Multiphase Nuclear Fuel Cavity Reactor for Power Generation

B. PINKEL* AND E. C. GRITTON†
The Rand Corporation, Santa Monica, Calif.

Theme

AN exploratory analysis is made of the cavity-type nuclear reactor with the fissile material (uranium or plutonium) in the various possible combinations of solid, liquid and gaseous states to determine whether a regime exists in which heat generation rates attractive for electric power systems are indicated and in which materials, and other practical problems which appear tractable.

Contents

A study of a cavity reactor for electric power systems, in which the fissile material is entirely in the gaseous phase, was reported in Ref. 1. It was necessary in that reactor to hold the cavity wall temperature above the boiling point of the fissile material and, although there was little information on the interaction between fissile gas and solid materials at that temperature, it was suspected that the interaction would be unacceptably large for long-term operation. When the wall temperature is progressively dropped, the fissile material condenses as a liquid film on the wall and eventually hardens into a solid film. The present study explores whether an attractive operational regime exists at these reduced temperatures, where part or all of the fissile material is in the solid or liquid film.

The study was made on a spherical cavity. Because the fissile film thickness is small compared with the cavity reactor, a one-dimensional analysis of the heat flow, as indicated in Fig. 1, was employed. Most of the analysis is made for a reference reactor having the following parameters: the cavity radius is 5 ft (152.5 cm), the fissile material content is 200 kg U^{235}, the cavity container wall is molybdenum with a wall thickness L_w of 0.10 cm and a thermal conductivity of 1.0×10^{-6} Mw/cm°C, the mean coolant temperature (lithium) is 350°C (662°F), while the coolant surface heat-transfer coefficient is 1.0×10^{-5} Mw/cm²°C. The effects on reactor performance of variation (with respect to the reference parameters) in reactor size, uranium content, fissile material, container material, and coolant heat-transfer coefficient are also investigated.

The outside wall surface of the cavity container (see Fig. 1) was assumed to be cooled by lithium flowing at a velocity of about 50 ft/sec. The temperature T_1 at the interface between the container wall and the fissile film is important because it controls the rate of penetration of the fissile material into the container wall. The temperature T_3 at the free surface of the fissile film controls the amount of fission debris retained in the film. The higher T_3, the greater the percentage of fission debris evaporated into the cavity space from which it can be continuously removed in a cleansing cycle and, therefore, the greater is the operating duration before the reactor must be shut down for removal of the residual fission debris. (Fissile material burn-up can, of course, be compensated by the continuous introduction of fissile material into the cavity during operation.)

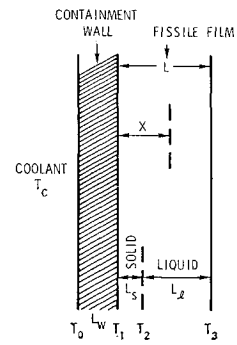

Fig. 1 Film model for one-dimensional heat flow analysis.

Figure 2 shows the thermal power as a function of T_1 and T_3 for a 5-ft radius reactor having a uranium content of 200 kg. Vertical lines are shown at the following temperatures: 1130°C (2065°F), melting point of uranium; 3564°C (6452°F), boiling point of uranium at 1 atm of pressure (Ref. 2); 4650°C (8401°F), boiling point of uranium at nine atmospheres of pressure (Ref. 2). It is arbitrarily assumed in Fig. 2 that the gaseous phase starts at $T_3 = 3564$°C where the vapor pressure of uranium is one atmosphere. The zones in which the various uranium state combinations occur are indicated in Fig. 2. The dashed line marked $L_w = 0.10$ cm shows how the performance of the reference reactor cuts through these zones as T_1 and T_3 are changed.

The reactor performance at the zone boundaries in Fig. 2 is listed in Table 1. Point A, where the $L_w = 0.10$ cm line crosses the $T_3 = 1130$°C line, represents the highest power attainable with the uranium all contained in a solid film on the wall. Although an interesting power level is obtained in

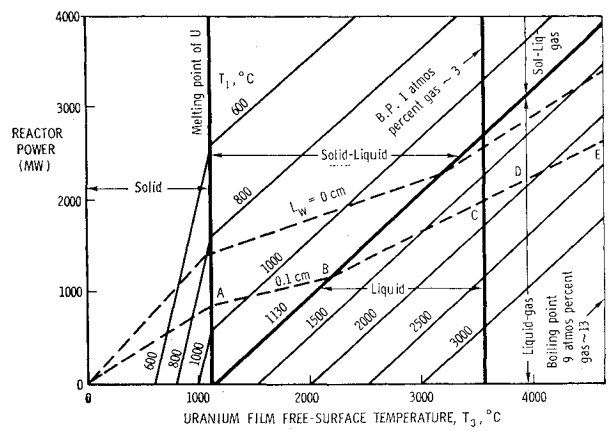

Fig. 2 Composite plot of power of reference cavity reactor for various fuel states.

Presented at the 2nd Symposium on Uranium Plasmas: Research and Applications, Atlanta, Ga., November 15–17, 1971; submitted December 10, 1971; revision received July 5, 1972. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $1.00; hard copy, $5.00. Full paper also is included in bound volume of symposium preprints, which is available from AIAA, 1290 Avenue of the Americas, New York, N.Y. 10019. Price: $28.40. Full paper also is Rand Corp. Rept. R-890, April 1972. Price: $3.00.

Index categories: Electric Power Generation Research; Spacecraft Electric Power Systems.

* Staff. Associate Fellow AIAA.
† Staff.

Table 1 Illustrative reactor powers and temperatures for the reference reactor[a]

	Reactor power (Mw)	T_1 °C	T_2 °C	Fuel phase, % Solid	Liquid	Gas	Uranium pressure atmos[b]
A	875	950	1130	100	0	0	–
B	1140	1130	2160	0	100	0	–
C	2025	1738	3564	0	97	3	1
D	2170	1840	3800	0			
E	2710	2204	4650	0	87	13	9

[a] Radius 5 ft, U^{235} content 200 kg, $L_w = 0.10$ cm.
[b] The vapor pressures are very small for *A* and *B*.

this mode of operation, unfortunately most of the fission debris is retained in the solid uranium film, and thus would cause shutdown of the reactor in roughly several months.

Point B, where the $L_w = 0.10$ cm line crosses the $T_1 = 1130$°C line, represents the lowest power at which all of the uranium is in the liquid state. At this point, the fission debris retention in the uranium film is still excessive. Points C and E represent the performance where the $L_w = 0.10$ cm line crosses the vertical lines at $T_3 = 3564$ and 4650°C, respectively (the increased amounts of the uranium in the gaseous phase are noted). Interpolated between these two points is point D at which $T_3 = 3800$°C. This point is of special interest because at a free surface temperature of 3800°C, most of the fission debris is boiled from the liquid film into the cavity, from which it may be removed in the cleansing cycle. Only Mo^{95} and Tc^{99} and their derivatives by neutron absorption remain in the film. At this condition, operation for durations of five years or more may be permitted before stoppage for fission debris removal is required.

The wall temperature T_1 corresponding to point D is 1840°C. It may be possible to find ceramic coatings capable of resisting penetration by uranium at this temperature. However, ceramic coatings that will adhere and not crack under thermal cycling conditions are difficult to develop. The metallic material which the literature indicates is most resistant to penetration by uranium is tungsten. Even in the case of tungsten, it is necessary to reduce the wall temperature T_1 to 1130°C to obtain adequate operational life for the wall. The value of T_1 can be reduced to 1130°C while still maintaining T_3 at 3800°C by increasing the reactor uranium content from 200 kg to about 500 kg (see Fig. 3). Unfortunately, natural tungsten has an excessively high neutron capture cross section. The tungsten isotope 184 has a low capture cross section, but its separation cost is high. The use of molybdenum for the cavity container wall with tungsten as a protective surface coating may be a practical compromise. The decrease of T_1 to 1130°C results in a decrease in reactor power to 1140 Mw. Thus, from the standpoint of resistance of the wall to uranium penetration and long operational duration before shutdown by fission debris poisoning, the combination of $T_1 = 1130$°C and $T_3 = 3800$°C constitute an interesting operational regime.

In space applications of the reactor, flow of the uranium

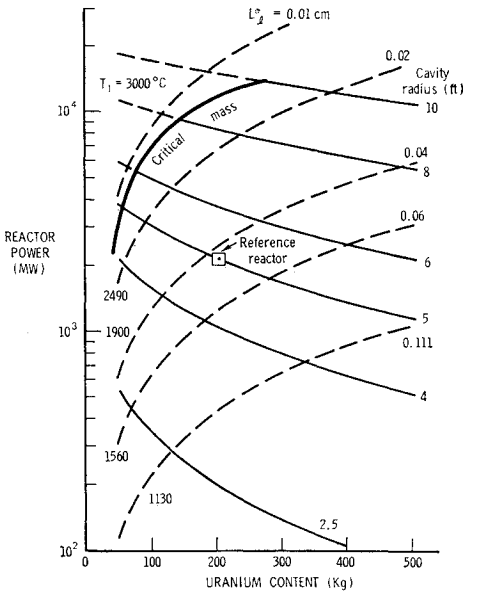

Fig. 3 Effect on reactor power of variation in uranium mass and cavity radius for $T_3 = 3800$°C.

liquid along the reactor wall would not be a problem under nonaccelerating conditions. However, in terrestrial applications, flow of uranium along the wall under the influence of gravity would be appreciable when a large part of the uranium content of the reactor is in the liquid film. It may be possible to impede this flow by the use of a surface mesh. Furthermore, although not analyzed in this report, dynamic systems in which the liquid uranium flows along the wall to the bottom of the reactor where it vaporizes and redeposits on the wall (of the type suggested by Rom[3]) may be feasible.

The smaller reactor critical mass possible when U^{233}, rather than U^{235}, is employed is not a significant advantage in the present application. Plutonium 239 boils at a much lower temperature than U^{235}, and hence the temperature T_3 of 3800°C desired for fission debris removal would be accompanied by excessive vapor pressure. Therefore, little is to be gained by operating with anything other than U^{235} as the fissile material. Variation in the other parameters explored did not change the broad implications of this study.

References

[1] Gritton, E. C. and Pinkel, B., "A Gaseous-Core Reactor Concept for Electric Power Generation," *Nuclear Applications and Technology*, Vol. 8, April 1970, pp. 355–369; also RM-5721-PR, June 1969, The Rand Corp., Santa Monica, Calif.

[2] Randol, A. G., III and Schneider, R. T., "Experimental Determinations of the Boiling Point of Uranium," *Transactions of the ANS*, Vol. 12, No. 2, Nov. 1969, pp. 541–452.

[3] Panel discussion on "Directions and Needs for Future Research on Uranium Plasmas and Their Technological Applications," Univ. of Florida, Gainesville, Fla., Jan. 7–8, 1970, NASA SP-236, p. 404.