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PERFORMANCE EVALUATION OF A THERMIONIC CONVERTER
USING A GRAPHITE INTEGRAL RESERVOIR

by

A. J. Gietzen

Prepared under
Contract AT(04-3)-167
Project Agreement No. 14
for the
San Francisco Operations Office
U. S. Atomic Energy Commission

April 16, 1969

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ABSTRACT

This report describes an analytical evaluation of a graphite integral reservoir as a cesium supply in a thermionic converter. The reservoir is thermally coupled to the emitter and collector such that its temperature is determined by the electrode temperatures. The collector temperature depends in a passive manner on the thermal power rejected. The thermal model of the converter and reservoir is presented.

The analysis includes performance obtained with specific designs incorporating the reservoir into the converter. The current-voltage characteristics are computed over the entire range of input power from startup to full power. The results indicate that close coupling of the graphite reservoir to the collector causes a peak in emitter temperature in the input power range of 30 to 60% of full power, resulting from inadequate cesium coverage for good electron emission. The difficulty can be overcome by incorporating a small amount of control ($\pm 50^{\circ}\text{K}$) on collector temperature, or by increasing the reservoir thermal coupling to the emitter.

The ability to maintain near-optimum cesium pressure through large variations in output power is investigated and found to require strong thermal coupling to the emitter.

Performance losses due to changes in the thermal coupling characteristics are calculated.

1. INTRODUCTION

The common method used to supply low pressure cesium vapor to a thermionic converter is to provide an external reservoir of liquid cesium. The cesium pressure is the vapor pressure of the liquid cesium and is varied by varying the liquid temperature.

For application to thermionic reactor design, the liquid reservoir presents two difficulties; (1) the reservoir temperature range for optimum performance (575 to 640°K) lies considerably below the lowest temperature within the reactor core (~1000°K), requiring location of the reservoirs outside the reactor with small tubes to carry the cesium to the converters, and (2) the reservoirs do not directly respond to temperature changes within the converters so that performance penalties and temperature instabilities may result.⁽¹⁾

During the past few years, attention has been given^(2,3) to reservoirs in which the cesium is adsorbed on the surfaces of a porous material or contained in the material as a chemical compound. The amount of cesium contained in these reservoirs (cesium loading) can be chosen to provide the desired vapor pressure with reservoir temperatures high enough that the reservoir can be placed within the converter envelope. The temperature at which the integral reservoir operates must be between the emitter and collector electrode temperatures and the influence of each electrode on the reservoir temperature is determined by the thermal coupling conditions.

In a thermionic converter, the current density which can be obtained is strongly influenced by the cesium pressure. In addition, the current density influences the electrode temperatures (and, therefore, the reservoir temperature) because of the electron cooling heat transfer. Thus, there is an additional interdependence of thermal and thermionic characteristics with an integral reservoir which does not exist with external liquid reservoirs. An advantage gained from this interdependence is the possibility of optimum following characteristics (i.e., the cesium pressure varies with the electrode temperatures in just the right way to maintain optimum performance).

There are, however, certain problems regarding reproducibility of thermal coupling coefficients and operational constraints for conditions far from the operating point, such as those experienced during startup.

This study focuses attention on one particular reservoir material; graphite (which presently appears the most promising in terms of material properties) applied to a specific converter design using a high work function tungsten emitter and a niobium collector. The analysis investigates the thermal coupling requirements for optimum following characteristics, the performance characteristics for specific designs over a wide range of operating conditions, and the effects of uncertainties in the reservoir temperature. The calculations assumed the dependence of collector temperature on rejected heat to be that of a passive, forced convection loop-radiator system except where noted.

2. SUMMARY

For a reservoir closely coupled to the collector, the reservoir temperature and cesium pressure would be too low in the 30 to 60% reactor power range and would cause the emitter temperature to rise 150°K above the design point of 2040°K during startup or shutdown. If this peaking in temperature is not tolerable, it can be reduced significantly by changing the dependence of collector temperature on rejected thermal power, or by changing the thermal coupling of the reservoir. An increase in collector temperature of 40°K above the reference point of 1000°K in the range of 30% to 60% power would maintain the temperature no greater than the design temperature. Other kinds of thermal coupling such as (a) conduction to both emitter and collector at design reservoir temperature of 1300°K , or, (b) radiation from emitter and half conduction, half radiation to collector at a temperature of 1300°K were shown to produce a peak emitter temperature below 1950°K at about 40% of full thermal power.

Analysis of the uncertainties in the coupling heat transfer coefficients indicate reservoir temperature uncertainties of $+15^{\circ}\text{K}$ and -40°K . A decrease in reservoir temperature of 40°K results in a 10% loss in power; a loss which is considerably reduced by choice of an operating point about 20°K above optimum. A temperature increase of 15°K results in a power loss of about 5%. The negative uncertainty could result in as much as 200°K increase in the emitter temperature peak during startup.

3. THERMAL MODEL

Figure 1 is a diagram of the thermal model used in the analysis. This model is incorporated in a computer program, CPOP, which calculates each of the terms shown as well as the thermionic performance of the converter for various values of emitter, collector, and reservoir temperatures and current density, J . For given values of J and T_e (or Q_e) the collector temperature is calculated iteratively from a heat balance. The relation used to relate the collector temperature and rejected heat is

$$T_c = Q_r \left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} \right) + \frac{Q_r}{K} + \left(\frac{Q_r}{H} \right)^{\frac{1}{4}} \quad (1)$$

where k_1 , k_2 and k_3 are the thermal conductances across collector, sheath insulator and sheath, respectively

K = heat transfer coefficient from sheath to radiator surface

H = radiation coefficient

The coefficients K and H are computed from a thermal analysis of the heat rejection system performed by a separate program written for that purpose.⁽⁴⁾

With values for T_e and T_c , the reservoir temperature can be found from a heat balance on the reservoir. The heat transferred through the reservoir, Q_R , is given by

$$Q_R = h_{re} (T_e^4 - T_R^4) + h_{ce} (T_e - T_R) \quad (2)$$

or, by energy balance

$$Q_R = h_{rc} (T_R^4 - T_c^4) + h_{cc} (T_R - T_c) \quad (3)$$

where h_{re} = radiation coefficient from emitter
 h_{ce} = conduction coefficient from emitter
 h_{rc} = radiation coefficient to collector
 h_{cc} = conduction coefficient to collector
 T_R = integral reservoir temperature

- Q_e - Thermal power to emitter
- Q_{re} - Heat radiated from emitter to reservoir
- Q_{ce} - Heat conducted from emitter to reservoir
- Q_{ec} - Electron cooling heat transfer
- Q_c - Conduction from emitter to collector
- Q_{rad} - Radiation from emitter to collector
- Q_{rc} - Radiation from reservoir to collector
- Q_{cc} - Conduction from reservoir to collector
- Q_r - Heat rejected to radiator

Fig. 1. Schematic of thermal model

If Equations 2 and 3 are combined, they can be written in the form

$$AT_R^4 + BT_R - C = 0 \quad (4)$$

where $A = h_{re} + h_{rc}$

$B = h_{ce} + h_{cc}$

$C = h_{re}T_e^4 + h_{ce}T_e^4 + h_{rc}T_e^4 + h_{cc}T_e^4$

which can be solved iteratively using Newton's method to obtain the reservoir temperature.

For most sorption-type reservoirs, the equilibrium cesium pressure is related to reservoir temperature by

$$P_g = \exp \left[-C_1 \left(\frac{1000}{T_R} - C_0 \right) \right] \quad (5)$$

where the constants C_0 and C_1 depend on the reservoir material and cesium loading.

The possibility of incorporating an integral reservoir which will have optimum following characteristics is of interest. The requirements on the thermal characteristics for a given operating mode can be investigated by expressing the coupling coefficients in terms of the fraction of the heat through-put which is transferred by radiation. If:

α_{re} = fraction of Q_R transferred from emitter to reservoir by radiation, at the design conditions,

α_{rc} = fraction of Q_R transferred from reservoir to collector by radiation, at the design conditions,

then the coupling coefficients can be expressed as

$$h_{re} = \frac{\alpha_{re} Q_R}{T_e^4 - T_R^4} \quad h_{ce} = \frac{(1 - \alpha_{re}) Q_R}{T_e^4 - T_R^4} \quad (6)$$

$$h_{rc} = \frac{\alpha_{rc} Q_R}{T_R^4 - T_c^4} \quad h_{cc} = \frac{(1 - \alpha_{rc}) Q_R}{T_R^4 - T_c^4} \quad (7)$$

For temperature variations which do not result in significant changes in thermophysical properties, these coupling coefficients are constants. If the optimum reservoir temperature is known for an off-design point as well as the normal operating point, the coupling conditions required for maintaining the optimum at both points can be found. This is done by first evaluating the four coupling coefficients, Eqs. 6 and 7, in terms of α_{re} and α_{rc} at the design point temperatures. These values for the coefficients are then applied in Eq. 3 for an off-design condition. The resulting equation may be written as

$$\begin{aligned} \frac{(T_e^4 - T_R^4)_1}{(T_e^4 - T_R^4)_2} \alpha_{re} + \frac{(T_e - T_R)_1}{(T_e - T_R)_2} (1 - \alpha_{re}) = \\ \frac{(T_R^4 - T_c^4)_1}{(T_R^4 - T_c^4)_2} \alpha_{rc} + \frac{(T_R - T_c)_1}{(T_R - T_c)_2} (1 - \alpha_{rc}) \end{aligned} \quad (8)$$

where subscript 1 refers to off design conditions,

subscript 2 refers to design point conditions.

A solution to this equation provides a relationship between α_{re} and α_{rc} which must be satisfied to obtain optimum reservoir temperature at both points. With appropriate values for these two parameters and a chosen value for Q_R , numerical values for the coefficients can be obtained from Eqs. 6 and 7.

4. RESULTS

4.1. DESIGN CALCULATIONS

All calculations were based on the geometry of the converter design used for the 300 kWe reactor design study.⁽⁵⁾ The performance characteristics of the electrodes were chosen to match those of a tungsten emitter surface with {110} crystal planes preferentially exposed and a niobium collector, with a 0.025 cm (0.010 in.) spacing. The design operating point is

$$\begin{aligned}T_e &= 2040^\circ\text{K} & J &= 10 \text{ amp/cm}^2 \\T_c &= 1000^\circ\text{K} & Q_e &= 49.5 \text{ W/cm}^2 \\P_{cs} &= 4.1 \text{ torr}\end{aligned}$$

representing the average converter in the reactor. The coefficients describing the heat rejection system response (H and K in Eq. 1) were obtained from calculations done by the LISA program.⁽⁴⁾ The converter performance calculations were done with the CPOP program which incorporates the integral reservoir model as shown in Fig. 1.

The characteristics of the graphite reservoir material are discussed in Ref. 3. The operating temperatures of interest are in the range of 1050°K to a maximum of about 1300°K. The pressure-temperature relation can be expressed by Eq. 5 in which the constants depend on the loading (mass of Cs/mass of graphite) and the type of graphite.

4.2. OPTIMUM PERFORMANCE

Investigations were done to determine the thermal coupling conditions required for optimum following characteristics for four modes of operation - constant voltage, constant current, constant load, and constant emitter temperature.

The optimum cesium pressure for the reference converter is shown in Fig. 2 as a function of current density, emitter temperature and relative thermal power. Using this information and calculation of the variation of

Fig. 2. Dependence of optimum cesium pressure on temperature and power

converter conditions with input power level, the variation of T_e and T_c , and the T_R required for optimum performance at each point could be determined. An example plot of the three temperatures is shown in Fig. 3, which is for the constant voltage mode for a reservoir whose loading is such that it operates at 1300°K at the design point.

The relationship between the optimum reservoir temperatures and the electrode temperatures is sufficiently linear that optimum reservoir temperature at two values of input power insures very nearly optimum temperature over the range between. Using the approach discussed in Section 3, the relationship between α_{re} and α_{rc} defining optimum coupling (Eq. 8) was evaluated for operating points below the design point with the coefficients defined by design point conditions.

The design point cesium pressure is about 1 torr above optimum resulting in output about 4% below optimum. It was assumed, then, that optimum is defined as within $\pm 5\%$ of maximum output. It was found that optimum conditions could be maintained down to 10% of design output power for all operating modes only if the reservoir was strongly coupled to the emitter, i.e., conduction from emitter (α_{re} near 0) and radiation to collector (α_{rc} near 1.0). A design giving this coupling is very difficult to attain. These results assumed a design reservoir temperature of 1300°K.

For a reservoir design temperature of 1050°K and strongly coupled to the collector, optimum conditions were not maintained below 75 to 85% of design output power, depending on operating mode. Below this point the output decreased rapidly.

This analysis indicates that the performance characteristics are improved by the use of a higher temperature reservoir (lower loading) which can be more closely coupled to the emitter.

4.3. EVALUATION OF SPECIFIC DESIGNS

The initial design which was evaluated for incorporation of a graphite sorption reservoir is shown in Fig. 4. Thermal analysis of the design showed the reservoir to operate about 50°K above the mean collector temperature with the thermal coupling characterized by conduction to the collector; i.e., the reservoir temperature is sensitive to changes in collector temperature. The analysis of these designs again assumes a completely passive

Fig. 3. Electrode and optimum reservoir dependence on input power

heat rejection system, i.e., the rejection temperature varies strictly as required to dissipate the rejected heat by radiation. The cesium level in the reservoir was chosen to give 4.12 torr of cesium pressure which is about 1 torr above optimum. The constants for the reservoir P-T relation (Eq. 5) for this condition are $C_0 = 1.0548$ and $C_1 = 14.0$.

Fig. 4. Reference design for a graphite integral reservoir

The current-voltage characteristics for this design were calculated for emitter temperature isotherms. The results are shown in Fig. 5. The peculiar nature of the curves at lower current densities results from the dependence of cesium pressure on current density (the reservoir temperature follows the collector temperature; the collector temperature is determined by the amount of rejected heat and a large portion of the heat rejected is directly proportional to the current density). At low current densities (and emitter temperatures below 2200°K) the cesium pressure is not sufficient to maintain positive voltage. The phenomenon is more clearly seen in Fig. 6 which shows the variation in current density and emitter temperature as the thermal power is increased, assuming equilibrium conditions and constant

Fig. 5. Converter performance characteristics with reference reservoir design

Fig. 6. Emitter temperature and current density dependence on input power at constant load resistance

load. As the power is initially increased, the temperatures increase proportionally until the cesium pressure becomes high enough to allow a rapid increase in current emission. As the current increases, an additional emitter to collector heat transfer mode is added (i.e., electron cooling), resulting in an increase in reservoir temperature and a decrease in emitter temperature until a new proportionality is reached. Since equilibrium conditions are assumed at each point, the curves would apply to either increasing or decreasing power.

The results imply that for this type of thermal coupling, i.e., close coupling of reservoir to collector, temperature cycling of the emitter can occur during startup and shutdown unless there is some control on the heat rejection system response.

This illustrates that a reservoir design must meet minimum cesium pressure requirements at low powers. Further analysis was done to investigate methods of reducing the emitter temperature peak. The analysis was directed toward meeting the minimum requirement that the converter could be brought to design power without the emitter temperature exceeding 2000°K at low current densities. A design point reservoir temperature of 1300°K was selected.

Three possibilities were investigated for meeting the minimum requirement imposed:

1. Increasing the Cs loading in the reservoir to provide higher pressures (resulting in a performance penalty at the design point because of higher than optimum Cs pressure)
2. Changing the basic design to provide coupling coefficients which meet both the design point and minimum requirements
3. Controlling the heat rejection system to reduce the collector temperature swing as thermal power is varied.

The minimum requirements can be met by increasing the Cs loading; however, as is seen by comparing Figs. 5 and 7, the performance penalties are severe. The output at 10 amp/cm^2 is reduced by about a factor of 2.

In changing the basic design, calculations were done (using the same method as described in Section 3 for determining optimum following

Fig. 7. Performance characteristics with increased reservoir loading

characteristics) to determine the thermal coupling required to meet the minimum requirement that the emitter temperature not exceed 2000°K during startup. The results are shown in Fig. 8, which shows the coupling requirements in terms of the design point radiation heat transfer fractions as previously defined. Design points which fall below the line will not meet the minimum requirements, while any points which fall above the line are acceptable. As previously discussed, the most nearly optimum following conditions are obtained at $\alpha_{re} = 0$ (conduction from emitter) and $\alpha_{rc} = 1.0$ (radiation to collector) which is in a region requiring a difficult converter design. The reference configuration analyzed represented the simplest design and was very near $\alpha_{re} = 1.0$ and $\alpha_{rc} = 0.0$.

The performance characteristics were calculated for two different coupling combinations, conduction ($\alpha_{re} = 0$, $\alpha_{rc} = 0$) and a combination of conduction and radiation ($\alpha_{re} = 1.0$, $\alpha_{rc} = 0.5$). In both cases, the power could be increased to the design point without T_e exceeding 2000°K. The performance characteristics of these couplings, for a graphite reservoir with a design point temperature of 1300°K, are shown in Figs. 9 and 10.

The possible configurations are limited by the places in the converter where a reservoir will fit, the temperatures at which it must operate, and by material compatibility and structural considerations. The conduction-coupled design could be coupled directly to the emitter stem or upper region of the converter. The combination coupling design could be effected by placing the reservoir in the same area as was done in the reference design but separated from the collector by low conduction supports.

Controlling the heat rejection system to reduce the collector temperature swing could be accomplished by allowing a portion of the coolant to bypass the radiator, or by incorporating gas-charged heat pipes in the radiator to reduce the effective radiator area as the power is reduced. If it is possible to have some control such as this over the collector temperature to sufficiently reduce the sensitivity of the collector temperature to the thermal power, then the operational problems associated with the thermal coupling are solved. If the collector temperature could be increased by as little as about 40°K in the input power range from 30 to 60% full power,

Fig. 8. Thermal coupling limitations

Fig. 9. Performance characteristics for conduction-conduction coupling

Fig. 10. Performance characteristics for combination coupling

then the converter could be started up at constant load conditions without exceeding the design point temperature.

The uncertainty in the reservoir temperature was estimated for the reference design (Fig. 4) resulting from changes in the effective heat transfer coefficients. The changes investigated included $\pm 20\%$ change in the thermal conductivity of niobium, $\pm 16\%$ change in the collector-to-coolant heat transfer coefficient, and the possible loss of conduction through the Belleville spring. The extremes of uncertainty in reservoir temperature for these variations were $+17^\circ\text{K}$ and -40°K .

An increase of 17°K above the design point would result in a 5% loss in power. A decrease in temperature of 40°K will result in a power loss of 10%. Since the design point is about 1 torr above optimum, initial decreases in temperature (up to 25°K) result in increased output (up to 4%). The -40°K temperature change could result in as much as a 200°K increase in the emitter temperature peak during startup.

The effect of uncertainties in the analytical model was not evaluated.

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