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URANIUM DIOXIDE VENT LOSS IN AN EXTERNALLY FUELED THERMIONIC REACTOR CONCEPT

by James J. Ward and Robert B. Ruch

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ABSTRACT

An analysis of fuel losses through a fission gas vent in a nuclear thermionic reactor concept is presented. The converters are externally fueled with ceramic uranium dioxide (UO_2), and fuel losses during both steady-state operation and temperature excursions are estimated. Calculations were performed for element fuel-volume fractions of 0.275 and 0.55 with converter heat fluxes of 50 and 100 W/cm^2 at an emitter temperature of 2000 K. The absolute UO_2 loss during a temperature excursion and the ratio of UO_2 loss during an excursion to the yearly steady-state loss are presented as functions of time for each case.

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SUMMARY

A preliminary study was made of uranium dioxide (UO_2) losses in a vented, externally fueled reactor concept during both steady-state operation and a temperature excursion, in which complete separation of the fuel from the emitter was assumed. The UO_2 loss was calculated from element fuel-volume fractions of 0.275 and 0.55, corresponding to electrical output power levels of several megawatts and several hundred kilowatts, respectively. The calculation are based on emitter heat fluxes of 50 and 100 watts per square centimeter with the emitter temperature fixed at 2000 K.

For a fission gas vent diameter of 0.0254 centimeter, the calculated steady-state fuel losses ranged from 0.85 gram per year per converter at a fuel-volume fraction of 0.275 and a heat flux of 50 watts per square centimeter to over 800 grams per year per converter at a fuel-volume fraction of 0.55 and a heat flux of 100 watts per square centimeter.

The time required for a complete excursion (complete separation of fuel and emitter to complete redeposition of fuel on the emitter) ranged from 12 minutes at a fuel-volume fraction of 0.55 and a heat flux of 100 watts per square centimeter to about 8 hours for a fuel-volume fraction of 0.275 and a heat flux of 50 watts per square centimeter. The time dependences of maximum fuel temperatures and UO_2 loss rates were also determined. The results indicated that the fuel loss during a single temperature excursion is insignificant; the highest relative loss, occurring at a fuel-volume fraction of 0.55 and a heat flux of 50 watts per square centimeter, was less than 1 percent of the yearly steady-state loss.

INTRODUCTION

In-core nuclear thermionic electric power conversion systems are being investigated for space applications. In such systems, cylindrical thermionic converters are placed within the reactor core and may be either internally fueled (fuel enclosed by the converter and coolant) or externally fueled (converter and coolant enclosed by the fuel). The externally fueled concept has several advantages over the internally fueled concept (ref. 1), among which are ease of fuel element testing prior to core assembly, lower maximum fuel temperature during both normal and open-circuit operation, and ready access to the fuel for fission-gas venting. Testing a complete externally fueled element is simplified since heating can be accomplished by radiofrequency induction from the outside. The lower maximum fuel temperature during normal operation is due simply to the geometry, while the open-circuit temperature rise is reduced since heat can be transferred by radiation to adjacent fuel elements. Fission gas venting is simplified because the fuel is outside the converter and coolant containment lines.

The use of externally fueled converters may, however, be disadvantageous if ceramic (undiluted) uranium dioxide (UO_2) fuel is used in the reactor. Since UO_2 releases fission gases at temperatures of 2000 K and above, a vent must be provided to relieve internal pressure in the fuel element. The vent design must be such as to allow the fission gases to escape while maintaining the UO_2 loss rate at a minimum. Typical designs allow for losses on the order of 1 to 2 percent of the fuel inventory during the mission life. A thermal instability in the externally fueled system will lead to fuel losses in excess of those determined for normal operation. The instability exists because of the difference in thermal expansion coefficient between UO_2 and the refractory metal emitter of the converter. During a positive temperature excursion, the fuel will tend to pull away from the emitter. If complete separation of the fuel and emitter occurs, a significant increase in maximum fuel temperature will result since the inner fuel surface-to-emitter heat transfer would occur principally by radiation rather than by conduction. The fuel loss rate in a simple vented system is established by the maximum fuel temperature, the corresponding fuel vapor pressure, and the vent hole area. The UO_2 loss rate increases significantly over the design rate if the maximum fuel temperature significantly exceeds the normal steady-state temperature. The situation is self-correcting, however, since fuel will vaporize from the inner fuel surface and deposit on the cooler emitter, the rate of deposition being dependent on the respective surface temperatures.

In order to assess the severity of this problem, a study was conducted to determine the time required for one complete excursion (i.e., complete separation to complete redeposition) and the resulting UO_2 loss in a vented system. Calculations were performed for conceptual thermionic reactor designs with element fuel-volume fractions of 0.275 and 0.55 which correspond to electrical output power levels of several megawatts and several hundred kilowatts, respectively. Emitter surface heat fluxes of 50 and 100 watts per square centimeter were considered with the emitter temperature fixed at 2000 K. Maximum fuel temperature, UO_2 loss during the transient, and the ratio of UO_2 loss during the transient to the yearly steady-state UO_2 loss are presented as functions of time.

SYMBOLS

A	area of fission product vent, cm^2
k	thermal conductivity of fuel block, W/(cm)(K)
L	length of fuel block structure, cm
l	latent heat of vaporization for UO_2, J/g
M	molecular weight of UO_2, g/mole
m	mass flux across void, $g/(sec)(cm^2)$
P	vapor pressure of UO_2, N/cm^2
Q	heat generation in fuel, W
q	heat flux, W/cm^2
$q(T_1, T_2)$	total heat flux across void, W/cm^2
R	gas constant (for UO_2 vapor), J/(g)(K)
r	radius, cm
T	temperature, K
W	UO_2 loss rate, g/sec
γ	ratio of specific heat at constant pressure to specific heat at constant volume for UO_2 vapor
ϵ	emissivity of UO_2 surface
ϵ_{eff}	effective emissivity
ρ	density of UO_2, g/cm^3
σ	Stefan-Boltzmann constant, $W/(cm^2)(K^4)$

Subscripts:

A	region A of fuel
B	region B of fuel
m	mass transfer
rad	radiation
0	outer surface of emitter
1	outer surface of region A
2	inner surface of region B
3	outer surface of region B

DESCRIPTION OF MODEL

A schematic diagram of a typical externally fueled converter is shown in figure 1. The structure includes the liquid-metal coolant channel, collector-insulator assembly, emitter, fuel and outer clad. The element dimensions shown are from a conceptual design of a 5-megawatt electric, UO_2 fueled thermionic reactor. A heat flux of 100 watts per square centimeter was assumed at the emitter-fuel interface, with the converters producing an average of 10 watts of electrical power per square centimeter of emitter area. The element fuel-volume fraction is 0.275. Increasing the fuel volume fraction to 0.55, corresponding to a conceptual reactor design for generating several hundred kilowatts of electrical power, results in a thicker fuel layer and larger outer clad diameter, with the remainder of the structure fixed. In all cases, a single orifice was provided in the outer clad of each fuel element to vent fission gases.

The behavior of the fuel body in such a design during a positive temperature excursion is illustrated in figure 2. During normal steady-state operation (fig. 2(a)), the fuel is assumed to be in intimate contact with the emitter and heat is transferred from the fuel body to the emitter by conduction. The emitter temperature is designated as T_0, while the maximum fuel temperature is designated as T_3. Under steady-state conditions the UO_2 loss rate through the fission gas vent is established by a relatively low value of T_3 and the corresponding UO_2 vapor pressure.

If a positive temperature excursion occurs, the fuel body will expand more than the refractory metal and will tend to pull away from the emitter. In the cases considered, complete axisymmetric separation of the fuel and clad was assumed (fig. 2(b)). Upon separation, the maximum fuel temperature as well as the inner fuel surface temperature (T_2) will increase since heat transfer from the fuel to the emitter then occurs by radiation and mass transfer. The increase in T_3 will significantly increase the UO_2 loss rate. The situation is self-correcting, however, since fuel which vaporizes from the inner-fuel surface will redeposit on the cooler emitter wall and both T_3 and T_2 will begin to decrease.

The system is pictured at an intermediate point in the excursion in figure 2(c). A portion of the heat is now generated in region A and transferred to the emitter by conduction. The heat generated in region B is then assumed to be transferred across the void by a combination of radiation and mass transfer since, upon condensing, the fuel will give up its latent heat of vaporization. The UO_2 loss rate continues to be established by T_3 and the rate of deposition is established by the temperatures T_2 and T_1. The excursion is complete when all the fuel returns to the steady-state configuration of figure 2(a).

METHOD OF ANALYSIS

Calculations were performed to determine the maximum fuel temperature and corresponding UO_2 loss rate as a function of time, as well as the total UO_2 loss during one complete excursion. With the emitter temperature and heat flux fixed, the volume of fuel in region A was incrementally varied and the total amounts of heat generated in regions A and B were determined. The values of T_1, T_2, and T_3 were then determined for each increment of fuel volume in region A. The outer clad surface was assumed to be adiabatic in the heat-transfer analysis, and sensible heat effects were assumed negligible. Values of T_1 and T_2 were used to calculate the heat transferred across the void and the rate at which the void moves through the fuel body (void velocity). The rate at which UO_2 is lost through the vent is established when T_3 and the corresponding UO_2 vapor pressure are known. Finally, the summation of losses for each volume increment yields the total UO_2 loss during the excursion. The calculational procedures are described in this section.

The temperature of the outer surface of fuel in region A is given by

$$T_1 = T_0 + \frac{Q_A}{2\pi Lk}\left(-\frac{1}{2} + \frac{r_1^2}{r_1^2 - r_0^2}\ln\frac{r_1}{r_0}\right) + \frac{Q_B}{2\pi Lk}\ln\frac{r_1}{r_0} \tag{1}$$

The second term on the right (eq. (1)) represents the temperature drop in region A due to internal volume heat generation, while the third term is the temperature drop associated with conduction of the heat generated in region B through region A to the emitter.

Once T_1 is known, T_2 can be determined by setting the total internal heat generation of region B equal to the net heat transferred across the void as follows:

$$Q_B = 2\pi r_1 L q(T_1, T_2)$$

or in terms of flux,

$$\frac{Q_B}{2\pi r_1 L} = q(T_1, T_2) = q_{rad} + q_m \tag{2}$$

where

$$q_{rad} = \epsilon_{eff}\sigma\left(T_2^4 - T_1^4\right) \tag{3}$$

with

$$\epsilon_{eff} = \frac{\epsilon}{2 - \epsilon}$$

and

$$q_m = m l \tag{4}$$

The net UO_2 mass flux across the void is given by

$$m = 4.37 \sqrt{M} \left(\frac{P_2}{\sqrt{T_2}} - \frac{P_1}{\sqrt{T_1}} \right)$$

which is obtained from the following equation (ref. 2)

$$m = 4.37 \sqrt{M} \frac{P}{\sqrt{T}}$$

where it is assumed that

(1) Vapor is effused from each surface as if to a void
(2) There is no scattering due to collisions in the void
(3) The sticking probability of a molecule which leaves the void and strikes the surface is unity

The assumption of no collisions in the void region also eliminates any conduction contribution to the heat transfer across the void. Substituting equations (3) and (4) in equation (2) yields

$$\frac{Q_B}{2\pi r_1 L} = \epsilon_{eff}\sigma\left(T_2^4 - T_1^4\right) + 4.37 \sqrt{M} \left(\frac{P_2}{\sqrt{T_2}} - \frac{P_1}{\sqrt{T_1}} \right) l \tag{5}$$

The value of T_2 is found by iteration. The void velocity is obtained by dividing the net mass flux m by the density of solid UO_2.

The peak fuel temperature T_3 is then calculated from the following equation:

$$T_3 = T_2 + \frac{Q_B}{2\pi L k} \left(-\frac{1}{2} + \frac{r_3^2}{r_3^2 - r_2^2} \ln \frac{r_3}{r_2} \right) \tag{6}$$

The expression used to determine UO_2 loss rate through the vent under either steady-state or transient conditions is

$$W = \sqrt{\frac{\gamma \times 10^3}{R}\left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/(\gamma-1)}} \frac{AP_3}{\sqrt{T_3}} \tag{7}$$

(ref. 3). The various vapor pressures in equations (4), (5), and (7) are calculated for a given temperature from

$$\log_{10} P = 11.429 - \frac{3.7194\times 10^4}{T} + \frac{3.5162\times 10^6}{T^2} + \frac{2.6178\times 10^9}{T^3}$$

(ref. 4). This procedure was applied at 100 points for each excursion, each point representing the time interval required to transfer 1 percent of the fuel from region B to region A (fig. 2(c)).

The following is a list of the property values of UO_2 used in the analysis:

Thermal conductivity of fuel k, W/(cm)(K)	0.02
Latent heat of vaporization for UO_2, J/g	2260
Molecular weight of UO_2, g/mole	267
Gas constant (for UO_2 vapor), J/(g)(K)	3.12×10^{-2}
Ratio of specific heat at constant pressure to specific heat at constant volume for UO_2 vapor	1.3
Emissivity of UO_2 surface	0.6
Density of UO_2, g/cm^3	10.2

Calculations were performed for converter fuel-volume fractions of 0.275 and 0.55 at heat fluxes of 50 and 100 watts per square centimeter. In all cases, the emitter temperature was fixed at 2000 K and the fueled structure length was taken to be 20.3 centimeters (8 in.).

RESULTS AND DISCUSSION

A reference case was chosen to illustrate the time dependence of temperature distributions, fuel loss, and fuel geometry. In this case, the heat flux at the emitter wall is 100 watts per square centimeter, the fuel-volume fraction of the structure is 0.275, and the vent diameter is 0.0254 centimeter (10 mils).

Variables of interest for the reference case are presented in figure 3. The first and last scales indicate the fractional volume of fuel in region A. Each of the remaining variables may be referenced to the fractional volume of fuel in region A or to each other.

As shown in scale 2, the time required for a complete fuel excursion is 1850 seconds (about 1/2 hr), but most of the fuel is redeposited on the emitter during the initial stages of the excursion. For instance, about 50 percent of the fuel is redeposited in the first 120 seconds, and over 90 percent is redeposited in the first one-half of the excursion time.

An examination of temperatures T_1, T_2, and T_3 (scales 3, 4, and 5) at random points during the excursion indicates that the sum of the temperature drops in the fuel, exclusive of the void, is nearly constant. Therefore, the difference between T_3 and the steady-state value of T_3, 2340 K, approximates the temperature drop across the void. The high initial temperature drop across the void, over 600 K, is the reason for the high initial rate of redeposition.

The velocity at which the void moves through the fuel block also serves to emphasize the rapid initial changes followed by a near equilibrium state. The void velocity decreases by a factor of 100 from its initial value during the first one-half of the excursion time.

The total heat flow across the void is directly proportional to the mass of fuel in region B. As shown by scales 10 and 11, about 80 percent of the heat flow is due to thermal radiation with the remainder being due to mass transfer. Note the rapid initial changes in heat flow across the void followed by a near steady-state condition.

The UO_2 loss rate through the capsule vent is strongly influenced by the UO_2 vapor pressure. Since vapor pressure increases rapidly as T_3 increases, the loss rate (scale 6) is initially quite high and decreases rapidly as the excursion continues. As a result, over 90 percent of the total UO_2 loss in one excursion occurs in the first half of the excursion (scale 7). This is also shown in figure 4, where the UO_2 loss rate is presented graphically for the reference case to further illustrate its time dependence.

The total UO_2 loss during the excursion is, as shown in scale 7 of figure 3, 0.007 gram. Based on a steady-state maximum fuel temperature of 2342 K, the UO_2 loss during normal operation through a 0.0254-centimeter- (0.010-in.-) diameter vent is 10.1 grams per year. The loss during a single excursion for the reference case is, therefore, less than 0.1 percent of the normal yearly loss.

The effect of converter heat flux on peak fuel temperature, excursion time, and absolute and relative UO_2 loss is shown in figure 5 for a fuel-volume fraction of 0.275 and a vent diameter of 0.0254 centimeter. As shown in figure 5(a) the peak fuel temperature varies from 2590 K at a heat flux of 50 watts per square centimeter to over 2900 K at a heat flux of 100 watts per square centimeter. The time required for a complete excursion is much greater at the lower heat flux. About 8 hours (2.7×10^4 sec) are required for an excursion at a flux of 50 watts per square centimeter, while only 1/2 hour (1.8×10^3 sec) is required at a heat flux of 100 watts per square centimeter.

The absolute UO_2 loss during an excursion is presented in figure 5(b) and, as shown, ranges from approximately 4×10^{-3} gram at a heat flux of 50 watts per square centimeter to approximately 7×10^{-3} gram at a heat flux of 100 watts per square centimeter.

As indicated in figure 5(c), the fuel loss during one excursion is insignificant compared to the loss during 1 year of steady-state operation. For example, the loss per excursion is 0.41 and 0.07 percent of the yearly steady-state loss for heat fluxes of 50 and 100 watts per square centimeter, respectively.

The 0.55 fuel-volume fraction conceptual design is considered in figure 6. Again a vent diameter of 0.0254 centimeter was assumed. As shown in figure 6(a), the time for a complete excursion decreases from almost 3 hours (1.0×10^4 sec) to about 12 minutes (7.0×10^2 sec) as the heat flux increases. At a heat flux of 50 watts per square centimeter, the peak temperature is 2770 K while at a heat flux of 100 watts per square centimeter, the peak temperature is over 3300 K, which exceeds the UO_2 melting temperature (about 3025 K). Potential problems with molten UO_2 such as incompatibility with the refractory metal clad have not been thoroughly investigated and remain as design considerations.

The absolute fuel losses during an excursion are presented in figure 6(b) for a fuel-volume fraction of 0.55. The fuel loss per excursion is 2.5×10^{-2} gram at a heat flux of 50 watts per square centimeter and 0.15 gram at a heat flux of 100 watts per square centimeter. These losses are about 15 to 450 times higher than the losses at corresponding heat fluxes for the lower fuel volume fraction case (fig. 5(b)). In contrast, the fuel losses relative to yearly steady-state losses, ranging from 0.2 percent to approximately 0.02 percent (fig. 6(c)) are at least a factor of 2 lower at the higher fuel volume fraction than the corresponding relative losses at the lower fuel volume fraction (fig. 5(c)).

The fuel loss during steady-state operation is presented in table I for each case considered. The losses presented in table I were calculated for a vent diameter of 0.0254 centimeter. As shown, the losses range from 0.8 gram per year to over 800 grams per

TABLE I. - UO_2 STEADY-STATE LOSS RATE

Element fuel-volume fraction	Emitter heat flux, W/cm^2	
	50	100
	Loss rate, g/yr	
0.275	0.85	10.1
.55	12.6	830

year. The total initial fuel inventories for the 20.3-centimeter (8-in.) reference diode length are 129 grams at a fuel-volume fraction of 0.275 and 322 grams at a fuel-volume fraction of 0.55.

Fuel losses exceeding 1 to 2 percent of the inventory may not be tolerable from a nuclear criticality and reactor control standpoint. The loss, relative to total inventory, can be reduced by decreasing the vent area and allowing the fission gas pressure in the fuel element to build up. This is illustrated in figure 7 for the reference case, fuel-volume fraction of 0.275 and heat flux of 100 watts per square centimeter. The ratio of the steady-state fuel loss for a variable vent diameter to the loss for a vent diameter of 0.0254 centimeter is presented as a function of total pressure in the element. The curves were constructed as follows: The fission gas pressure in the element was determined for several vent diameters from equation (7) by substituting the production rate of fission gas for the flow rate. The sum of the fission gas pressure and the UO_2 vapor pressure is the total pressure in the element. The UO_2 loss rate was calculated from equation (7) by using the predetermined vent diameters and the UO_2 vapor pressure. These loss rates were then divided by the loss rates for a 0.0254-centimeter vent diameter to obtain the loss ratio presented. As shown, the total pressure in the element for the 0.0254-centimeter reference vent diameter is 2.6×10^{-4} newton per square centimeter. The steady-state fuel loss can be reduced by 2 decades by allowing the total pressure in the element to reach 1.9×10^{-3} newton per square centimeter at a vent diameter of 0.00254 centimeter. The lower limit on vent diameter will be established by the creep strength of the element clad material and/or by plugging of the vent with UO_2. The absolute fuel loss during a temperature excursion also decreases in proportion to the square of the vent diameter. However, the ratio of fuel loss during an excursion to the steady-state loss is independent of vent diameter.

CONCLUDING REMARKS

The results of the study reported herein indicate that (for complete axisymmetric separation of fuel and emitter) the UO_2 loss occurring during a single thermal transient will not significantly increase the overall UO_2 loss incurred in a representative vented externally fueled reactor system. Specifically, for the reference case, fuel-volume fraction of 0.275, emitter heat flux of 100 watts per square centimeter, and vent diameter of 0.0254 centimeter, calculations showed that the UO_2 loss during one excursion was 0.007 gram, which is less than 0.1 percent of the loss calculated for 1 year of normal steady-state operation. It was also shown that a complete excursion takes place, for the reference case, in approximately 1/2 hour.

When these results are evaluated, several factors should be kept in mind. First, for calculations of the rate of redeposition of fuel on the emitter wall the effect of collisions of particles in the void region was not considered. Vapor pressures as high as 0.006 newton per square centimeter are realized in the void region at the start of an excursion, while the equations used to describe mass transfer are strictly true only at pressures of 1×10^{-5} newton per square centimeter or less. Collisions would tend to decrease the redeposition rate, increase the excursion time, and increase the UO_2 loss.

Second, sensible heat effects were not considered in the analysis. The addition of sensible heat terms to the heat transfer equations would give lower peak outer fuel surface temperatures and longer excursion times than predicted. However, these two results have offsetting effects on fuel loss and preliminary calculations indicated that the inclusion of sensible heat effects would not significantly influence the calculated fuel loss per excursion.

In addition, it is not possible to determine analytically the frequency at which excursions will occur. If several excursions of the type considered occurred during the mission, the effect on fuel loss would be insignificant. However, if a repetitive series of fuel-emitter separations took place, the overall fuel loss would be significantly increased. For example, in the reference case such an instability would result in a yearly fuel loss of 123 grams, which is over 12 times greater than the calculated steady-state loss.

Also, since some degree of bonding will exist at the fuel-emitter interface, it is unlikely that complete axisymmetric separation of the fuel from the emitter will occur. A partial fuel-emitter separation will result in higher than steady-state temperatures over part of the outer fuel surface, resulting in high local vapor pressures. The fuel loss rate, established by the vapor pressure at the vent, would then depend on the position of the vent relative to the separated region.

SUMMARY OF RESULTS

The following results were obtained from a study of uranium dioxide (UO_2) loss in a vented, externally fueled converter during a single thermal transient. In the calculations, the emitter temperature was fixed at 2000 K, and complete axisymmetric separation of the fuel and emitter, followed by complete redeposition of the fuel on the emitter, was assumed.

1. Total UO_2 loss during a single excursion for a vent diameter of 0.0254 centimeter

Element fuel-volume fraction	Emitter heat flux, W/cm^2	
	50	100
	Absolute fuel loss, g	
0.275	3.65×10^{-3}	7.0×10^{-3}
.55	2.5×10^{-2}	.15

2. Ratio of UO_2 loss during a single excursion to steady-state loss during 1 year of operation

Element fuel-volume fraction	Emitter heat flux, W/cm^2	
	50	100
	Relative fuel loss	
0.275	4.1×10^{-3}	7.0×10^{-4}
.55	2.0	1.8

3. Peak fuel temperature

Element fuel-volume fraction	Emitter heat flux, W/cm^2	
	50	100
	Peak fuel temperature, K	
0.275	2590	2930
.55	2770	3310

4. Time for complete excursion

Element fuel-volume fraction	Emitter heat flux, W/cm^2	
	50	100
	Excursion time, sec	
0.275	2.7×10^4	1.8×10^3
.55	1.0×10^4	7.0×10^2

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 27, 1968,
120-27-06-06-22.

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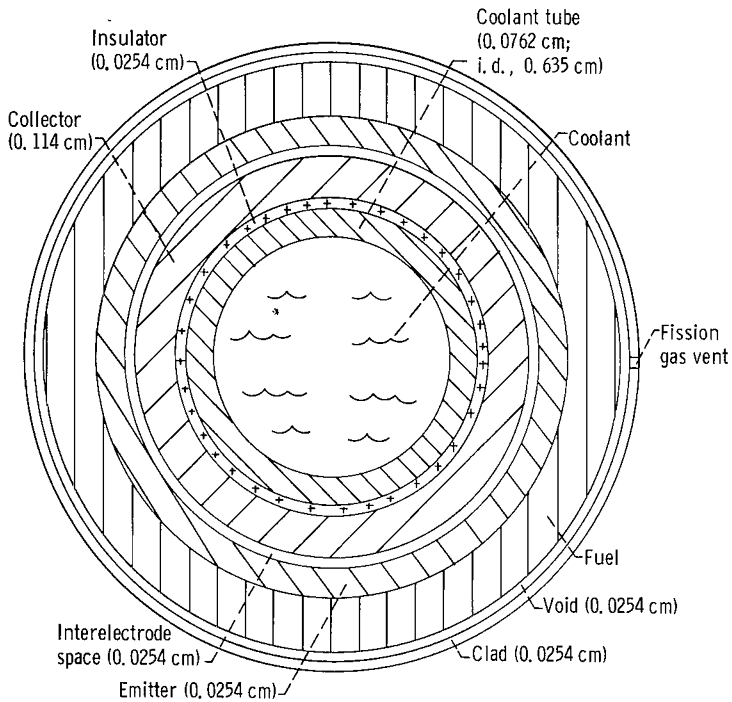
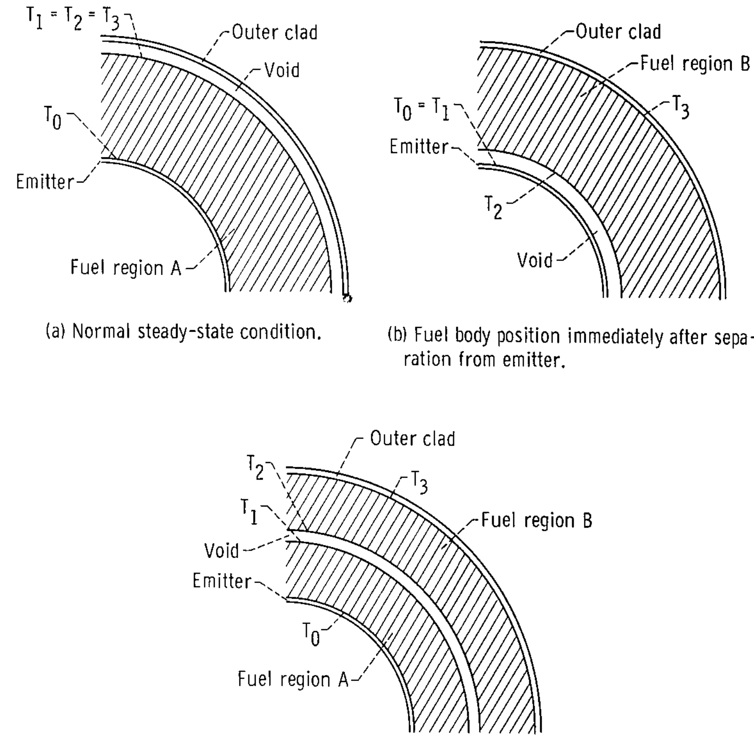


Figure 1. - Cross section of 8 inch long (20.3 cm) externally fueled cylindrical thermionic converter. Fuel thickness, 0.1396 centimeter for f_f of 0.275; 0.3374 centimeter for f_f of 0.55.



(a) Normal steady-state condition.

(b) Fuel body position immediately after separation from emitter.

(c) Fuel body position at intermediate point in excursion.

Figure 2. - Behavior of fuel body during both steady-state operation and temperature excursion.

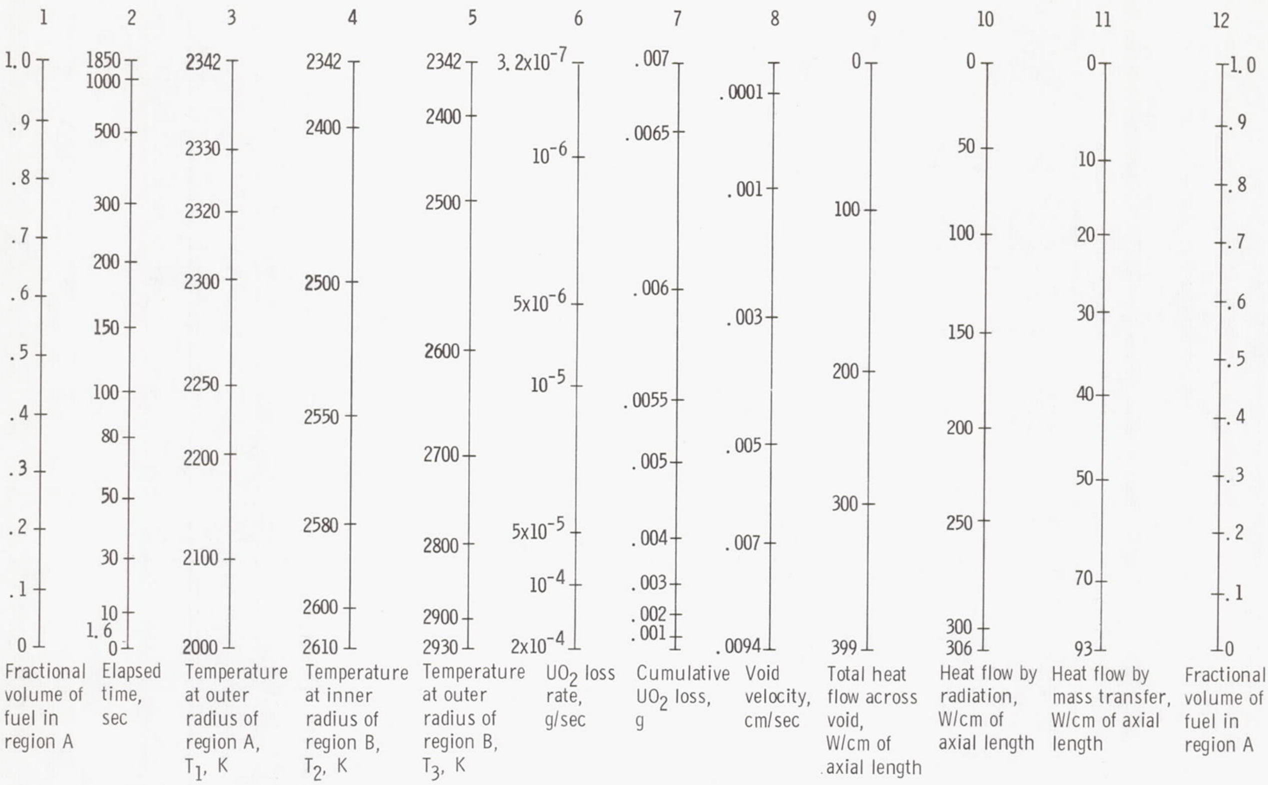


Figure 3. - Principal variables calculated for reference case. Fuel-volume fraction, 0.275; emitter heat flux, 100 watts per square centimeter; vent diameter, ±0.0254 centimeter (10 mils).

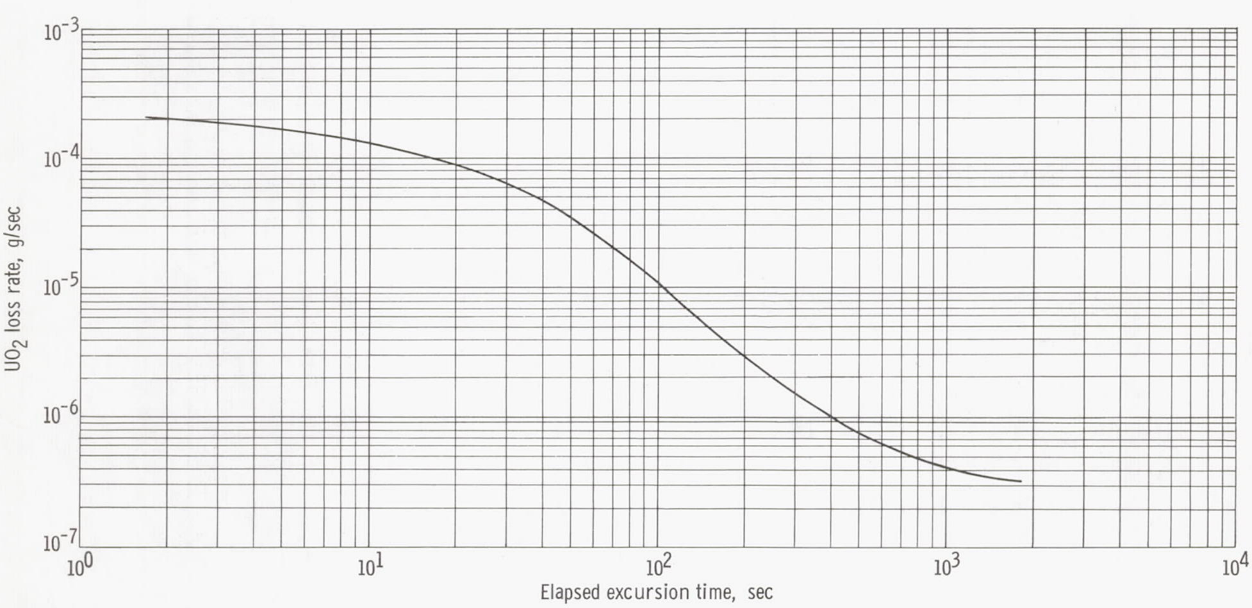


Figure 4. - Fuel loss rate for reference case. Fuel-volume fraction 0.275; emitter heat flux, 100 watts per square centimeter; vent diameter, 0.0254 centimeter (10 mils).

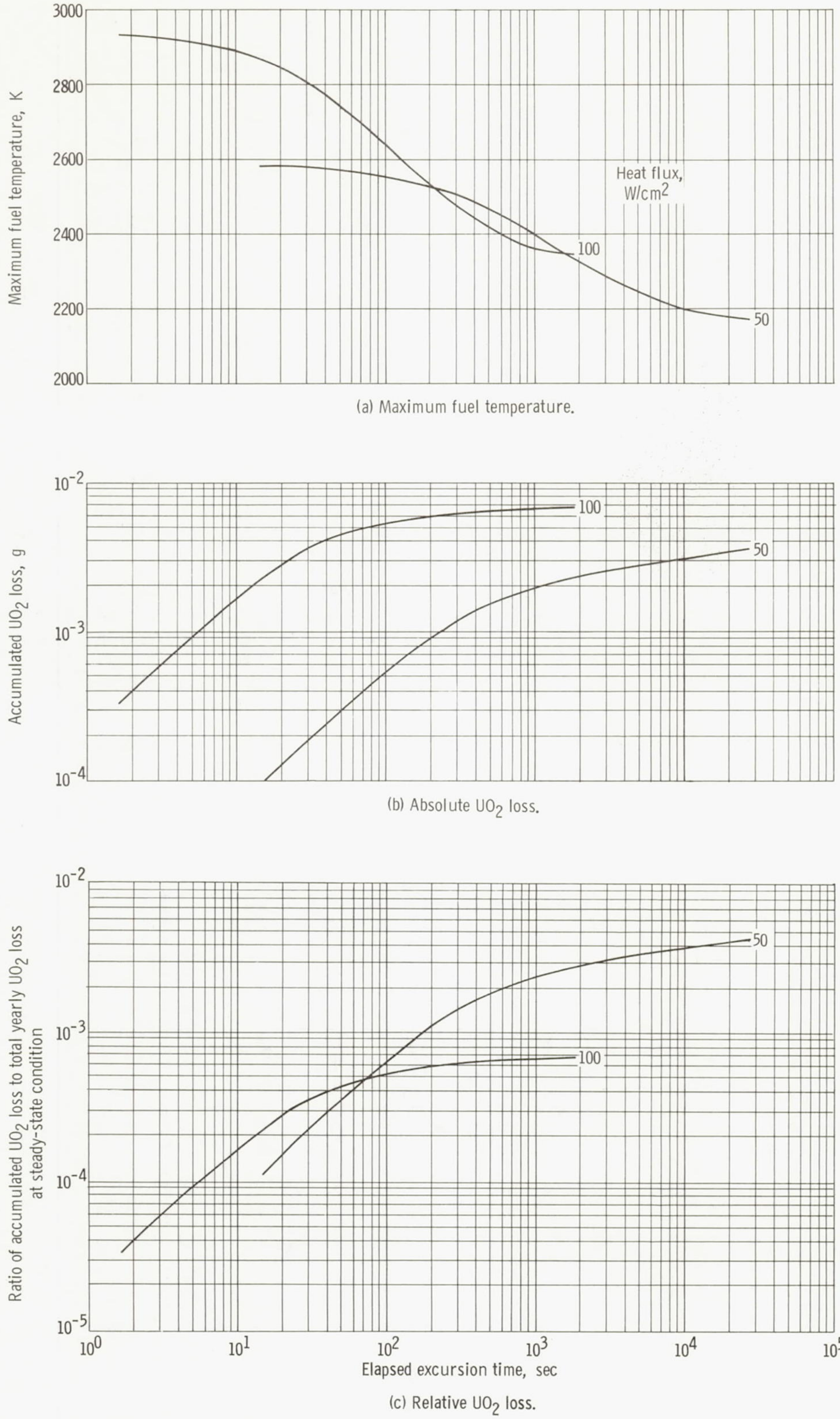


Figure 5. - Time dependence of maximum fuel temperature and cumulative UO_2 loss for a fuel-volume fraction of 0.275 and vent diameter of 0.0254 centimeter (10 mils).

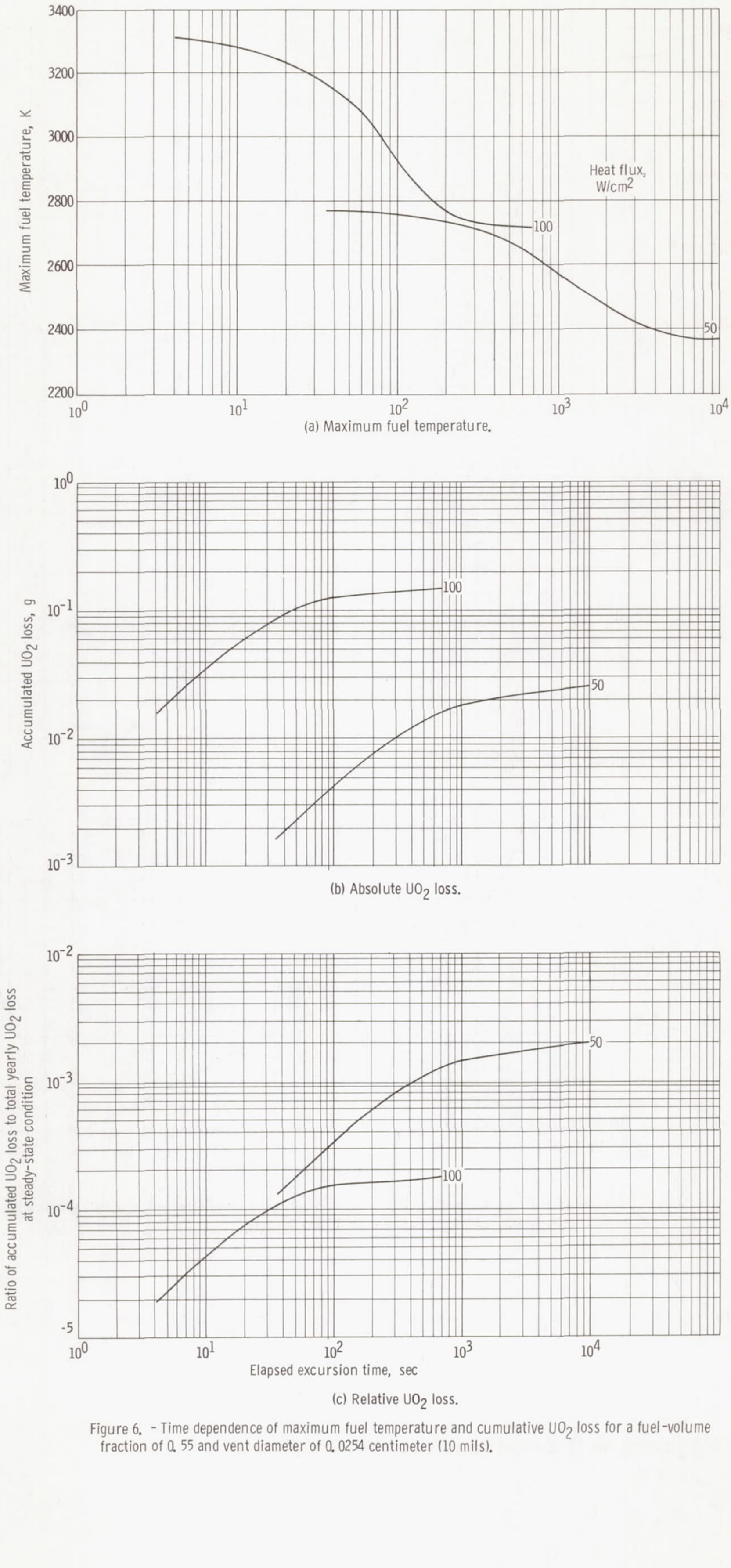


Figure 6. - Time dependence of maximum fuel temperature and cumulative UO_2 loss for a fuel-volume fraction of 0.55 and vent diameter of 0.0254 centimeter (10 mils).

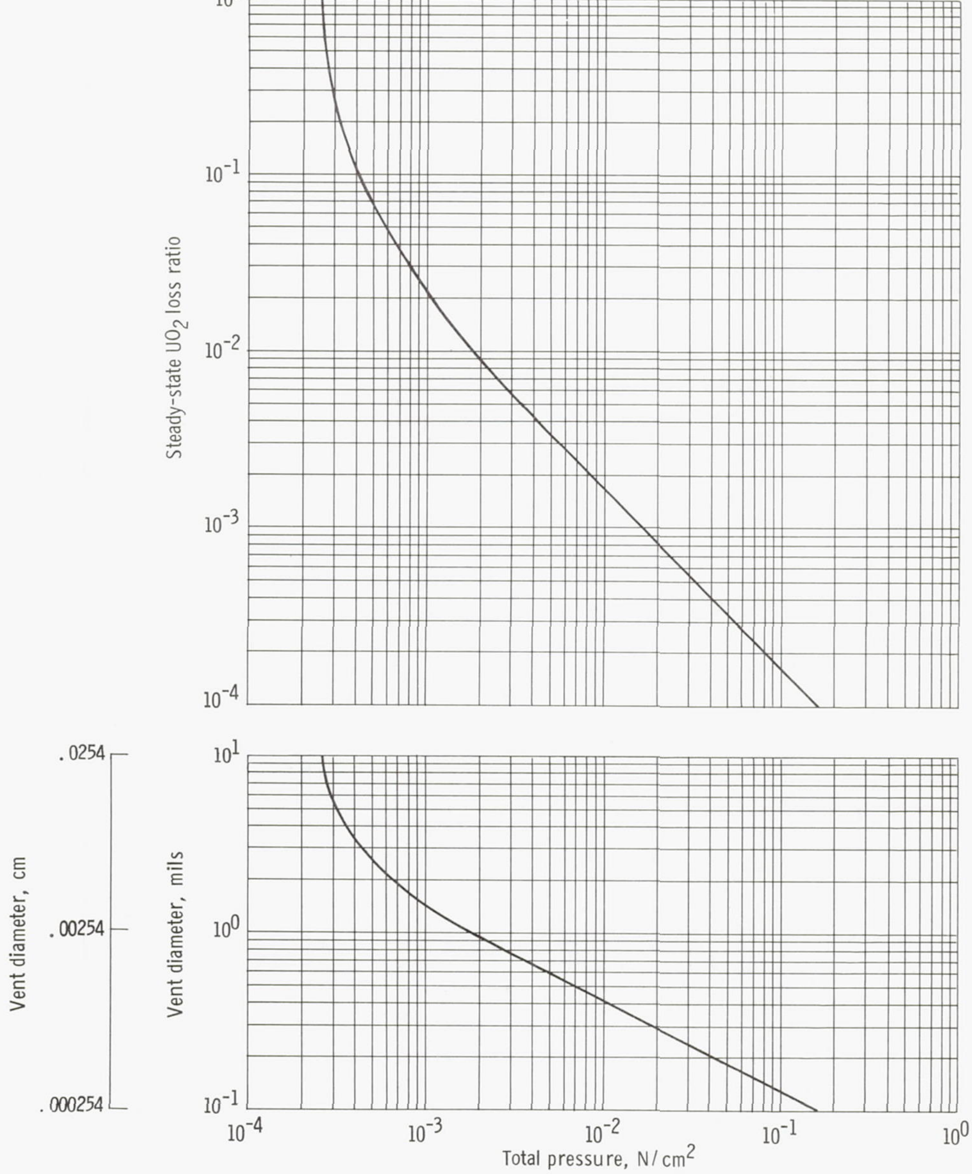


Figure 7. - Steady-state UO_2 loss referenced to loss through 0.0254-centimeter vent as function of total pressure in fuel element.

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