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EVALUATION OF CRITICAL MASS FOR OPEN-CYCLE, GAS-CORE ROCKET REACTORS

by Robert E. Hyland
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TECHNICAL PAPER proposed for presentation at
Sixteenth Annual Meeting of the American Nuclear Society
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2. Nuclear propulsion system

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

A nuclear analysis using transport theory was made of an open-cycle gas-core reactor for assumed operating conditions. Calculations were made for cavity diameters from 8 to 16 feet, for hydrogen (cavity) bypass variation from 0 to 99 percent, for reflector thickness from 2 to 3.5 feet, and for both isotopes ^{235}U and ^{233}U as fuel. For these configurations the results indicated that ^{233}U and some bypass hydrogen may be necessary to keep critical mass levels low enough to give system pressures of less than 1000 atmospheres.

SUMMARY

A criticality study was performed for an open-cycle gas-core reactor to determine the critical mass (uranium fuel) required. The basic design considered was a spherical geometry with an inner variable fuel diameter, a structural wall (equivalent of 0.1 in. molybdenum), and an external three region moderator-reflector (D_2O, Be, and D_2O). The analysis was performed with an S_n transport code TDSN with a 19 energy group structure and S_4 angular approximation. The critical mass was determined as a function of fuel-to-cavity radius ratio (0.55 to 0.75), cavity diameter (8 to 16 ft), hydrogen bypass (0 to 99 percent), reflector overall thickness (2 to 3.5 ft) and for uranium isotopes ^{235}U and ^{233}U.

The critical masses were compared to those of an engine parametric study. The following results for the above configurations were obtained:

(1) The use of ^{235}U as a fuel produces critical masses that would require pressure levels above 1000 atmospheres.

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The use of ^{233}U as a fuel reduces the critical mass approximately 40 percent and results in critical mass that could allow cavity pressure levels less than 1000 atmospheres.

(3) Bypassing a fraction of the hydrogen propellant around the cavity lowers critical mass because of the reduced neutron up-scattering and absorption by hot hydrogen.

(4) Cavity diameters much greater than 16 feet in diameter offer limited return on reducing pressure because of the rapid increase in fuel required which results in a leveling off of fuel density.

(5) Reflector (basically D_2O) thicknesses between 2 and 3 feet offer the most reduction in critical mass.

(6) It is necessary to maintain fuel-to-cavity radius ratios greater than 0.6 in order to have cavity pressures less than 1000 atmospheres.

INTRODUCTION

The feasibility of the open-cycle gas-core reactor as proposed for propulsion is highly dependent on the answers to two questions. The questions are (1) how much uranium flows out of the cavity relative to propellant, and (2) is the pressure level low enough to be practical so that the powerplant weights would not greatly exceed the thrust level? The answer to the first question is primarily a hydrodynamics problem. Progress in this area has been reported in references 1 to 3. These studies have shown that large improvements in hydrogen flow rates relative to uranium flow rates are possible while maintaining a sufficient volume of uranium fuel for criticality.

The answer to the second question involving realistic pressure levels is directly related to the critical mass requirement. For a given volume, the higher the critical mass, the higher the pressure. Thus, a good determination of critical mass is necessary to determine feasibility. Ragsdale, in reference 4, has presented the effect of parametrically varying the fuel mass on engine parameters. He found that engine performance was highly dependent on critical mass requirements. Many cavity reactor critical experiments have been performed to determine the critical mass under a wide variety of conditions. Those experiments which are basically all for isothermal room temperature conditions are reported in references 5 to 9, and partially summarized in reference 10.

The purpose of this report is to calculate the critical mass for an operating hot "reference" engine, which cannot, at present, be experimentally determined. The analysis is patterned after one used in reference 1 to analyze the experimental results. The reference cavity size is one used in reference 4, and the effect of variations in cavity size, fuel-to-cavity radius ratio, reflector thickness and percent of hydrogen bypass flow on critical mass are presented. Because of the desire to obtain low critical mass, the effect of using uranium-233 as a fuel instead of uranium-235 was also explored.

ANALYSIS

Description of Reactor

The open-cycle gas-core reactor as considered in the past had been based on coaxial flow. Typically, the geometry considered has been cylindrical. However, when more recent concepts such as the porous wall system, reference 1, and the required high pressures, reference 4, are considered, the geometry most acceptable is one that is basically spherical. Figure 1 illustrates the open-cycle gas-core reactor reference engine that is presently being investigated. The reflector consists of three regions. The inner region is D_2O with sufficient thickness to help minimize critical mass, but without taking all of the gamma-neutron heating load. The second region is composed of a higher temperature material, which acts as a main heat barrier for gammas. Its thickness is the minimum required to provide a high temperature region for the deposition of gamma energy. From a moderator-reflector viewpoint, D_2O would be preferable but because of its low operating temperature, an additional heat exchanger would be required. The outer reflector is composed of D_2O to make up the remaining required thickness. The total reflector thickness is established by a trade off between critical mass and total engine weight.

The cavity region contains the uranium gas and propellant (H_2). The propellant flows around the heavier uranium gas and establishes a low velocity pocket for the uranium fuel. It has been shown in reference 12 that only a portion of the total hydrogen is needed to pick up the thermal radiation, which is the primary heat-transfer mode, from the hot uranium gas. The remaining hydrogen flow is introduced downstream where it is used for secondary cooling of the walls and the exhaust nozzle.

The average temperatures for the various regions that were assumed are given in table I. These conditions correspond to a gas-core engine with a specific impulse of 1800 seconds and thrust level of 500,000 pounds.

TABLE I

Fuel temperature, $^{\circ}R$	80,000
Propellant temperature, $^{\circ}R$	12,000
Cavity wall, $^{\circ}R$	2500
Inner D_2O reflector, $^{\circ}R$	800
High temperature reflector, $^{\circ}R$	1500
Outer D_2O reflector, $^{\circ}R$	660

The reference dimensions of the cavity are shown in table II. The values of cavity diameter, fuel-to-cavity radius ratio, and the thickness of the outer D_2O region were varied about the reference values indicated in the table.

TABLE II

Cavity diameter, ft	12
Fuel radius to cavity radius	0.67
Fuel to hydrogen atom ratio (in fuel region)	2:1
Cavity wall thickness (assumed to be Mo), in.	0.1
D_2O inner region, in.	6
Be reflector, in.	4
D_2O outer region, in.	20

Method of Calculation

As was shown in an analysis, reference 11, of an experimental gas-core critical, the use of two dimensional S_n transport equations requires long running time (20 hr for a single calculation). Since the geometry for this design is spherical, one dimensional geometry is used. The effect of the exit nozzle will be discussed later.

The energy group structure was the same as used in reference 11 with a total of 19 groups. GAM-II and GATHER-II were the source of cross sections and the temperature assigned for GATHER-II was the average temperature for each region. The reactor code used was TDSN, reference 13. The S_4 angular approximation was used because it gave good agreement, reference 11. The method was applied in reference 11 and also for predicting critical mass of a spherical geometry critical experiment shown in figure 2. The experimental critical mass was 8.3 kilograms of ^{235}U contained in UF_6 gas. The analysis predicted a mass of 9 kilograms.

In performing a parametric study on criticality, knowledge of uranium worth at various loadings of fuel was used in determining the critical mass for cases where the reactor is not quite critical. Figure 3 shows the results of all experiments conducted on the cavity reactor. The curve shows uranium worth as percent of ΔK per kilogram of fuel. With this curve it was necessary to calculate only single loadings of fuel for various configurations, and then apply the correction of the number of kilograms to achieve the desired increase or decrease in K. This method was checked for several configurations by a rerun of the calculation. These cases were in good agreement.

The fuel to cavity radius ratio was varied from 0.55 to 0.75. The cavity diameter was varied from 8 to 16 feet, and the reflector thickness was varied from 2 to 3.5 feet. All combinations were not calculated, but sufficient calculations were performed to establish basic effects of each of the variables.

As noted earlier, not all of the hydrogen is needed to absorb the radiated heat, so the percentage of the total hydrogen flow passing through the cavity was varied from 100 to 1 percent.

The exhaust nozzle hole as shown in figure 4 was not included in the calculation. However, an experimental measurement of nozzle "worth" has been made for a 1 foot diameter hole through a 3 foot reflector of D_2O on a cavity of 6 feet in diameter by 4 feet in length. The results reported in reference 5 showed that an unfueled hole was worth -0.698 percent ΔK. An amount of fuel representative of the amount that would be present in the gas flowing through was placed in the exhaust hole and was worth +0.636 percent ΔK. Because these effects are small and tend to cancel, no effect on reactivity was assumed for the exhaust nozzle in the present calculations.

In addition to uranium-235, uranium-233 was also considered in order to determine how much reduction in critical mass could be obtained.

RESULTS

As pointed out in the introduction, Ragsdale (ref. 4) indicated that in order to maintain pressure levels of 1000 atmospheres or less, the fuel (uranium) mass in a 12 foot diameter cavity should be approximately 50 kilograms or less. To establish what the critical mass requirement would be, calculations on geometries similar to those of reference 4, as shown in figure 1 and 4 of this report, were conducted.

Reference Configuration Results

The initial calculations were performed on the reference configuration (table II) with uranium-235 as the fuel. In the first calculation all of the hydrogen was passed through the cavity. A guess of 60 kilograms of U-235 was selected for the TDSN code. The eigenvalue, or criticality factor, generated was 0.891. Using the experimental results of figure 3, a uranium worth of 0.1 percent ΔK per kilogram of fuel was selected. This indicated a critical mass of approximately 170 kilograms was necessary. This was well in excess of the 50 kilogram value considered to provide a pressure of 1000 atmospheres in reference 4. In order to reduce the critical mass, two approaches were selected. One approach was to decrease the amount of hydrogen in the cavity so as to decrease the absorpiton and up-scattering caused by the hydrogen in the cavity between the uranium and the moderator. The second approach was to use U-233 as the fuel because it has a much higher fission absorption probability per atom. A combination of these methods was also investigated.

The results of these changes are presented in table III. The use of uranium-233 isotope results in a substantial reduction (>50 percent) in critical mass with all hydrogen ($\rho = 1.2\times10^{21}$ atoms/cm^3) through the cavity. For lower percents of hydrogen, the reduction in critical mass is approximately 40 percent for ^{233}U over ^{235}U. The remainder of the configurations discussed in this report use ^{233}U as the fuel and 10 percent hydrogen flow in the cavity (90 percent bypass).

TABLE III. - CRITICAL MASS FOR BASIC CORE WITH ^{235}U AND ^{233}U, KILOGRAMS

Fuel, percent H_2 bypass	^{235}U	^{233}U	^{233}U (50 percent) - ^{235}U (50 percent)
0	~170	66	>100
90	74	46	60
99	70	44	55

Neutron Balance for Basic Configuration

It is interesting to note the effect on the neutron balance. The neutrons are either absorbed by the various nuclei present or leak out of the system. If a neutron is absorbed, it can either cause a fission (productive) or not (nonproductive). In the calculation all neutrons must be accounted for from birth to final process (i.e., from fission to either absorption or leakage). A neutron balance for the basic configuration is presented in table IV. In this table we see the comparison between ^{233}U and ^{235}U for both 100 percent hydrogen ($\rho = 1.2\times10^{21}$ atoms/cm^3) in the cavity (zero bypass flow) and 1/10 of that value (90 percent bypass flow).

It is of interest to note that a high fraction of the absorption is due to the 0.1 inch molybdenum wall. Approximately 18 to 22 percent of the neutrons leak out of the system which indicates that some reduction in critical mass could be made by increasing the reflector thickness above the reference value. This point will be discussed later.

TABLE IV. - NEUTRON DISTRIBUTION BALANCE

BASIC REACTOR CONFIGURATION

Neutron losses	U^{235}	U^{233}	U^{235}	U^{233}
	No H_2 bypass		90% H_2 bypass	
Absorption -				
(Fuel)	0.4770	0.4230	0.4861	0.4431
(H_2)	.0530	.0640	.0053	.0062
(Mo)	.1770	.2000	.1743	.1948
(D_2O)	.0480	.0516	.0536	.0564
(Be)	.0671	.0718	.0757	.0795
Leakage	.1779	.1896	.2050	.2200
Total	1.0000	1.0000	1.0000	1.0000

The effect of reducing hydrogen flow through the cavity resulted in a linear reduction of neutron absorption by hydrogen (i.e., factor of ten reduction in hydrogen resulted in factor of ten reduction in absorption). However, in order to maintain the neutron balance, the neutron leakage increased and the neutron absorption by fuel D_2O and Be increased. Notice that in contrast to the increase in absorption by Be and D_2O, the absorption by the molybdenum wall decreased with the decreased amount of hydrogen which indicates that there was a decrease in the moderation effect by the hydrogen. It should be pointed out that since the hydrogen moderates neutrons, some significant up-scattering by hot hydrogen of the cooler neutrons from the D_2O occurs in hot cavity reactors. The uranium mass using isotope 233 is not affected by up-scattering as much as the isotope 235 because the cross sections do not fall off as rapidly with increased neutron energy. The use of uranium-233 should lead not only to a lower critical mass but also to a more constant critical mass over a wide temperature range (start to operating conditions).

Cavity Diameter Variations

The variations of critical mass and critical fuel density with cavity diameter are shown in figure 5. For these calculations with ^{233}U as the fuel, the reference geometry, table II, was held fixed, except for the cavity diameter. The density of hydrogen in the cavity region between the fuel and the wall was 1.2×10^{20} atoms/cm^3. This density represents 10 percent (90 percent bypass flow) of the hydrogen at 500 atmospheres or 5 percent (95 percent bypass flow) at 1000 atmospheres for the assumed average temperature.

The curves in figure 5 indicate that cavity diameters much greater than 16 feet may not be desirable. Even though critical mass increases with increasing diameters, the critical fuel density decreases. However, the fuel density seems to be leveling off at 16 feet or higher and, therefore, the cavity pressure would tend to level off.

Reflector Thickness

When the reference configuration, table II, was calculated with the thickness of the outer D_2O region as the variable, the results shown in figure 6 were obtained. Below 2 feet of reflector thickness the critical mass increases rapidly. Above 3 feet little reduction in critical mass is obtained. The Be portion of the reflector was fixed in thickness at 4 inches. The thickness of the inner D_2O was selected based on experimental data, reference 5. The data indicated that the loss due to Be replacing D_2O is minimized if 4 inches of D_2O is placed between the Be and cavity. However, since the D_2O is at a higher temperature and density than the experiment, 6 inches of D_2O was selected for the inner region between the cavity wall and the Be.

Some Be reflector coolant (H_2) was included in the calculation. The hydrogen atom density was 1.2×10^{20} atoms/cm^3. The average temperature for the Be was assumed to be 1500° R. The temperature of the inner D_2O was 800° R, and the outer D_2O was 660° R. The inner D_2O region also contained a small amount of hydrogen, at a density of 0.42×10^{21} atoms/cm^3 to account for some coolant to cavity wall and a normal low percent for H_2O in D_2O.

Variation in Fuel Radius Within Fixed Cavity

With the reference geometry, table II, fixed, the fuel radius was varied. This was done for a hydrogen density of 1.2×10^{20} atoms/cm^3 in the cavity propellant region (10 percent H_2 at 500 atm, 90 percent bypass flow). The critical mass for a range of fuel-to-cavity radius ratios of 0.55 to 0.75 are shown in figure 7. The critical mass increases rapidly with decreasing radius ratio. Values of 50 kilograms of ^{233}U are achieved for radius ratios greater than 0.63. For 100 percent hydrogen through the cavity (no bypass flow), a value of 66 kilograms was obtained at a radius ratio of 0.67. This radius ratio is about the value that was used in the experiments, and that was used in the engine calculations of reference 4.

SUMMARY OF RESULTS

A parametric analytical study of critical mass requirements was performed on open-cycle gas-core reactor engine configurations. The parametric analysis was performed about a reference geometry. The reference spherical cavity reactor selected contained a 12 foot diameter cavity inside of a combination reflector-moderator of D_2O and Be. Both ^{235}U and ^{233}U isotopes were used as fuel. Variations of hydrogen density (corresponding to varying amounts of hydrogen in bypass flow), fuel-to-cavity radius ratio, reflector thickness, and core diameter were analyzed.

The following major results were obtained:

1. The use of ^{235}U as a fuel may produce critical masses in excess of the mass necessary to allow pressure levels below 1000 atmospheres in a 12 foot diameter cavity.

2. The use of ^{233}U as a fuel reduces the critical mass approximately 40 percent below that of ^{235}U, and results in critical masses that correspond to cavity pressures less than 1000 atmospheres.

3. A reduced hydrogen density in the cavity lowers critical mass because of the reduced neutron up-scattering and absorption by hot hydrogen.

4. Cavity diameters much greater than 16 feet in diameter will probably not yield lower cavity pressures because of the tendence for fuel density to level off above 16 feet.

5. Reflector thicknesses between 2 and 3 feet yield minimum critical masses without excessive moderator weight.

6. For the particular cavity reactor configurations investigated herein, it is necessary to have a fuel-to-cavity radius ratio greater than about 0.6 in order to have a reactor pressure less than 1000 atmospheres.

REFERENCES

1. Lanzo, Chester D.: A Flow Experiment on a Curved-Porous-Wall Gas-Core Reactor Geometry. Nucl. Appl. Tech., vol. 8, no. 1, Jan. 1970, pp. 6-12.

2. Johnson, Bruce V.: Exploratory Experimental Study of the Effects of Inlet Conditions on the Flow and Containment Characteristics of Coaxial Flows. Rep. H-910091-21, United Aircraft Corp. (NASA CR-107051), Sept. 1969.

3. Dundas, Peter H.: Induction Plasma Heating: Measurement of Gas Concentrations, Temperatures, and Stagnation Heads in a Binary Plasma System. NASA CR-1527, 1970.

4. Ragsdale, Robert G.: Relationship Between Engine Parameters and the Fuel Mass Contained in an Open-Cycle Gas-Core Reactor. Presented at NASA and University of Florida Symposium on Research on Uranium Plasmas and Their Technological Applications, Gainsville, Fla., Jan. 7-9, 1970. Available as NASA TM X-52733, Jan. 1970.

5. Pincock, G. D.; and Kunze, J. F.: Cavity Reactor Critical Experiment, Vol. I. General Electric Co. (NASA CR-72234), Sept. 6, 1967.

6. Pincock, G. D.; and Kunze, J. F.: Cavity Reactor Critical Experiment, Vol. II. Rep. GESP-35, vol. 2, General Electric Co. (NASA CR-72415), May 31, 1968.

7. Pincock, G. D.; and Kunze, J. F.: Cavity Reactor Critical Experiment, Vol. III. Rep. GESP-129, vol. 3, General Electric Co. (NASA CR-72384), Nov. 15, 1968.

8. Pincock, G. D.; and Kunze, J. F.: Cavity Reactor Critical Experiment, Vol. IV (Waves and Control Methods). Rep. IN-1336, Idaho Nuclear Corp. (NASA CR-72550), Oct. 1969.

9. Pincock, G. D.; and Kunze, J. F.: Cavity Reactor Critical Experiment, Vol. V (Complete Co-axial Flow Mockup). Rep. IN-1340, Idaho Nuclear Corp. (NASA CR-72577), Nov. 1969.

10. Kunze, J. F.; Pincock, G. D.; and Hyland, R. E.: Cavity Reactor Critical Experiments. Nucl. Appl. Tech., vol. 6, no. 2, Feb. 1969, pp. 104-115.

11. Henderson, W. B.; and Kunze, J. F.: Analysis of Cavity Reactor Experiments. Rep. GEMP-689, General Electric Co. (NASA CR-72484), Jan. 1969.

12. Kascak, Albert F.: The Radiant Heat Flux Limit of By-Pass Flow in a Uranium Plasma Rocket. Presented at NASA and University of Florida Symposium on Research on Uranium Plasmas and Their Technological Applications, Gainesville, Fla., Jan. 7-9, 1970. Available as NASA TM X-52739. Jan. 1970.

13. Barber, Clayton E.: A Fortran IV Two-Dimensional Discrete Angular Segmentation Transport Program. NASA TN D-3573, 1966.

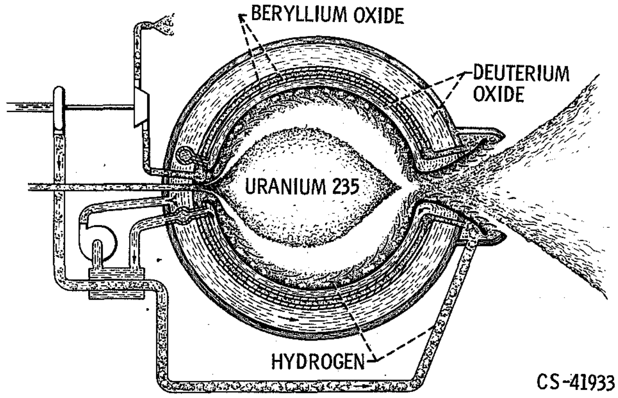

Figure 1. - Conceptual open cycle gas-core rocket engine.

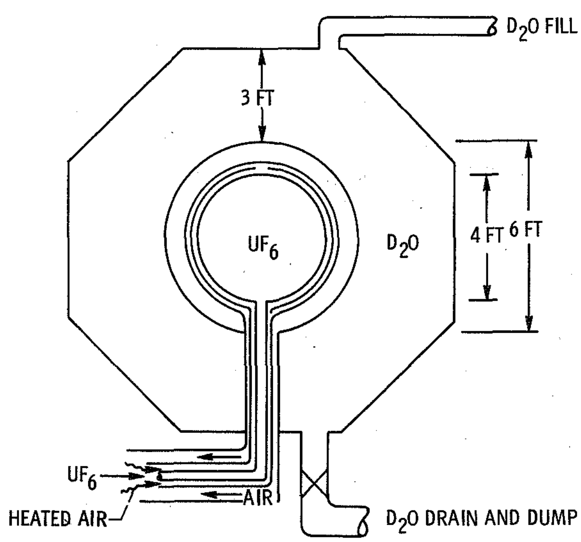

Figure 2. - Spherical core cavity reactor critical.

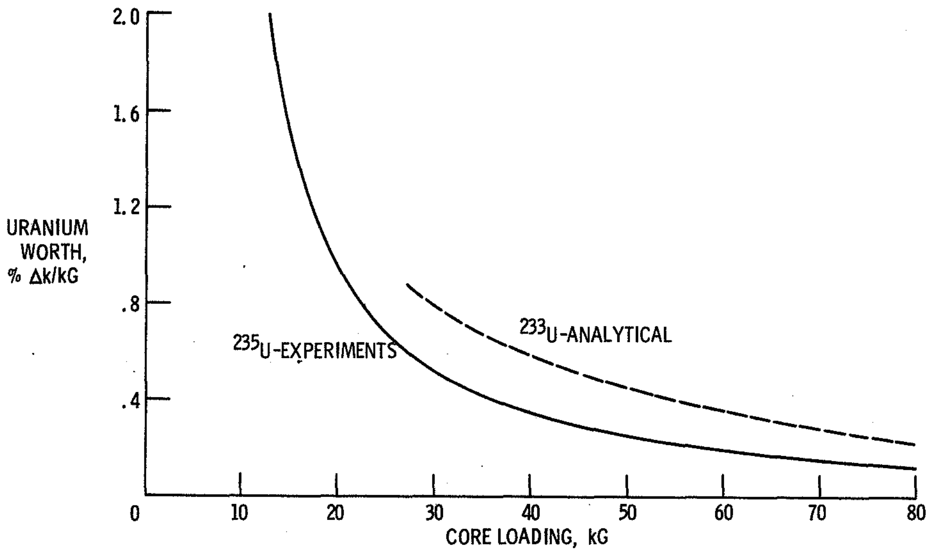

Figure 3. - Cavity reactor fuel worth ^{235}U curve: Cavity 6 feet diameter, 4 feet length, 3 feet reflector (D_2O, D_2O + Be) variations on H_2 and stainless steel.

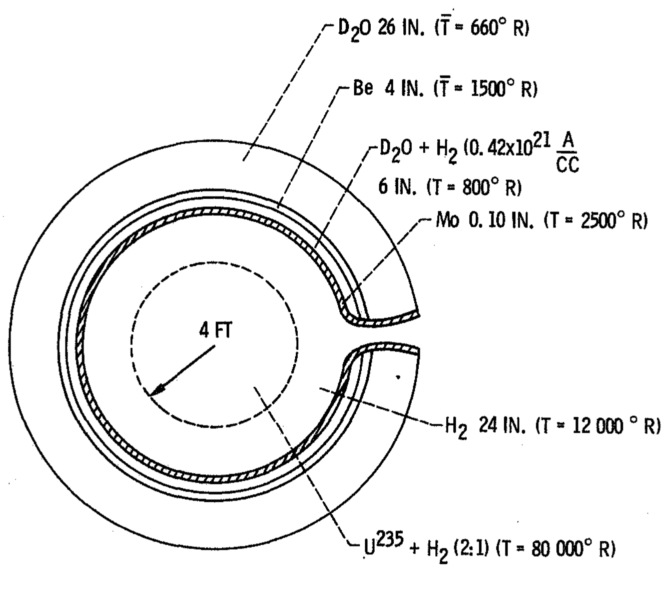

Figure 4. - Spherical gas-core design model.

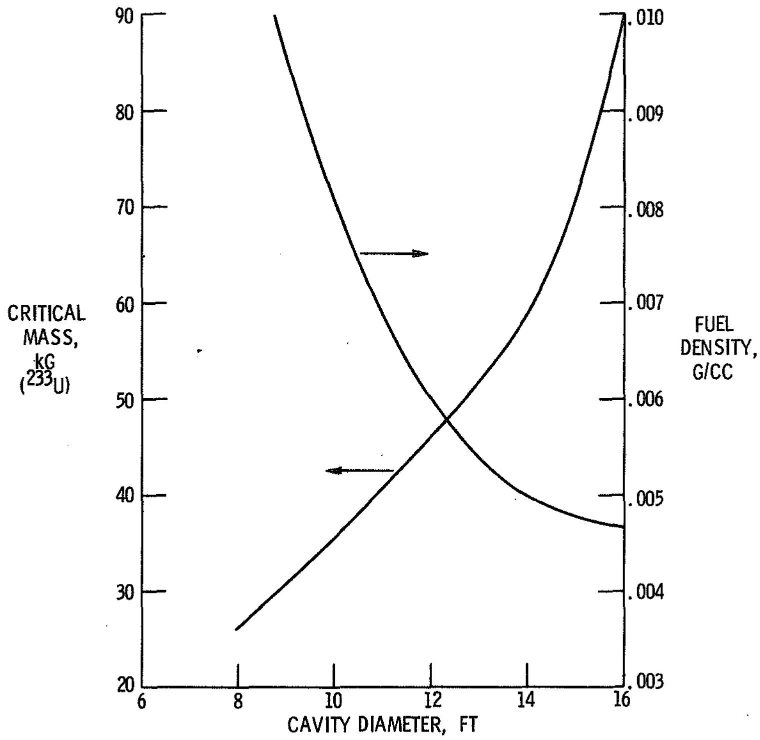

Figure 5. - Cavity diameter variation. R_F/R_C = 0.67, reflector, 2.5 feet (D_2O + Be), H_2 by-pass, 90 percent.

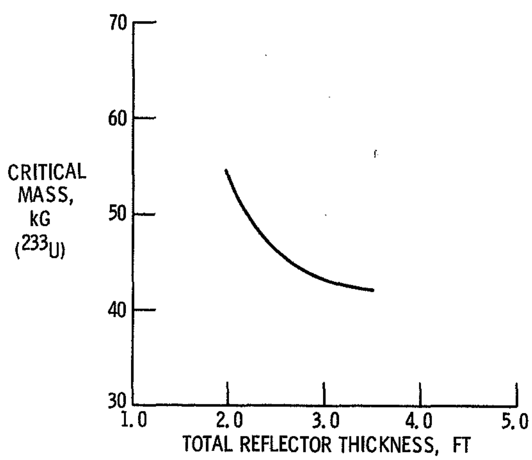

Figure 6. - Total reflector thickness variation cavity diameter, 12 feet, R_F/R_C = 0.67, H_2 by-pass, 90 percent.

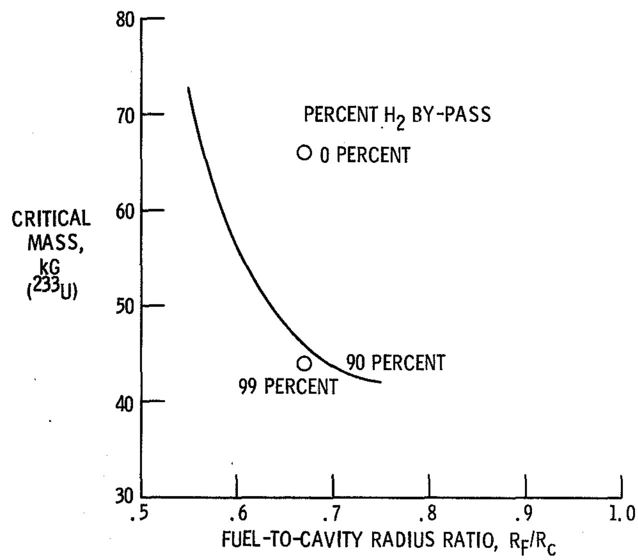

Figure 7. - Fuel-to-cavity radius effect for variable hydrogen by-pass cavity diameter 12 feet (3.657 m), reflector 2.5 feet (D_2O + Be).