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TECHNICAL PAPER proposed for presentation at
Winter Meeting of the American Nuclear Society
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E-3568

Present day nuclear reactors generally employ neutron absorbing rods for reactor control. Reactivity is adjusted by positioning these rods in the reactor. The presence of control rods in the reactor core carries certain penalties. Not only do they generally require elaborate positioning devices, but local neutron flux and power perturbations can be very severe.

In conventional power plants, these penalties have not been sufficient to forbid the use of control rods. However, new requirements imposed by space systems necessitate a reevaluation of control techniques. Not only are we interested in low weights, but high performance and high efficiency space power systems require close attention to power profiles. Any technique which permits minimum perturbation of power distribution offers a real advantage in high performance cores.

The concept that will be presented is a control system for a water-moderated reactor that uses a neutron absorbing gas, helium-3. It should be mentioned at this point that, while we specifically refer to a water system here, any reactor system which could provide cooling might also be able to use this concept. Helium-3 is chemically inert, has a thermal neutron absorption cross section of about 5000 barns and is available today for about \$100/liter at STP.

The helium-3 would be contained in a number of metal containers evenly distributed through the core. Reactivity control is accomplished by adjusting the pressure of the static gas in these containers.

Figure 1 is a schematic of a water-moderated rocket reactor concept. The hydrogen propellant, stored in liquid form, is first used to cool the nozzle walls and then cools the moderator in heat exchangers located in the peripheral region of the reactor core. After passing through turbomachinery, not shown, the propellant is heated in the reactor core and is exhausted through the nozzle. The water moderator circulates in a closed circuit through the core and heat exchangers. The heat exchangers remove heat generated in the water due to neutron heating and heat transferred to the water from the structure.

The control system containers or control elements would be placed in the core as illustrated in Figure 2. The actual control elements are aluminum annuli running the axial length of the core. In this diagram, we have shown a fuel element array on a triangular pitch with control elements in the interstitial positions. Also shown is a distribution system connecting the individual gas containers. This system is rectangular in cross section, about $\frac{1}{4}$ inch wide and $1\frac{1}{4}$ inches high. This particular cross section is necessary to provide the required volume in this plenum. We shall elaborate further on this later.

Looking at the plan view of the reactor core (Fig. 3) we see the distribution system among the fuel array. The annular control elements are at each of the "corners" of the distribution system. Two independent circuits are illustrated here. These two circuits could be operated independently or connected with the valve shown. Under emergency conditions, for instance, a single circuit could control the reactor.

Figure 4 illustrates the two control circuits (designated by primed and unprimed numbers) superimposed on the reactor schematic. The tanks labeled "1" contain the helium supply. The opening of valves 2 and 4 introduce gas into the system to insert control gas and reduce reactivity. Reactivity is increased by venting through valve 3 with valve 2 closed. The orifice at location 9 is required to restrict the rate of reactivity increase during gas venting, or in the case of piping failure, around the supply tank. By the same token, gas insertion would be restricted by this orifice, so an auxiliary one-shot scram tank is included at 6. This tank could be refilled from the main high pressure reservoirs for subsequent scrams.

In order to study the feasibility of this gas control concept, certain criteria were set which we felt such a system should satisfy. These criteria are listed in Figures 5(a) and (b). Under reactivity, we have listed the worth of gas to be held in the core under certain specified conditions. These criteria as well as those for addition and removal rates have been arbitrarily set but are considered reasonable. The environmental requirements are characteristic of a water-moderated propulsion reactor for space operations.

Specific additional requirements for this control system are satisfactory containment and steady state operation. Furthermore, an overall negative power coefficient of reactivity should be built into the system.

Two specific design features permit adequate containment in a space reactor system:

(1) Flow restriction orifices can be placed in the distribution line, as indicated in Figures 3 and 4, such that all of the gas in the control elements must pass through an orifice before leaving the core.

This device will apply to any accidental situation which involves failure outside the core. The loss rate through the orifice is held below acceptable limits with gas system pressure exhausting to vacuum. This orifice size (in our case, 0.018") requires the addition of the one-shot scram tanks (item 6 in Fig. 4). The required pressure of tank 1 to force $10/sec worth of gas through this orifice would be about 12,000 psi. Therefore, a scram is initiated through valve 5. After successful reactor shutdown, this tank (6) could be isolated from the core and recharged from tanks (1).

(2) The second design feature involves maintaining the gas pressure in the control system below the moderator pressure.

This water seal will prevent rapid loss of helium into the moderator system. On the other hand, flooding of the control system will be impeded because the water will compress the gas in a given system against the closed valves.

The second major design requirement is satisfactory steady state operation. The main problem is presented by internal heat generation in the control gas due to the neutron absorption reaction. Recoil protons and tritons transfer their energy to the gas within very short distances, and since helium-3 is a poor conductor of heat, large temperature gradients might drive control material away from the most important region of the core.

The solution to this problem lies within the design of the control element. Under operating conditions, the recoil proton has a range of about 2 cm in helium-3, the triton about 1/4 cm. The control element can be designed such that the largest portion of the recoil energy is absorbed in the aluminum walls of the element as opposed to the helium gas. The aluminum walls of the control element, with their high thermal conductivity are much more easily cooled with the moderator water flowing around them.

In Figure 2, the mean free path within the gas is restricted by the narrow annulus width of 0.037 inch. Another possible configuration is shown in Figure 6. Here we have large hexagonal control elements which completely surround the fuel elements. The "Y" shaped aluminum structures which are attached to the control element walls are the recoil particle traps. In this configuration, the distribution system is an integral part of the construction, so construction problems associated with the previous distribution systems may be bypassed.

An analysis has to be made of possible nuclear-thermal coupling within the gas system. Even though the gas temperature gradients are low, gas movement away from high flux regions might promote higher flux in those regions. A steady state iterative analysis was performed coupling S_n transport theory and heat transfer calculations for the control element.

The analysis involved the usual "modified-cosine" axial flux profile (shown in Fig. 7) associated with a forward reflected core. It was found that, even with gas redistribution calculated, the axial flux profile is practically identical. The gas density profile within the gas due to this flux shape is shown in Figure 8. The reactivity worth of a control element having a variable helium-3 density as shown in Figure 8 is about one cent less than the reactivity worth of a constant density absorber having the same mass of helium-3.

A negative power coefficient of reactivity is provided in the system by the relative width of the gas passage in the distribution header compared to the width or thickness of the gas passage in the control element. As reactor power is increased, the gas temperature in the distribution header will increase more than that in the control element if the heat removal path is greater in the distribution header. The greater temperature rise in the distribution header causes displacement of neutron absorber from the distribution header into the control element and subsequent reduction in reactivity.

A study was also performed of the local nuclear effects of this system as minimum power perturbation offers an important advantage. A calculation of radial perturbations due to a control annulus were made with the so-called "reverse-cell." In this type of calculation the centerline of the control element is taken as a cell centerline and adjoining fuel cylinders are smeared into an outer "drive-region" for the calculation.

Figure 9 shows the results of this calculation. The "with-poison" case represents the annulus containing about 0.37×10^{-3} grams/cm^3 of helium-3 which represents a typical hot-critical configuration for the rocket reactor. The thermal flux is seen to be perturbed in the moderator region surrounding the control element, but the power profile in the fuel region remains constant. Note that a comparison of no gas to operating conditions represents a maximum configuration difference, not just small changes anticipated during operation.

A potentially more perturbing component is the rectangular cross-sectioned distribution header. While it appears that the local power will not be perturbed, it is necessary that the gross axial distribution also be undistrubed. A two dimensional R-Z transport calculation was performed on the distribution header. The boundaries of the calculation are represented by the dashed lines shown in Figure 10. The location of the edge of the fuel region is indicated by the vertical solid line. The rectangular distribution system is also indicated. The four traverses A, B, C, and D represent radial and axial profiles through the distribution header and away from it which will indicate the flux perturbation caused by the system.

Figure 11 represents a radial thermal flux profile in the neighborhood of the distribution system. Traverse A passes through the gas plenum, traverse B through a position 4 centimeters removed. Here again, the perturbation in the fuel region of the core is minor. Figure 12 compares axial traverses through the fuel region and through the moderator and distribution system. The upper traverse (D) represents axial flux perturbation profile due to our distribution system, while the lower traverse (C) represents the perturbation in the fuel region.

In summary, we show the calculated reactivity worth curve for a helium-3 gas control system (Fig. 13). This curve includes the effects of different temperatures in the gas at different operating pressures. The hold down level corresponds to approximately 90 psia, and hot critical to approximately 60 psia within the control element.

We feel that the concept of a helium-3 gaseous control system offers definite advantages for high performance reactor cores. The major advantage lies in the fact that reactor control can be maintained without perturbing a desired power shape. Furthermore, this concept, as proposed, weighs considerably less than a conventional system. Not only are we using high cross-section low-density poison material, but the valving system is less complex than a control rod drive.

Our study has shown that the system is feasible in terms of pressure ranges, operating temperatures, element sizes, and control worths. Furthermore, the modes of operation can be established quite readily and are not very complex. We have established that the system has a stable configuration under steady state conditions which is only slightly different in control worth from a constant density poison.

Initial investigation has indicated that a helium-3 gaseous control concept is feasible in a water-moderated space nuclear reactor and merits further investigation.

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WATER MODERATED ROCKET REACTOR CONCEPT

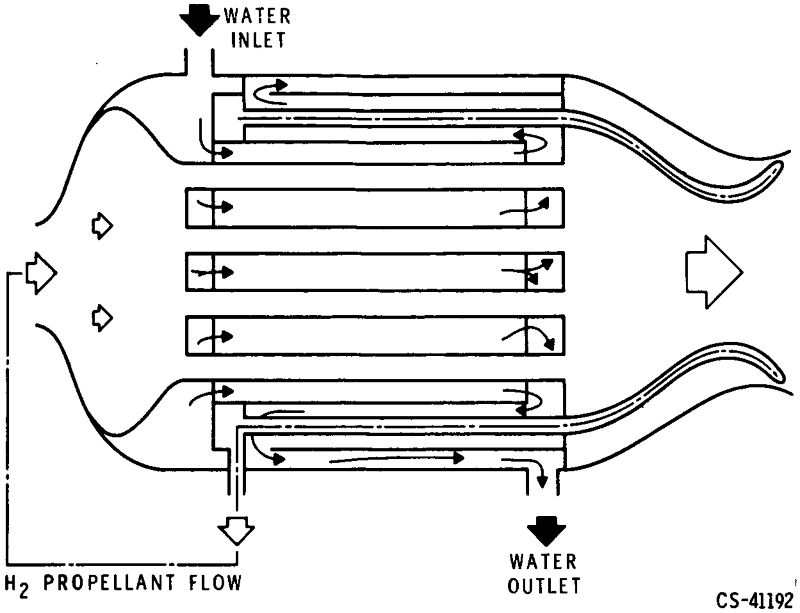

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Figure 1

ANNULAR CONTROL ELEMENT

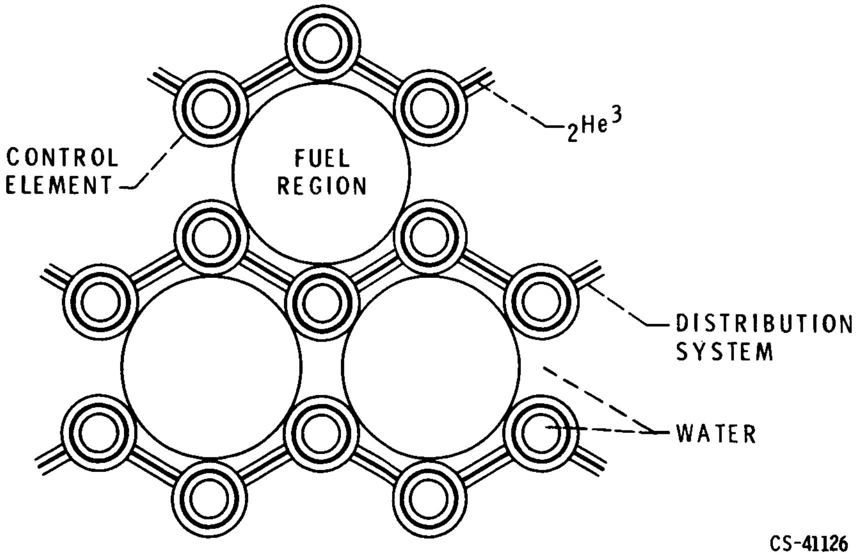

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Figure 2

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REFERENCE CONTROL SYSTEM SCHEMATIC

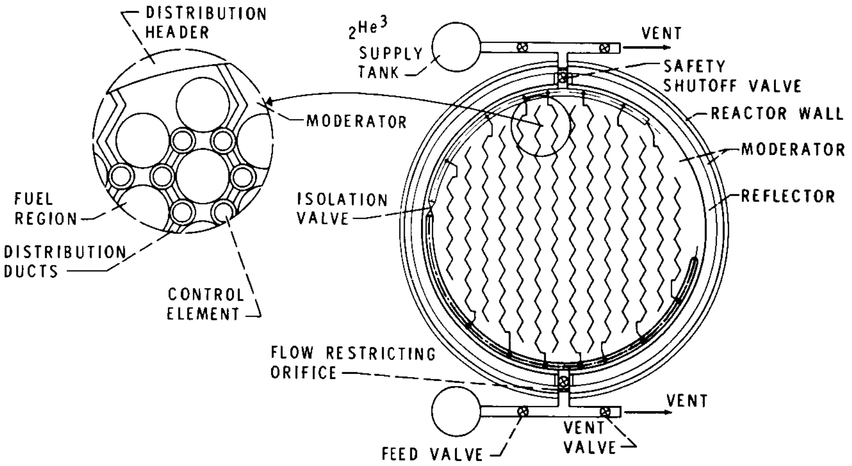

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Figure 3

REACTOR WITH GASEOUS CONTROL SYSTEM

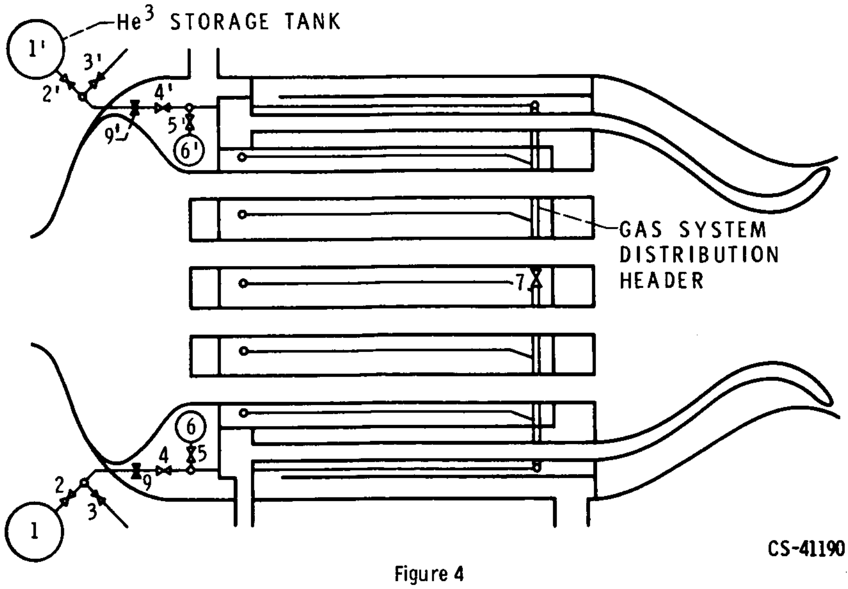

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Figure 4

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CONTROL SYSTEM DESIGN REQUIREMENTS

I. REACTIVITY
  - A. WORTH OF HELIUM-3 HELD IN THE REACTOR ($\Delta k/k$)
    - 1. AT COLD SHUTDOWN 16.1$
    - 2. AT HOT CLEAN CRITICAL 10.7$
    - 3. AT XENON OVERRIDE 0.4% 0.5$
  - B. ADDITION AND REMOVAL
    - 1. MAXIMUM REMOVAL RATE = 6¢/SEC
    - 2. MINIMUM SCRAM RATE = 10$/SEC
    - 3. INCREMENTS OF FINE CONTROL = ±1/2¢
  - C. MAXIMUM ALLOWABLE VARIATION OF POISON MASS BETWEEN ELEMENTS = ±5%

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Figure 5A

CONTROL SYSTEM DESIGN REQUIREMENTS

II. ENVIRONMENTAL
  - A. PRESSURE OUTSIDE CONTROL SYSTEM
    - 1. IN CORE (MODERATOR REGION)
      - (a) NORMAL OPERATION = 600 PSIA
      - (b) SHUTDOWN = 100 PSIA
    - 2. OUTSIDE OF REACTOR CORE = 0 PSIA
  - B. WATER COOLANT
    - 1. INLET TEMP = 656° R
    - 2. FLOW PER LATTICE CELL = 30 GPM
  - C. ALUMINUM TEMP LIMIT = 760° R
  - D. AVERAGE HEATING RATES AT 100% POWER
    - 1. IN WATER = 150 W/CC
    - 2. IN ALUMINUM = 360 W/CC
  - E. REACTOR OPERATING TIME = 1 HR
  - F. NUMBER OF REACTOR STARTUPS = 5

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Figure 5B

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HEXAGONAL CONTROL ELEMENT CONCEPT

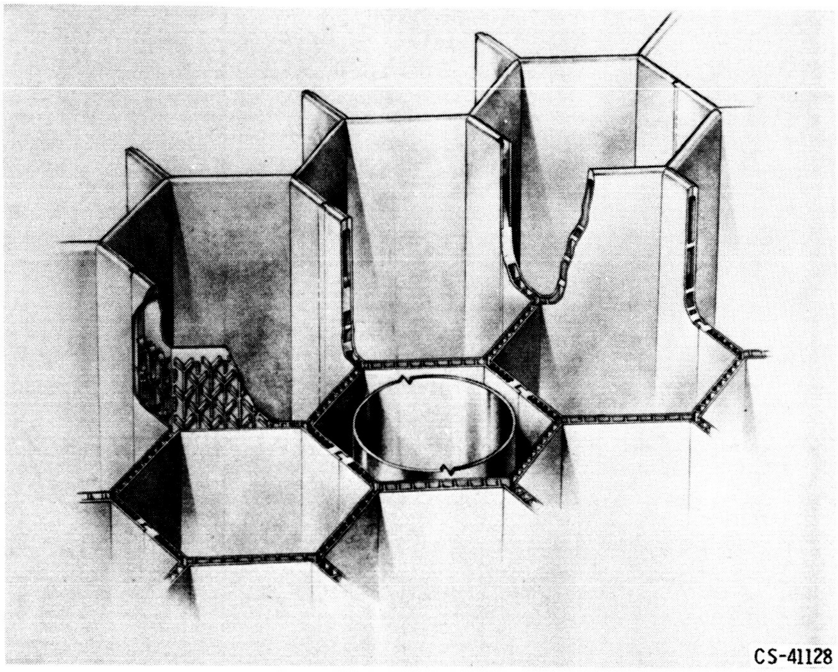

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Figure 6

EFFECT OF VARIABLE GAS DENSITY ON AXIAL FLUX PROFILE

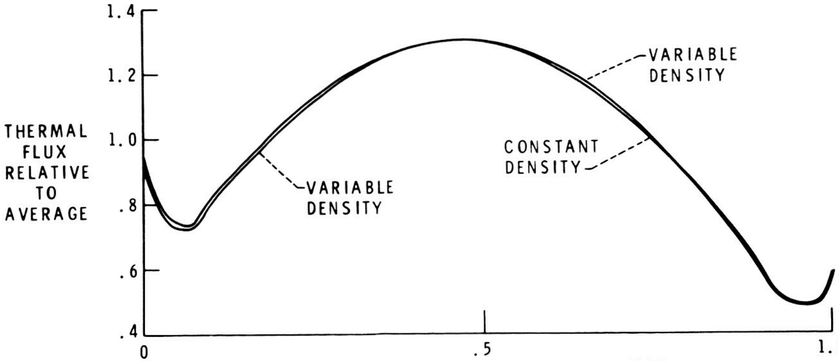

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Figure 7

HELIUM-3 DENSITY DISTRIBUTION IN CONTROL ELEMENT

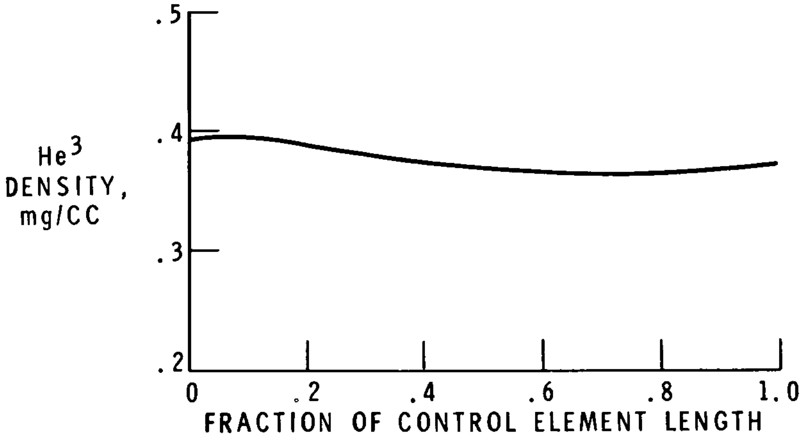

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Figure 8

THERMAL FLUX PROFILES IN "REVERSE-CELL" CALCULATIONS

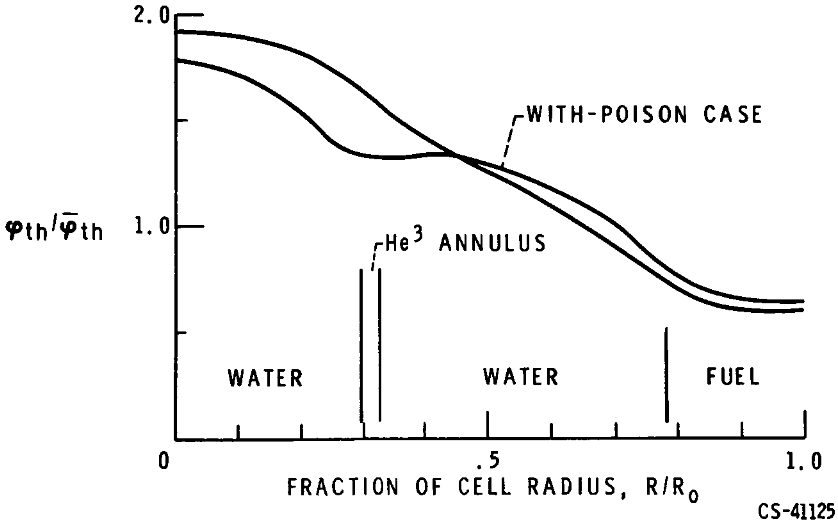

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Figure 9

GEOMETRY OF DISTRIBUTION SYSTEM

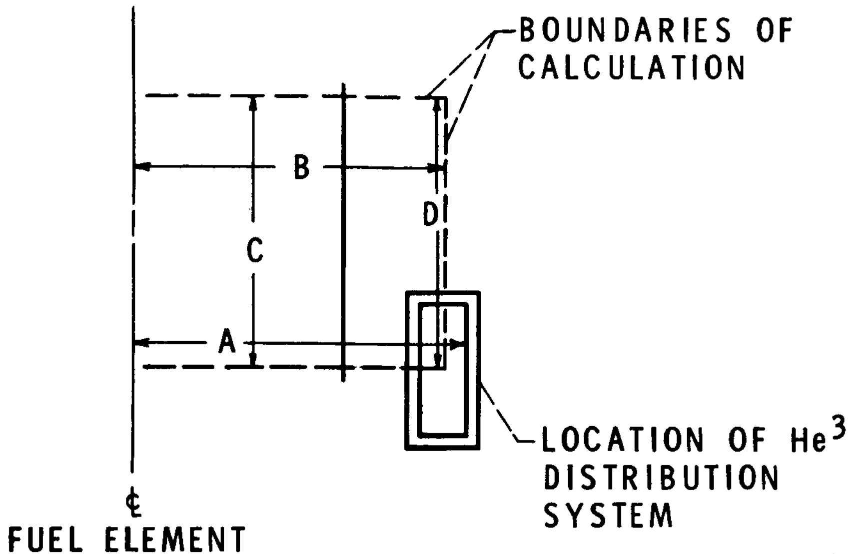

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Figure 10

RADIAL FLUX PROFILE NEAR DISTRIBUTION SYSTEM

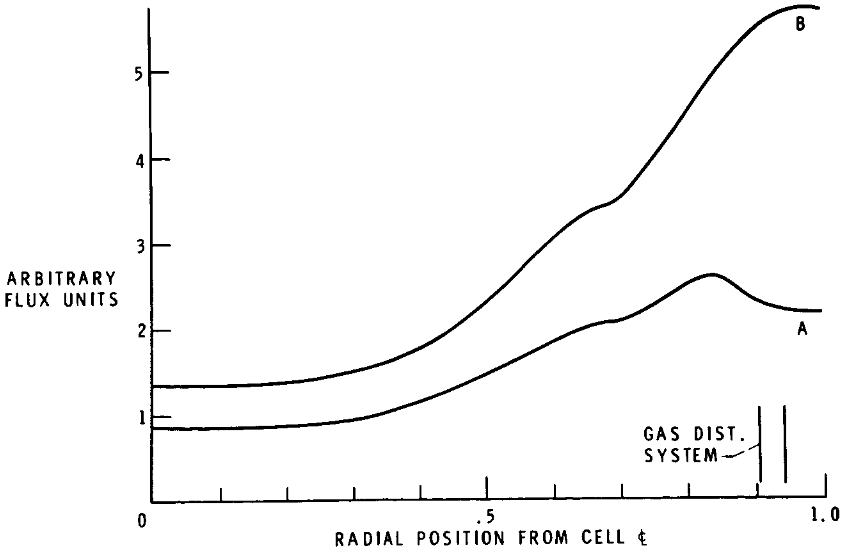

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Figure 11

AXIAL FLUX PROFILE NEAR DISTRIBUTION SYSTEM

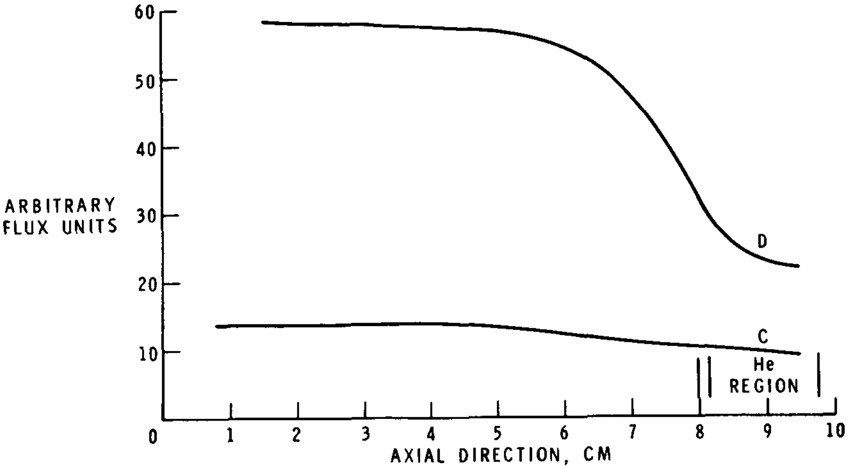

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Figure 12

TYPICAL REACTIVITY CURVE FOR HELIUM-3 SYSTEM

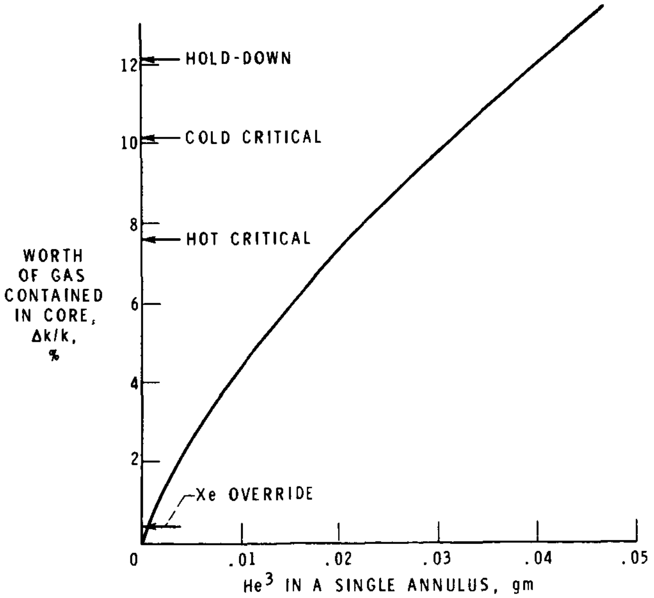

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Figure 13