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CAVITY REACTOR ENGINEERING MOCKUP CRITICAL EXPERIMENT

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GENERAL ELECTRIC COMPANY

Nuclear Systems Programs

Idaho Falls, Idaho

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GENERAL ELECTRIC COMPANY

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INTRODUCTION

For the past two years, the General Electric Company has been performing a number of cavity reactor critical experiments for the Lewis Research Center of the National Aeronautics and Space Administration and these experiments are currently in operation at the National Reactor Testing Station in Idaho. Previous reactor experiments have been reported including various configurations fueled with solid uranium sheets 0.0025 cm (0.001 in.) thick as well as actual gaseous UF_6 to fuel the reactors [1], [2], [3], [4]

During the past six months, three major configurations have been tested. These are as follows:

1. A stainless steel lined cavity with 2.0×10^{21} atoms/cc hydrogen in the void region between the active core and cavity wall. Polyethylene (CH_2) was used to mockup the hydrogen propellant that would be present in an operating reactor.

2. A stainless steel lined cavity with variable hydrogen density in the outer portion of the fueled region and in the void between the active core and cavity wall. Polyethylene and polystyrene (CH) were used to mockup hydrogen. This configuration simulated the hydrogen density variation that would be expected in a high temperature cavity.

3. A stainless steel lined cavity with an annulus of MTR type fuel plates in the radial reflector. The use of fuel in the reflector is an attempt to reduce the critical mass within the cavity, and therefore, reduce the pressure requirements.

These experiments have produced critical mass and related data to further evaluate the cavity reactor concept. These configurations have provided models for correlation of computer calculations and experimental results, and provided insight into the difficulties of performing adequate calculations on these systems.

DESCRIPTION OF REACTOR

The overall Cavity Reactor Critical Experiment layout is shown in Figure 1. A split table arrangement was used with one of the tanks consisting of an end reflector mounted on a 4-wheel dolly. With the two tanks separated, there was easy access to the cavity region, as seen from Figure 1. The cavity was contained within the fixed table tank and was 122 cm (4 ft) long by 183 cm (6 ft) in diameter. The surrounding tanks contained D_2O which served as a reflector-moderator. The D_2O was nominally 88.9 cm (35 inches) thick. The reactor was controlled with stainless steel clad boron carbide rods which were actuator driven into the end of the fixed table tank.

Solid sheets of uranium were used to fuel the reactor. These sheets were nominally 0.0025 cm thick and contained 93.2% U^{235}. A special core structure was used to position the fuel within the cavity region. The basic structure is shown in Figure 2 and consisted of several cells into which fuel trays could be inserted. This structure was made of thin type 1100 aluminum. The fuel sheets were loaded into fuel trays as shown in Figure 3. Since the fuel within the cavity was relatively dilute, it was necessary to space the fuel within the fuel tray as shown in Figure 3. The fuel sheet orientation was staggered, as shown in this figure, thus reducing to a minimum the low-absorption streaming paths for neutrons through the fueled region. With 208 of these fuel trays in the reactor, the effective core diameter was 124.5 cm.

Since the reactor coolant will be hydrogen and no arrangement was available to actually use pure hydrogen, it was necessary to provide a mockup material. Polyethylene (CH_2) was chosen for the uniform hydrogen density experiment and a special structure was built as shown in Figure 4. This structure was specially designed not only to give the correct hydrogen density within the void between the active core and the cavity wall, but also to provide a path for heating the structure to approximately 180°F by flowing hot air. This arrangement is shown in Figure 5. The air was heated electrically and forced through the polyethylene structure as shown in this figure.

The steel liner on the inner surface of the cavity wall consisted of 0.0965 cm thick 304 stainless steel. This liner covered both ends of the cavity as well as the cylindrical wall and weighed 83.1 kg.

The hydrogen worth in the gap between the core and the cavity D_2O wall depends on its position in the gap and can vary by a factor of 2. Hydrogen is worth the most when adjacent to the fuel, least when near the D_2O wall. For instance, a shift of 19 kg of CH_2 (2.6 kg of hydrogen) from a location near the wall and 10 cm wide, to a location against the fuel and 10 cm wide was calculated to reduce reactivity by 3.7%. This result was confirmed by perturbation measurements on the system. Also, the worth of hydrogen on the outer edges of the fuel is negative and does not become positive until a depth of approximately 3-inches within the fuel. Beyond this point, hydrogen within the fuel has a highly positive reactivity effect. For instance, a uniform flooding of the fuel region with 2.6 kg of hydrogen results in a calculated increase in reactivity of 3%Δk.

The variable hydrogen experiment, which mocked up a typical hydrogen flow including mixing with the fuel, required a large range of hydrogen densities within the outer portion of the active core and in the void between the core and cavity wall as shown in Figure 6. Because of the low densities required in some regions, and the desire to avoid heterogenieties as much as possible, it was decided to use a less dense material than polyethylene for the base structure. Foamed polystyrene (CH) was selected and this material was cut into a "Swiss cheese" arrangement as shown in Figure 7, such that the lowest hydrogen density would be attained in the foamed polystyrene alone. The higher densities were produced by sandwiching polyethylene sheet in between the layers of foam. It required eight sectors as shown in Figure 7 to fill in the void region between the core and cavity wall.

Each of the above configurations contained an annulus of Be in the radial reflector. The Be was 10.16 cm thick by 107 cm long and its inner surface was located at an average distance of 6.5 cm from the wet surface of the cavity wall. The use of beryllium is to simulate a required heat shield and flow baffle. Beryllium replacing D_2O (commercial reactor grade) is a very minor reactivity penalty unless the beryllium is moved close to the cavity wall (penalty of approximately 5%Δk). An additional reactivity penalty would be produced by extra structure required to support the beryllium. In the case of this experiment, the support structure was worth -2.7%Δk.

The experiments involving an annulus of fuel in the radial reflector were performed without the Be reflector annulus and the hydrogenous material in the cavity. The stainless steel liner remained in the wall of the cavity region. MTR-type* fuel plates were used to form the fuel annulus in the D_2O. The fuel in each plate was nominally 50.6 cm long by 6.2 cm wide and consisted of 8.4 grams of U^{235} in an aluminum matrix which was clad with aluminum. The total thickness was 0.15 cm. Each fuel plate was clamped onto an aluminum backup plate which was 56.4 cm long by 7.0 cm wide by 0.075 cm thick. Special hardware was constructed to position a single layer of these fuel plates around the cavity region at the desired distance from the cavity wall. The fuel plates were placed parallel to the cavity wall. Since the fuel plate length was less than the cavity, the plates were centered over the cavity. Only a single fuel plate length and thickness were used to mockup the annulus.

CRITICAL MASS

For the first configuration in the series presented in this paper, the stainless steel and polyethylene were loaded into the cavity in three steps. After each step a critical assembly was established. The critical mass at each of these points is given in Table 1. This table also contains the critical mass for the variable hydrogen reactor and for the assemblies with an annulus of fuel at 7.6 cm and 19 cm from the cavity wall.

The fuel support structure and fuel tray assemblies for the hydrogen experiments weighed 186.1 kg. The two configurations containing a fuel annulus in the D_2O had 7.2 kg more aluminum in the fuel region because of the need to use more aluminum spacers in the fuel trays with the lighter loading. In all other respects, the cores of the various configurations had identical dimensions and structural material.

CORE MATERIAL WORTHS

The core average fuel worth was measured on most of the configurations covered by this report. The relationship of fuel worth vs core loading is shown in Figure 8 and is approximately a negative exponential function.

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* These plates are of the same general dimension as the MTR plates, but were not curved.

A core average reactivity worth of type 1100 aluminum was also measured over a wide range of core loadings and these data are given in Figure 9. The data are also presented in terms of kg of Al/kg of uranium so that when correcting for the aluminum in the core, (which would not be present in an operating gaseous reactor), corrections to core fuel loading can readily be made. Beyond a core loading of about 80 kg, the relationship appears to be relatively constant at about 15 kg of Al/kg of U.

POLYETHYLENE TEMPERATURE REACTIVITY COEFFICIENT

The polyethylene structure in the uniform hydrogen experiment was heated several times and k-excess and temperature were recorded vs time over each cycle. Figure 10 shows the observed changes and it will be noted that for a 57°C temperature increase, k-excess increased about 0.8%Δk. The temperature coefficient from 20 to 50°C averaged 0.015%Δk/°C and from 50 to 75°C was 0.013%Δk/°C.

EFFECTS OF URANIUM IN D_2O REFLECTOR

With the polyethylene and beryllium removed from the reactor and an annulus of fuel (739 gm U^{235}) in the radial reflector 7.6 cm from the cavity wall. The critical mass in the cavity was reduced to 20.7 kg (from a nominal 28 kg without the fueled sector). A sector of the fueled annulus was moved out to several other radial locations in the D_2O and the worth of the sector was extrapolated to a full annulus of fuel containing 739 gm U^{235}. These data are given in Figure 11. Included here are the ratios of the fuel annulus power to core power. The peak power ratio and the minimum critical mass occur at about 20 cm from the cavity wall. The core critical mass and power generation in the fuel annulus would, of course, be governed by how much fuel was used in the D_2O and how much power could be tolerated in the annulus. An extrapolation to complete removal of the fuel annulus gives a critical mass of 28 kg. For the similar configuration with a beryllium annulus, the critical loading was 34 kg. The data show that a 25% savings in core loading could be obtained for a condition where 10% of the total nuclear power generation was in the annulus. This latter condition means that as much as 17% of the total thermodynamic energy is deposited in the reflector regions (10% of the direct nuclear power plus most of the neutron energy and the gamma energy that originated in the cavity core). These are probably the maximum conditions that could be tolerated, if the average exit temperature of the hydrogen coolant out of the rocket nozzle of the propulsion system is to be 10,000°R and the hydrogen is to enter the system as liquid (approximately 35°R).

POWER AND FLUX DISTRIBUTION

Bare and cadmium covered gold and catcher foils were exposed within the cavity region to determine power and flux distribution. The results are summarized in Table 2. The actual physical uranium mass in the two hydrogen simulation experiments differed only by 3 kg, the variable hydrogen experiment containing the least. The variable hydrogen system had a large k-excess which was controlled by the rods in the end reflector. The gold foils showed very little or no change. However, there was more fission power reduction from the outside to the center of the active core and all of the uranium cadmium ratios within the cavity region were smaller in the variable hydrogen reactor.

CALCULATION EXPERIENCE

Results of calculations have been cited above. Most of these were obtained with one dime-~ional diffusion theory using 19 groups, 4 of which were in the thermal range. In general, up-scattering has not been included because of the convergence difficulties. These simple calculations have been successful in predicting differences in multiplication factor, but, of course, have failed to accurately predict absolute values for k. Transport calculations with 19 groups, 7 of which were thermal with up-scattering are being performed in one dimension. Two dimensional transport calculations with the desired space and energy detail require very large machine storage and have not been tried to date.

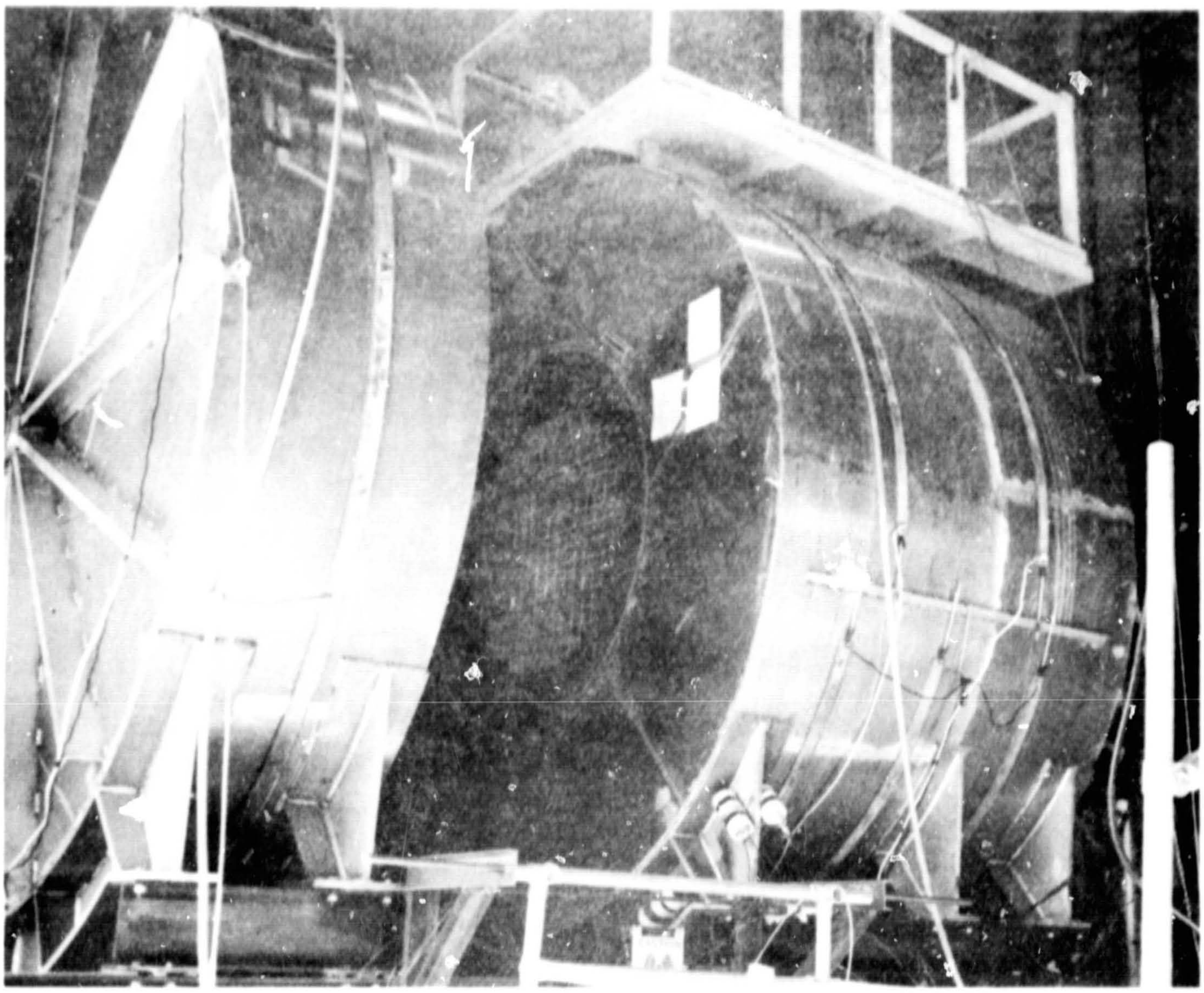

Fig. 1 Photograph of mockup of cavity reactor critical experiment

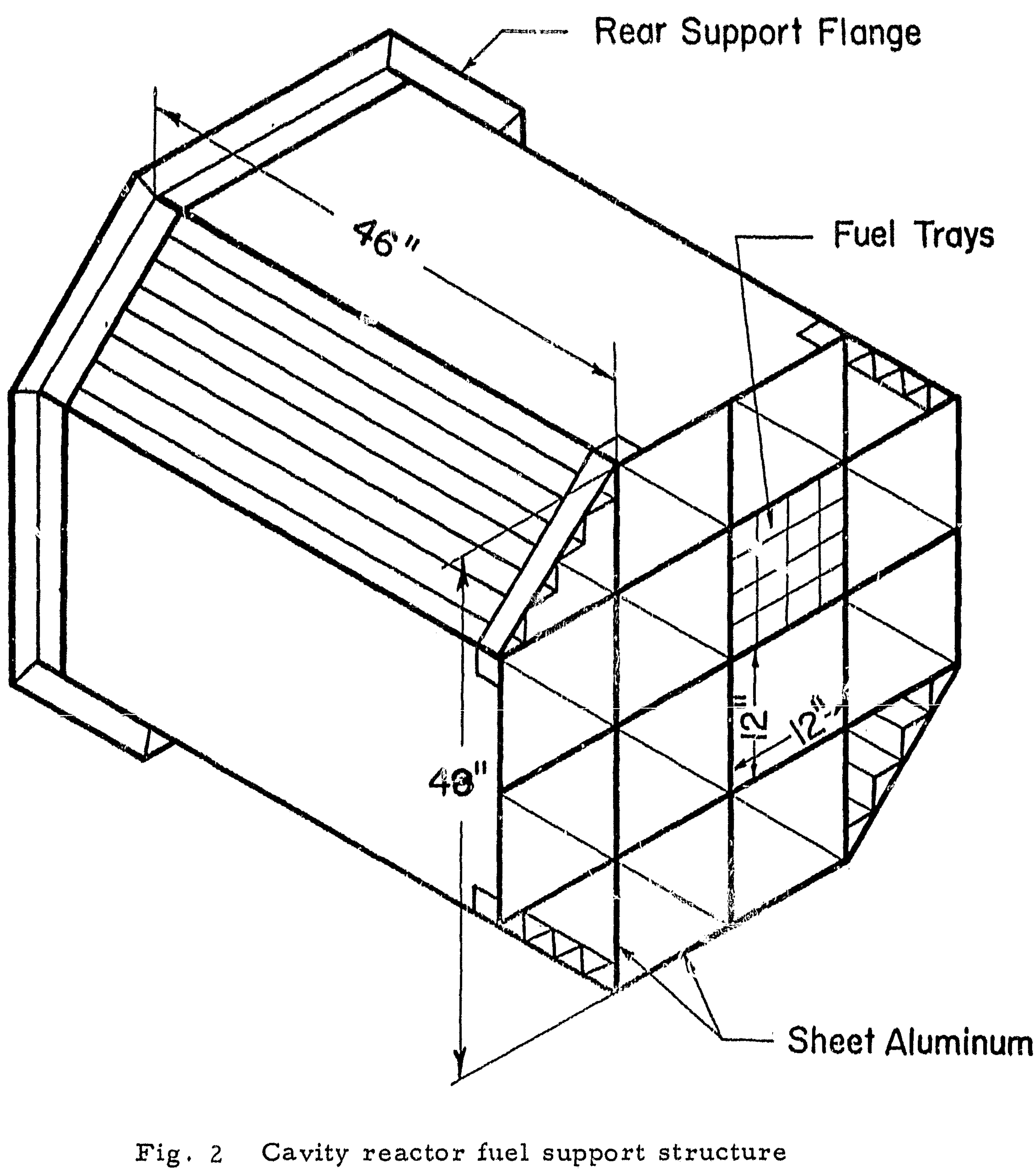

Fig. 2 Cavity reactor fuel support structure

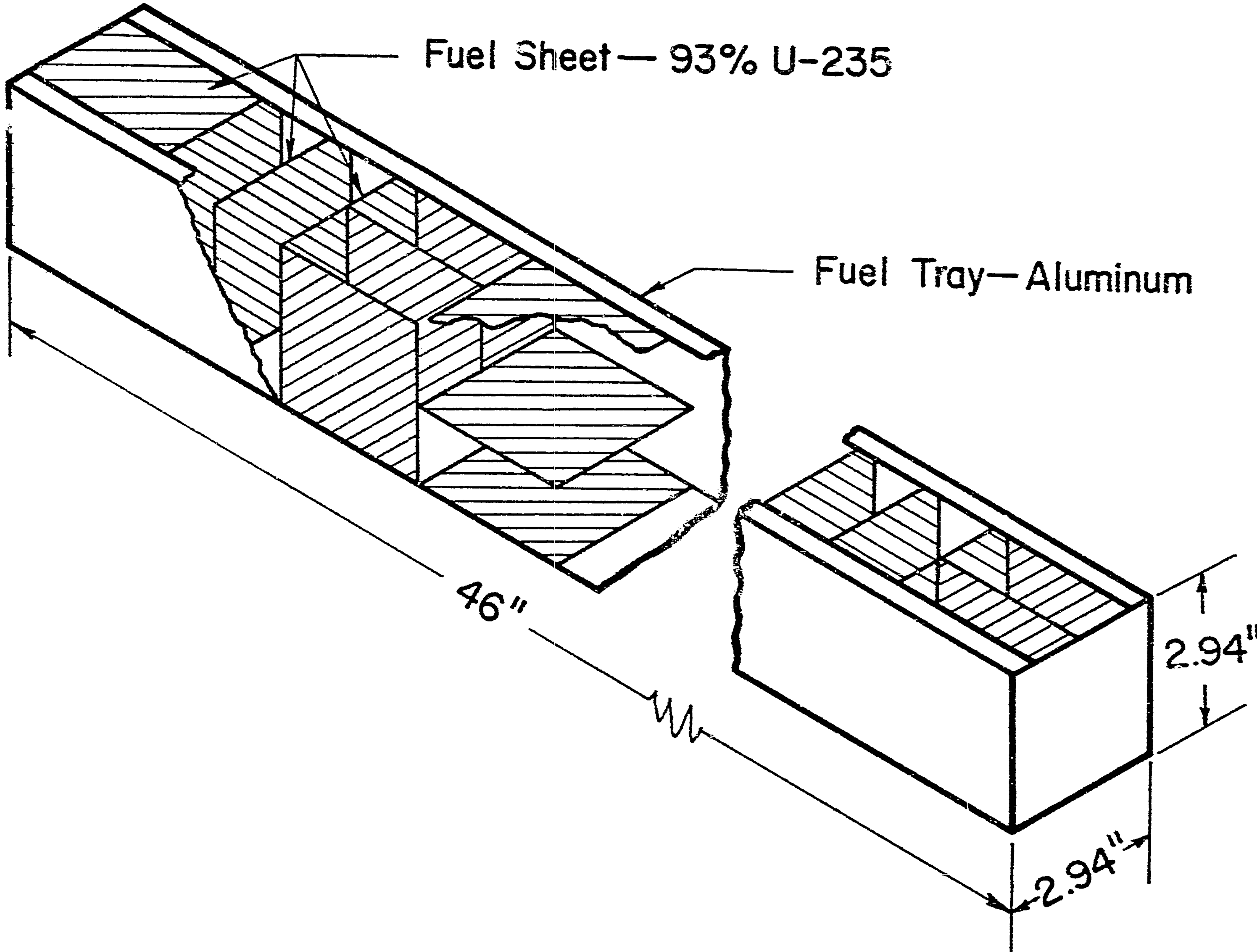

Fig. 3   Cavity reactor fuel element

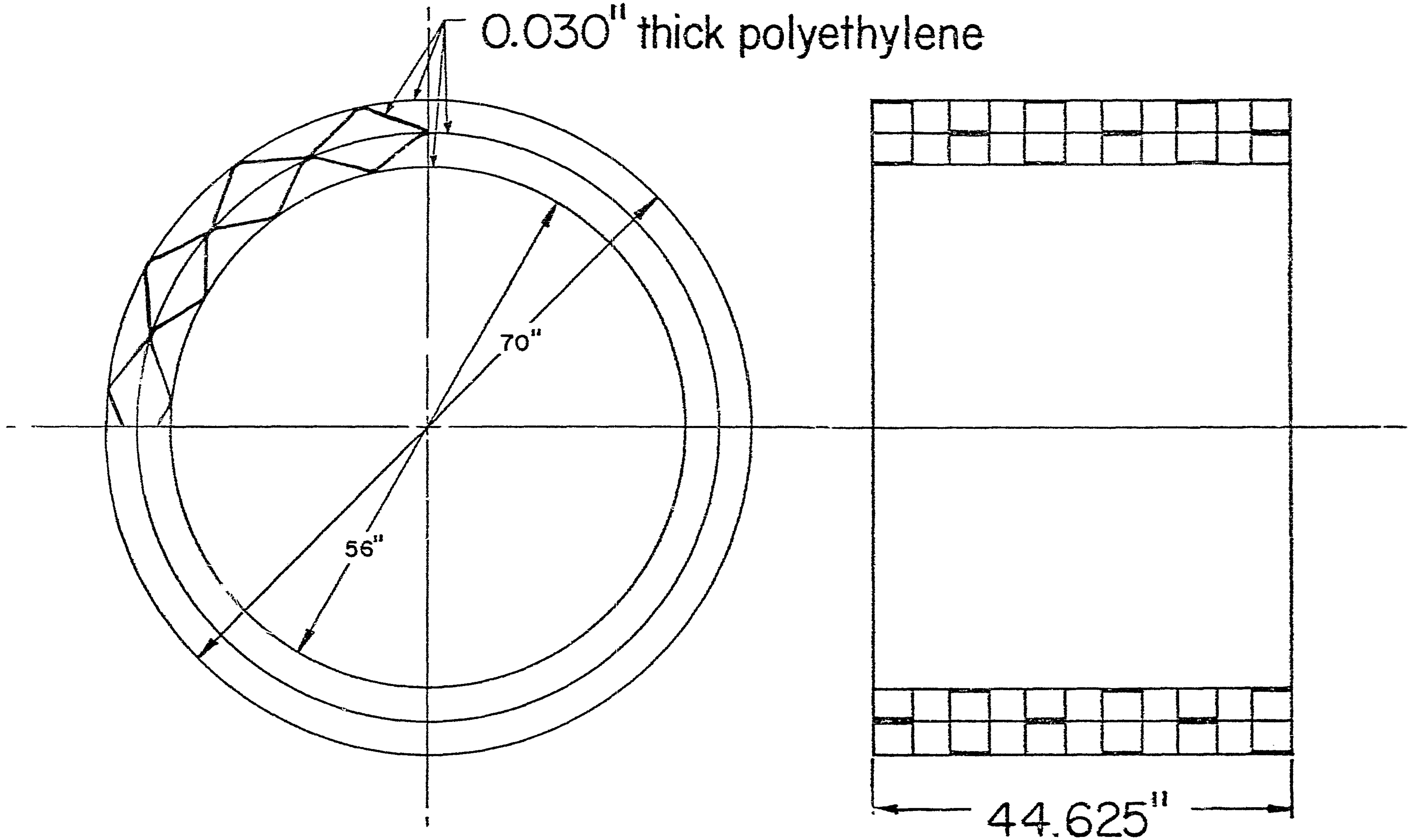

Fig. 4 Hydrogen mockup structure (polyethylene)

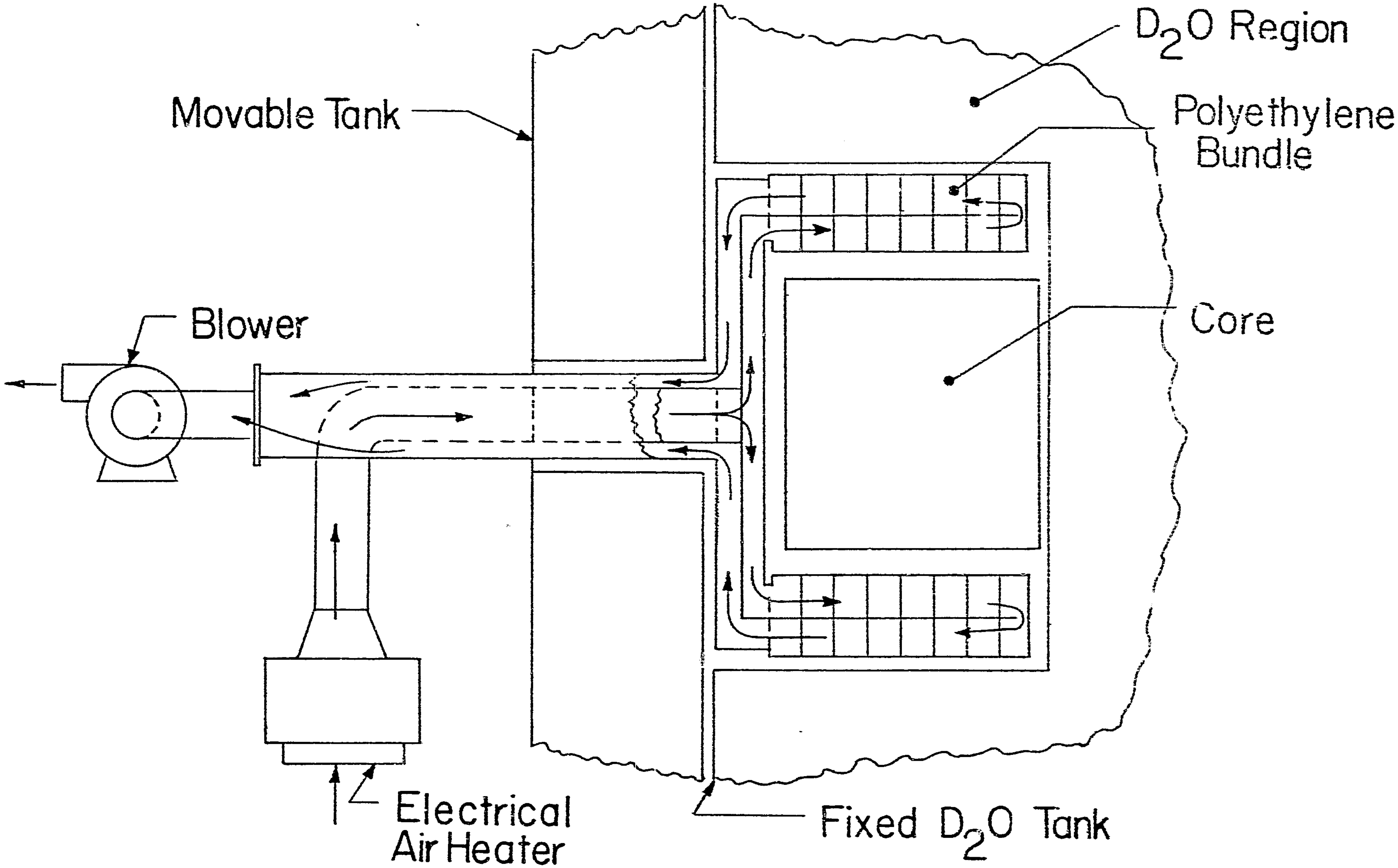

Fig. 5 Schematic of polyethylene heating system

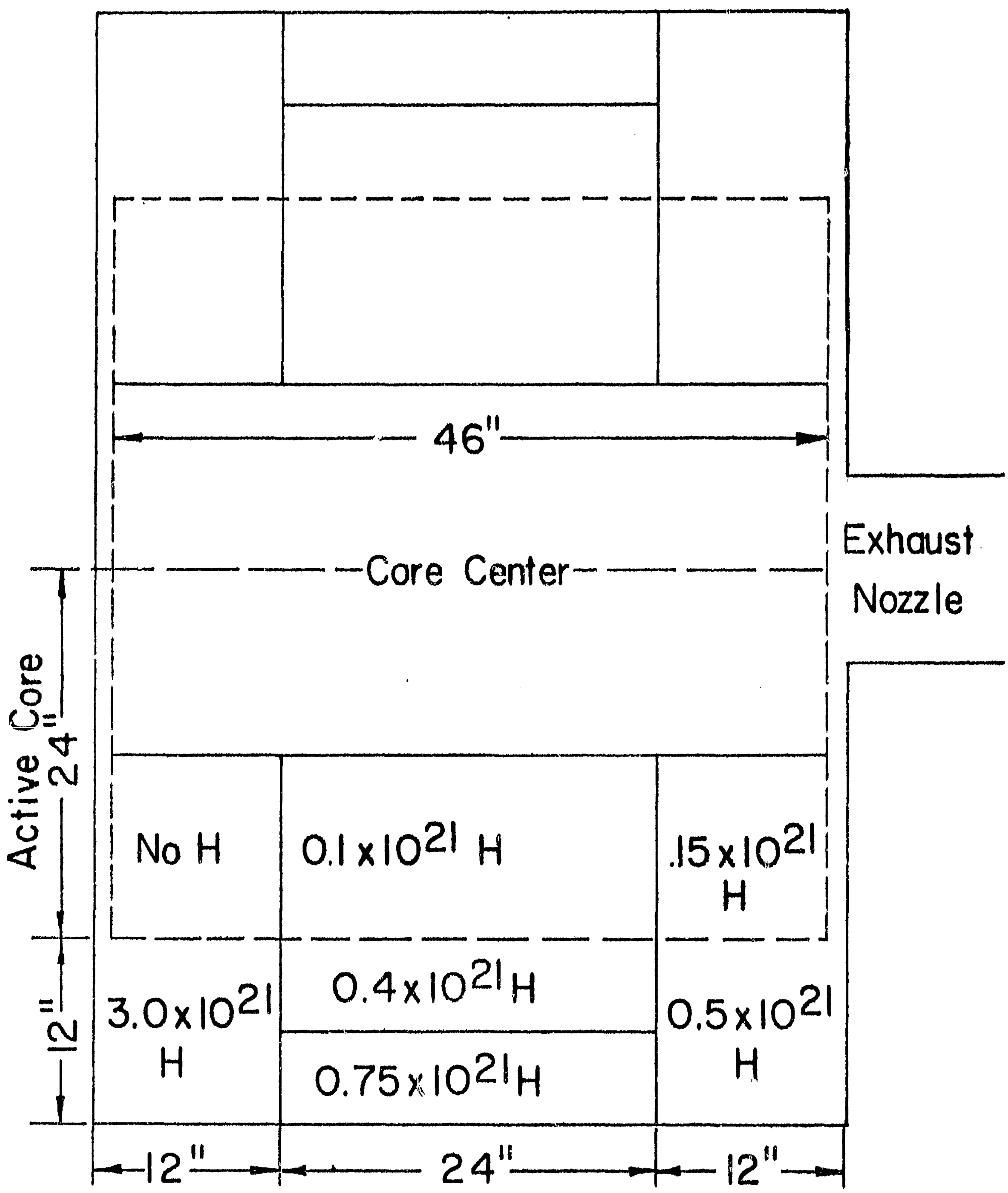

Fig. 6 Hydrogen concentration in variable hydrogen experiment

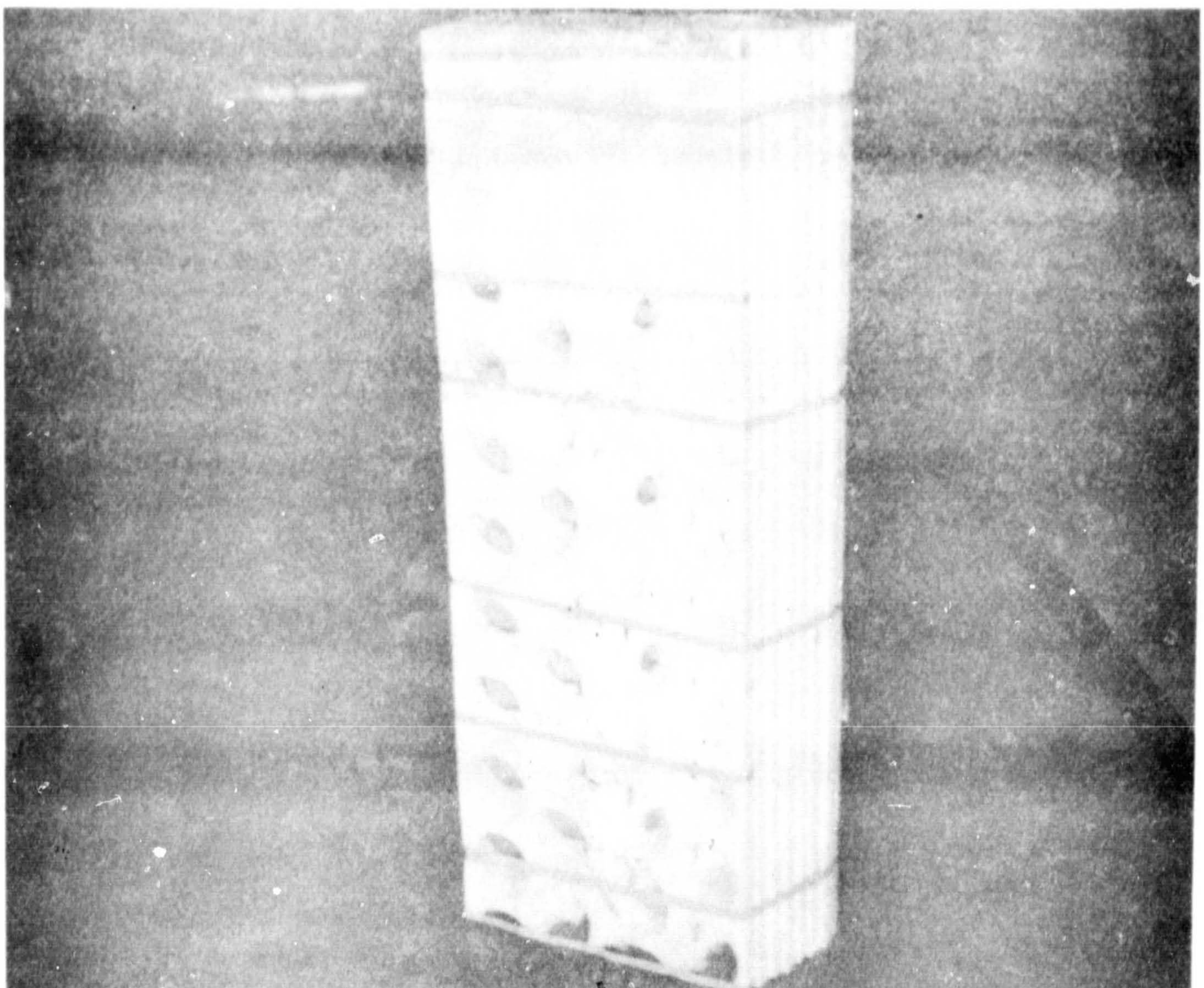

Fig. 7 Photograph of one sector of polystyrene and polyethylene

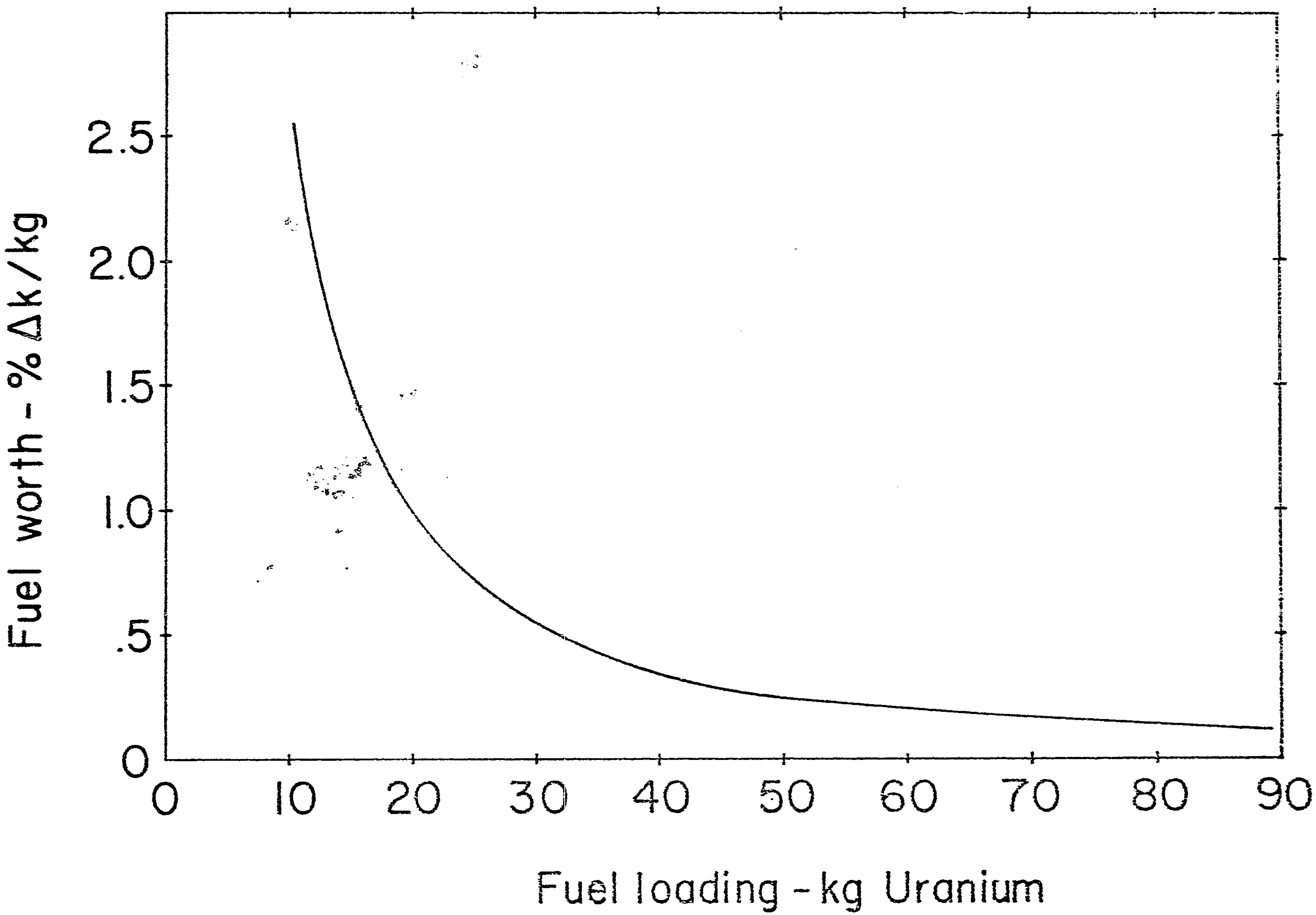

Fig. 8 The effect of core loading on fuel worth

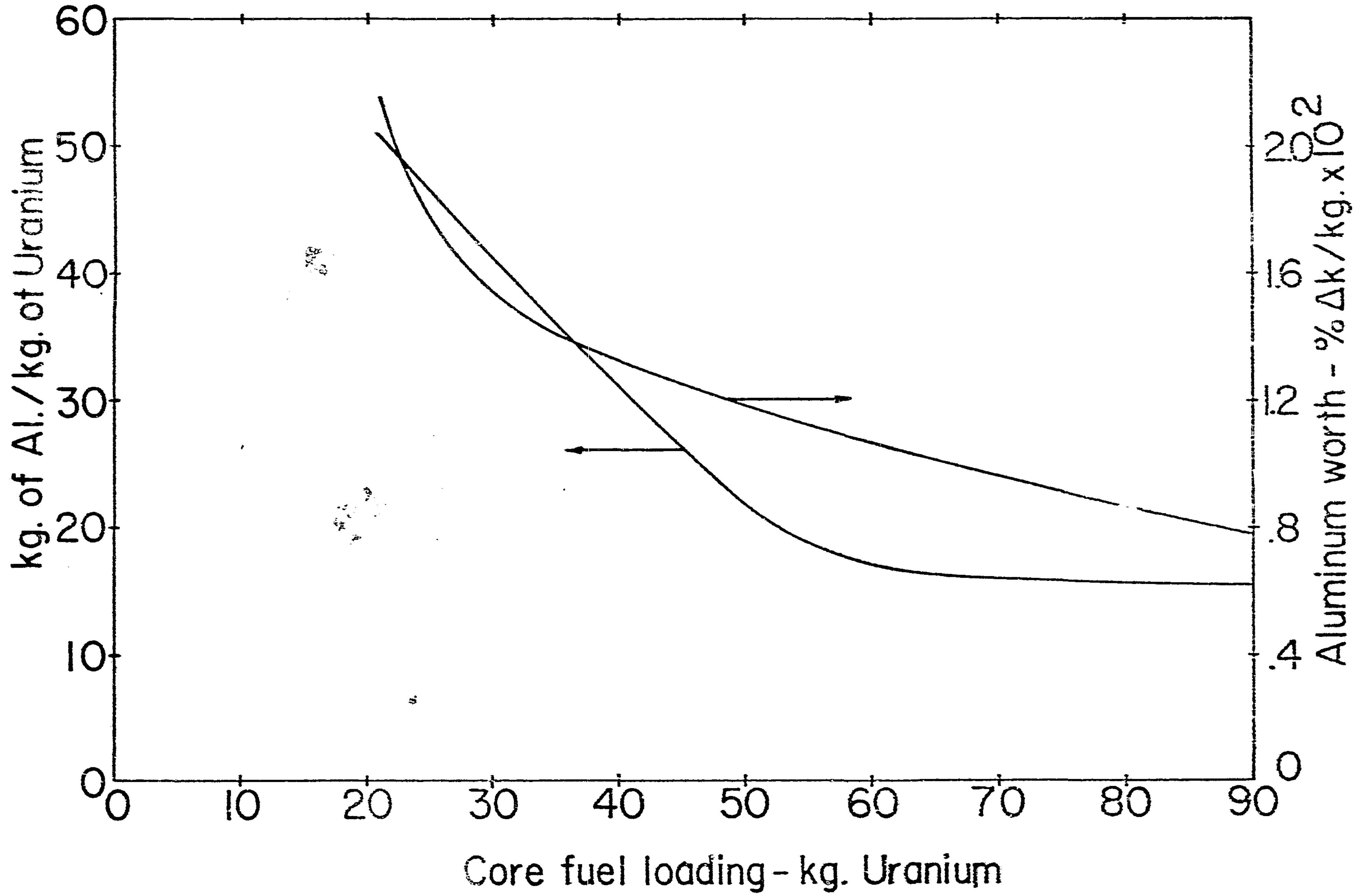

Fig. 9 Core loading effects on aluminum worth

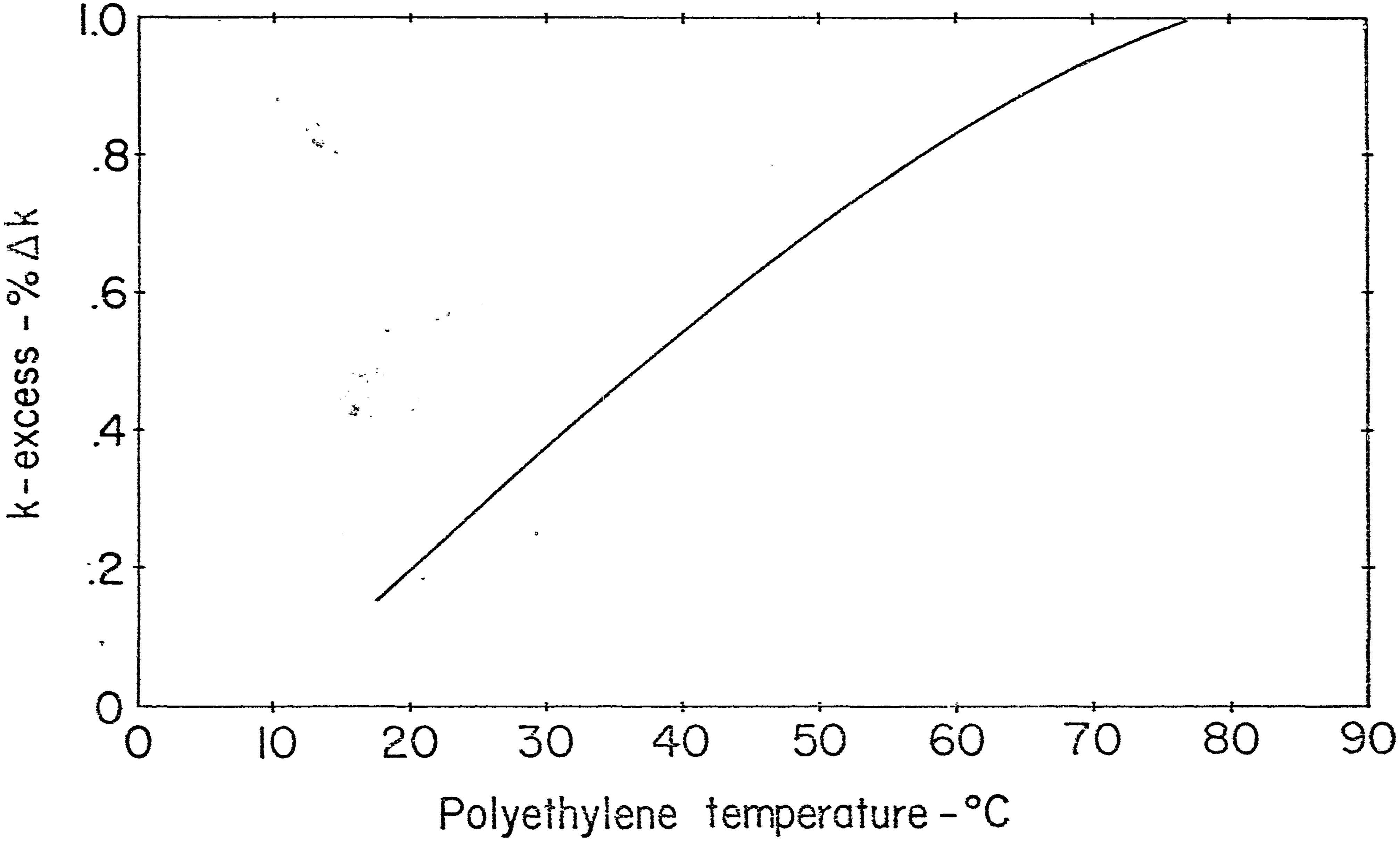

Fig. 10 Changes in k-excess due to heating polyethylene

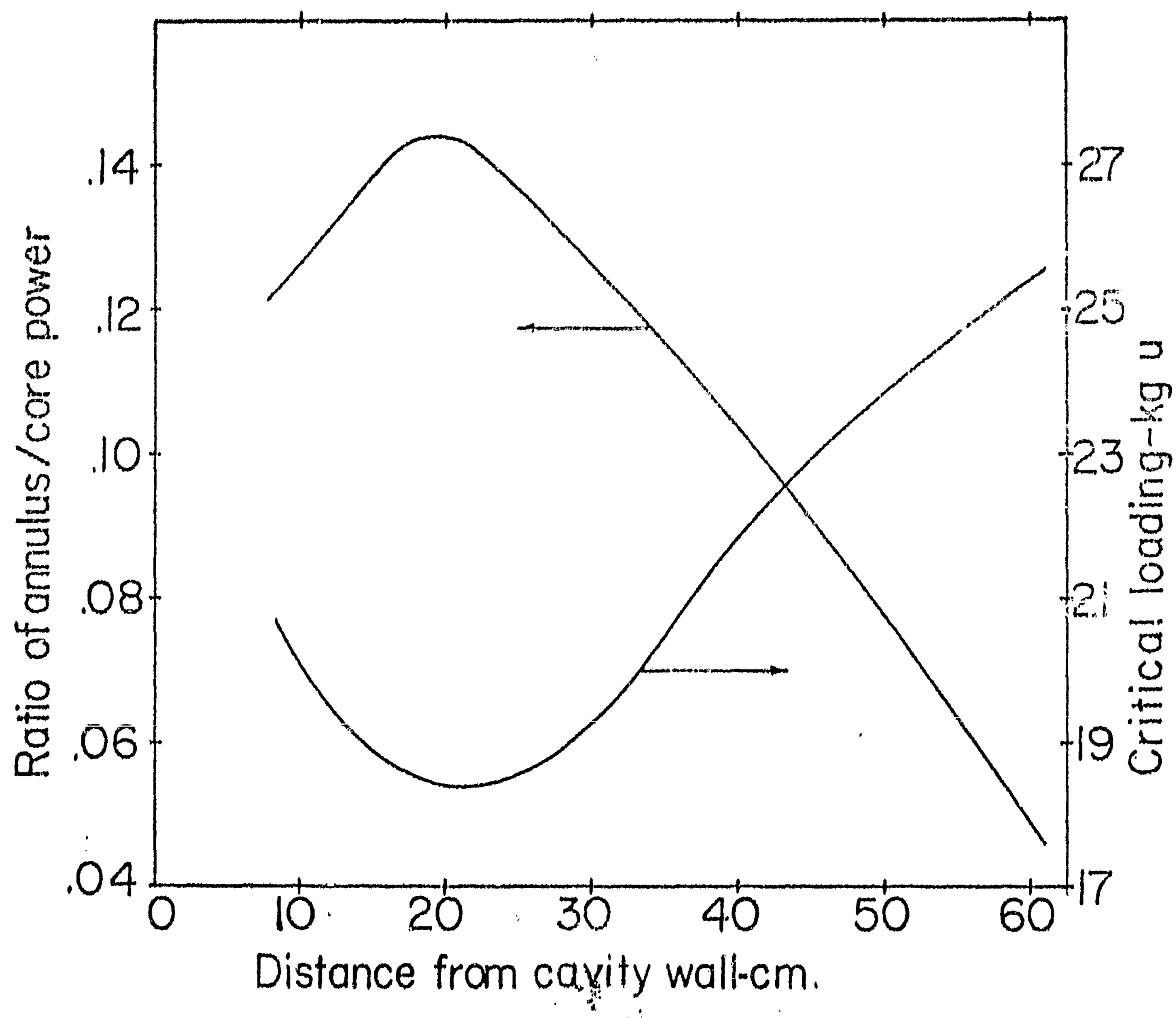

Fig. 11 Effect of fuel annulus in D_2O containing 739 gm U^{235} on critical mass and power generation with respect to core power

TABLE 1

Critical Mass (k = 1.0)

	Configuration	Critical Mass kg of U
1.	Stainless steel on cavity wall (83.1 kg)	34.1
2.	Stainless steel on cavity wall and 18.1 kg of polyethylene in cavity (N_H = 0.95 x 10^{21} atom/cc)	54.1
3.	Stainless steel on cavity wall and 38.3 kg of polyethylene in cavity (N_H = 2.0 x 10^{21} atom/cc)	86.0
4.	Variable hydrogen reactor	69.3
5.	Fuel annulus (793 gm U^{235}) at 7.6 cm from cavity wall in radial reflector	20.7
6.	Fuel annulus (839 gm U^{235}) at 19 cm from cavity wall in radial reflector	18.7

TABLE 2

Summary of Power and Flux Distribution Within the Cavity

	38.3 kg Polyethylene in Cavity	Variable Hydrogen in Cavity
Power ratio from edge of fuel to center of core	9.0	9.6
Uranium cadmium ratios *		
Core center	2.8	1.7
Edge of fuel	11.3	9.9
Cavity wall	22.0	16.5
Gold foil cadmium ratios *		
Core Center	1.03	1.04
Edge of fuel	1.34	1.39
Cavity wall	1.77	1.60

* All cadmium ratios are for infinitely dilute detectors.

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