studied. The characteristics of these reactors are described and performance estimates for power plants containing them are given. All of the reactors contain the six-cell thermionic fuel elements (TFE) which are presently under development at GGA. Two reactors contain only thermionic fuel elements in the core. One of them, fueled with U-235, is criticality limited, and has about twice as many thermionic cells as are necessary to produce 100 kWe. With U-233, the minimum critical reactor is in the 50 to 100 kWe power range. Reactors fueled with U-235 containing UN and U-ZrH driver fuel elements in addition to thermionic elements were also studied.

All-cell reactors fueled with U-233 were shown to produce the lightest power plants in the 50 to 100 kWe power range. At 100 kWe, power plants containing the U-235 all-cell reactor, the UN driver reactor, or the U-ZrH driver reactor are all comparable in weight. Driver reactors provide a lighter power plant than the all-cell U-235 reactor for power levels below 100 kWe.

INTRODUCTION

In the past year, reactor and power plant design studies have concentrated on the 50 to 100 kWe power range. The aim of these studies, which are summarized here, has been to show the performance characteristics that can be obtained from reactor power systems which employ the six-cell TFEs with 1.1 in. emitter diameter which are presently under development.⁽¹⁾ These studies are described in more detail in Refs. 2 and 3.

REACTOR TYPES FOR 50 to 100 kWe

The design of thermionic reactors for the 50 to 100 kWe power range is strongly affected by the criticality limit which results from dilution of nuclear fuel in the reactor core with thermionic conversion hardware. If the only fuel elements in the reactor core are TFEs fueled with U-235,* 162 TFEs are required for criticality, and the power capacity of the reactor is greater than 200 kWe. This reactor can be turned down to 100 kWe or less with a small loss in efficiency and a substantial reduction in thermal power. This turned-down reactor is one of those studied and is identified here as the all-cell U-235 reactor.

An alternative for the 50 to 100 kWe power range is to use U-233* instead of U-235 as the fuel in the TFEs. U-233 has the same chemical properties as U-235 but different neutronic properties. In a small, fast-spectrum thermionic reactor, each atom of U-233 has a worth, as far as criticality is concerned, which is nearly as great as two atoms of U-235. The smallest critical U-233 reactor contains only 46 TFEs and produces about 65 kWe when operated at full power. It can be turned down in power level if less than 65 kWe is required or made larger by the addition of more TFEs if more than 65 kWe is required. This reactor is referred to in this study as the all-cell U-233 reactor.

Another alternative for producing power in the 50 to 100 kWe range is to use as many U-233-fueled TFEs as necessary to produce the required electrical power output, and to add driver fuel elements to the reactor core to achieve criticality. Reactors with two types of driver elements have been

*In oxide or carbide form

studied. One type, identified as the UN driver reactor, contains dense UN fuel clad in tungsten coated niobium. The other driver reactor, which is referred to as the U-ZrH driver reactor, contains U-ZrH driver fuel elements clad in Hastelloy.

The four reactor types studied are summarized in Table 1.

Thermionic Reactor Power Plant Components

The thermionic reactor power plant consists of the reactor, heat rejection system, nuclear radiation shield, power conditioning equipment, power transmission lines, and the instrumentation and control system. The arrangement of the major components is shown in Fig. 1. A very brief description of these components is given in this section.

The reactor consists of thermionic fuel elements and coolant in the core surrounded by a BeO neutron reflector as shown in Fig. 2. Most of the radial reflector consists of rotating, poison-backed control drums. A few of the major characteristics are given in Table 2.

The heat rejection system transfers waste heat from the reactor core to space. The major characteristics of the heat rejection system are given in Table 3. For unmanned applications, there is a single loop carrying heat from the reactor directly to the radiator. For manned applications, there are two loops with an intermediate heat exchanger located in the gallery within the shield. The radiator surface consists of heat pipes which serve as extended fins.

The characteristics of nuclear radiation shields for manned and unmanned applications are given in Table 4. The shield for unmanned applications is designed to protect sensitive electronic components in the power conditioning equipment. The shield for manned applications protects the crew located in the shadow cone for periods of a year or more of continuous exposure. It is a partial 4π shield which reduces the hazard of brief exposures outside of the shadow cone which might result from errors during rendezvous operations or extravehicular activity. It is based on specifications established for the application of the U-ZrH reactor thermoelectric power system to the NASA Space Station.⁽⁴⁾

The power conditioning system consists of an array of modules, each of which radiates its waste heat directly from a magnesium chassis. The major characteristics of the power conditioning equipment are given in Table 5. The transmission lines to the power conditioning equipment are copper with an average temperature of 400°C. No design work was done on the instrumentation and control systems, which were assumed to be similar in weight to the systems for U-ZrH reactors for space applications.⁽⁴⁾

Results of Performance Studies

The scaling of weight with power is shown in Fig. 3 for the thermionic reactor power plants for unmanned applications. The weight given here is the total weight of all the components described above. The power output is the net power output after power consumption in coolant circulation pumps and transmission lines has been deducted. As shown in Fig. 3, the all-cell U-233 reactor produces the lightest power plants. This is because the U-233 fuel allows a smaller and lighter reactor to be used at lower power levels.⁽⁵⁾ In addition, the TFEs operate at full power and higher efficiency.

The all-cell U-235 reactor and the two driver reactors give similar power plant weights for power levels above 100 kWe. At 50 kWe, the all-cell U-235 reactor power plant is considerably heavier because of the large reactor and shield. The driver reactors are smaller and lighter, but are less efficient than the all-cell reactor because of power produced in the driver elements. The larger, heavier heat rejection systems required for driver reactors tend to offset the advantage of smaller size for power levels of 100 kWe and above.

Similar curves of power plant weight for manned applications are shown in Fig. 4. The power plants for manned applications weigh more than twice as much as those for unmanned applications, primarily because of the larger, heavier nuclear radiation shields. There is a noticeable break in the curve for the U-233 reactor at a power output of 65 kWe, which is the criticality limit for the U-233-fueled thermionic reactors. The same reactor is used below 65 kWe and is turned down in power output.

As shown in Figs. 3 and 4, reactors fueled with U-233 are clearly superior in performance for both manned and unmanned applications in the 50

to 100 kWe power range. If U-235 is selected as the fuel for reasons of safety, ease of handling, or familiarity, driver reactors should be considered as competitors to the all-cell reactor. While they offer little or no performance advantage at power levels of 100 kWe or above, at 50 kWe the driver reactors offer a significant weight saving over the all-cell U-235 reactor.

TABLE 1
REACTOR TYPES

- All-Cell U-235

162 U-235-fueled TFEs required for criticality - turned down in power output

- All-Cell U-233

Number of U-233-fueled TFEs selected to produce required power - 46 or more TFEs required for criticality

- UN Driver

Number of U-235-fueled TFEs selected to produce required power - UN driver elements added to reach criticality

- U-ZrH Driver

Number of U-235-fueled TFEs selected to produce required power - U-ZrH driver elements added to reach criticality

TABLE 2

REACTOR CHARACTERISTICS

TFE diameter	1.335 in. (3.39 cm)
TFE length	17.4 in. (44.2 cm)
Coolant volume fraction	0.100
Reflector	BeO
Reflector thickness	3 in. (7.6 cm)
Control device	poison-backed reflector drums
Control poison	B ₄ C

TABLE 3

HEAT REJECTION SYSTEM CHARACTERISTICS

Coolant	NaK 78
Loop material	316 stainless
Maximum coolant temperature	1300°F (705°C)
Coolant temperature rise	180°F (100°C)
Radiator surface	Na heat pipes
Heat pipe wall material	316 stainless
Approximate mass (unmanned)	1.5 lb/kWt (0.7 kg/kWt)
Approximate mass (manned)	2.4 lb/kWt (1.1 kg/kWt)

TABLE 4
RADIATION SHIELD CHARACTERISTICS

Shield configuration	Shadow	Partial 4π
Materials	LiH	LiH, W, U-238
Dose rate	10^{12} nvt, 10^6 rad/ 10^4 hr @ power conditioning	2.8 mrem/hr @ 120 ft
Dose rate at side		200 rem/hr @ 100 ft
Cone half-angle	$7^\circ 30'$	$10^\circ 20'$

TABLE 5
POWER CONDITIONING EQUIPMENT CHARACTERISTICS

Input voltage	7.5 V dc
Output voltage	200 V dc
Switching components	Silicon transistors
Specific mass	6.2 lb/kW (2.8 kg/kW)
Efficiency	86%
Radiator area	$1.2 \text{ ft}^2/\text{kW}$ ($0.11 \text{ m}^2/\text{kW}$)

Fig. 1. Flashlight reactor power plant

Fig. 2. Thermionic reactor

Fig. 3. Weights of power plants for unmanned applications

Fig. 4. Weights of power plants for manned applications

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