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THE OPEN-CYCLE GAS-CORE NUCLEAR ROCKET ENGINE - SOME ENGINEERING CONSIDERATIONS

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THE OPEN-CYCLE GAS-CORE NUCLEAR ROCKET ENGINE - SOME ENGINEERING CONSIDERATIONS

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Abstract

A preliminary design study of a conceptual 6000-MW open-cycle gas-core nuclear rocket engine system was made. The engine has a thrust of 44 200 lb and a specific impulse of 4400 sec. The nuclear fuel is uranium-235 and the propellant is hydrogen. Critical fuel mass was calculated for several reactor configurations. Major components of the reactor (reflector, pressure vessel) and the waste heat rejection system were considered conceptually and were sized.

Introduction

The suitability of an open-cycle gas-core nuclear rocket engine for very fast round trips to nearby planets, e.g. the 80-day Mars courier, has been pointed out in Ref. 1. It was reported that for engine thrust ranging from 4500 to 90 000 lb and engine pressures from 493 to 1975 atm the maximum specific impulse could be 2500 to 6500 sec. These high specific impulses can be achieved only by disposing of the heat generated in the moderator due to the attenuation of gamma and neutron radiation. This waste heat is about 7 percent of the reactor power and can be disposed of with a space radiator.

A number of conceptual studies of an open-cycle gas-core reactor have been made but with only a cursory approach to component design.[2-4] The one study of the major components is for a high thrust (405 000 lb), low specific impulse (1730 sec) engine,[5] rather than the low thrust, high specific impulse reported herein.

This paper chronicles the preliminary design study of some of the major components (moderator, pressure vessel, and heat rejection system) of an open-cycle gas-core reactor system. The thermodynamic and fluid dynamic phenomena associated with the gas-core rocket reactor concept were accepted as a basis for this study.[1] Only steady state operation conditions were considered. A goal of the study is to make a first-order approach to design and sizing of several major components, and to make weight estimates of these components.

There is no "best" engine at present but rather a range of engine parameters from which one can select the best engine for a particular mission. For the design study a 44 200 lb thrust, 4400 sec impulse, 6000 MW engine with a hydrogen propellant flow rate of 10 lb/sec was selected. The reactor configuration is assumed to be a spherical cavity surrounded by a reflector-moderator and a pressure shell. The reflector-moderator is cooled by an inert gas and the heat is rejected to space by an external gas radiator.

Of primary concern in the design of the reactor is the calculation of the critical fuel mass required to operate the reactor. This cannot be calculated directly, however, because critical mass is dependent on reactor configuration, materials of construction, and hydrogen temperature and pressure in the cavity. Hydrogen temperature and pressure, though, are dependent on engine thrust, specific impulse, and fuel mass. Obviously, an iterative procedure is required to arrive at a consistent set of reactor conditions to be used for component design. Additional constraints on the design include cavity wall cooling limitations and pressure vessel strength limitations.

This report will describe the open-cycle gas-core nuclear rocket engine, chronicle the design and give both the results of this study and recommendations for future studies.

Description of Engine

The major components of the engine system are shown schematically in Fig. 1. In this design study the emphasis was placed on the reactor components (reflector-moderator, pressure vessel, etc) and the waste heat rejection system (space radiator, intermediate heat exchanger). These components will be discussed in detail in later sections.

The proposed reactor shown in Fig. 2 is spherical in shape and is composed mainly of a titanium alloy (Ti-6Al-4V) pressure shell, a beryllium oxide reflector-moderator and a porous or slotted cavity liner. A section of the reactor is shown in Fig. 3. The sketch shows the uranium plasma, the hydrogen propellant flow area, the reactor components and the various flow passages. The cooling passages in the reflector moderator are to remove 7 percent of the reactor power which is deposited by the attenuation of high-energy gamma and neutron radiation. The uranium plasma is fissioning uranium enriched to 98 percent U-235.

The 7 percent of total reactor power which is removed from the reflector-moderator must be rejected by the waste heat system. There are two types of systems being considered. The first system consists of a helium gas radiator which operates at the same pressure level as the cavity. The helium which cools the reflector-moderator and carries the heat directly to the high pressure radiator. In the second system the high pressure helium carries the heat from the reflector-moderator through the tubes of a shell and tube heat exchanger where the heat is transferred to a low pressure liquid metal such as lithium. The lithium is then pumped to a space radiator where the heat is rejected. The choice of which system to use depends on factors such as weight and ease of fabrication.

There are other components which make up the engine which have not received much attention in the present design study. They are the propellant storage tank, hydrogen turbopump system, hydrogen-seed system, uranium storage and injection system, the porous cavity liner, the reactivity control system, shielding, and the rocket nozzle. Little can be done to design these components until the operating conditions and size of the reactor itself

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have been determined.

Criticality Calculations

A design procedure was developed to determine the fuel mass and propellant pressure required for a reactor configuration composed of any combination of cavity diameter, reflector-moderator thickness, and amount of structural material contained in the reflector. Ancillary data from the criticality calculations are presented in the form of flux spectra and reactivity effects.

Design Procedure

In a gas-core reactor, fuel mass and propellant chamber pressure are mutually dependent. Pressure as a function of fluid dynamics and heat-transfer phenomena was derived by Ragsdale.[2]

$$P = 14.6 \frac{M_F^{1.385} F^{0.383} I_{sp}^{0.383}}{D_C^{4.54}(V_F/V_C)^{1.51}} \qquad (1)$$

where

P = pressure in reactor cavity, atm
M_F = fuel mass, kg
F = thrust, lb_f
I_{sp} = specific impulse, sec
D_C = cavity diameter, ft
V_F/V_C = volume fraction of fuel in the cavity

In addition, the fuel mass must attain nuclear criticality as represented by:[6]

$$M = M(\text{ref})(1 + R) - \left[\text{percent}\,\frac{\Delta k}{k}\left(\frac{H}{\text{press}}\right) + \text{percent}\,\frac{\Delta k}{k}\left(\frac{H}{\text{temp}}\right)\right]\frac{\Delta M}{\text{percent}\,\frac{\Delta k}{k}} \qquad (2)$$

where

M_c = critical mass, kg
$M(\text{ref})$ = critical mass of reference model, kg (fig. 4)
R = relative critical mass increase caused by inclusion of separated molybdenum (greater than 98 percent Mo^{98} and Mo^{100}) as structural material (coolant tubes) in the reflector
$\text{percent}\,\frac{\Delta k}{k}\left(\frac{H}{\text{press}}\right)$ = reactivity worth of hydrogen pressure, percent (fig. 5)
$\text{percent}\,\frac{\Delta k}{k}\left(\frac{H}{\text{temp}}\right)$ = reactivity worth of hydrogen temperature, percent (table I)
$\frac{\Delta M}{\text{percent}\,\frac{\Delta k}{k}}$ = reciprocal of specific fuel reactivity worht, kg/percent (fig. 7)

Reactor design conditions must satisfy both Eqs. (1) and (2) in order to have a critical fuel loading that can be contained by the coaxial flow of the hydrogen propellant.

Calculation of the reactivity effects required in Eq. (2) has been reported in detail in Ref. 6 and therefore will only be summarized here. Reference model (hydrogen propellant at 19 100° R and 400 atm, and a fuel volume fraction of 0.3) calculations were made using the neutron transport code TDSN[7] with spherical geometry. A series of calculations were performed for cavity diameters of 10 ft, 12 ft, and 14 ft and reflector thicknesses of 1.5 ft, 2 ft, and 2.5 ft which show critical mass increasing with increasing diameter and decreasing reflector thickness (fig. 4). Relative critical mass increase as a function of volume percent structural material contained in the reflector was shown to be nearly independent of cavity diameter and reflector thickness.[c] This allowed a single correlation to be applicable to all configurations considered herein. At 3.035 volume percent Mo the relative critical mass increase (R) was 0.63 and at 6.07 volume percent Mo it was 1.68. For calculational use these data can be represented by Eq. (3)

$$\left.\begin{array}{ll} R = 0.208/\%\ \text{Mo} & \text{for}\ \ \text{Mo} \le 3\% \\ R = 0.346/\%\ \text{Mo} & \text{for}\ \ 3\% < \text{Mo} \le 6\% \end{array}\right\} \qquad (3)$$

The extreme sensitivity of criticality in the gas-core reactor to neutron absorbers necessitated the use of Mo which was isotopically separated to obtain a product containing greater than 98 percent Mo^{98} and Mo^{100}. Structural material is required in the reflector for coolant tubes which would be constructed of the Mo alloy TZM. Effect of pressure on criticality for the reference reactor configurations is shown in Fig. 5. The rate of change of reactivity worth with pressure increases as diameter increases because the thickness of hydrogen in the cavity also increases with diameter. For calculational ease the reference model was assumed to have a constant temperature hydrogen propellant region whereas in an operating engine a gradient exists from the fuel-hydrogen interface to the cavity wall. A better analytical representation was attempted by assuming five hydrogen zones with temperatures varying from 7500° to 40 000° R (fig. 6). The difference in reactivity was -0.25 percent $\Delta k/k$ for a 10 ft diameter configuration and -0.50 percent $\Delta k/k$ for a 12 ft diameter configuration (Table 1). The 14 ft diameter configuration was assumed to have a -0.70 percent $\Delta k/k$ hydrogen temperature distribution worth. These values were assumed constant for all cavity pressures.

To compensate for negative reactivity of the hydrogen pressure and temperature, fuel mass is increased. Fuel reactivity worths are plotted in Fig. 7 for 10 ft, 12 ft, and 14 ft diameter reactor configurations. Decreasing fuel worth per unit mass with increasing fuel loading is attributed to increasing self shielding effect within the plasma ball and decreasing relative mass change per unit mass addition.

To determine the required fuel mass and propellant pressure for a particular configuration, appropriate values are selected for M(ref) from Fig. 4, R from Eq. (3), percent $\Delta k/k\left(\frac{H}{\text{temp}}\right)$ from Table 1, and percent $\Delta k/k\left(\frac{H}{\text{press}}\right)$ from Fig. 5 for an estimated cavity pressure. The required fuel addition to compensate for the negative reactivity is determined from Fig. 7 and solution of Eq. (2) follows. If this agrees with the pressure from Eq. (1), a solution has been obtained. Otherwise the estimated pressure must be iterated until consistent values for M_F and P are obtained.

Calculational results are summarized in Fig. 8

for reactors which satisfy both fluid dynamic and criticality operating conditions. However these designs have no structural material in the reflector. As the fuel requirement for criticality is increased by a reduction of reflector thickness, the negative reactivity of the additional hydrogen associated with that increased fuel loading (Eq. (1)) necessitates that even more fuel be added. The result is a rapidly increasing fuel loading (and hydrogen pressure) as reflector thickness is decreased. Similarly the smaller diameter configurations, which have higher pressure levels, are more sensitive to changes in reflector thickness. Comparison with constant pressure results in Fig. 4 indicates the importance to the design calculations of accurately determining the hydrogen pressure in an operating engine.

When separated Mo is added to the reflector (to simulate structural material), a significant increase in critical fuel loading occurs (fig. 9). Neutron absorption in the Mo increases the critical fuel requirement which in turn requires a higher hydrogen pressure to contain the higher fuel loading.

In an effort to reduce fuel mass and propellant pressure (and, therefore reactor weight), uranium-233 was substituted for U-235 fuel in the reactor configuration of 14 ft cavity diameter and 2 ft reflector thickness with 1.9 percent Mo in the reflector. Fuel mass was reduced from 107.7 to 32.9 kg and hydrogen propellant pressure from 550 to 105 atm. This effect can be utilized in the design to reduce reactor size and/or increase the amount of structural material.

Several items which could effect the neutronics design calculations and which were not included in this analysis are fission product buildup in the core, structural material in the cavity liner, fuel dilution by the propellant and variations of fuel to cavity diameter ratio. No attempt is made to assign any relative significance to these but they should be considered when a more definitive study is desired.

Maximum Propellant Pressure

Based on Eq. (1) for a given fuel loading, thrust, specific impulse, and fuel volume fraction, there is a hydrogen pressure required to contain that fuel mass in a gas-core reactor. Criticality depends on the positive reactivity worth of the fuel less the negative reactivity worth of the hydrogen propellant. For a given cavity diameter specific fuel worth decreases with increased loading (fig. 7). However, the negative reactivity worth of hydrogen per unit of pressure is nearly constant up to 1200 atm. Therefore, the net worth of fuel plus hydrogen decreases with increased fuel loading. In fact, this net worth becomes negative at some fuel loading. The pressure corresponding to that fuel loading is the maximum pressure (or fuel loading) at which the reactor can be made critical. If any additional fuel is added, the hydrogen pressure increase required for fluid dynamic stability would make the reactor subcritical. For the configuration in this study (thrust = 44 200 lb specific impulse = 4400 sec, fuel volume fraction = 0.3) the limiting pressure was determined to be 620 atm, 680 atm, and 730 atm for reactors with cavity diameters of 14 ft, 12 ft, and 10 ft, respectively (fig. 10). These values establish the upper limits for the fuel loading curves presented in Figs. 8 and 9.

Core Characteristics

Both total and fast (energy greater than 5 MeV) flux levels throughout a reactor are listed in Table 2. These data indicate the spectral shift from a fast core region to a more thermalized reflector region. Also, of interest is the nearly constant flux level through the core. This indicates that the fuel is sufficiently dilute that self shielding does not appear to be important in the core at expected fuel loadings (fig. 8). These flux data are useful in calculating radiation exposure damage to materials. However, it should be noted that the data are sensitive to both reactor materials and geometry and that the values in Table 2 are for a specific configuration.

Another indication of the flux spectrum in these high temperature gas-core reactors is the median fission energy, $\bar{E}_f$. The configuration calculated in this study $\bar{E}_f$ varied from 0.2 to 0.7 eV. Previous calculations and experiments on this type reactor had indicated reactor fluxes to have a more thermalized flux spectrum.[8] This spectral change is attributed to the presence of high temperature hydrogen gas (in the high impulse design) which is located between the fuel and the reflector. Neutrons which are thermalized in the reflector region represent the principal source of fission and these must pass through the hydrogen region before reaching the fuel. Since the hydrogen atoms have energies considerably in excess of most of these neutrons (for example, at 19 000° R the hydrogen atoms has a most probable energy of 0.91 eV and an average energy of 1.36 eV), scattering collisions tend to increase the energy of the neutrons. This upscattering effect hardens the low energy spectrum of neutrons entering the core. This reduces criticality because the ratio of capture to fission cross section of U-235 decreases in the epithermal energy range (compared to lower energies). This upscattering effect (decreased reactivity is directly related to hydrogen temperature and therefore will become increasingly important for higher impulse engine designs. Since the effect on criticality is also a function of fuel cross sections, engine designs with other fuels may react differently.

Moderator Design

Requirements

The moderator-reflector is required to thermalize and return neutrons to the reactor core to provide the source for next generation fissions. About 7 percent of the reactor power will be deposited in the reflector so it must also serve as a heat exchanger to transfer this heat to a radiator for disposal. In order to minimize radiator size it is important to operate the reflector at as high a temperature as possible. Therefore, BeO was selected as the principal material of construction because of its superior nuclear properties and high temperature capability. Because of the extreme sensitivity of gas-core criticality to neutron absorption external to the core, nuclear considerations took precedence over mechanical and physical properties in material selection.

Since BeO is a ceramic and therefore limited in mechanical application, the use of a structural material will be required for heat exchange tubes, containment, etc. For this purpose, a molybdenum alloy TZM will be used. The Mo will be isotopically separated to greater than 98 percent Mo^{98} plus Mo^{100} to reduce neutron absorption. Low neutron absorption, material compatibility, and good heat-transfer properties led to the selection of helium (He) as the coolant.

Two methods of operating the heat exchanger have been considered, each with its particular advantages. A low pressure system would utilize a low coolant pressure contrasted with a high cavity pressure in the reactor. This system reduces complexity and weight of the radiator and the coolant transfer lines and pumps. A high pressure system has the coolant at the same pressure as the propellant (reactor cavity) in order to reduce tube thickness and therefore structural material.

The helium inlet temperature to the moderator was set at 2300° R with the outlet temperature set at 2500° R. The resulting helium temperature change of 200° R requires a flow rate of 1596 lb/sec to remove the 420 MW of energy deposited in the moderator by the attenuation of high energy gamma and neutron radiation.

Design Concept

The design which has been used in this study is shown in Fig. 11. In this design the helium coolant flows through passages formed by two concentric tubes arranged in triangular array. The outer tube is TZM and the inner tube is made of BeO. The two tubes can expand and contract independently thereby minimizing thermal stresses in the tubes. Thermal stress in the BeO can be minimized by using the modular arrangement shown in Fig. 11. Thermal fracture of some of the hexagonal BeO blocks will not impair the structural integrity of the reflector because they are locked in place in the design. The porous cavity liner and hydrogen propellant flow passage are shown in Fig. 11. The manifold can be fabricated of ordinary TZM since it is outside of the moderator and will have no effect on the neutronics of the reactor.

The density of the BeO moderator used in the nucleus calculations was reduced by the proper amount to account for the void spaces required by the moderator coolant passages. The effect of neutron streaming through these passages was neglected.

Radiation Damage

The principal effect of neutron irradiation on BeO is volume expansion, with associated microcracking, which results from atom displacement and from helium gas generation. Experimental data at 2300° R indicate that BeO can withstand neutron doses of 9×10^{21} N/cm^2 with little or no microcracking and a total volume expansion of 3 to 5 percent.[9] Strength tends to increase until microcracking occurs and then decreases until failure. Thermal conductivity exhibited a 7 percent decrease after irradiation to 2.5×10^{21} N/cm^2 at 2300° R.

Radiation damage effects in TZM tend to be annealed out at the operating temperature in the reflector. Data on material tested at 2450° R after irradiation to 2.4×10^{20} N/cm^2 indicated about a 10 percent increase in yield strength and 30 percent decrease in total elongation.[10]

Reactor operating time for a Mars round trip should be about 8×10^4 sec. With fast flux values (radiation damage mechanisms are fast neutron phenomena) from Table 2, the maximum dose to the reflector should be about 1.5×10^{20} N/cm^2 per trip. Thus it appears that multiple trips could be completed before the dose limit of BeO is reached, whereas insufficient data are available to evaluate TZM behavior in that dose range.

Coolant Tubes

Calculations of possible coolant tube arrangements were performed primarily to determine if cooling of the reflector might present any special problems. Also of interest was the approximate amount of tube material (TZM) required because of the importance of structural material to critical mass determination. Thus, only nominal results were obtained for a system with low coolant pressure (5 atm) and a system with the coolant pressure equal to reactor pressure at 400 atm. No attempt was made to optimize the tube design. Principal criteria were that the maximum temperature in the BeO reflector not exceed about 3500° R and that the coolant pressure drop be about 15 atm or less. Tube wall thickness was based on the creep collapse criterion developed by Richard Morris of Lewis Research Center for 1000 hours operating at 2000° F. Tube spacing was selected as a compromise between fraction of structural material in the reflector and thermal stresses resulting from radial temperature gradients.

The analytical model assumed the coaxial tube design with tube centerlines located on spherical radii through the reflector. The outer tube is constructed with TZM and the inner tube (which has essentially no pressure differential across its wall) is of BeO. Tubes were arranged in a triangular lattice. Standard heat conduction and convection equations were used to obtain the data listed in Table 3. These data indicate that volume fraction for structural material of up to about 0.05 would be the range of interest and coolant volume fractions will be around 0.05 to 0.1. Initial estimations of radial stresses from thermal gradients which were made using Ref. 13 indicated that BeO limits would be exceeded. The situation could be alleviated somewhat by the use of zirconium beryllide, $ZrBe_{13}$, which has higher heat-transfer and strength properties than BeO at temperatures of interest, 2000° to 3000° R.[12]

Pressure Vessel

The reactor is contained in a pressure vessel which must be able to withstand the cavity pressure. The material should be compatible with hydrogen at pressures up to about 680 atm and temperatures to about 720° R. Also a high strength to weight ratio is particularly required for this application because the pressure vessel represents a significant portion of the total system weight.

Titanium alloys qualify as unique metals for aerospace constuction, mainly because of their high strength and low density. The titanium alloy used in this design study is annealed Ti-6Al-4V. This particular alloy was used both because of its properties and of the state-of-the art of fabricating large pressure vessels of this material. A 7 ft diameter hemispherical head of Ti-6Al-4V with 4 in. thick wall has been hot pressed for the Department of the Navy.

The ultimate and yield stress for annealed Ti-6Al-4V was taken from Ref. 13. The allowable stress is the ultimate stress divided by a factor of safety of 2, and is 65 000 psi at the operating temperature of about 530° R. Reference 14 concluded that there is no embrittlement of unnotched Ti-6Al-4V specimens by 680 atm hydrogen at room temperature. Based on flux values from Table 2, radiation damage to the titanium is of little consequence. An exposure of 2×10^{17} N/cm^2 sec (100 Mars trips) causes very little effect on material properties.[15]

The wall thickness, t, of the spherical pressure vessel can be calculated with the relation

$$t = \frac{P_W D}{4 S_A E} \tag{4}$$

where P_W is the maximum allowable working pressure, D is the inside diameter of the sphere, S_A is the allowable stress, and E is the weld efficiency (taken as 0.9). The Ti-6Al-4V material is assumed to be in the annealed condition and at room temperature.

A weight estimate was made for a pressure vessel with a diameter of 19 ft. With Ti-6Al-4V as the material of construction and a 10 000 psi design pressure, the wall thickness would be $9\frac{1}{2}$ in. and the weight about 245 000 lb.

Qualitative consideration was given to the possibility of excessive heating in the vessel walls resulting from gamma ray absorption. If excessive temperatures should occur, the walls could be laminated and cooled with hydrogen.

Waste Heat Rejection Systems

The two candidate heat rejection systems considered were a single-loop helium coolant system and a two-loop, helium gas and secondary lithium liquid metal coolant with an intermediate heat-exchanger system. The helium moderator coolant flow rate must be 1596 lb/sec to remove 420 MW of heat with a 200° R temperature rise. In both systems the helium gas is operated at the same pressure as the propellant in order to minimize stresses in the coolant tubing of the reflector-moderator. A nominal value of 10 000 psi was selected for the calculations. In the single loop system the radiator is designed to contain the high pressure gas. In the two-loop system the radiator is designed for low pressure liquid metal.

Because of the large heat rejection requirement, it was decided to carry out calculations for four radiators (and four heat exchangers in the two-loop system), each one-fourth the total size required. The temperatures, areas, and weights of the two systems are shown in Table 4 and are for four radiators in the single-loop system and four radiators and four heat exchangers in the two loop system.

Radiator weight was observed to be quite sensitive to pressure level. The radiator in the one loop system with a gas coolant at 680 atm was almost twice as heavy as the radiator (lithium at 194 atm) in the two loop system even though its surface temperature was 150° R higher. However, the additional heat exchangers required in the two loop system led to essentially the same total weights for the two heat rejection systems. Thus, system selection should be on same basis other than weight, e.g., mechanical complexity.

Data in Table 4 are representative of a reactor design with a propellant pressure (and therefore primary coolant pressure) of 680 atm. For designs at other pressures the weight of the gas pressure bearing components was scaled directly with pressure level.

System Weight

One basis for selection of major components is weight minimization of the total system. Only the moderator-reflector, pressure shell, and radiator were considered in this analysis because the weight contribution of all other components (pumps, structure, piping, etc.) was assumed small enough not to effect the results.

For a given cavity diameter, pressure varies inversely with reflector-moderator weight. Both pressure shell and radiator weight vary directly with pressure. The net result of pressure on system weight is shown in Fig. 12 for cavity diameters of 10 ft, 12 ft, and 14 ft.

Cavity pressure is a function of fuel mass which in turn depends on the reflectivity of the reflector-moderator. For the case of no structural material in the BeO reflector-moderator, reflectivity is determined by reflector-moderator thickness. Thus, for a given cavity diameter, at low pressures the reflector-moderator becomes excessively heavy (or thick) and at high pressures the radiator plus pressure shell become excessively heavy. Somewhere in between, the tradeoff between pressure and reflector-moderator thickness results in a minimum weight. It is interesting to note that the larger reactors have lower minimum weights (fig. 12). This results from the fact that the effect of lower pressure on radiator plus pressure vessel weight tends to override the effect of larger dimensions on weight.

Component weights for the minimum weight configurations are itemized in Table 5. In all cases the heaviest component is the radiator which represents 40 to 50 percent of the total. The relative importance of the various component weights as a function of pressure is shown in Fig. 13 with the reflector-moderator dominant at lower pressure and the radiator at higher pressure.

For an operating engine, the weights in Fig. 12 and Table 5 are underpredicted because the cavity liner and the reflector-moderator were assumed to be only BeO. As indicated in Criticality Calculations, fuel mass (and therefore cavity pressure) is extremely sensitive to the presence of any neutron absorbing material (fig. 9). For the particular design discussed herein about 2 percent structural material would be needed in the reflector-moderator to provide tubes for the helium coolant. In only the largest configuration considered (14 ft diameter and 2.5 ft thick reflector-moderator) could more than 2 percent separated Mo be added without exceeding the limiting critical pressure.* The system weight increases 42 percent 264 000 lb when 2.5 percent separated Mo is added to the reflector-moderator (Table 6). Weights for smaller configurations with 1.5 percent Mo are included to show the greater sensitivity of those systems. For example, at smaller diameters the reactors show relatively greater weight increases when structural material is added to the reflector-moderator.

Also indicated in Table 6 is the trend to lower weight at larger reactor sizes for the Mo range of interest (1.9 percent) which emphasizes the dominant effect of cavity pressure on weight. Thus somewhat lower weights might be obtained at larger diameters and reflector thicknesses than were considered in this study.

Recommendations

1. Because U-235 fueled reactors have such high pressures (and consequently high total weights) future conceptual designs should utilize or at least investigate in more detail U-233 fuel in order to reduce critical mass. For example, for a reactor configuration with a 14 ft diameter cavity and a 2 ft thick reflector containing 1.9 percent separated molybdenum, the fuel mass was reduced from 107.7 kg to 32.9 kg and the cavity pressure was reduced from 550 atm to 105 atm. These reductions can be utilized in future designs by reducing reactor size and/or in the amount of structural material in the reactor.

2. The use of zirconium beryllide $ZrBe_{13}$ as the moderator material at operating temperatures up to ~3000° R could reduce thermal stress problems associated with the use of BeO. The $ZrBe_{13}$ has both higher strength and thermal conductivity than BeO and would minimize thermal stress in the reflector-moderator. The nuclear penalty should be acceptably small.

3. The sensitivity of fuel critical mass to neutron absorption in reactor materials requires a very careful choice of materials for the porous cavity liner. From a nuclear standpoint the choice of material is limited to low absorption cross section materials such as separated molybdenum, beryllides, or carbon.

4. The very high weight of the heat rejection system warrants a more detailed evaluation of the design options available. For example, increasing the surface temperature of the radiator above the value of 2460° R used in this analysis can be a big factor in lowering radiator area and weight.

5. Such problems as the hydrogen turbopump system, the hydrogen-seed system, the uranium storage and injection system, the reactivity control system, shielding, the rocket nozzle, and the transient operational behavior are still to be considered.

*That pressure above which the reactor could not be made critical.

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	Cavity diameter = 10 ft Reflector thickness = 2.0 ft		Cavity diameter = 12 ft Reflector thickness = 2 ft	
	H zone at 19 000° R average temperature*	H separated into zones on Fig. 6	H zone at 19 000° R average temperature*	H separated into zones on Fig. 6
Multiplication constant	0.9995	0.9970	1.0039	0.9988
Median fission energy, eV	.36	.34	.39	.37
Ratio of neutron captures to fissions in fueled region	.227	.235	.229	.236
Absorptions in cavity H region per source neutron	.0127	.0133	.0156	.0165
Reactivity worth of zoning, percent $\Delta k/k$ (H temp)	-.25		-.50	

*Temperature corresponding to average H density in cavity.

TABLE 1 EFFECT OF HYDROGEN DISTRIBUTION OF CORE PROPERTIES

Location	Fast flux $E > 0.5$ MeV N/cm^2 sec	Flow flux $E < 0.12$ eV N/cm^2 sec	Total flux N/cm^2 sec
Core center	5.2×10^{15}	1.1×10^{14}	1.7×10^{16}
Fuel-propellant interface	3.5×10^{15}	1.4×10^{14}	1.6×10^{16}
Propellant-cavity liner interface	2.1×10^{15}	1.1×10^{15}	1.8×10^{16}
Inner edge of reflector-moderator	1.8×10^{15}	1.8×10^{15}	1.8×10^{16}
Outer edge of reflector-moderator	1.2×10^{12}	9.1×10^{14}	4.3×10^{15}
Inner edge of pressure shell	2.4×10^{10}	5.1×10^{13}	2.9×10^{14}
Outer edge of pressure shell	5.4×10^{9}	8.7×10^{10}	3.7×10^{12}

TABLE 2 FLUX LEVELS IN A 6000 MW GAS-CORE REACTOR WITH A CAVITY DIAMETER OF 14 FT AND A REFLECTOR THICKNESS OF 2 FT

Outer tube (TZM) od id	0.5 in. 0.4 in.	0.5 in. 0.46 in.
Inner tube (BeO) od id	0.311 in. 0.251 in.	0.352 in. 0.292 in.
Tube pitch Outer reflector surface Inner reflector surface	 1.5 in. 1.188 in.	 1.5 in. 1.188 in.
Number of coolant passages	75 100	75 100
Heat transfer area	19 700 ft^2	19 700 ft^2
Frictional pressure drop	214 psi	1.3 psi
Maximum reflector temperature*	3500° R	3500° R
Reflector volume fraction Coolant Outer tube	 0.062 0.046	 0.088 0.020

*Based on an assumed peak-to-average value of 10 for heat deposition near the inner edge of the reflector.

TABLE 3 NOMINAL REFLECTOR COOLANT TUBE ARRANGEMENT FOR THE FOLLOWING REACTOR CONFIGURATION: CAVITY DIAMETER = 14 FT, REFLECTOR THICKNESS = 2 FT, PROPELLANT PRESSURE = 400 ATM

Parameter		One loop	Two loop
Radiator coolant		He	Li
Maximum radiator pressure	atm	680	194
Average radiator temperature	^{o}R	2 360	2 210
Radiator surface area	ft^2	50 800	67 800
Radiator planform area	ft^2	25 600	34 400
Radiator weight	lb	407 800	231 400
Heat exchanger weight	lb	-------	171 700
Total heat rejection system	lb	407 800	403 100

TABLE 4 HEAT REJECTION SYSTEM CHARACTERISTICS

Minimum weight configurations			Weight, lb			Total
Cavity diameter, ft	Reflector thickness, ft	Cavity pressure, atm	Reflector-moderator	Pressure vessel	Radiator	
14	1.65	254	209 000	82 000	230 000	521 000
12	1.85	350	184 000	87 000	267 000	538 000
10	2.5	450	204 200	97 000	307 000	608 200

TABLE 5 COMPONENT WEIGHTS OF SELECTED REACTOR CONFIGURATIONS WITH BeO REFLECTOR-MODERATORS

Configuration				Weight, lb			
Separated Mo in reflector-moderator, volume percent	Cavity diameter, ft	Reflector thickness, ft	Cavity pressure, atm	Reflector-moderator	Pressure vessel	Radiator	Total
0	12	2.5	275	274 000	85 000	238 000	597 000
1.5	12	2.5	550	274 000	170 000	350 000	763 500
0	14	2.0	200	265 600	74 000	212 000	551 600
1.5	14	2.0	375	265 600	137 000	276 000	678 600
1.9	14	2.0	550	265 600	201 000	350 000	816 600
0	14	2.5	175	353 500	73 000	203 000	629 500
1.5	14	2.5	285	353 500	120 000	242 000	715 500
1.9	14	2.5	345	353 500	146 000	264 000	763 500
2.5	14	2.5	490	353 500	210 000	330 000	893 500

TABLE 6 EFFECT OF SEPARATED Mo ON COMPONENT WEIGHTS OF SELECTED REACTOR CONFIGURATIONS

E-6588

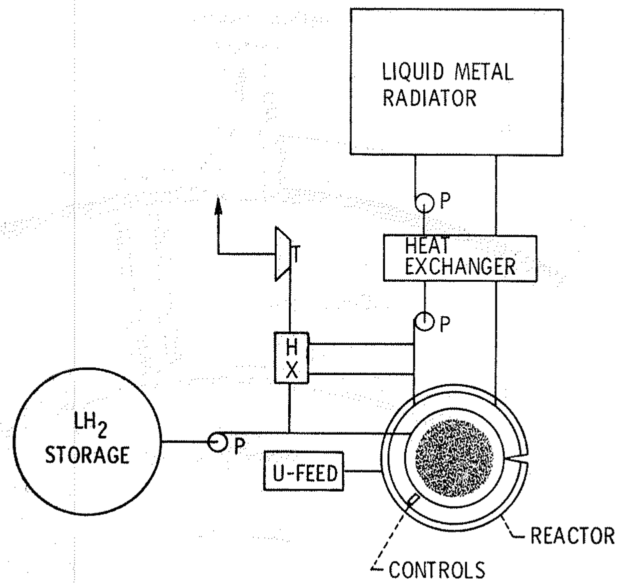

Figure 1. - Schematic of the open-cycle gas-core reactor engine not to scale.

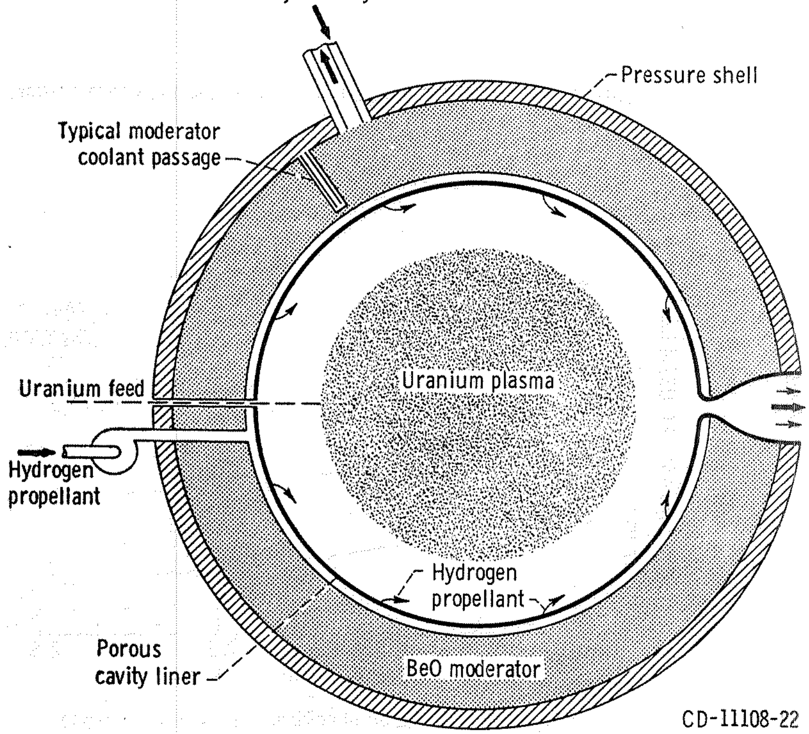

Figure 2. - Schematic of open-cycle gas-core reactor.

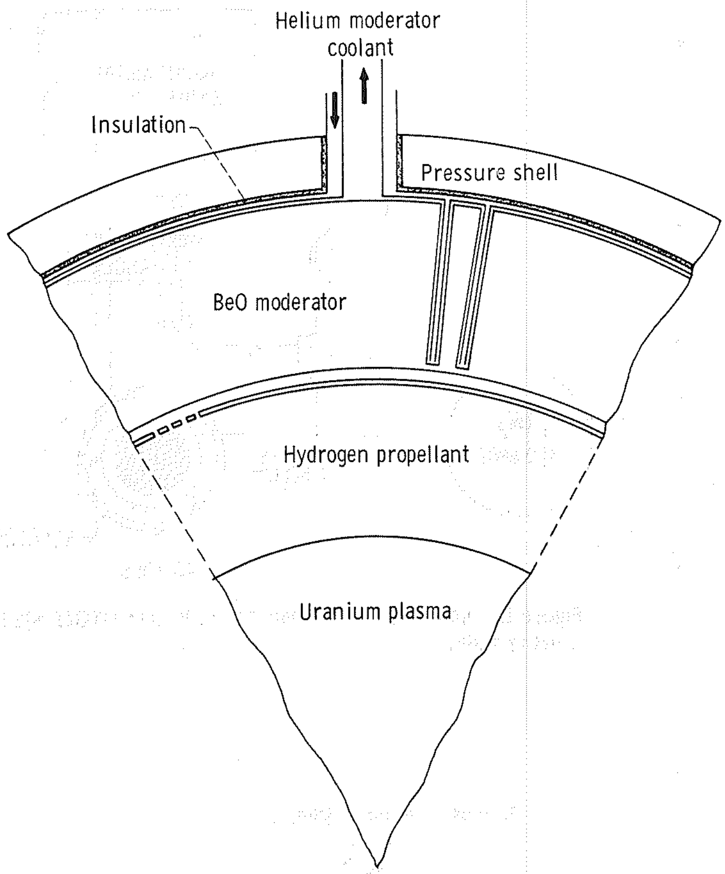

Figure 3. - Schematic of a section of the open-cycle gas-core reactor.

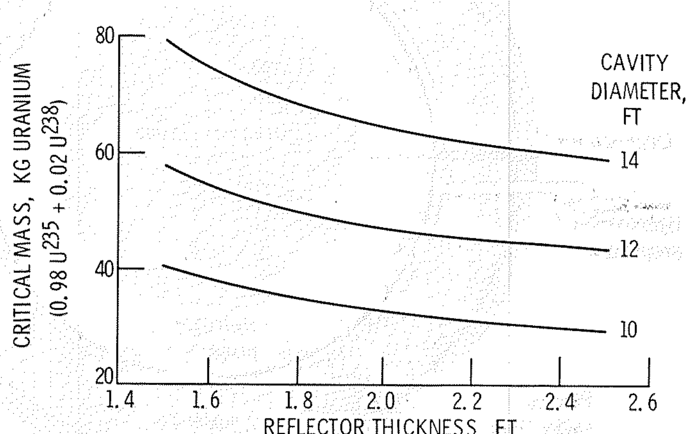

Figure 4. - Variation of critical mass of the reference reactor configuration with hydrogen propellant at 1900^0 R and 400 atm.

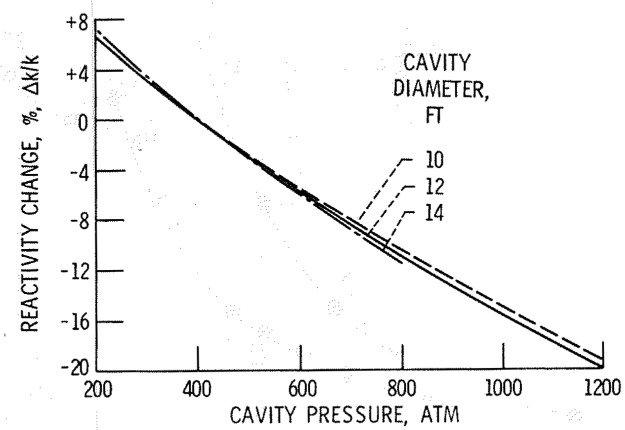

Figure 5. - Variation of reactivity change with hydrogen pressure for reference reactor configuration.

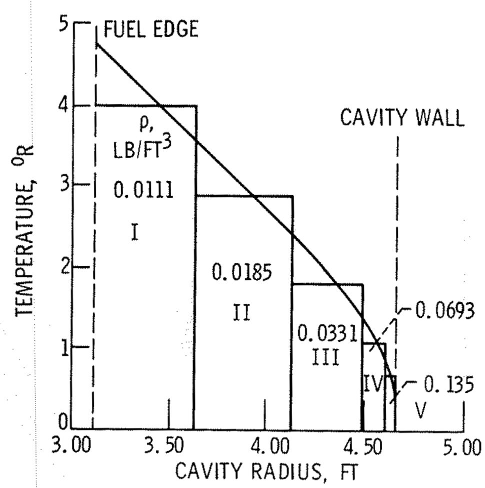

Figure 6. - Calculational model representation of the hydrogen propellant temperature distribution in the cavity of a 10 foot diameter, 400 atm pressure, 44 200 pound thrust, 4400 second specific impulse gas core reactor.

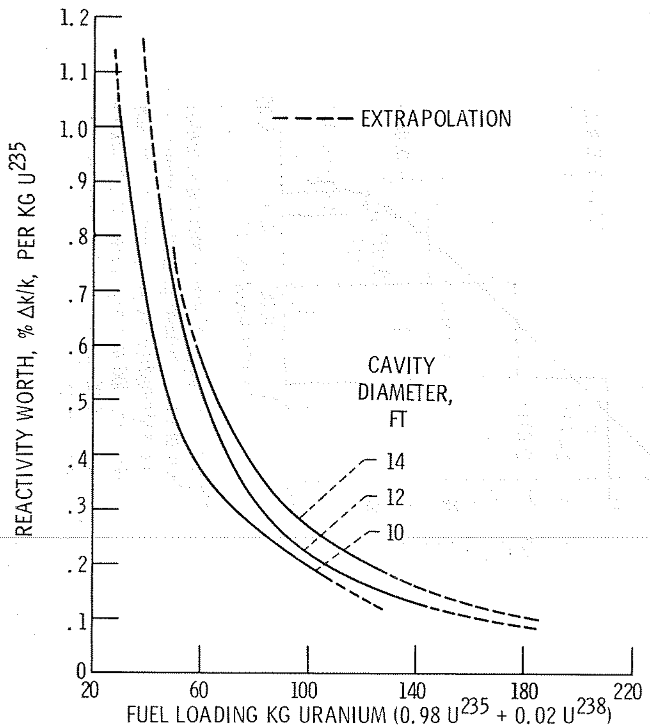

Figure 7. - Fuel reactivity worth for reference reactor configuration.

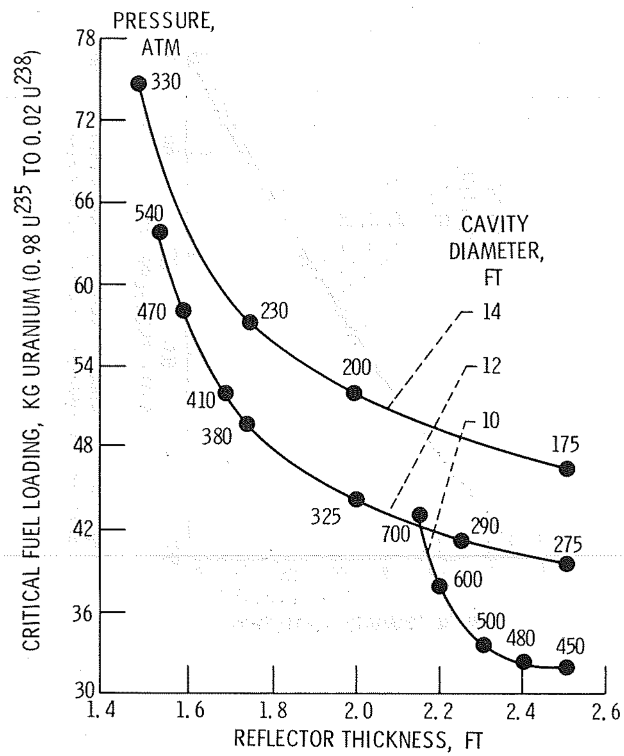

Figure 8. - Variation of critical fuel loading and hydrogen propellant pressure with reflector thickness and cavity diameter for gas-core reactor with BeO reflector.

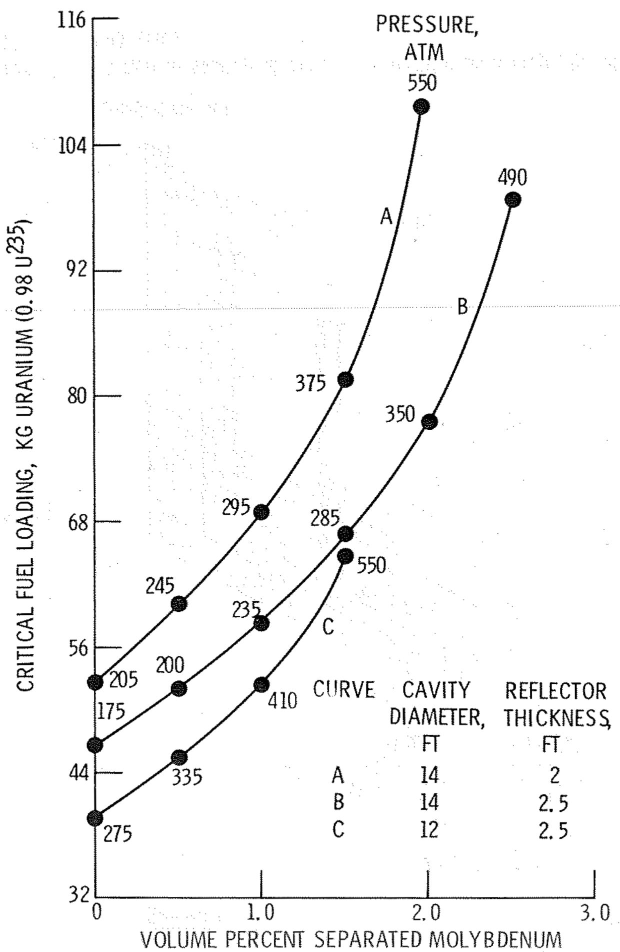

Figure 9. - Variation of fuel loading and hydrogen propellant pressure as a function of separated Mo content in the reflector-moderator of reference reactor configurations.

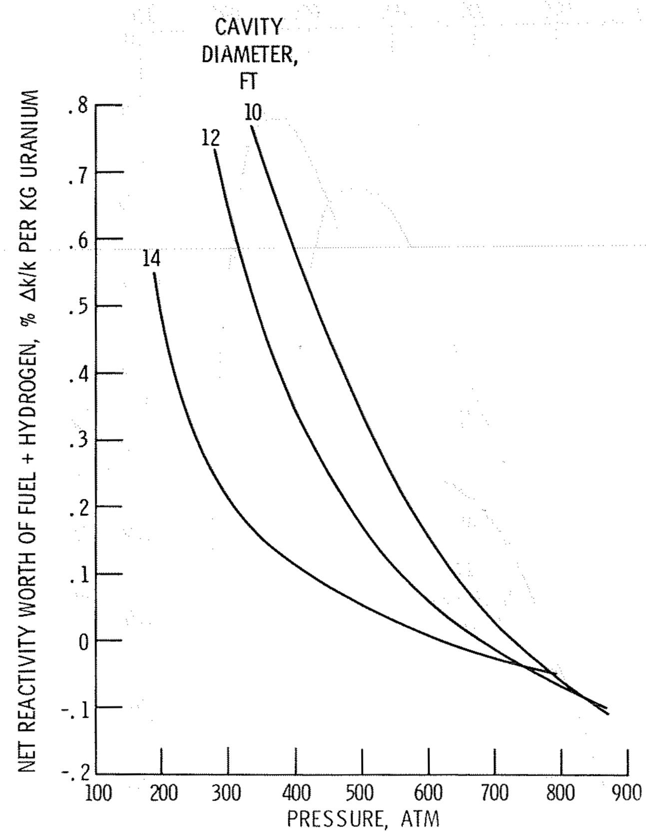

Figure 10. - Variation of net specific reactivity worth of fuel addition to the reference reactor configuration for three cavity diameters with 44 200 pounds of thrust and a 4400 second specific impulse.

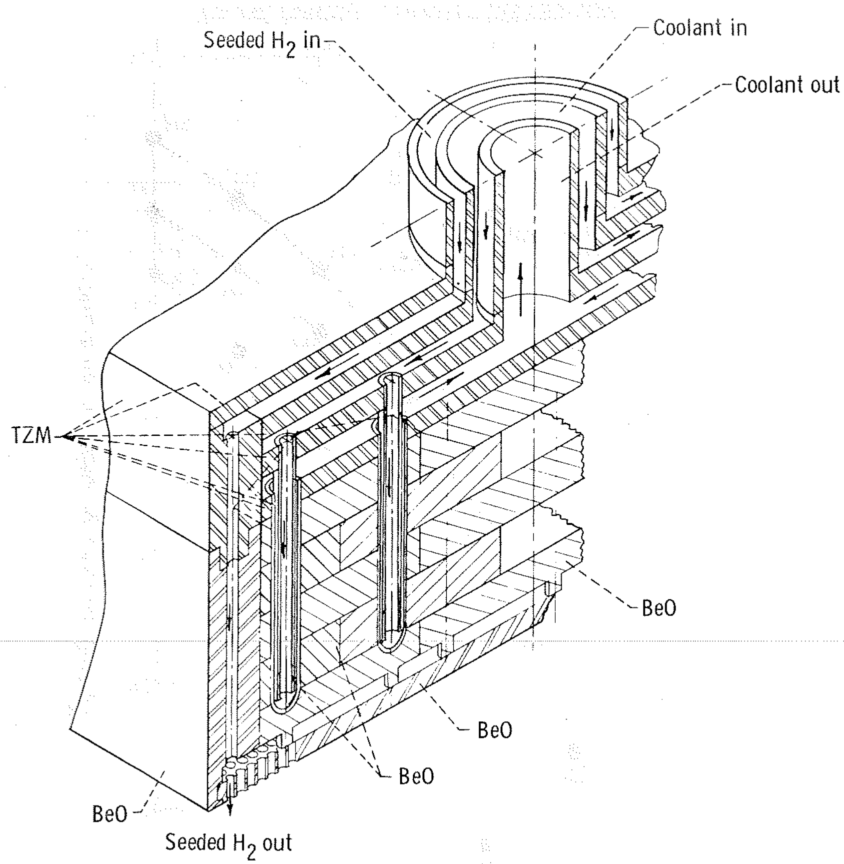

Figure 11. - A typical section of the BeO moderator as it might be fabricated using TZM and BeO tubes.

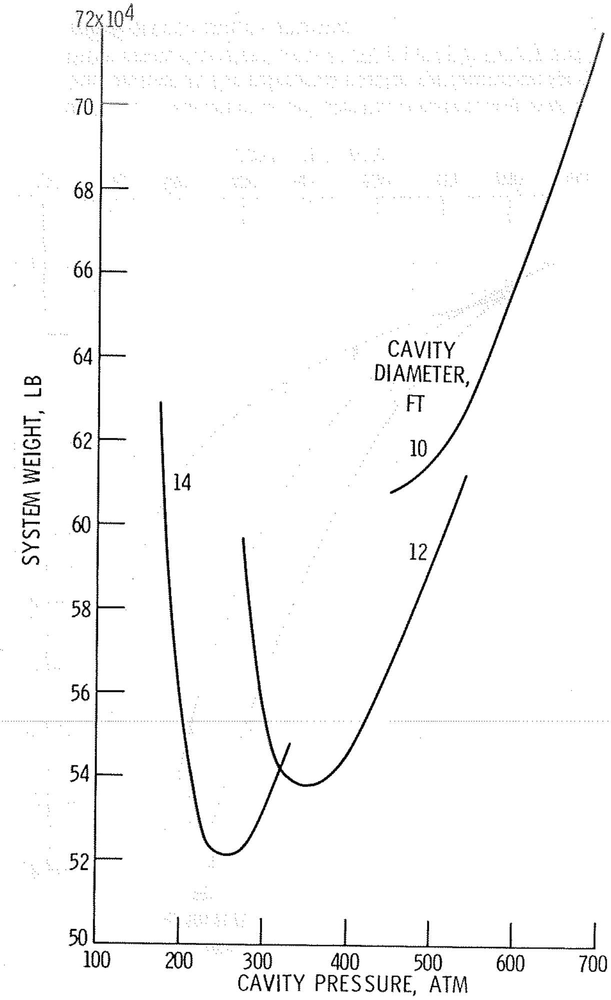

Figure 12. - Variation of total system weight with cavity pressure for cavity diameters of 10, 12, 14 feet for a reactor with a BeO reflector-moderator.

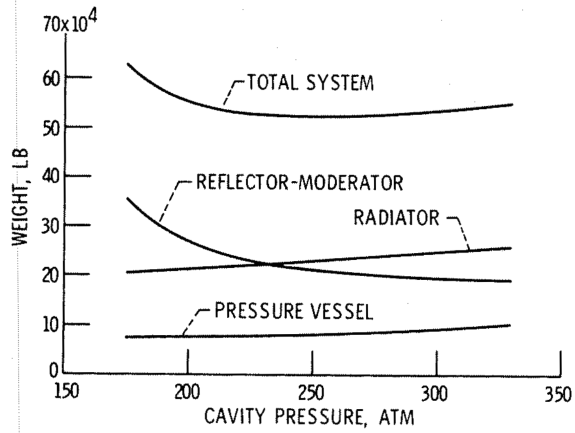

Figure 13. - Variation of component weights with cavity pressure for the reference reactor configuration with a cavity diameter of 14 feet and a BeO reflector-moderator.

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