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PRELIMINARY NEUTRONIC ANALYSIS OF A CAVITY TEST REACTOR

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16. Abstract

A reference configuration was calculated for a cavity test reactor to be used for testing the gas-core nuclear rocket concept. A thermal flux of 4.1×10^{14} neutrons per square centimeter per second in the cavity was provided by a driver fuel loading of 6.4 kg of enriched uranium in MTR fuel elements. The reactor was moderated and cooled by heavy water and reflected with 25.4 cm of beryllium. Power generation of 41.3 MW in the driver fuel is rejected to a heat sink. Design effort was directed toward minimization of driver power while maintaining 2.7 MW in the cavity during a test run. Ancillary data on material reactivity worths, reactivity coefficients, flux spectra, and power distributions are reported.

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PRELIMINARY NEUTRONIC ANALYSIS OF A CAVITY TEST REACTOR

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SUMMARY

A neutronic analysis was performed on a cavity test reactor to be used to test the gas-core nuclear rocket concept. This reactor would provide a thermal flux of 4.1×10^{14} neutrons per square centimeter per second to a 60.96-centimeter-diameter centrally located spherical test cavity in order to produce 2.7 megawatts in the 375 grams of enriched uranium plasma fuel contained there. A major constraint imposed on this study was that fuel elements of the type used in the Materials Testing Reactor (MTR) be used for the driver fuel.

The analysis was directed toward minimization of power generation in the driver fuel (because all such heat must be rejected to a sink) by varying dimensions and materials. A reference configuration was obtained that consisted of a spherical test cavity surrounded by driver fuel elements arranged in a cylindrical annulus. A heavy water moderator region between the cavity and the driver fuel provided thermalization of the neutron source to the cavity. The reactor was reflected both radially and axially with 25.4 centimeters of beryllium. Driver fuel loading was 6.4 kilograms of enriched uranium, and driver power generation was 41.3 megawatts. Required control swing for 1200-megawatt hours of operation was 18 percent reactivity $\Delta k/k$. This could be adequately provided by steel-clad cadmium hollow control rods. Twelve rods containing 0.152-centimeter-thick cadmium provided 50 to 60 percent $\Delta k/k$ when interspersed in the driver fuel region. Ancillary results of material reactivity worths, reactivity coefficients, flux spectra, and power distributions were reported.

INTRODUCTION

Experimental and analytical work on a coaxial-flow, open-cycle gas-core nuclear rocket concept has been in progress for 10 to 15 years (refs. 1 to 3). This concept is basically a critical mass of nuclear fuel in the form of a plasma ball suspended by fluid dynamic forces in the center of a flowing propellant. The propellant is contained in a reflector and pressure vessel assembly. Since all structural parts are thermally shielded by the propellant (via an injected seed material), fuel temperatures on the order of 50 000 K can be theoretically achieved. Consequently, propellant temperatures required to obtain specific impulses around 2000 to 5000 seconds are theoretically possible. The concept also has the capability of producing thrusts on the order of 10^5 to 10^6 newtons. This combination of high specific impulse and high thrust would represent a major breakthrough in rocket propulsion technology if sufficiently low engine weights and fuel loss rates could be achieved.

As part of recent gas-core studies, a cavity test reactor has been proposed (ref. 4). This facility would be used to experimentally test the fundamental phenomena upon which the gas-core rocket concept is based. Conceptually, the test reactor would be a conventional solid-core reactor with a large test chamber in the center. Thus, a driver core would be used to provide neutron flux to a plasma fuel in the test chamber. In this manner the plasma fuel criticality requirement is removed, thereby significantly reducing core size and pressure that would be required for a gas-core reactor.

This report presents the neutronics information generated from a preliminary design study of such a cavity test reactor. Although a feasible configuration was obtained in the study, the final design was not optimized. The design presented herein was aimed primarily at minimizing the reactor power level within the constraints of the study. An optimized design would require a tradeoff between operating and capital costs, and the necessary information for such a determination was not obtained during the study.

Major constraints of the study were that existing fuel-element technology be used in the driver core and that the capability exist for tests in the cavity. Thus, the driver core was designed around MTR fuel elements, thereby using considerable reactor operating experience at the Plum Brook Reactor. Also, the cavity will be 60.96 centimeters (2 ft) in diameter. Under test conditions (calculated from methods described in ref. 5) the cavity will contain 375 grams of enriched uranium, which will generate 2.7 megawatts of power. All configurations will be restricted to single fluid systems; that is, if a liquid moderator proves desirable, that material will also be used to cool the fuel elements and the reflector.

ANALYSIS

Objective

The neutronics design effort was directed at varying materials and configurations in order to minimize the reactor power generated in the driver fuel region while maintaining the required power in the test cavity. All driver power must be rejected to a heat sink and will be subsequently referred to as throwaway power.

Since the cavity power was fixed at 2.7 megawatts, the power split P_D/P_C or the ratio of driver power to cavity power, can be considered a measure of throwaway power. The power split can be represented by

$$\frac{P_D}{P_C} = \frac{\dfrac{M_D}{V_D}\displaystyle\int_0^{V_D}\int_0^{\infty} \sigma_f(E)\varphi(E, \vec{V})dE\, d\vec{V}}{\dfrac{M_C}{V_C}\displaystyle\int_0^{V_C}\int_0^{\infty} \sigma_f(E)\varphi(E, \vec{V})dE\, d\vec{V}} \tag{1}$$

where

M_D	driver fuel mass, kg
M_C	cavity fuel mass equal to 0.375 kg of uranium 235
$\sigma_f(E)$	energy dependent microscopic fission cross section, cm^2
$\varphi(E, \vec{V})$	energy and space dependent neutron flux, neutrons/cm^2-sec
V_D	driver fuel volume, cm^3
V_C	cavity fuel volume, cm^3

To simplify equation (1) we can assume that the flux spectra are the same in both fuel regions and that all power is produced by thermal fissions. Then

$$\frac{P_D}{P_C} = \frac{M_D \varphi_{th, D}}{0.375\, \varphi_{th, C}} \tag{2}$$

Equation (2) indicates that in order to minimize P_D/P_C, M_D should be minimized and/or the ratio of thermal fluxes in the driver and the cavity regions reduced. Another variable to consider is the fast flux from the driver fuel region $\varphi_{f, D}$, which is the source for $\varphi_{th, C}$.

Unfortunately, all these quantities are interdependent, and physical changes in the reactor design tend to have offsetting effects on P_D/P_C. For example, a moderating reflector tends to lower M_D but reduces $\varphi_{f, D}$, which in turn increases $\varphi_{th, D}/\varphi_{th, C}$. However, there does exist some combination of reactor materials and configuration that will certainly tend to minimize P_D/P_C. In general one can expect that hardening the spectrum in the driver region will increase M_D and lower $\varphi_{th, D}/\varphi_{th, C}$. Also, for a given moderator material some optimum thickness exists that will balance the slowing down and absorption effects on $\varphi_{f, D}$.

Calculational Model

To satisfy both mechanical design and experimental test requirements, the reactor consists of a spherical test cavity surrounded by a neutron moderating region, a cylindrical driver fuel region, reflector, and pressure vessel. A description of the reactor and local cavity conditions are shown in figure 1. The cavity conditions are those required for a gas-core reactor test. The thickness of the driver fuel region is fixed by the selection of an MTR fuel element used in the Plum Brook reactor (fig. 2), although the absolute location of this region is variable. Top and bottom reflectors were considered necessary both to reduce driver fuel mass and to produce an even flux distribution in the test cavity.

For initial parametric calculations a spherical model was used in which the various components were homogenized and arranged in spherical shell regions (fig. 3). However, because a spherical shell is a considerable deviation from the cylindrical arrangement of driver fuel elements, more accurate values for multiplication factors and flux levels were obtained from two-dimensional models in RZ (cylinder) and $R\theta$ (disk at reactor midplane) geometry. The RZ model (fig. 4) required that the driver fuel region be homogenized into a cylindrical annulus and that the cavity regions be cylindrical. In $R\theta$ geometry (fig. 5) it was possible to explicitly describe the driver fuel elements, but axial dimension effects had to be simulated by the use of axial leakages generated in an RZ calculation.

As noted previously, each calculational model contained certain restrictions. The best values for multiplication factor were considered to be those from the $R\theta$ calculation with appropriate correction factors for energy groups and cross section detail. With the use of zone dependent axial leakages, the $R\theta$ model could account for three-dimensional heterogeneity effects in the driver fuel elements.

Whenever the same reactor configuration was represented by different calculational models, dimensions were adjusted to conserve material volumes. This was considered a better technique than attempting to preserve mean free paths across regions.

The driver fuel height was set at 86.6 centimeters (cylindrical model) to provide a reasonable viewing angle from the test cavity fuel region. Hopefully, this geometry would provide an equal source of neutrons to the entire test cavity fuel region. No attempt was made to optimize the fuel height during this study.

Reactor Codes

All reactor calculations were performed with multigroup neutron transport codes; TDSN (ref. 6) for one-dimensional calculations and DOT (ref. 7) for two-dimensional calculations. Generally, the one-dimensional (spherical) calculations were in S_4P_1 19 group detail, and the two-dimensional (cylindrical and $R\theta$) calculations were in $S_2P_0$10 group detail. Correction factors were calculated so that two-dimensional $S_4P_1$19 group results could be synthesized.

Cross sections were generated with GAM-II (ref. 8) and GATHER-II (ref. 9) codes for energy groups above and below 2.38 electron volts, respectively. For the purpose of cross-section generation all groups above 2.38 electron volts were treated as fast neutrons and those below 2.38 electron volts were treated as thermal neutrons. Cross sections were flux weighted for the particular material regions in which they were to be used. The 19-group energy set (12 fast and 7 thermal) had been developed and used in previous analytical and experimental work (ref. 3). Full down-scattering was allowed between the fast groups and full down- and up-scattering were allowed between the thermal groups. The 10-group energy set (five fast and five thermal) was merely a consolidation of the 19-group structure. The same scattering provisions were retained in the 10-group energy set. In the high temperature regions in the test cavity free atom scattering kernels were used to determine temperature effects on cross sections.

Calculation Interpretation

For the most part the calculated configurations were noncritical and contained two fuel zones, which were neutronically coupled. Thus, each calculation produced a multiplication factor for the test cavity k_C and one for the driver fuel k_D; the sum of which represented the multiplication factor of the reactor k (see appendix A). Reactivity effects for noncritical systems were determined from

$$\Delta\rho = \rho_2 - \rho_1 = \frac{k_2 - k_1}{k_1 k_2} \cong \frac{\Delta k}{k} \tag{3}$$

where ρ is reactivity and the subscripts 1 and 2 are the initial and perturbed states, respectively, of the reactor.

For a reactor with two fuel zones, local reactivity effects were calculated from

$$\frac{\Delta k_C}{k} \cong \frac{k_{C2} - k_{C1}}{k_1 k_2} \tag{4}$$

and

$$\frac{\Delta k_D}{k} \equiv \frac{k_{D2} - k_{D1}}{k_1 k_2} \tag{5}$$

The use of reactivity effects to adjust the multiplication constants of a calculated configuration is facilitated by manipulating equations (4) and (5) to obtain

$$k_{D2} = \frac{k_{D1} - k_1\left[\left(\frac{\Delta k_C}{k}\right)k_{D1} - \left(\frac{\Delta k_D}{k}\right)k_{C1}\right]}{1 - k_1\left(\frac{\Delta k_C}{k} + \frac{\Delta k_D}{k}\right)} \tag{6}$$

and

$$k_{C2} = \frac{k_{C1} - k_1\left[\left(\frac{\Delta k_D}{k}\right)k_{C1} - \left(\frac{\Delta k_C}{k}\right)k_{D1}\right]}{1 - k_1\left(\frac{\Delta k_C}{k} + \frac{\Delta k_D}{k}\right)} \tag{7}$$

Equations (6) and (7) can then be used to calculate k_D and k_C of a perturbed reactor if the initial conditions and the reactivity effect of the perturbation are known.

RESULTS AND DISCUSSION

Fuel Loading

Neutronic coupling of the two fuel zones can be observed by varying the fuel loading of the driver fuel region M_D. Data plotted in figure 6 show k_D increasing and k_C decreasing with increasing M_D. Increased neutron absorption caused by the addition of driver fuel tends to decrease cavity flux thereby decreasing k_C. Since $P_D/P_C \equiv k_D/k_C$, the conclusion is obvious that for a given configuration the best power split is obtained with the lowest driver fuel loading.

Specific fuel reactivity worths can be derived from figure 6 by

$$F = \frac{\Delta k/k}{\Delta M/\overline{M}} \tag{8}$$

where $\Delta M/\overline{M}$ represents the change in fuel mass divided by the average fuel mass. Values for the test cavity and driver fuel regions are presented in table I and figure 7. These data are useful in adjusting the fuel loading of a calculated configuration to obtain a given multiplication constant.

Moderator Thickness

Materials considered for the moderator were H_2O, beryllium, D_2O (0.25 vol. % H_2O). For each moderator material some optimum thickness exists for which throwaway power is a minimum at a given cavity power. Thinner moderators would not provide sufficient neutron thermalization, and thicker regions would cause excessive neutron absorption. In either case fewer fissions per unit source occur in the cavity test region. Also, changes in driver fuel volume resulting from varying moderator thickness produce a second-order effect on power split. At smaller fuel volumes (smaller moderator thickness) driver fuel mass tends to decrease thereby decreasing the power split. This occurs because the driver fuel region approximates an infinite slab with constant thickness; therefore, its fuel density required for criticality is nearly constant.

Calculated results show throwaway power to be quite sensitive to H_2O thickness (fig. 8). A minimum of 65 megawatts occurred at 2.54 centimeters (1 in.). Values of 99 megawatts were obtained at the lower limit (no moderator) and 200 megawatts at 7.62 centimeters (3 in.). The ratio P_D/P_C for D_2O was lower than for H_2O and was relatively flat as a function of moderator thickness, although a minimum of 52 megawatts did occur at 15.24 centimeters (6 in.). One point at a 15.24-centimeter (6-in.) thickness was calculated for beryllium (D_2O cooled), which indicated a P_D/P_C of 60 megawatts, somewhat higher than for D_2O. In all cases the driver fuel was cooled with the moderator material (except when Be was used). Greater absorption in the H_2O fuel coolant contributes to the H_2O minimum being greater than the D_2O minimum.

Heavy water was selected as the moderator material for two reasons: its lower throwaway power (and therefore P_D/P_C) and its insensitivity to thickness, which was considered desirable from a mechanical design standpoint because the moderator-region has a spherical inner surface and a cylindrical outer surface. This selection also fixed D_2O as the coolant for the driver fuel and the reflector because of the decision to maintain a single fluid system.

The effect of the moderator on reactivity is assumed to be directly related to total collisions. Therefore, in a highly moderated reactor where the scattering is nearly isotropic, this effect will be retained between calculational models by keeping the moderator volume constant when relating a spherical model to the reference configuration. Thus, the minimum thickness of 15 centimeters from figure 8 was not as significant as the corresponding volume of 3.9×10^5 cubic centimeters.

Since the purpose of figure 8 is to show the relative effect of moderator material and thickness, data based on an early model of the cavity test reactor were plotted. These data are not consistent with the final configuration because the cavity contained 559 grams of uranium-235 at 2200 K and hydrogen propellant at 5000 K with 17 weight percent uranium-238 seed. Also, the results are from spherical calculations and have not been corrected to a cylindrical model.

The magnitude of relative effects from the use of different moderator materials was observed to be sensitive to the particular configuration. For example, if coolant-filled control rod channels were included in the driver fuel zone, the resulting change in region composition would affect the throwaway power comparison of the H_2O and D_2O moderated reactors. Since a greater volume fraction of the fuel zone would be occupied by coolant, the effect of changing coolants would be magnified.

Reflector Thickness

Materials considered for the reflector were beryllium and D_2O. The decision to use D_2O as moderator eliminated H_2O as a possibility because of the single-fluid groundrule. The primary effect of the reflector appears to be a reduction of driver fuel critical mass. A secondary effect is to provide a portion of the neutron source to the test cavity by reflecting fast neutrons that would penetrate the driver fuel region. As reflector thickness increases, critical mass decreases, which tends to decrease throwaway power. The primary effect is enhanced by a moderating reflector material whereas the secondary one requires a fast neutron reflector (generally a high molecular weight material). This would indicate that some material with intermediate properties and/or a composite reflector would be desirable. In addition, absorption of neutrons in the reflector should be minimized to decrease driver fuel mass required for criticality.

Calculated results are presented in figure 9 for various reflector thicknesses, all of which are backed by a 10.16-centimeter (4-in.) steel pressure vessel. Reflector thickness refers to a cylindrical radial reflector plus top and bottom slabs, all of equal thicknesses. Spherical model reflector thicknesses have been converted from this model by preserving total reflector volume. All results have been normalized to a cylindrical model of the reference configuration with a test cavity power of 2.7 megawatts. The lowest throwaway power Q_D, 40.1 megawatts, was obtained with the largest beryllium reflector thickness (35.6 cm (14 in.)) that was calculated. The throwaway power Q_D increased at decreasing beryllium thickness to a value of 49.4 megawatts at 10.16 centimeters (4 in.). The throwaway power Q_D for D_2O reflectors was about 16 megawatts higher for equivalent thicknesses. One composite reflector (8.89 cm Be + 12.45 cm D_2O) resulted in a 3-megawatt increase in Q_D for the same total thickness.

Based on these results, a 25.4-centimeter (10-in.) thick beryllium reflector was selected for the reference configuration. On an equivalent thickness basis beryllium was clearly the better material. However, the particular thickness selected was somewhat arbitrary. For a final selection, cost data would be required to evaluate the tradeoff between capital cost of the material, and the operating cost of rejecting Q_D. Also, if the beryllium material costs are particularly high, D_2O could be used to supplement a thinner beryllium reflector, or perhaps even eliminate it.

The fast neutron reflectivity contribution of the pressure vessel was not explicitly determined in these calculations. Any change in pressure vessel thickness or material might have an effect on the results of the thin beryllium reflectors and on the D_2O reflectors. It is doubtful, though, that any effect would be noticeable for the case of the relatively thick beryllium reflected configurations considered.

Reference Core Characteristics

Based on data presented in this report, a D_2O moderator with a volume of 3.9×10^5 cubic centimeters and a 25.4-centimeter-thick beryllium reflector was selected. These items were included with the nonnuclear test dependent design features to obtain the reference model configuration of the cavity test reactor (table II). The neutronic characteristics of this reference reactor (itemized in table III) indicate that a driver fuel mass of 6.4 kilograms uranium (0.932 ^{235}U) is required to provide excess reactivity for 1200 megawatt-hours of operation. Other data include median fission energies of 0.06 and 0.04 electron volt in the test cavity and driver fuel regions, respectively. The higher value in the test cavity can be attributed to upscattering of neutrons in the high temperature propellant and fuel plasma regions. A power level of 41.3 megawatts in the driver region is required to produce the required flux level of 4.1×10^{14} neutrons per square centimeter per second to the cavity to generate 2.7 megawatts.

Fast ($E > 0.07$ MeV) and thermal ($E < 0.12$ eV) flux distributions along radial and axial midplanes of the reactor are plotted in figure 10. Of particular note is the flat distribution of thermal flux in the test cavity which predicts a flat power distribution. As expected the thermal flux showed peaks in the moderator materials and depressions in the absorbers. The fast flux peaked in the fuel regions and tended to drop off rapidly in the axial reflector. Although not shown in figure 10(b), the reduction from the center to the upper edge of the beryllium reflector was about 10^{-4}.

Median fission energies of 0.04 and 0.06 electron volt calculated for the driver and cavity fuel regions indicate that the reference model is a thermal reactor. Flux spectra for the two fuel regions are plotted in figure 11. Displacement of the slow neutron energy distribution in the cavity toward higher energy (compared with the driver fuel region) substantiates the calculated higher median fission energy for that region. Moderation in the D_2O tends to decrease the cavity spectrum at energies below the fission energy peaking (~1.6 MeV) until the upscattering effect becomes apparent around 2 electron volts.

Distribution of power generation in the test cavity fuel is important to heating rates and associated flow effects. Peak-to-minimum values of 1.1 for the power density are indicative of a flat distribution (fig. 12). Power density in the axial direction is slightly greater than along the radial midplane even though no fuel is located above or below the cavity. Apparently the axial reflector region acts as a flux trap for thermal neutrons and provides a source for the cavity region.

Variations from the average in figure 12 are somewhat deceptive because the linear dimension represents a radius and the power density is volume averaged. Also, it should be noted that these data are based on a homogeneous distribution of fuel atoms because of a lack of any experimentally predicted distribution for reference model conditions.

Power density traverses through the driver fuel elements in all three dimensions are presented in figure 13. The hot channel in a fuel element occurs along the inner plate (moderator side) where the local-to-average power ratio is about 1.3 (fig. 13(a)) at the axial average position. Power also peaked on the side of a fuel element adjacent to an empty control rod channel (occupied by D_2O). The maximum hot spot on that surface was 1.8 (fig. 13(b)) at an average axial position. Axial power distributions have been averaged and presented as relative values in figure 13(c). Therefore, multiplication by local-to-average ratios in figure 13(c) can be used to convert power density values in figure 13(a) and (b) to a specific axial location. The expected axial power shape (cosine distribution) was obtained with a sharp upturn near the edge caused by thermal neutrons from the beryllium reflector.

Control System

Excess reactivity requirements are based on reactor startup under nontest conditions and with the test cavity flooded with hydrogen at 300 K and 200 atmospheres. The negative reactivity effect of that hydrogen (-5.7 percent $\Delta k/k$) was the major component in the total 9 percent $\Delta k/k$ required (table IV). Other items were fuel depletion, 0.3 percent $\Delta k/k$; ^{135}Xe production, 0.4 percent $\Delta k/k$; other fission products, 1 percent $\Delta k/k$; D_2O temperature defect, 0.1 percent $\Delta k/k$; and an added contingency of 1.5 percent $\Delta k/k$. Fuel depletion was based on total absorption of neutrons by fuel atoms during the 1200-megawatt-hour operation. The xenon-135 penalty was calculated for a 30-minute test run. The temperature defect results from the average D_2O temperature rising from 300 to 325 K at full power. A contingency was added to account for calculational and design uncertainties.

Although the worth of 375 grams of uranium (0.932 ^{235}U) is about 7 percent $\Delta k/k$ (or about 10 dollars) a corresponding negative effect of -3 percent $\Delta k/k$ occurs in the driver fuel. Therefore, the net effect of adding fuel to the cavity for a test run is 4 percent $\Delta k/k$. The control system must have sufficient capacity to override this effect and to shutdown the reactor under test conditions with an estimated safety margin of 5 percent $\Delta k/k$. Consequently, total required control swing is 18 percent $\Delta k/k$, and the corresponding k's for excess reactivity and shutdown are 1.099 and 0.917, respectively.

Three control system configurations were proposed to obtain this control swing. All reference configuration calculations were based on MTR control rods (type A) inserted directly into every third driver fuel element position, for a total of 12 rods in the reference configuration. These rods were hollow, 7.62-centimeter-square rectangular boxes. The walls were 0.952-centimeter-thick stainless steel with a 0.1524-centimeter-thick sheet of cadmium (Cd) sandwiched in the stainless steel. The hollow portion of the rods was occupied by a coolant. Types B and C were hollow tubes with 6.98-centimeter outside diameters. Materials and their thicknesses were the same as type A. These tubes were inserted into a stationary channel formed by a zircalloy-4 tube with a 0.635-centimeter-thick wall and a 7.62-centimeter outside diameter. Types B and C differed only in the control rod coolant, H_2O for type B and a gas for type C.

Control swings were obtained from spherical calculations using smeared control rod regions and a spatial self-shielding factor of 0.02 for the cadmium (appendix B). Reactivity differences for rods in and rods out calculations indicated a swing of about 50 percent $\Delta k/k$ could be obtained for any of these configurations (table V). In order to increase confidence in the spherical calculations, a two-dimensional calculation in $R\theta$ geometry was performed in which control rods and fuel elements were explicitly defined. Control rod cross sections were obtained from a one-dimensional cell calculation. The resulting control swing was 66 percent $\Delta k/k$, thereby indicating that control swing predictions from the spherical calculations are probably conservative. Thus, either type A, B, or C would provide adequate control swing. In a more detailed design excess swing could be reduced by varying the cadmium content. Also, the rods would be assigned various functions, such as scram, shim, and regulating, and the poison content and/or drive mechanism would be adjusted accordingly.

In addition to control swing, the control system configuration also affects the multiplication factor of a reactor. For comparison purposes variations in k are translated to required power generation in the driver fuel by normalizing all systems to a test cavity power of 2.7 megawatts. Thus, the reference power of 41.3 megawatts is increased to 48.1 and 42.9 megawatts when type B and C control systems are used (table VI). Added neutron absorption from inclusion of the zircalloy-4 tubes and the H_2O coolant could account for this increase.

Reactivity Coefficients

For use in reactor dynamics analyses, a number of reactivity effects were obtained from static calculations of various design perturbations. The data are presented in table VII explicitly for each fuel zone of a reactor under test conditions. Reactivity changes in each fuel region were calculated from equations (4) and (5). In general, opposing reactivity changes occurred in the two fuel regions when an operating condition was perturbed. Such changes should be amenable to regulation by the control system. Insertion of control rods into the driver fuel region tended to reduce reactivity in both fuel zones at a relative rate k_D/k_C of about 100 to 1.

These results represent a partially self-regulating system from the standpoint of overall reactor control. However, an additional function of the control system is the maintenance of sufficient flux in the test cavity to produce 2.7 megawatts.

Perturbations used in table VII are relatively straightforward except for propellant temperature, in which only the effect of temperature on microscopic cross section was considered. Hydrogen atom density was not changed corresponding to the temperature change. The effect of hydrogen atom variation can be derived from the calculated propellant pressure coefficient.

Material reactivity worths determined during the course of the study are itemized in table VIII. Of particular note is the small penalty incurred if tungsten (W) is used as the propellant seed material (since W is a high absorbing material) and/or if the D_2O is contaminated to 1 percent of its volume with H_2O. To maintain the 2.7-megawatt test cavity power, the use of W would require a 0.8-megawatt increase in throwaway power and contamination by 1 percent H_2O, a 1.3-megawatt increase. Addition of hydrogen uniformly to the fuel plasma in the test cavity significantly reduced local reactivity thereby requiring increased throwaway power generation. If the 375 grams of cavity fuel were to deposit (at the plasma density) on the inner surface of the cavity liner, cavity reactivity would increase 2 percent $\Delta k_C/k$ but a negative effect of 1 percent $\Delta k_D/k$ in the driver fuel tempers the overall effect.

SUMMARY OF RESULTS

A neutronic analysis of a cavity test reactor, designed to test the feasibility of the gas-core reactor concept, was performed. The spherical cavity test section is 60.96 centimeters in diameter and is surrounded by a neutron moderator region, a cylindrical driver fuel region containing MTR fuel elements, a neutron reflector, and a pressure vessel. Primary consideration in component material selection and sizing was given to minimizing throwaway power; that is, power generated in the driver fuel in order to provide sufficient flux to the test cavity to produce the 2.7 megawatts necessary for gas-core reactor experiments. Thus, heavy water (D_2O) was selected to moderate the source flux to the cavity and to cool the driver fuel elements. Moderator volume is 3.9×10^5 cubic centimeters. The reflector is a 25.4-centimeter-thick cylindrical annulus of D_2O cooled beryllium with 25.4-centimeter-thick end pieces. A 10-centimeter-thick steel pressure vessel is required to contain the operating pressure of 200 atmospheres. Twelve control rods and 24 fuel elements are arranged in a 8.4-centimeter-thick cylindrical annulus with an inner radius of 45.94 centimeters. This driver fuel region contains 6.4 kilograms of enriched uranium (0.932 ^{235}U) and generates 41.3 megawatts.

Specific results of the study are the following:

1. Throwaway power was increased by 25 and 14 percent (compared with D_2O), when water (H_2O) and beryllium, respectively, were used as moderator materials, primarily because of greater parasitic absorption of neutrons. These numerical values are sensitive to the assumed configurations, in particular, the volume fraction of coolant in the driver fuel region.

2. For the reflector thicknesses of interest (<36 cm), a lower throwaway power is obtained using a beryllium reflector than a D_2O reflector because of reduced critical mass and reflectivity of fast neutrons. These neutrons penetrate the driver fuel region and contribute to the flux in the test cavity.

3. An excess multiplication factor of 1.099 for a clean reactor with a void test cavity is required based on 1200-megawatt-hour operation with an outlet coolant temperature of 325 K. Total required control swing is 18 percent $\Delta k/k$, which includes a 5 percent $\Delta k/k$ shutdown margin.

4. Fuel required for a gas-core reactor test (375 g U) is worth 7 percent $\Delta k/k$ locally but only 4 percent $\Delta k/k$ for the overall reactor. This results from neutronic coupling between test cavity and the reactor fuel zones.

5. Hollow rod control rods containing cadmium can provide a control swing of about 50 to 60 percent $\Delta k/k$. A control rod is located in every third position in the 36-element annular fuel channel.

6. Reactivity coefficients were calculated for various system perturbations. In general, a system change affects the reactivity of the cavity test fuel and the reactor driver fuel in opposite directions.

7. Required power output was insensitive to the selection of seed material and to contamination of D_2O with H_2O (up to 1 percent).

8. Average thermal flux ($E < 0.12$ eV) in a void test cavity is 4.1×10^{14} neutrons per square centimeter per second and at gas-core test conditions is 1.6×10^{14} neutrons per square centimeter per second. Neutron spectra are near thermal as evidenced by median fission energies of 0.06 and 0.04 electron volt in the test cavity and driver reactor fuel regions, respectively.

9. Power distribution in the test cavity is relatively flat with a peak-to-minimum value of 1.1. In the reactor fuel elements, three-dimensional power distributions were calculated which showed local peaking at the axial center, in the inner fuel plate, and along the side next to a coolant filled control rod channel.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 22, 1972,
503-04.

APPENDIX A

CALCULATED MULTIPLICATION CONSTANTS

Comparison of the various design configurations was made on the basis of required power output in the driver fuel to obtain 2.7 megawatts of power in the test cavity. To do this, all designs were normalized to a k_D that would provide the required reactivity margin.

Based on fuel depletion, temperature defect, cavity hydrogen flooding, and fission product buildup, an excess reactivity of 9 percent $\Delta k/k$ is required for a reactor under nontest conditions (no fuel or hydrogen in the test cavity). The corresponding k is 1.099. Under the assumption that an $R\theta$ $S_4P_1 19$ group result using RZ calculated axial leakages represents the best accuracy that is obtainable within the practical limits of computer capacity and running time, correction factors are used to adjust the k from the spherical calculations used in the parametric analyses. To reduce the number of calculations needed, the related k_D for a system under test conditions is used for normalization. In effect, normalizing the results to this k_D should provide the best calculational accuracy (within the limits of the study) and a basis for comparing different design configurations.

Calculated values for adjusting multiplication factors are listed in table IX. Inclusion of fuel and hydrogen in the test cavity significantly reduced k_D (by 3.18 percent $\Delta k_D/k$) because of increased absorption of neutrons, which had the potential of causing fissions in the driver fuel. This is another illustration of neutronic coupling between the fuel zones. Because of this coupling, adjustments of k_D must be made with equation (6). Since cylindrical calculations were limited by machine capacity and running time to $S_2P_0 10$ group models without pressure vessels, a correction factor was calculated using spherical models. The $R\theta$-to-spherical model correction of 5.48 percent $\Delta k_D/k$ was primarily due to changing the driver fuel from a cylindrical arrangement to a spherical shell. Application of all correction factors leads to the result that a spherical $S_4P_0 19$ group calculation of $k_D = 1.135$ for a reactor under gas core test conditions would have a "best calculation" value of 1.099 for a reactor with a void cavity.

Variation between calculational models also occurs in k_C. This is accounted for by comparing k_D/k_C for two-dimensional and spherical calculations. Thus, spherical power splits $P_D/P_C \equiv k_D/k_C$ are multiplied by 0.956 to obtain the more accurate two-dimensional results.

In practice a 1D $S_4P_1 19$ group calculation is performed on a given configuration; k_D is normalized to 1.135 by adjusting the fuel loading (fig. 7). The term k_C is adjusted, because of the change in fuel loading, using figure 7 and equation (7). Then the ratio of k_D/k_C is multiplied by 0.956 and driver power P_D is calculated based on 2.7 megawatts cavity power P_C.

APPENDIX B

SPATIAL SELF SHIELDING IN CADMIUM

For use in smeared control rod regions used in spherical calculational models, a self shielding factor f was calculated in order to account for the thermal flux depression in the cadmium section of the control rod. In theory, f is needed because a similar flux depression would not exist in a smeared region. Therefore, the cadmium cross section must be adjusted by f so that the total reaction rate will be preserved.

It was assumed that the rectangular channel geometry of an MTR control rod could be approximated by a slab model. For large values $f = 1/2\Sigma t$ where Σ is the total cross section in barns and t is the thickness in centimeters of the cadmium (ref. 10). Energy dependent values for f were determined to be about 0.02 for the energy range where most reactions are expected to occur (table X). Therefore, a single value of 0.02 was used for all energy levels in the study presented herein. Based on later calculations with cell averaged cross sections, a somewhat higher value for f would have been more accurate.

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TABLE I. - SPECIFIC REACTIVITY WORTH

OF DRIVER FUEL

Average driver fuel, hg	Mass ratio, $\Delta M/\overline{M}$, percent	Cavity reactivity effect, $\Delta k_C/k$, percent	Driver reactivity effect, $\Delta k_D/k$, percent	Specific fuel reactivity worth[a], F	
				In cavity	In driver
5.85	15.39	-0.196	2.97	-0.0126	0.193
6.75	13.33	-.146	2.15	-.0110	.161
7.65	11.76	-.120	1.75	-.0102	.149
8.56	10.75	-.091	1.42	-.0085	.132

[a] $F = (\Delta k/k)/(\Delta M/\overline{M})$; where $\overline{M} = (M_1 + M_2)/2$.

TABLE II. - REFERENCE MODEL CONFIGURATION

Component	Material	Shape	Radius, cm	Height, cm	Wall thickness, cm
Test cavity liner	Aluminum	Sphere	30.48	-------	0.635
Hydrogen plenum	---------	Sphere	31.115	-------	2.54
Moderator inner liner	Aluminum	Sphere	33.655	-------	.635
Moderator	Heavy water (D_2O)	------	[a]34.29 [b]45.315	34.29 43.3	------ ------
Moderator outer liner	Zircalloy-4	Cylinder	45.315	43.3	.635
Driver fuel channel	MTR fuel elements and D_2O coolant	Cylinder	[a]45.94 [b]54.347	43.3	------
Fuel channel liner	Zircalloy-4	Cylinder	54.347	-------	.635
Reflector	Beryllium and D_2O coolant	Cylinder	[a]54.982 [b]80.382	[a]43.935 [b]69.335	------
Pressure vessel	Steel	Cylinder	80.382		10.16

[a]Inner.
[b]Outer.

TABLE III. - NEUTRONIC CHARACTERISTICS OF

CAVITY TEST REACTOR

Test cavity fuel loading[a], kg U	0.375
Driver fuel loading[a], kg U	6.4
Average thermal neutron flux in test cavity[b], neutrons/cm^2 sec	
For nontest conditions (void cavity)	4.1×10^{14}
For operating test conditions	1.6×10^{14}
Median fission energy, eV	
Test cavity fuel	0.06
Driver fuel	0.04
Power generation, MW:	
Test cavity fuel	2.7
Driver fuel	41.3

[a]Atomic fraction of ^{235}U in total U, 0.932.
[b]$E \leqq 0.12$ eV.

TABLE IV. - REACTIVITY REQUIREMENTS FOR

1200 MILLIWATT-HOUR OPERATION

	Reactivity, $\Delta k/k$
Excess:	
Fuel depletion	0.003
Xenon-135 production	.004
Other fission production (estimated)	.010
Temperature defect (300 to 325 K D_2O)	.001
Hydrogen flooding of test cavity	.057
Subtotal	.075
Contingency	.015
Total	.090
Shutdown:	
Addition of test cavity fuel	.04
Margin allowance	.05
Total	.09
Required control swing	.18
Effective multiplication factor (void test cavity), k_{eff}	1.099
Shutdown multiplication factor, k_s	.917

TABLE V. - CALCULATED CONTROL SWING FOR VARIOUS CONTROL ROD CONFIGURATIONS

Type	Description	Coolant	Cadmium surface area, cm^2	Reactivity[a], $\Delta k/k$
A	MTR type, 7.62 cm^2	Heavy water	4.6×10^3	0.49 [b].66
B	Hollow tube, 6.98-cm o.d.	Water	3.3×10^3	.57
C	Hollow tube, 6.98-cm o.d.	Gas	3.3×10^3	.52

[a]Spherical calculations with smeared control rod regions and a cadmium spatial self-shielding factor of 0.02.

[b]Two-dimensional calculation using cell averaged cross sections for the control rod region.

TABLE VI. - REQUIRED POWER AS FUNCTION OF CONTROL SYSTEM CONFIGURATION

Control system	Description	Driver fuel power, MW
A	MTR type, heavy water cooled	41.3
B	Tube type, water cooled	48.1
C	Tube type, gas cooled	42.9

TABLE VII. - REACTIVITY EFFECTS OF DESIGN PERTURBATIONS

IN THE REFERENCE CONFIGURATION

Variable	Range		Specific fuel reactivity worth[a]	
	Lower	Upper	F_C	F_D
Test cavity fuel, kg	0.3375	0.375	0.035	-0.017
Test cavity fuel expansion, cm	19.2	20.42	.023	-.011
Propellant pressure, A	160	200	-.017	.0094
Propellant temperature, K	2560	5000	-.0186	.0183
Plenum pressure, A	160	200	-.0015	-.0118
D_2O pressure, A	1	200	0	3.5×10^{-6}
D_2O temperature, K	300	325	0	-.0097

[a] $F = (\Delta k/k)/\Delta p/\bar{p}$ where Δp represents the change in the particular property and $\bar{p}$ is the arithmetic average of the lower and upper limits.

TABLE VIII. - MATERIAL REACTIVITY WORTHS IN

THE REFERENCE CONFIGURATION

Variable	Cavity reactivity effect, $\Delta k_C/k$	Driver reactivity effect $\Delta k_D/k$	Change in driver throwaway power, ΔQ_D, MW
Addition of 12.6 g of hydrogen uniformly to test cavity fuel	-0.0121	0.0069	8.7
Redistribution of test cavity fuel onto inner surface of cavity liner	.020	-.010	---
Substitution of W in place of ^{238}U seed	-.0004	-.001	.8
Inclusion of 1% H_2O in D_2O	-.0005	-.0061	1.3

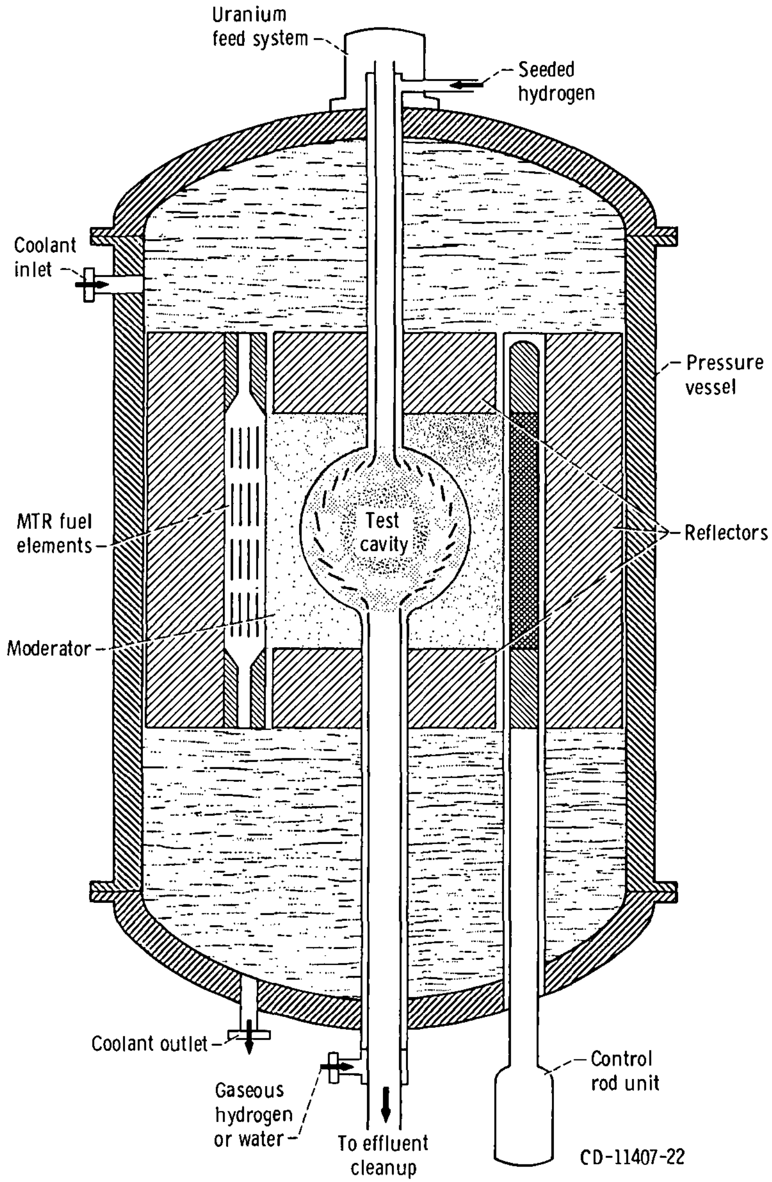
TABLE IX. - REACTIVITY CORRECTIONS FOR ADJUSTING CALCULATED MULTIPLICATION CONSTANTS

Variable	Driver reactivity effect, $\Delta k_D/k$ percent	Cavity reactivity effect, $\Delta k_C/k$ percent	Driver multiplication factor, k_D
Initial reactor with no cavity fuel or hydrogen	-----	----	1.099
Inclusion of 375 g uranium and hydrogen in cavity at test conditions	-3.18	4.70	1.060
$S_2P_0$10 group (no pressure vessel) to $S_4P_1$19 group model	.24	-.02	-----
$R\theta$ model[a] to spherical model	5.48	.10	1.135

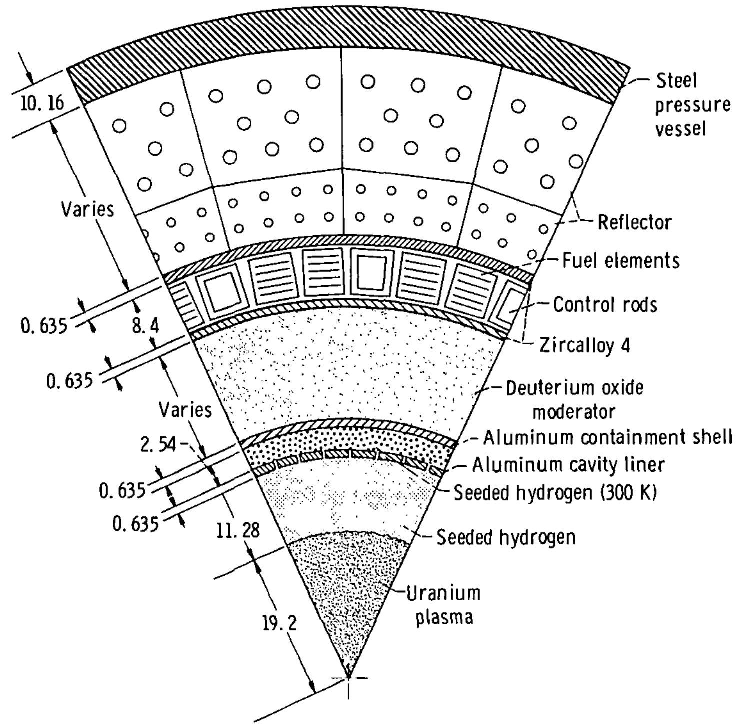
[a]Using axial leakages from an RZ cylindrical calculation.

TABLE X. - SELF-SHIELDING FACTOR FOR 0.1524-CENTIMETER-THICK CADMIUM SLAB

Upper energy of group, eV	Total cross section, b	Self-shielding factor, f
2.38	21.1	0.16
.414	56.2	.058
.12	168.6	.0281
.08	117.0	.0281
.0253	137.1	.0239

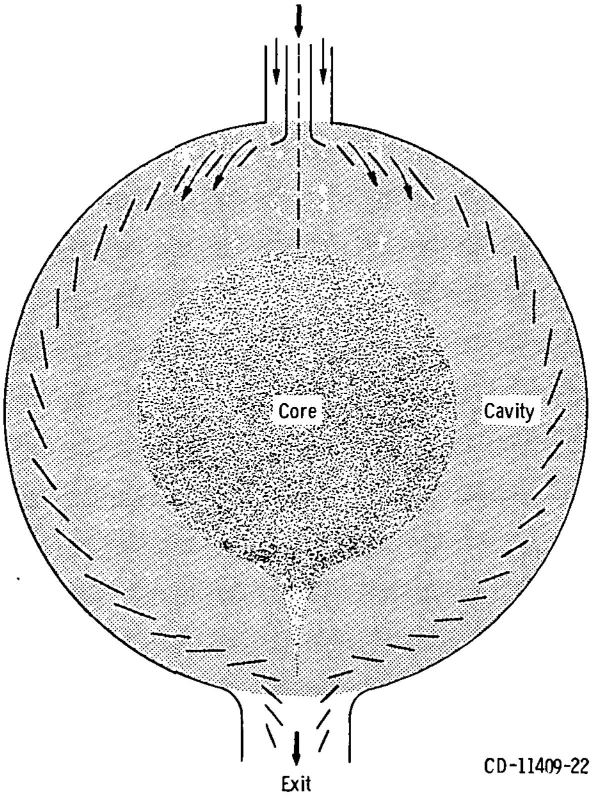


(a) Reactor schematic.



(b) Plan view of reactor center. (All dimensions are in cm.)

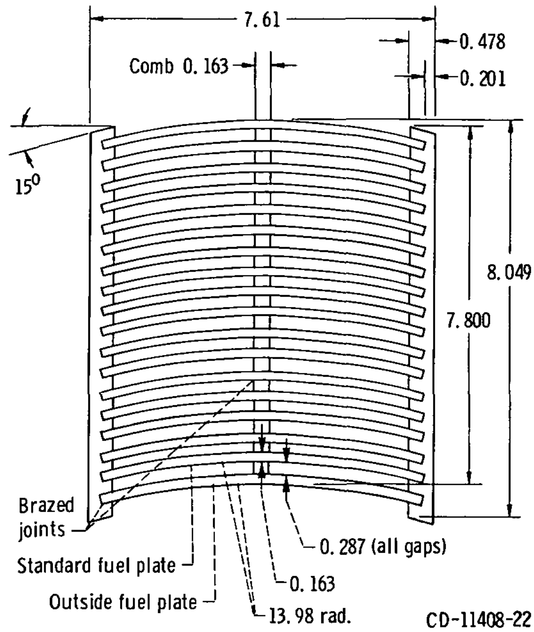
Figure 1. - Cavity test reactor.



Fuel region composition:	
Uranium nuclei (U^+, U^{++}), percent	36
Hydrogen nuclei (H, H^+), percent	24
Electrons, percent	40
Entrance:	
Rate of fuel injection, $\dot{m}_F$, g U/sec	1.1
Rate of propellant flow (at 300 K), $\dot{n}_H$, g H/sec	34
Rate of seed flow, $\dot{n}_U$, g ^{238}U/sec	11
Core:	
Uranium mass, g	375
Hydrogen mass, g	1
Temperature, K	18 900
Average dwell time, θ, sec	330
Cavity:	
Hydrogen mass, g	172
Uranium-238 mass, g	59
Average temperature, K	2500
Average dwell time, θ, sec	55
Average exit temperature, K	3900

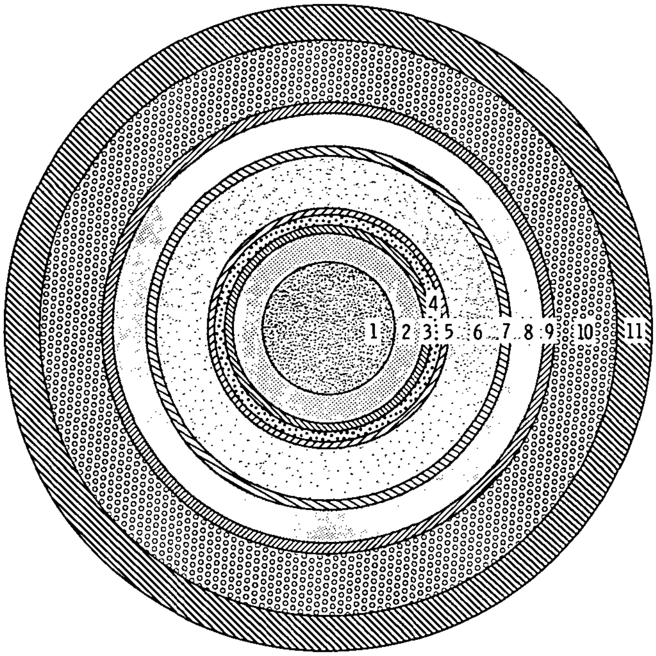
(c) Average conditions in test cavity.

Figure 1. - Concluded.



*Comb is at ends only.

Figure 2. - MTR fuel element. Fuel volume fractions: aluminum, 0.415; coolant, 0.583; fuel, variable. (All linear dimensions are in cm.)



Region	Component	Thickness, cm	Radius, cm
1	Plasma fuel	19.2	19.2
2	Propellant hydrogen	11.28	30.48
3	Aluminum cavity liner	.635	31.115
4	Hydrogen plenum	2.54	33.655
5	Inner moderator containment shell	.635	34.29
6	Moderator	Variable	Variable
7	Outer moderator containment shell	↓	↓
8	Driver fuel		
9	Fuel channel containment shell		
10	Reflector		
11	Pressure vessel	10.16	

Figure 3. - Spherical calculational model of cavity test reactor.

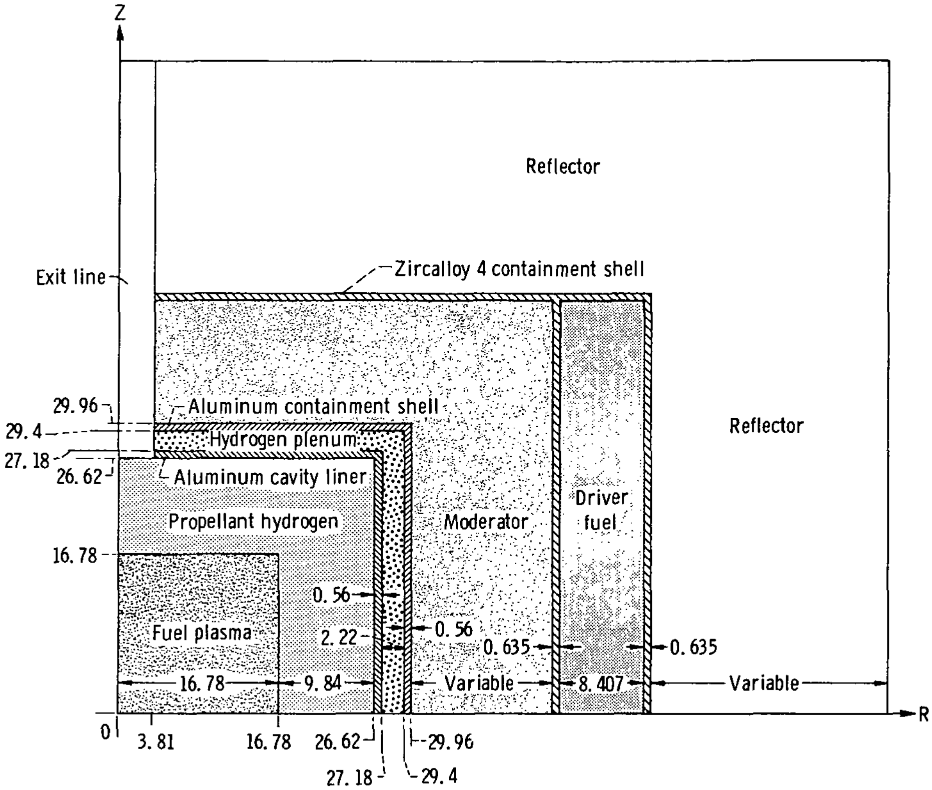


Figure 4. - Cylindrical calculational model of cavity test reactor. (All dimensions are in cm.)

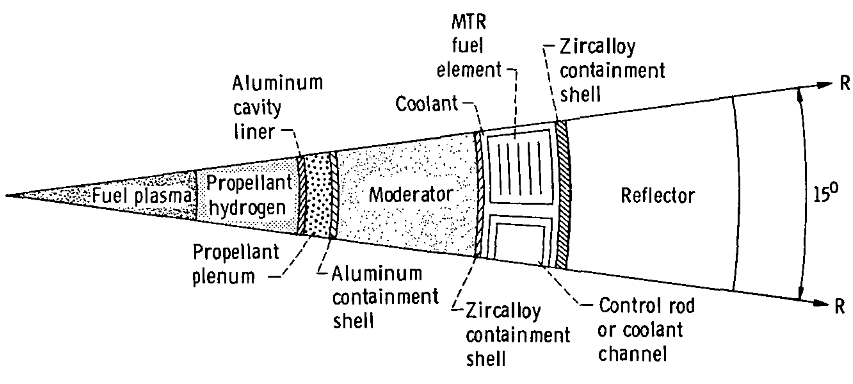


Figure 5. - R-θ Calculational model of cavity test reactor.

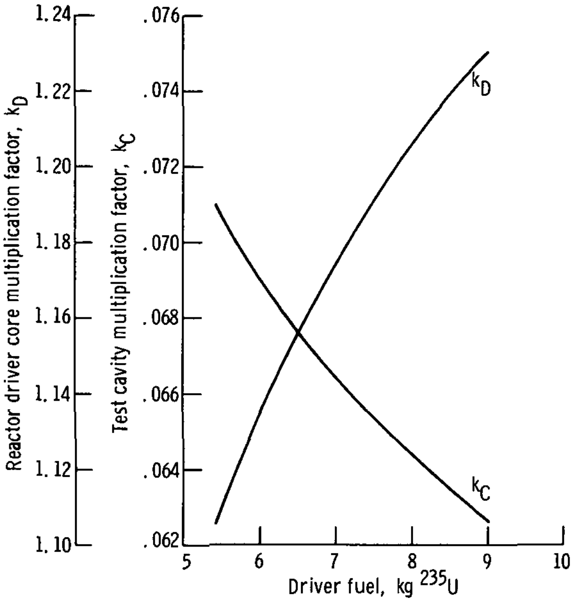


Figure 6. - Effect of driver fuel loading on multiplication constants in cavity and driver fuel regions of cavity test reactor at test conditions. Calculational model is spherical geometry and S_4-P_1-19 group.

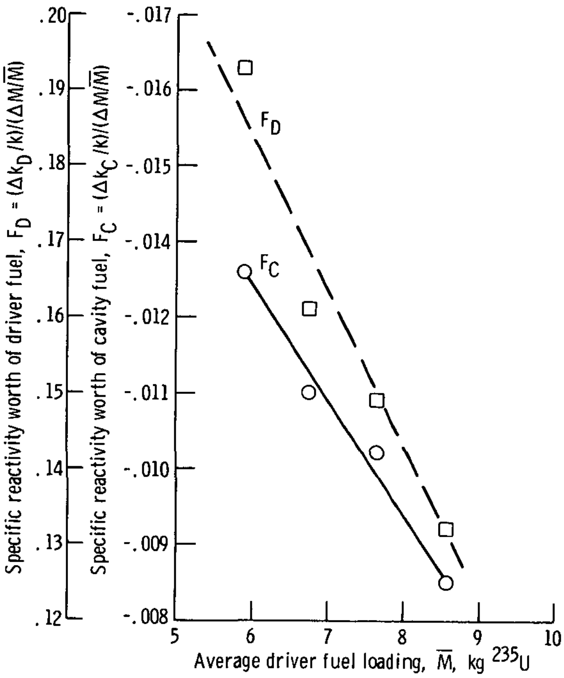


Figure 7. - Calculated specific reactivity worths of test cavity fuel and reactor driver fuel in cavity test reactor at test conditions.

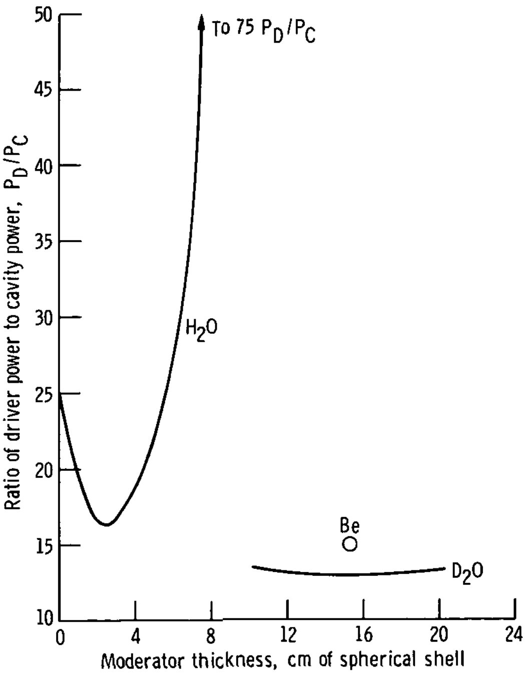


Figure 8. - Effect of moderator material and thickness on the ratio of driver power to cavity power in a cavity test reactor at test conditions. Calculation model is spherical geometry and S_4P_1 19 group.

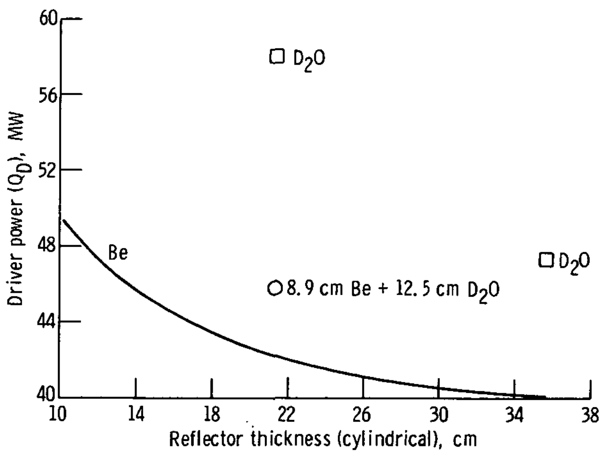


Figure 9. - Required driver power generation as function of reflector material and thickness in cavity test reactor at test conditions. Calculational model has reference model configuration (except for reflector thickness) and conditions and has been normalized to $S_4P_1$19 group with cylindrical geometry.

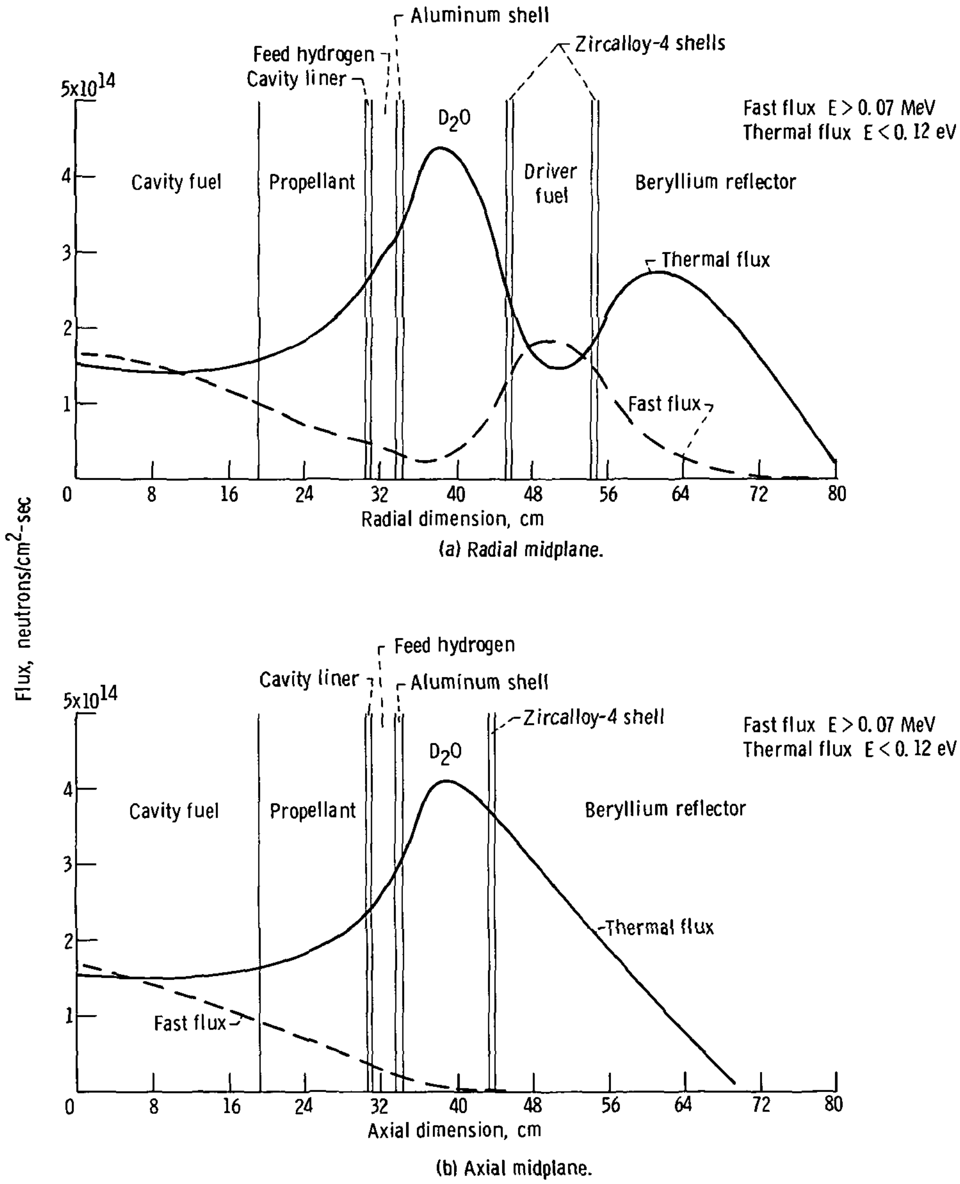


Figure 10. - Fast and thermal flux distributions in cavity test reactor at test conditions.

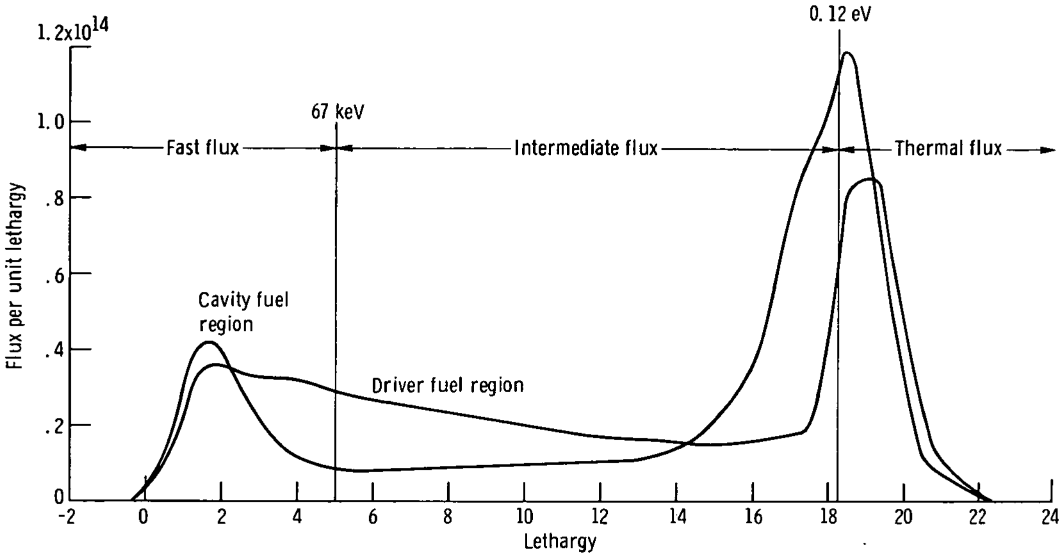


Figure 11. - Flux spectra in cavity and driver fuel regions of cavity test reactor at test conditions. Calculational model is spherical geometry and $S_4P_1$19 group.

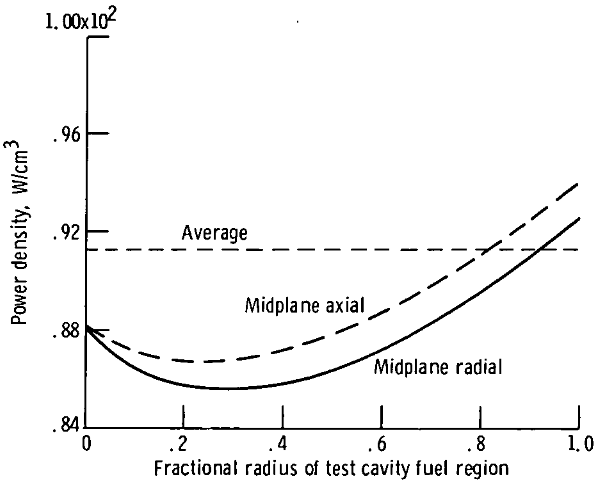


Figure 12. - Power density distribution in the test cavity of cavity test reactor at test conditions. Cavity power, 2.7 megawatts; fuel to cavity diameter ratio, 0.63; cavity fuel volume, 2.96×10^4 cubic centimeters.

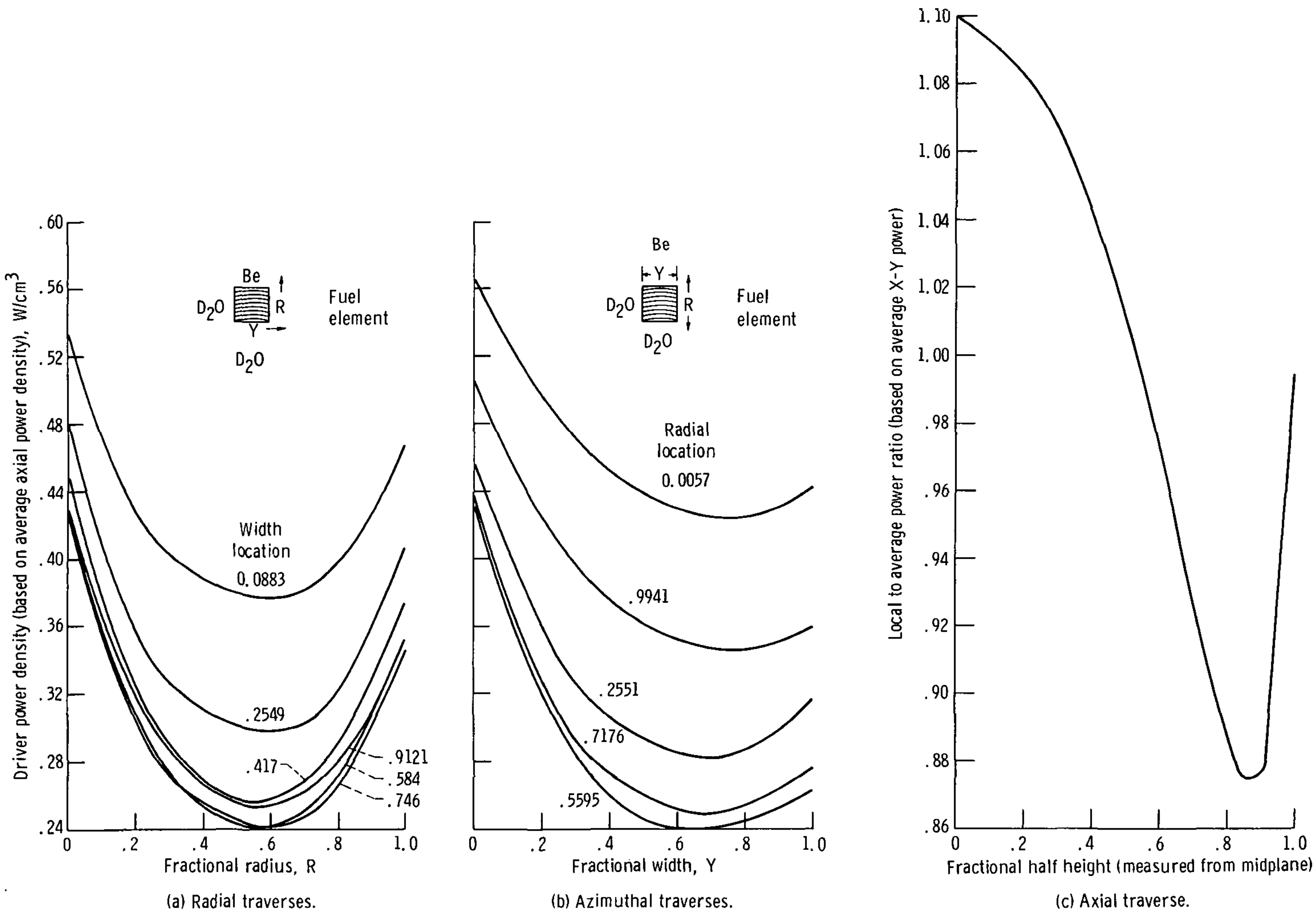


Figure 13. - Driver power density distribution in driver fuel of cavity test reactor at test conditions.

NASA-Langley, 1973 —— 22 E-7193

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