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## RESEARCH ON PLASMA CORE REACTORS

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### Abstract

Experiments and theoretical studies are being conducted for NASA on critical assemblies with one-meter diameter by one-meter long low-density cores surrounded by a thick beryllium reflector. These assemblies make extensive use of existing nuclear propulsion reactor components, facilities, and instrumentation. Due to excessive porosity in the reflector, the initial critical mass was 19 kg U(93.2). Addition of a 1'-cm-thick by 89-cm-diameter beryllium flux trap in the cavity reduced the critical mass to 7 kg when all the uranium was in the zone just outside the flux trap. A mockup aluminum UF<sub>6</sub> container was placed inside the flux trap and fueled with uranium-graphite elements. Fission distributions and reactivity worths of fuel and structural materials were measured. Finally, an 85,000 cm<sup>3</sup> aluminum canister in the central region was fueled with UF<sub>6</sub> gas and fission density distributions determined. These results will be used to guide the design of a prototype plasma core reactor which will test energy removal by optical radiation.

### Introduction

T. S. Latham and collaborators<sup>1</sup> at the United Technologies Research Center (UTRC) have recently suggested several attractive applications of cavity reactor systems aimed at meeting future critical energy needs. Uranium fuel in gaseous or plasma form permits operation at much higher temperatures than possible with conventional solid fueled nuclear reactors. Higher working fluid temperatures in general imply higher thermodynamic cycle efficiencies, which lead to proposals for advanced closed-cycle gas turbine driven electrical generators and MHD power conversion systems for electricity production. Cycle efficiencies ranging from 50 to 65 percent are calculated for these systems.

Further, the possibility of energy extraction in the form of electromagnetic radiation allows consideration of many photochemical or thermochemical processes such as dissociation of hydrogenous materials to produce hydrogen. Lasers may be energized either by direct fission fragment energy deposition in uranium hexafluoride (UF<sub>6</sub>) and lasing gas mixtures or by optical pumping with thermal or non-equilibrium electromagnetic radiation flowing out of the reactor.

The Los Alamos Scientific Laboratory (LASL) has a modest program to acquire experimental and theoretical information needed for the design of a prototype plasma core reactor which will test heat removal by optical radiation. Experiments are being conducted on a succession of critical assemblies with large low-density cores surrounded by a thick moderating reflector. Static assemblies, first with solid fuel, then with UF<sub>6</sub> in containers, will be followed by others with flowing UF<sub>6</sub>.

### Plasma Core Assembly (PCA) Design

In the first quarter of 1974, a joint working group formed by NASA from LASL and UTRC personnel produced an engineering feasibility design study revealing the possibility of constructing a large beryllium reflected cavity reactor from existing nuclear propulsion program materials and control components.<sup>2</sup>

### Reactor Component Availability

Substantial quantities of beryllium reflector parts were stored at Los Alamos and the Nevada Reactor Development Station after the termination of the nuclear propulsion program. Beryllium reflector assemblies from 11 Rover/NERVA reactors, representing an original cost of approximately \$5 million, were transferred to Los Alamos. Also, four additional beryllium reflector assemblies, including a set of 18 stepping motor driven control drum actuators, were available at Los Alamos.

### LASL Facilities

The facilities of the LASL Critical Experiments Group include three remotely controlled critical assembly laboratories, called Kivas, equipped with a variety of critical assembly machines of varying complexity. A central control building houses control rooms, offices, and laboratory space. Parts of these facilities are available for the initial phases of the plasma core reactor project.

The cavity-type assemblies will be on the "Mars" critical assembly machine (Fig. 1) located in Kiva 1. This machine was built early in the Rover program and was used for neutronic and core optimization studies for the Kiwi, Phoebus, and Nuclear Furnace reactors. Early beryllium-reflected cavity reactor experiments were also performed on this machine.<sup>3,4</sup> Figure 1 shows the Mars machine with a Phoebus II reflector installed. The overall size is similar to that of the planned cavity assemblies. Some of the 18 control drum actuators are visible above the

<sup>1</sup>This work was supported by the Research Division, Office of Aeronautics and Space Technology, National Aeronautics and Space Administration, NASA Contract No. W-13755.

reflector.

The principal features of the Mars machine are:

1. A framework that includes a base plate for supporting the reflector, an upper platform for mounting the existing control drums, and a personnel platform.

2. Provision for removing a fueled core from the reflector. The core is supported on the platen of a hydraulic cylinder, which is centered beneath the reflector and can be retracted as a safety device.

3. Provision for removing the core from beneath the machine. The lowered core assembly rests on a cart that may be rolled out on guide rails from beneath the reflector to provide easy access for alterations to the core.

#### Reflector Design

The critical assembly reflector design makes use of beryllium from most of the Rover reactor types. Figure 2 shows reflector parts from several of the Rover reactors assembled to form a cross section of the cylindrical reflector wall. Figure 3 identifies major Rover beryllium components by location. The end plugs of Nuclear Furnace, Pewee, and Honeycomb reflector pieces, shown in Fig. 2 and 3, consist of beryllium that averages 90% of normal density. Graphite fillers, 38-mm thick separate these from 190-mm-thick NXR and Kiwi B sectors of beryllium also at 90% normal density. A succeeding graphite annulus 44-mm thick is followed by a 203-mm-thick Phoebus II assembly which contains 18 control drums and is beryllium at 87.5% normal density.

All of the Rover beryllium reflector components have holes in them required for coolant flow, tie rod access, instrumentation lead channels, reflector density adjustment, and control drum containment. These lead to loss of neutrons by streaming and result in increased critical mass if left unfilled. Calculations indicate a reactivity loss of about 25¢ for each percent reduction in the density of the Be reflector.

Figure 4 shows the calculated penalty for substituting a 50-mm annular zone of graphite for beryllium as a function of the location of the graphite in the reflector. In the outer two-thirds of the reflector, high purity graphite is a good substitute for beryllium but is of little help in inner region. The reflector encloses a 1.02-m-diam by 1.05-m-high cavity in which the various solid and gaseous uranium fuel cores will be studied.

#### Experimental Program

##### Core Number 1

A homogeneous uranium distribution in the cavity, simulated by use of uranium

metal foils laid on a set of ten equally spaced aluminum discs, Fig. 5, had a critical mass of 19-kg U(93.2). The reactivity swing for the 18 control drums was 6.19. Figure 6 gives the control drum calibration curve. Measured reactivity worths of core materials are uranium 73¢/kg, aluminum -3¢/kg, and graphite 2.5¢/kg.

##### Core Number 2

An early goal for the Plasma Core Assembly was to operate with a central zone of UF<sub>6</sub> gas surrounded by a zone of solid uranium fuel. To mock up this situation core number 2 consisted of uranium metal foil attached to a 0.94-m-diam thin-walled aluminum cylinder, Fig. 7, centered within the cavity. A critical mass similar to that for core 1 was indicated by subcritical comparison.

The critical mass of about 19 kg is more than a factor of two higher than calculated for uniformly distributed fuel in an idealized reflector, indicating undermoderation in the reflector and/or contaminants having high thermal neutron absorption cross sections in the beryllium and graphite. Neutron leakage through the large number of small straight coolant channels in the beryllium also tends to increase the critical mass value.

The beryllium specification limited the iron content to less than 0.18% by weight. One-dimensional criticality calculations showed that this amount of iron would increase the critical mass by about 9%. Two-dimensional criticality calculations indicated that two hundred parts per million boron containment in the graphite would account for the excess critical mass if boron alone were the cause. The large critical mass is believed to be due to a combination of the effects discussed above.

##### Core Number 3

The simplest solution to the neutron undermoderation problem was to add a zone of beryllium to the cavity. A suitable beryllium annulus 0.55-m i.d. by 0.89-m o.d. by 1.04-m high, Fig. 8, was formed from Pewee and Honeycomb parts. This structure had a mean density 85% that for normal beryllium and was surrounded by a 0.94-m-diam aluminum cylinder to support uranium metal foil. The initial critical mass with all uranium in the outer fuel zone was 6.84-kg U(93.2).

The reactivity worth of the control drums is influenced by the amount of uranium in the core. Since core number 3 with its added inner beryllium zone sharply reduced the critical uranium loading, the control drums were recalibrated, using positive period measurements. The reactivity swing for one control drum is 22.4 cents, giving 4.03¢ for the 18 control drums. Figure 9 gives the calibration curve for the entire 18 control drums.

The control drum worth is now only two thirds that for the empty cavity configuration of cores one and two, but is considered adequate for the planned experiments.

Table I lists the reactivity worths of uranium, aluminum, and carbon for indicated positions in core number 3.

It should be noted that the uranium worth values of Table I imply an appreciably greater fission density in the central zone than in the outer fuel zone. The additional neutron moderation in the flux trap results in a central zone uranium reactivity worth six times that for uranium in the outer zone. As the fission density in a highly thermalized system varies as the square root of the reactivity,  $UF_6$  in the central zone will benefit from a fission density enhancement of about 2.4 over that for uranium in the driver zone.

The effects of flux trapping by an additional beryllium zone within a cavity surrounded by an undermoderating reflector was examined using one-dimensional neutron transport calculations on an equivalent spherical mockup of the PCA cylindrical geometry. The calculated fission density in the central zone was 2.3 times that for the outer or driver fuel zone.

#### Core Number 4

Core number 4 uses the beryllium flux trap of core 3 and uranium-graphite Rover

fuel elements in the outer driver zone, Fig. 10. The inner experimental zone is provided with a mockup of an aluminum  $UF_6$  container to be used in later experiments. Low density uranium-graphite fuel elements are used in this region to simulate  $UF_6$  loadings.

Table II gives the loading specifications for the uranium-graphite fuel elements.

Figure 11 shows the available fuel element holes in the driver and experimental zones. Figure 12 shows core No. 4 positioned to be raised into the PCA reflector.

#### Material Reactivity Evaluations

Reactivities for uranium and other materials were measured in the central experimental and driver zones. Results agreed with those found for core 3.

As seen in Table I, uranium has a much higher reactivity worth in the inner zone than in the outer or driver zone, so that the critical mass will decrease as uranium is added to the central region of the core. Figure 13 shows the measured variation of critical mass with the fraction of fuel in the inner zone.

#### Fission Density Measurements

Fission density distributions were determined for two different core loadings

TABLE I  
REACTIVITY WORTHS OF MATERIALS IN PCA CORE NO. 3.

<u>Material</u>	<u>Material location</u>	<u>Worth in cents/kg</u>
U	On axis	+ 3350
U	Near end of Al support	+ 554
Al	On axis	- 10.8
Al	At Al support	- 3.0
Honeycomb C	On axis	- 1.4
PCA Reflector C	On axis	- 3.2

TABLE II

<u>Element Location</u>	<u>Uranium Density</u>	<u>Uranium/Element</u>
Driver zone	400 mg U/cm <sup>3</sup>	82.8 g
Experimental zone	100 mg U/cm <sup>3</sup>	20.7 g

for the experimental and driver fuel zones by beta scanning U-loaded Al wires irradiated in the central holes of selected fuel elements. Figure 14 shows the fuel element configuration and wire locations. Figure 15 shows the core mid-plane radial fission distribution. The fission density rises slowly from the center outwards. The ratio of the central element to driver element fission density values is 2.40, in good agreement with the value of 2.4 noted in section III-c which was determined from uranium reactivity measurements. Figure 16 gives fission distributions for two central fuel zone axial positions.

#### Core Number 5

$\text{UF}_6$  gas was used as the fuel for this core in the inner zone using the UTRC double walled canister and gas handling system. A Be flux trap separated the gas from a driver fuel element zone composed of lightly loaded uranium - graphite fuel rods described in the previous section. Figure 17 is a photograph showing the canister mounted on a ram underneath the reflector ready for assembly. Two pie sections of the lower Be end plug have been removed to show the flex lines that connect the canister to the gas handling system in the foreground.

Figure 18 is a schematic of the gas handling system.  $^{235}\text{UF}_6$  in the supply bottle is a solid at room temperature. This bottle is immersed in a hot water bath and heated for one hour at about boiling temperature ( $88^\circ\text{C}$ ). This converts the solid to a gas and by suitable valving, a known amount of the gas is trapped in the transfer bottle of the same manifold. Verification of the amount of gas in the transfer bottle is obtained by weighing the bottle and contents. The entire gas system and canister are next heated to about  $66^\circ\text{C}$  using heat tapes and hot flowing He gas. This requires about three hours. The  $\text{UF}_6$  now remains in the gas phase for critical operations.

Recovery of the  $\text{UF}_6$  is accomplished by pumping down the canister and gas system through a glass liquid nitrogen (LN) trap. Material recovery is evaluated by weighing

the glass trap and contents. After completing the recovery cycle, we find very little residue in the canister, as affirmed by running the reactor at delayed critical. However, weighing showed that some  $\text{UF}_6$  remained in the transfer system. We suspect that the majority of this material is in the corrugated flex lines linking the gas system to the canister. Table III shows the results obtained from our two transfer operations.

#### $\text{UF}_6$ Reactivity Evaluation

A lightly loaded Kiwi fuel element was placed in the region between the canister and the Be flux trap in order to re-evaluate the reactivity worth of uranium in the central region. A value of 2.95 cents/g U was obtained which translates to 1.99 cents/g  $\text{UF}_6$ . An initial operational limit of one dollar for the gas in the core restricts the  $\text{UF}_6$  to a minimum of 50 grams.

Three fission density distributions were measured in the gas core along paths as indicated in Figure 19. U-loaded Al wires were placed on the central axis and on a parallel line displaced 10 cm radially from this axis. Another wire was on a diameter at the mid-plane of the core. The wires were irradiated for 10 minutes at a power level of about 70 watts and then scanned with a beta counter to obtain the data plotted in Figure 20. We found similar distributions for the two core loadings of 12 to 24 grams of  $\text{UF}_6$ . The radial traverse, not shown, is flat to within 0.1%, as expected for such a light uranium loading. An earlier experiment noted in section III-c, using 390 grams of uranium in a solid uranium-graphite fuel mock-up of the gas core, had a 3% rise in fission density from the center to the core edge, indicating a slight uranium self shielding effect. The axial fission density falls off about 8% from the mid-plane to the core end. This results from holes in the reflector end walls for plumbing and thinner beryllium in this region.

#### Concluding Remarks

A beryllium reflected critical

TABLE III  
SUMMARY OF DELAYED CRITICAL RUNS ON FCA

	$\text{UF}_6$ Gas Transferred (g)	Reactivity Change (cents)	$\text{UF}_6$ Recovered (g)	$\text{UF}_6$ left in canister (g)	$\text{UF}_6$ left in lines (g)
Run 1	12.0	20	3.6	2.2	6.2
Run 2	24.6	50	14.9	2.5	7.2

assembly has been constructed which is suitable for performing tests on static and flowing  $UF_6$  cores and ultimately on advanced models employing hydrodynamical containment of the  $UF_6$  by a flowing buffer gas. Dividing the core into a driver zone containing a major fraction of the fuel in solid form separated by a neutron flux trap from a central experimental zone for gaseous fuel has several advantages:

1. The fission density in the gas fueled region is boosted by a factor of 2.4 over that in the driver zone.
2. An ideal gas core geometry with length about three times the diameter is available.
3. Initial evaluation of reactor safety problems for the flowing  $UF_6$  fueled core critical.

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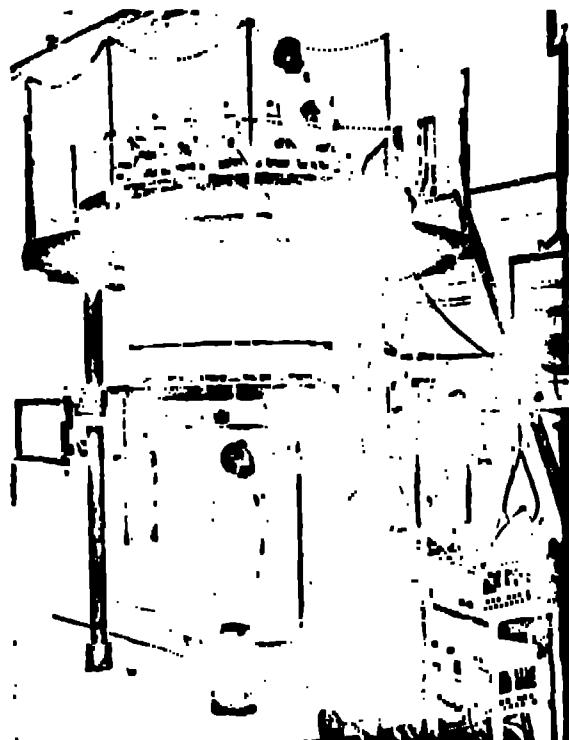


Fig. 1 Mars machine with Phoebus II, Rover Assembly.

2. Helmick, H. H., G. A. Jarvis, J. S. Kendall<sup>4</sup> and T. S. Latham<sup>5</sup>: Preliminary Study of Plasma Nuclear Reactor Feasibility. Los Alamos Scientific Laboratory report LA-5679, July 1974.
3. Jarvis, G. A. and C. C. Byers: Critical Mass Measurements for Various Fuel Configurations in the LASL  $D_2O$  Reflected Cavity Reactor. AIAA Paper No. 65-555, AIAA Propulsion Joint Specialist Conference, June 1965.
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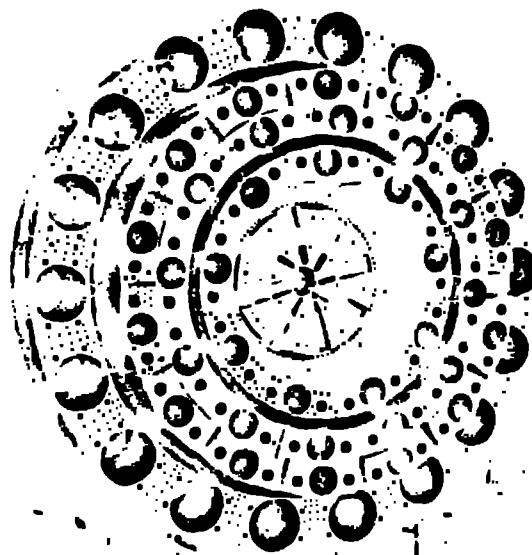


Fig. 2 Rover beryllium reflector components used in PCA.

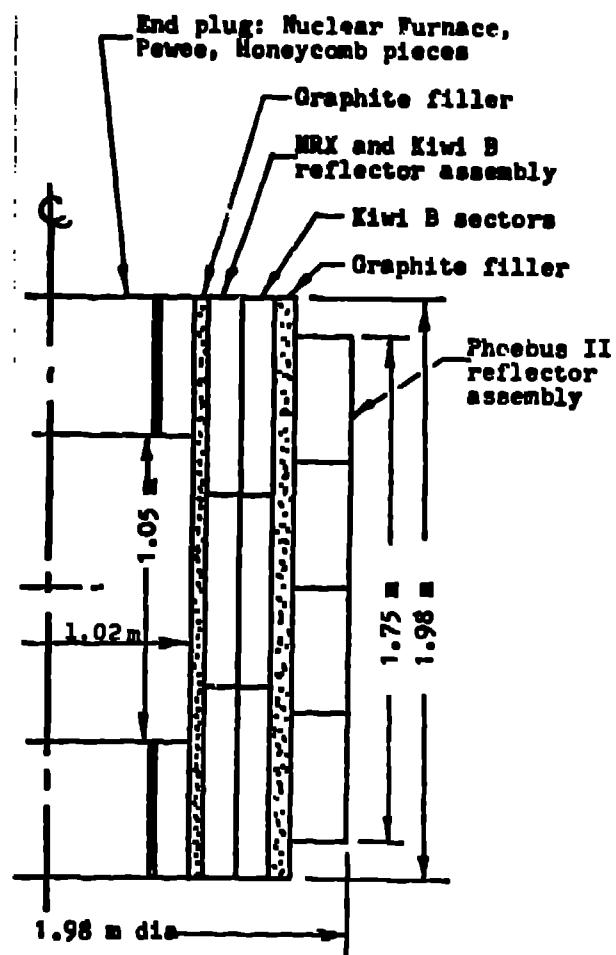


Fig. 3 Plasma core assembly reflector.

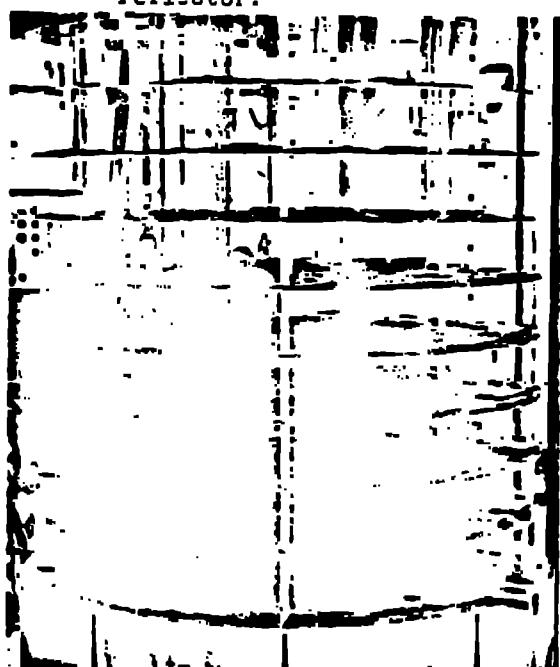


Fig. 5 Core No. 1

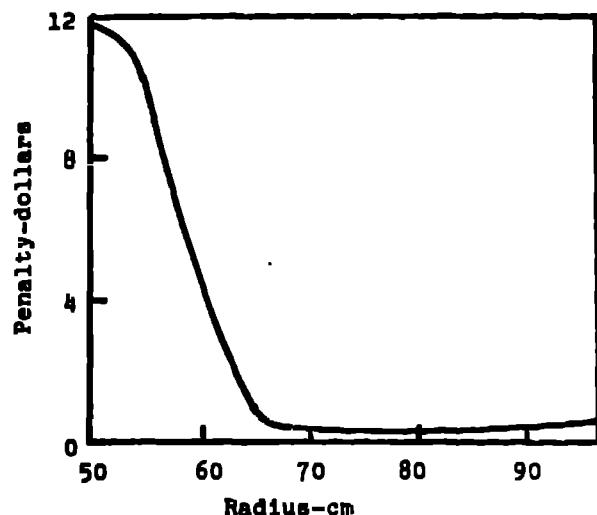


Fig. 4 Reactivity loss associated with substitution of graphite for Be.

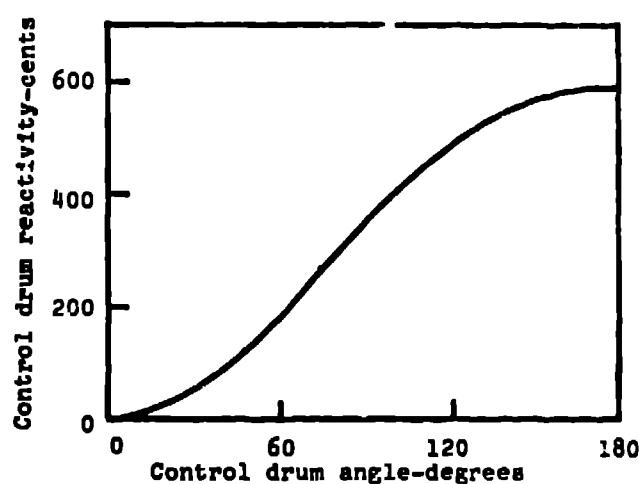


Fig. 6 Control drum calibration curve for core number one.

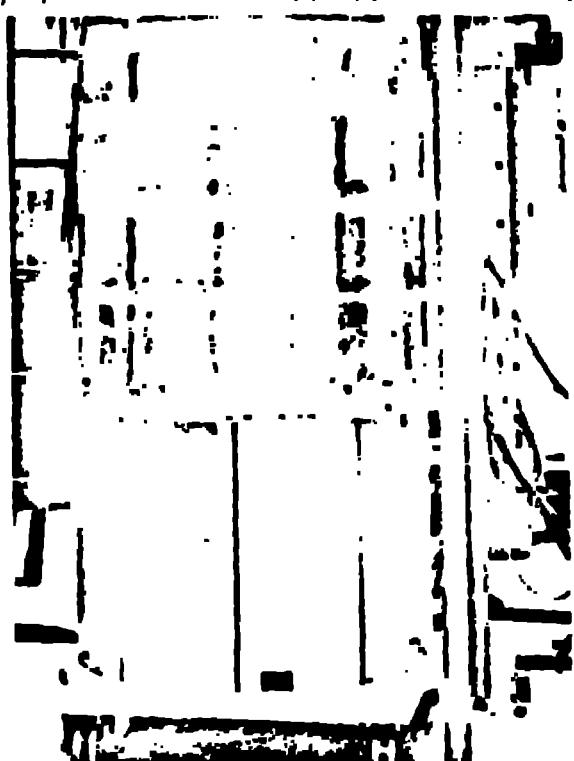


Fig. 7 Core No. 2

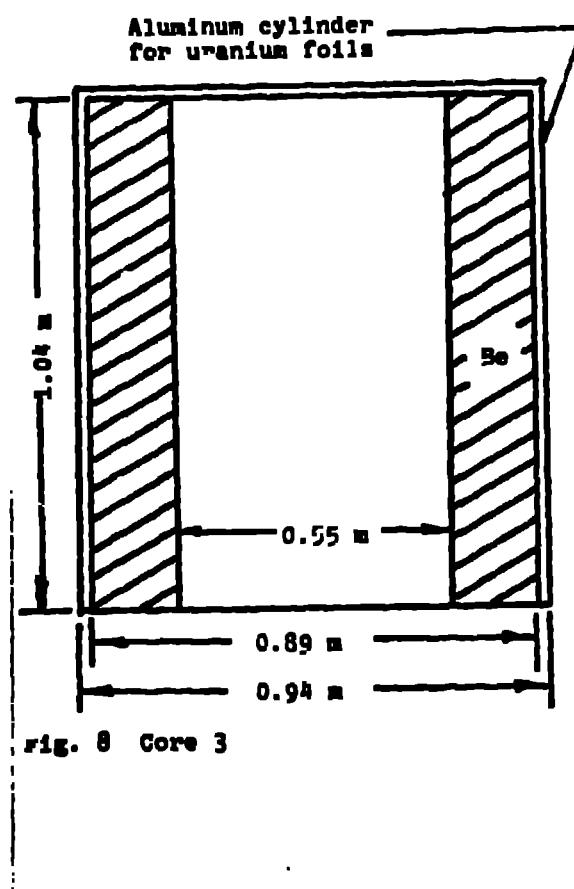


Fig. 8 Core 3

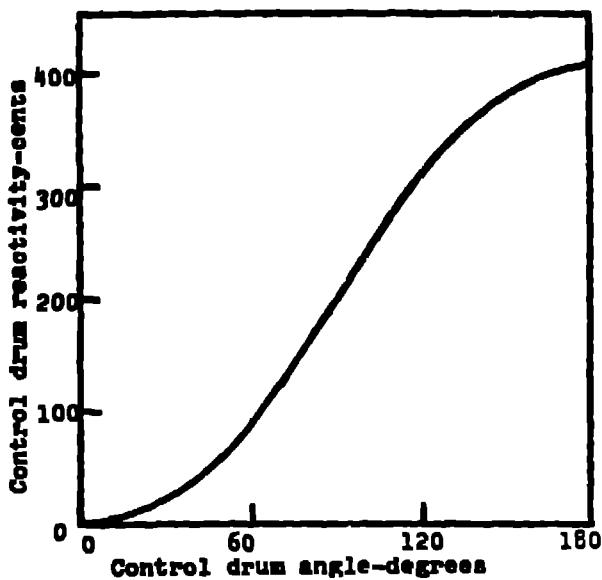


Fig. 9 Control drum calibration for core number three.

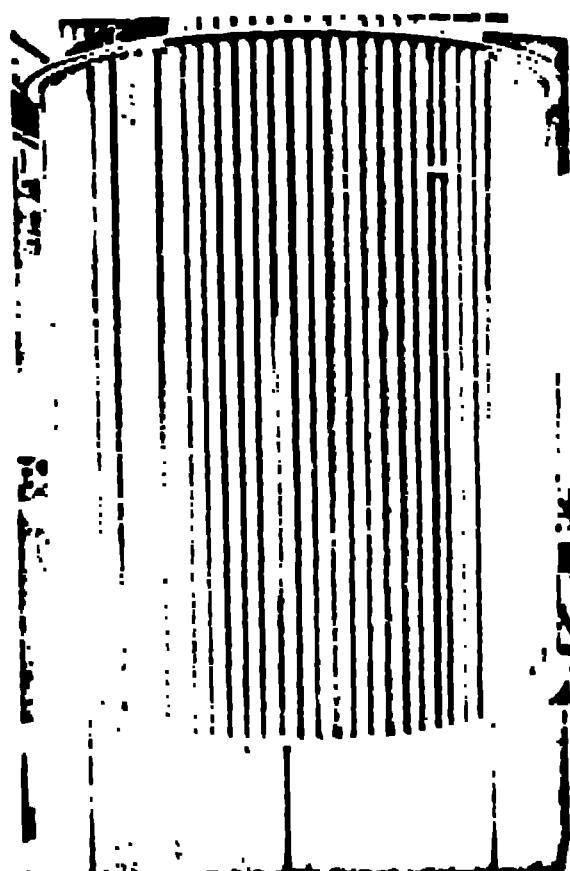


Fig. 10 Core number four with partial load of U-graphite driver fuel rods.

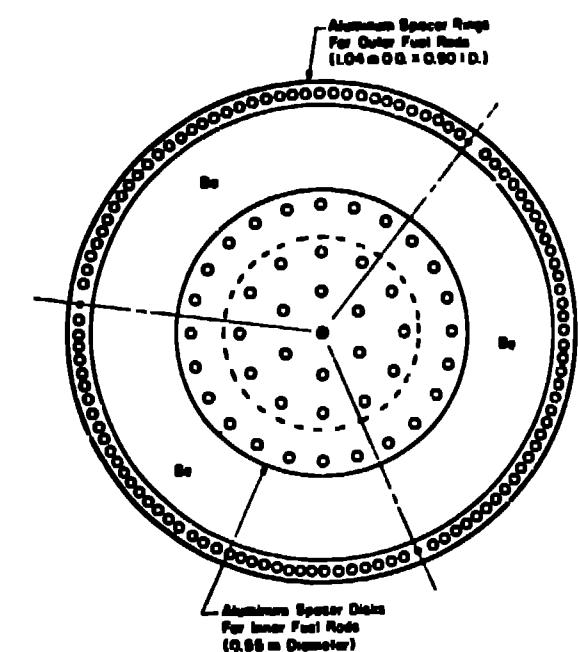


Fig. 11 Aluminum support structure for supporting U-graphite rods for core number four.

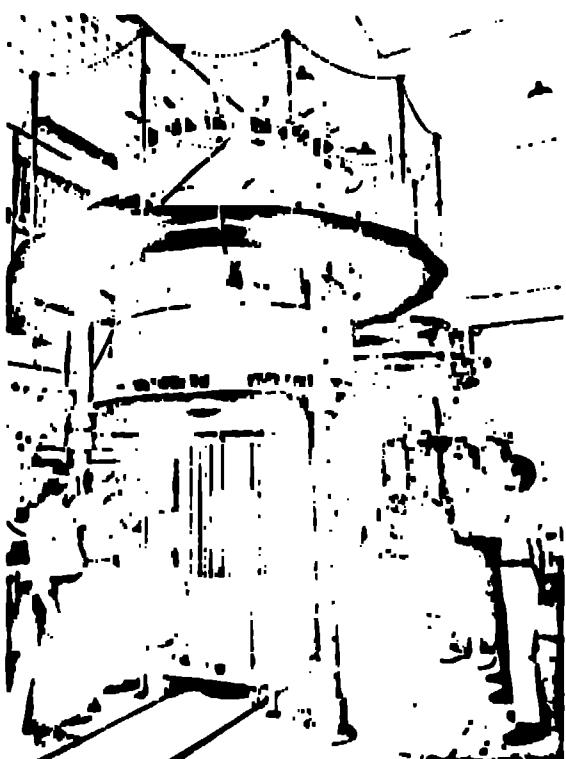


Fig. 12 Mars machine with core number four ready for assembly.

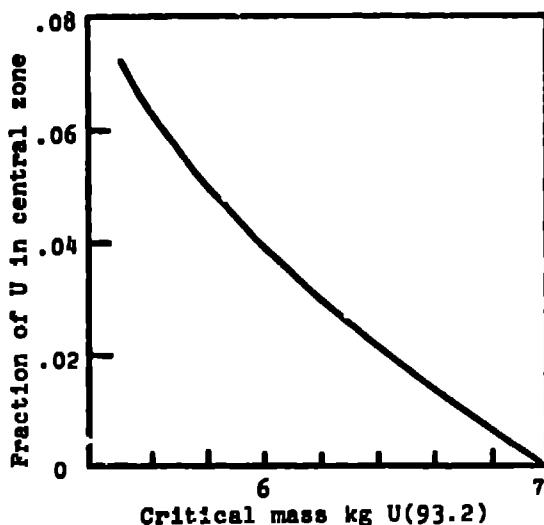


Fig. 13 Critical mass dependence on fraction of U in the center fuel zone.

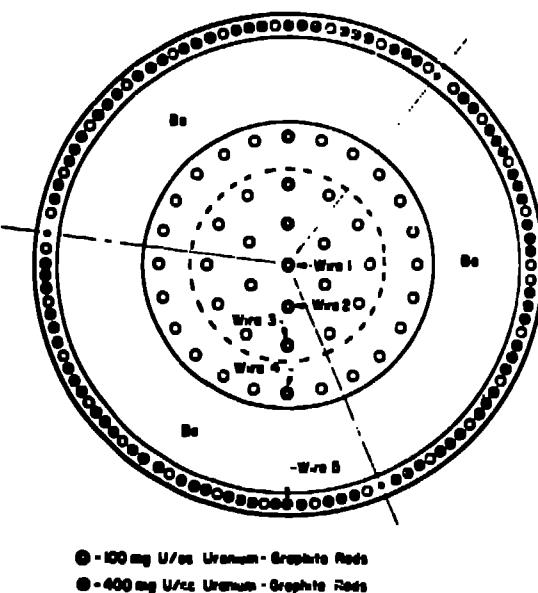


Fig. 14 Fuel element loading and wire positions for core No. 4

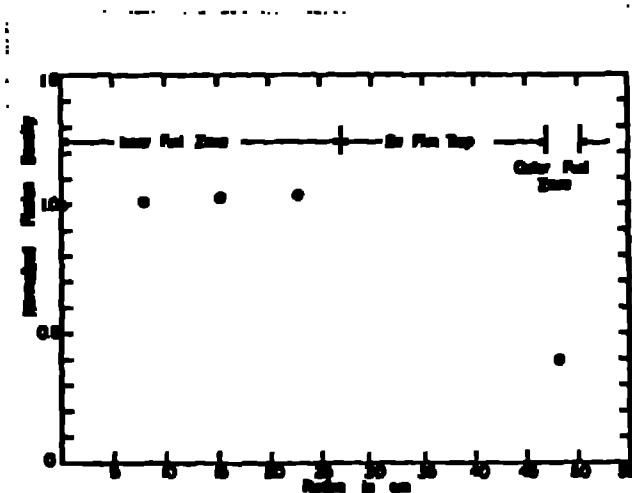


Fig. 15 Radial fission distribution,  
core No. 4



Fig. 17 Core number five with aluminum canister for  $UF_6$  gas.

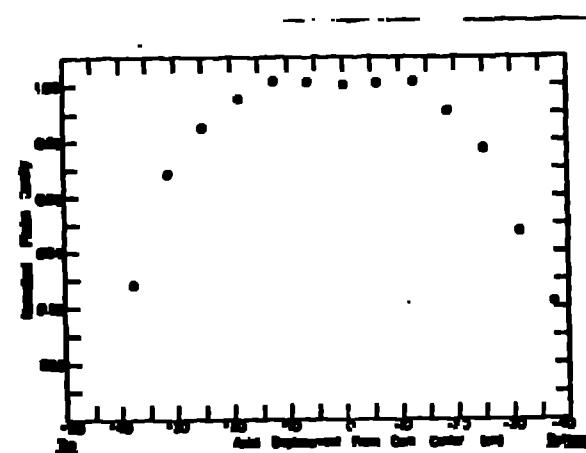


Fig. 16 Axial fission distribution, core No. 4

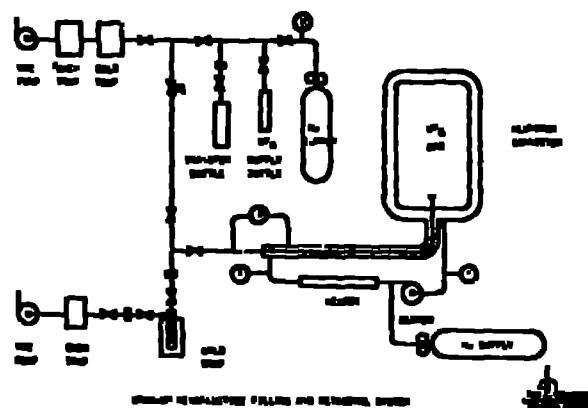


Fig. 18 Schematic of  $UF_6$  gas handling system.

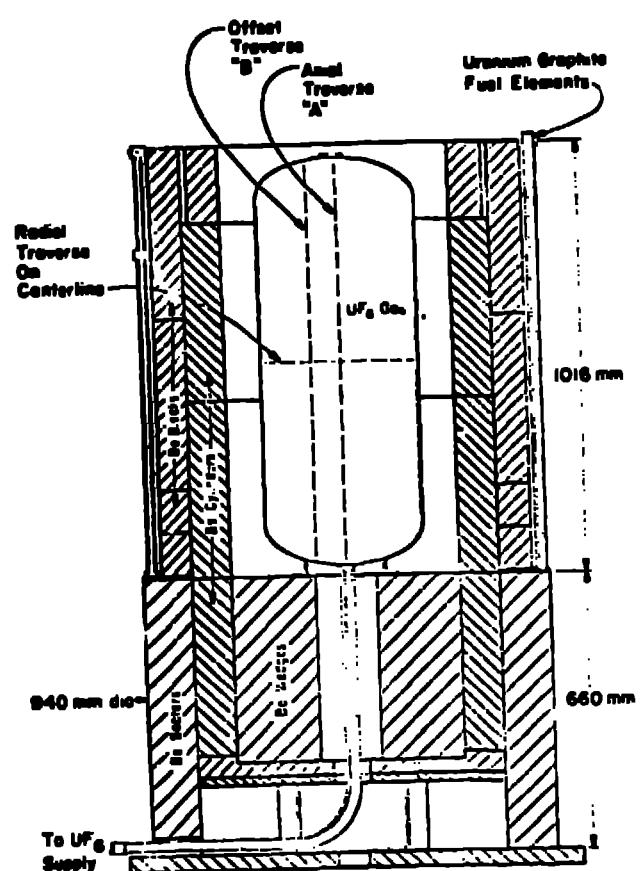


Fig. 19 Location of fission wires in core number five.

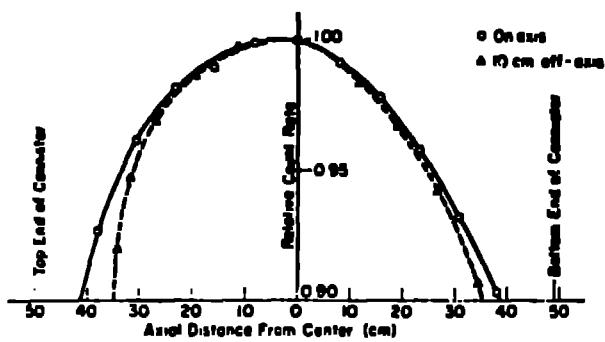


Fig. 20 Axial fission distributions, core No. 5