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# ANALYSIS OF FUEL LOADING REQUIREMENTS AND NEUTRON ENERGY SPECTRUM OF A FAST SPECTRUM, MOLYBDENUM-REFLECTED, CRITICAL ASSEMBLY

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## INTRODUCTION

A limited number of small, heavy-metal-reflected, fast reactor, critical experiments have been performed at Los Alamos (Reference 8). These have been used to check the accuracy of neutronic calculations. From these calculations it has been found that the amount of calculational error is strongly dependent on the materials in the reactor and in the neutron reflector.

Since for the materials of interest the available experiments supply only about one data point, and there are some materials such as nitrogen and hafnium for which there are no fast spectrum critical experiments, it was decided to embark on a critical experiment program wherein only the materials that were being considered for an actual, small, fast-spectrum reactor would be included. Also, in order to minimize the number of geometrical variables while determining the reactivity effects of the proposed materials, it was decided to make an initial critical experiment large enough and with sufficient void space so that all of the materials could be added sequentially without changing the overall geometry of the reactor. This critical experiment program is being carried out by Atomics International under contract to LeRC. (Contract No. NAS3-12982).

The conceptual reactor for which these experiments are being performed is a lithium-cooled, uranium-235 nitride fueled reactor. A cutaway drawing is shown in Fig. 1. Cylindrical uranium nitride pellets would be contained in tantalum alloy (T-111) tubes which would be lined with tungsten foil. A T-111 honeycomb would be used to maintain the position of the fuel elements. Six control drums containing both fuel and neutron absorber (T-111) would be used for reactivity control. The neutron reflector would be of a molybdenum alloy (TZM).

Since there are many ways (voluntary and involuntary) in which a neutronic calculation can be made to agree with a critical experiment after the experimental results are known, and since for a final reactor design one would like to be able to truly predict the core parameters, the purpose of this report is to present a precritical analysis of the fuel loading requirements and neutron energy spectrum of the first of a series of critical experiments which are to be performed by Atomics International.

## Description of the Critical Assembly

A cross section of a fuel element is shown in figure 2. It is depicted as filled with a full complement of fuel which is oralloy (93.2 percent uranium-235 with the remainder assumed to be uranium-238). The space between the fuel bundle and the fuel tube can be used to insert foils of other materials such as tungsten, hafnium, and tantalum. Both the fuel tube and honeycomb tube are made of tantalum. The fuel tube is centered offset from the center of the honeycomb tube by $0.020 \pm 0.002$ inch ($0.051 \pm 0.005$ cm) so that a fuel movement experiment can be performed simply by rotating the fuel elements. The eccentric annular space between the fuel tube and honeycomb tube can also be used for addition of materials of interest such as lithium nitride to simulate the lithium which, as lithium 7, may be used for coolant in a power reactor and nitrogen to simulate the nitrogen in uranium nitride fuel.

The end reflectors are built into the fuel elements as shown in figure 3, which shows one end of a typical fuel element. In each fuel element there are two molybdenum pieces at each end of the fuel element. One piece is a solid cylinder 3.94 inches (10.00 cm) long which fits within the fuel tube and rests against the ends of the 14.767-inch (37.508-cm) long fuel bundle. The other piece fits in the eccentric annular space between the fuel tube and honeycomb tube. Some support must be provided for this piece to prevent its sliding into the core region. Several small diameter molybdenum rods the same length as the fuel bundle could be used. For the purpose of the calculations presented later, three 0.030-inch (0.076-cm) diameter rods per fuel element are used.

The ends of the fuel element are closed with an aluminum jackscrew and rubber packing as shown in figure 3. The grid plate alinement pin provides a method of constructing a lattice of these fuel elements with a constant pitch by the use of top and bottom grid plates. Figure 4 shows a cross section of a quadrant of the critical assembly. Only the outline of the honeycomb tubes are shown to depict the lattice determined by the grid plate. The center-to-center spacing (pitch) between tubes in the nondrum region of the core is 0.872 inch (2.215 cm). Similarly grid plates for each control drum position the fuel elements as shown. The assembly consists of 247 fuel elements including 11 in each control drum. The individual pieces called out on figure 4 are described in more detail in figures 5 and 6 in table I. Figure 5(a) shows the molybdenum filler pieces that fit between the rotatable control drums and the core lattice. Figure 5(b) shows the radial reflector pieces that fit between the control drums. In the calculations, these pieces are assumed to be pressed and sintered with a density of 0.94 of theoretical (10.22 $gm/cm^3$). Four pieces as shown are used. Two of the pieces are turned upside down so that the arrangement of a pair of reflector pieces about a control drum as shown in figure 4 can be obtained. Two additional reflector pieces are required. These are the same as the others except that the piece is symmetric with the shape of side A (fig. 5(b)). Figure 6 shows a control drum in more detail. Table I gives additional data on individual pieces used in the reactor. Figure 7 shows a sketch of the assembled critical machine. This sketch was supplied by the contractor. Note that the safety scram device consists of moving two pairs of reflector pieces away from the core and that the machine is elevated to provide for a sample changer for the insertion of materials for reactivity measurements. The samples may be inserted into the center seven fuel element locations or into the six positions outer-most in the core lattice.

## Calculation Procedure

The calculations for this critical assembly uses basically the same techniques as described in references 1 to 3. As stated previously the purpose of these precritical calculations is to provide evidence as to the adequacy of these methods. Discrepancies, if any, between the experimental quantities and the calculations will be due to inadequate methods, inadequate cross section data, differences between the calculational geometric model and the "as-built" critical assembly, or any combination of these. A detailed post-critical analysis of the "as-built" critical assembly is desirable to evaluate all of the parameters used in the calculational procedure.

The calculations reported here are based upon the nominal dimensions and material specifications in the latest drawings available at this time. Three types of spatical calculations are used to obtain the expected critical mass of oralloy fuel. A two-dimensional (X,Y) calculation with the mesh grid superimposed over a quadrant of the reactor as shown in figure 4 allows explicit representation of the azimuthal asymmetry around the periphery of the core. An alternate calculation that is also suitable uses $(R,\theta)$ geometry; both (X,Y) and $(R,\theta)$ calculations are done for this critical experiment geometry. The geometry in the direction perpendicular to the (X,Y) or $(R,\theta)$ plane is accounted for by inclusion of an effective core height $He_{ff}$ from which axial neutron leakage terms may be computed. The procedure for determining $He_{ff}$ is as follows:

1. The (X,Y) or (R,Θ) geometry is converted into a series of annuli by volume averaging materials in the two-dimensional geometry that appear in these annuli. An (R,Z) model, such as in figure 7, is established which shows the core height and axial reflector regions explicitly within the restrictions implicit in the (R,Z) symmetry requirement.

2. A one-dimensional (R) calculation, based on the radial dimensions and materials of the (R,Z) model, is used to obtain $He_{ff}$ · $He_{ff}$ in the formula for the axial leakage probability per unit flux

$$\sum_{trg}^{i} \frac{B^2}{\left(\sum_{trg}^{i} He_{ff} + 1.42\right)^2}$$

is varied until the multiplication factor from the R calculation is the same as from the (R,Z) calculation. This $He_{ff}$ is then used in the (R,Θ) or (X,Y) calculation. In the above formula $\sum_{trg}^{i}$ is the transport cross section for group $g$ and material i in the R calculation; $B^2 = \pi/\sqrt{3}$.

The GAM-II program (Ref. 4) is used to obtain the cross sections. Three spectra are used in the averaging of the broad group microscopic cross sections. In each of the three cases, the spectrum is obtained allowing a uranium-235 fission spectrum to interact with the homogeneous materials. Both 13 group and 4 group cross sections with the energy groups as shown in table II are obtained. The spectra used in the averaging are representative of the homogeneous core, molybdenum radial reflector and homogeneous axial reflector regions. Additional materials appearing in these regions, or nearby, which would not contribute significantly to the spectrum are nevertheless averaged over the spectrum for use in the spatial calculations, as an example, the pressure vessel tantalum is averaged over the radial molybdenum reflector spectrum. The MACROS program is used to produce macroscopic cross sections for use in TDSN (Ref. 5) or DOT (Ref. 6) which are used for spatial solutions.

## RESULTS

Results of the analysis consist of the spectrum of neutrons at the center of the core, the prediction of critical mass, and some additional reactivity values calculated to determine the sensitivity of the multiplication factor to perturbations to the basic system either physically or strictly from a computational viewpoint.

## Flux Spectrum

The flux spectrum is obtained from the GAM-II computer program in order to show the spectrum in more detail than is possible with the broad energy group spatial solution programs. A homogeneous mixture of fuel cell materials (0.0692 volume percent v/o Ta, 0.2413 v/o oralloy, 0.0032 v/o Mo) corresponding to a reactor fuel loading of 179.49 kg of oralloy was used. Figure 9 shows the resulting spectrum. The median energy of this spectrum is 0.78 MeV.

## Criticality Calculations

Calculations for the critical assembly using computer programs and techniques currently available show considerable variation in the computed multiplication factors. This fact argues strongly in favor of a definitive critical experiment program to reduce computed uncertainties to acceptable values for the design of a nuclear space-power reactor. Table III shows computed multiplication factor $k_{eff}$ for a fuel loading of 179.49 kg of oralloy. The two-dimensional RZ calculation was performed to incorporate the effects of the end reflectors and structure and to be used in obtaining an effective core height for use in the other two-dimensional calculations (RΘ and XY).

For the XY calculations a mesh grid of 39 intervals in the X direction and 35 intervals in the Y direction were used. The pressure vessel was not included in these calculations although its worth (0.0056 Δk) has been added to the multiplication factors in table III. The worth was calculated using the RZ model. With the XY geometry, increasing the order of the angular quadrature from $S_2$ to $S_4$ increases the multiplication factor from 1.0256 to 1.0357. This increase has been observed previously for similar reactors though the effect was not as pronounced. The effect seems related to the mean free path of neutrons in the core; this core has long mean free paths due to the largo amount of void (about 69 volume percent). Similarly with calculations involving curved surfaces such as RZ and RΘ geometrices the tendency is for the multiplication factor to decrease in going from $S_2$ to $S_4$. Again, the magnitude of the decrease is related to the mean free path in the core. This decrease is seen in table III for the RΘ calculations and amounts to 0.0059 Δk. It is also disconcerting to note the tendency of the RΘ calculation to yield larger multiplication factor than the XY calculations. This tendency has also been noted in previous calculations for similar reactors.

The $S_4P_0$ 4 group XY calculations are used to estimate the critical loading of the critical assembly as shown in figure 10. The upper curve represents the computed values. The lower curve results from subtracting 3.6 percent Δk/k bias from the upper curve. The estimated critical mass of oralloy fuel is thus 179.7 kg. The -3.6 percent $\Delta k/k$ is based on the following:

1. The use of 4 energy groups instead of 13 or more accounts for about -0.4 percent $\Delta k/k$.

2. The use of $S_4P_0$ instead of a higher order calculations such as $S_8P_1$ accounts for about -0.9 percent $\Delta k/k$.

3. Structure around and at the ends of the reactor, such as drum drive motors, scram devices and sample changer mechanism (see Fig. 6), can add about +0.6 percent $\Delta k/k$.

4. Previous calculations of compact critical assemblies fueled with oralloy and containing or reflected by refractory metals have, in the past, tended to yield multiplication factors about 2 percent $\Delta k/k$ too large (Ref. 7). Table IV summarizes more recent calculations done by R. M. Westfall at this laboratory. These are to be compared with an experimental $k_{eff}$ = 1.000. From these it is concluded that the undefined part of the calculational bias should be -2.9 percent. The four items result in a net 3.6 percent $\Delta k/k$ that is removed from the 2DXY $S_4P_0$ 4 group calculated values.

Additional calculations have been made to determine the sensitivity of the multiplication factor to perturbations to the critical assembly. The results are described in table V. Cases 1 and 2 pertain to the effect of additional material around the reactor. Case 3 was calculated because the fuel rods are coated with a thin layer of protective material containing about 0.4 percent by weight of hydrogen. The atom density of hydrogen in a fuel cell is about $1 \times 10^{19}$ atoms/cm$^3$. Case 5 was computed with the RZ model to use as a correction for the XY model results. The relatively large worth of the pressure vessel indicated that materials outside the reactor as calculated could be important (Cases 1 and 2). Case 6 related to a way of supporting the upper eccentric molybdenum reflector piece by use of 3 molybdenum rods per fuel assembly between the honeycomb tube and fuel tube. Cases 3, 6 and 7 indicates the reactor is not overly sensitive to small amounts of material uncertainties in the core. Case 8 represents a fuel coefficient in the vicinity of 177 kg of oralloy. Cases 9 through 12 were computed using a one-dimensional radial calculation and were used in estimating the bias that might be expected for the $S_4P_0$ 4 group XY model used to estimate the critical loading.

## CONCLUDING REMARKS

An analysis of the fuel loading requirements and the neutron energy spectrum of a critical experiment which is to be performed by Atomics International under Contract No. NAS3-12982 is presented.

The critical loading is predicted to be about 179 kg of oralloy. The median energy of the neutron energy spectrum is predicted to be 0.78 MeV.

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TABLE I. - DESCRIPTION OF VARIOUS REACTOR COMPONENTS

| Description | Density $gm/cm^3$ | Material | Length, inch | Wall thickness, inch | Outside diam., inch | Nominal mass, gm |
|---|---|---|---|---|---|---|
| Fuel tube | 16.6 | Tantalum | 22.867±0.005 | 0.010±0.001 | 0.620 $^{+0.005}_{-.000}$ | 119.20 |
| Honeycomb tube | 16.6 | Tantalum | 23.997±0.005 | 0.010±.001 | 0.850 $^{+0.005}_{-.000}$ | 169.39 |
| End reflector cylindrical plug | 10.2 | Molybdenum | 3.940±0.005 | | 0.588±0.005 | 178.83 |
| End reflector eccentric cylinder plug | 10.2 | Molybdenum | 3.940±0.005 | See note (a) | 0.825 $^{+0.000}_{-.002}$ | 148.05 |
| Pressure vessel[b] | 16.6 | Tantalum | 24 | 0.25 | [c]1.260±0.030 | $116.75 \times 10^3$ |

[a]Inner diameter 0.628±0.00 with center [illegible] offset by 0.020±0.002 inch.

[b]Stock sheet-noncritical dimensions on length [illegible] thickness.

[c]Inner radius of pressure vessel.

TABLE II. - GAM ENERGY GROUP BOUNDARIES

| 13 Groups | | | 4 Groups | | |
|---|---|---|---|---|---|
| Group | $E^*_{lower}$ | $U^+_{lower}$ | Group | $E^*_{lower}$ | $U^+_{lower}$ |
| 1 | 3.6788 MeV | 1.0 | 1 | 0.8209 MeV | 2.5 |
| 2 | 2.313 | 1.5 | 2 | .1832 | 4.0 |
| 3 | 1.3534 | 2.0 | 3 | 40.868 KeV | 5.5 |
| 4 | 0.8209 | 2.5 | 4 | 0.414 eV | 17.0 |
| 5 | .4979 | 3.0 | | | |
| 6 | .3020 | 3.5 | | | |
| 7 | .1832 | 4.0 | | | |
| 8 | .1111 | 4.5 | | | |
| 9 | 40.8677 KeV | 5.5 | | | |
| 10 | 15.0344 | 6.5 | | | |
| 11 | 5.5308 | 7.5 | | | |
| 12 | 748.5 eV | 9.5 | | | |
| 13 | 0.414 | 17.0 | | | |

$^*E_{upper} = 14.9$ MeV

$^+U_{upper} = -0.4$

TABLE III. - CALCULATED MULTIPLICATION FACTORS

[Fuel loading 179.49 kg oralloy]
[4 Energy group Po calculations]

| Calculation geometry | Program | Sn | Multiplication factor |
|---|---|---|---|
| RZ | TDSN | $S_4$ | 1.0379 |
| XY | TDSN | $S_2$ | 1.0256 |
| XY | TDSN | $S_4$ | 1.0357 |
| Rθ | DOT | $S_2$ | 1.0490 |
| Rθ | DOT | $S_4$ | 1.0431 |

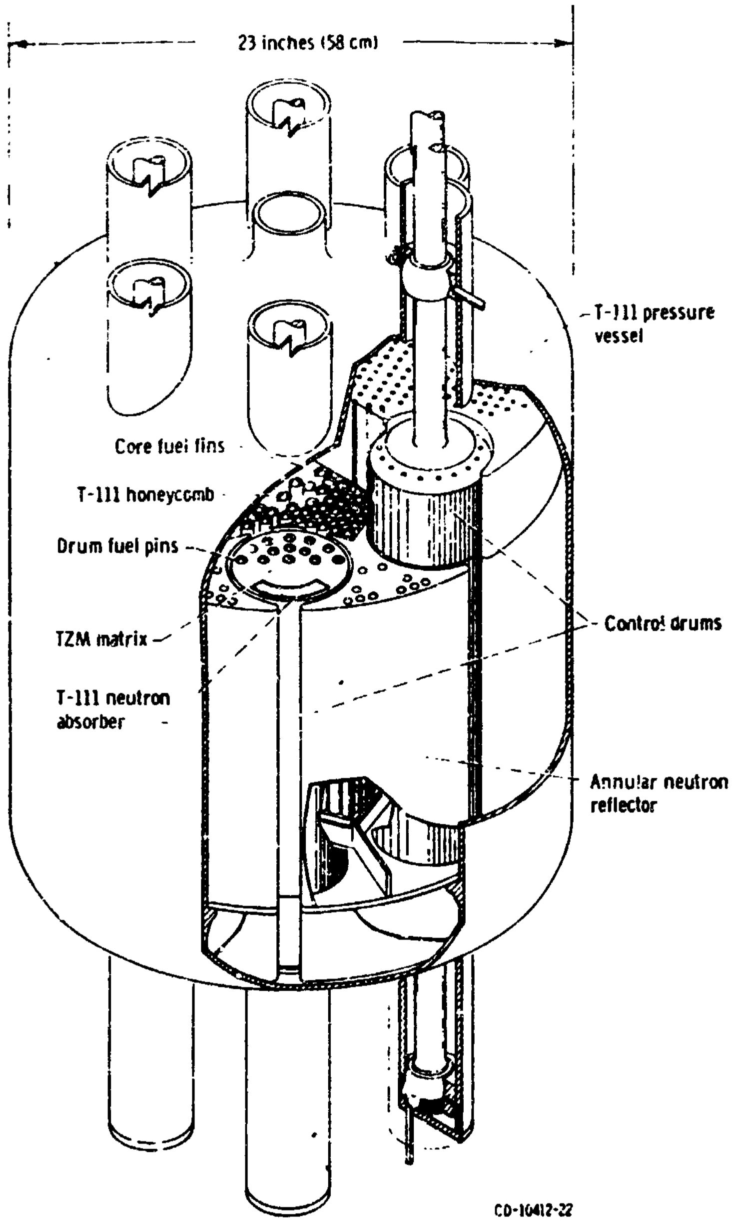
TABLE IV. - CALCULATED MULTIPLICATION FACTORS ($k_{eff}$) OF CRITICAL EXPERIMENTS

| Core composition | Reflector | Calculation | keff | Reference |
|---|---|---|---|---|
| 50.8 v/o Ta-Oralloy | None | $S_4P_1$ 13 group 2 D synthesis | 1.029 | 8 (P. 17) |
| Oralloy | 1" Molybdenum | $S_4P_1$ 13 group 2 D RZ | 1.029 | 8 (P. 17) |
| Oralloy | 1" Tungsten | $S_4P_1$ 13 group 2 D RZ | 1.007 | 8 (P. 28) |

TABLE V. - EFFECT OF PERTURBATIONS TO REACTOR ON MULTIPLICATION FACTOR

| Case | Perturbation | Change in multiplication factor, percent |
|---|---|---|
| 1 | Add 2 cm to end plate thickness (Fig. 7) | +0.34 |
| 2 | Add 6-30° sectors of 1.27 cm thick 0.9 dense stainless steel to pressure vessel in area between drums | + .31 |
| 3 | Worth of hydrogen in coating on fuel rods | + .09 |
| 4 | Core length increased 1 mm | + .048 |
| 5 | Removal of pressure vessel | - .56 |
| 6 | Removal of 3-0.030" dia. Mo rods per fuel tube in all fuel tubes | - .074 |
| 7 | Use of +10 percent tolerance (instead of nominal) on fuel and honeycomb tantalum tube radial tolerances; amount to ~0.7 v/o of a fuel cell | + .018 |
| 8 | Add 1 kg of oralloy fuel uniformly | + .33 |
| 9 | $S_4P_0$ 4 group $\rightarrow S_4$ $P_0$ 13 group | - .35 |
| 10 | $S_4$ $P_0$ 13 group $\rightarrow S_8$ $P_0$ 13 group | - .39 |
| 11 | $S_8$ $P_0$ 13 group $\rightarrow S_8$ $P_1$ 13 group | - .56 |
| 12 | $S_8$ $P_0$ 13 group $\rightarrow S_{16}$ $P_0$ 13 group | - .09 |

Fig. 1 Conceptual Reactor



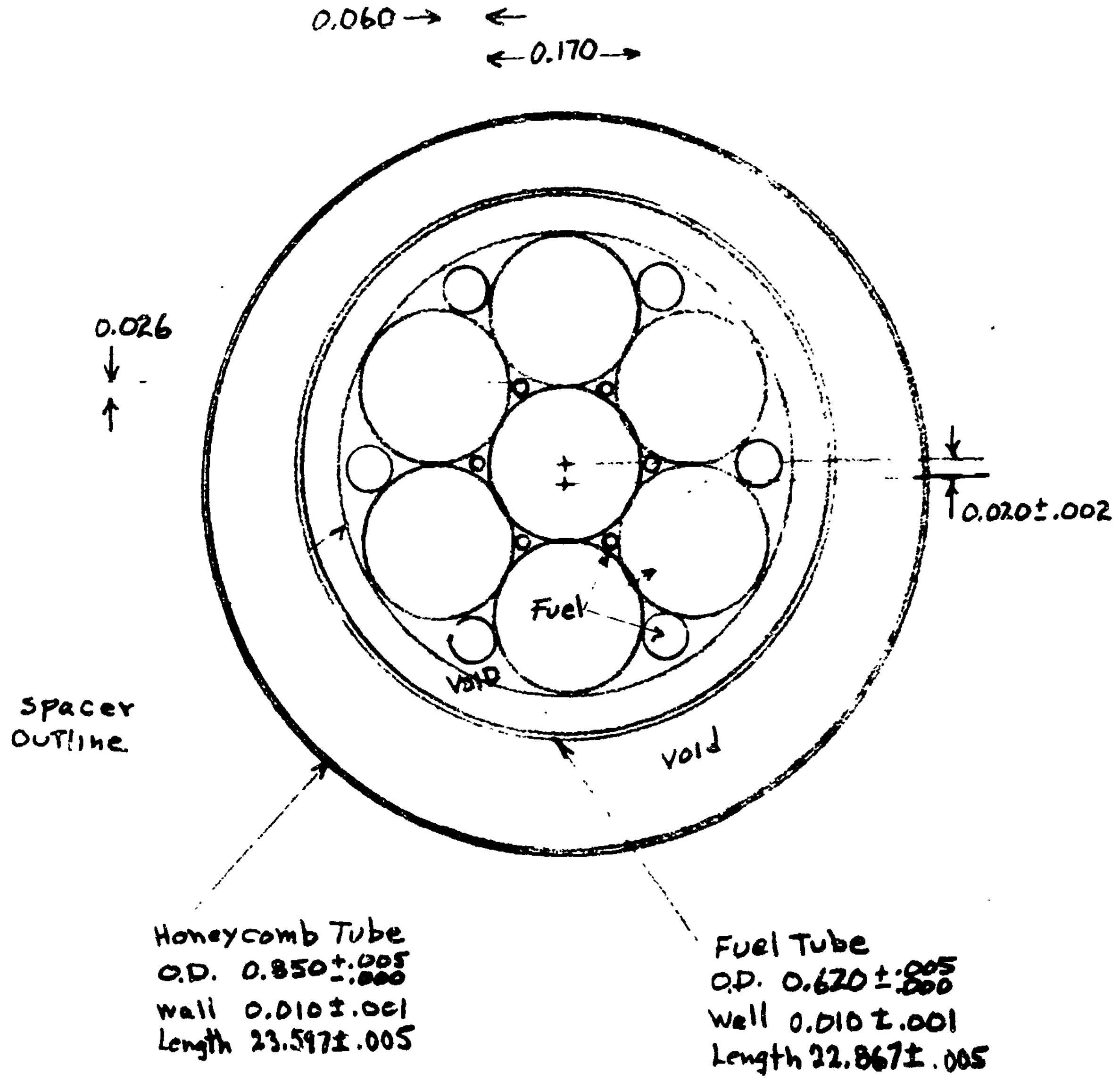



Fig. 2 Fuel Element Geometry
Dimensions in inches.

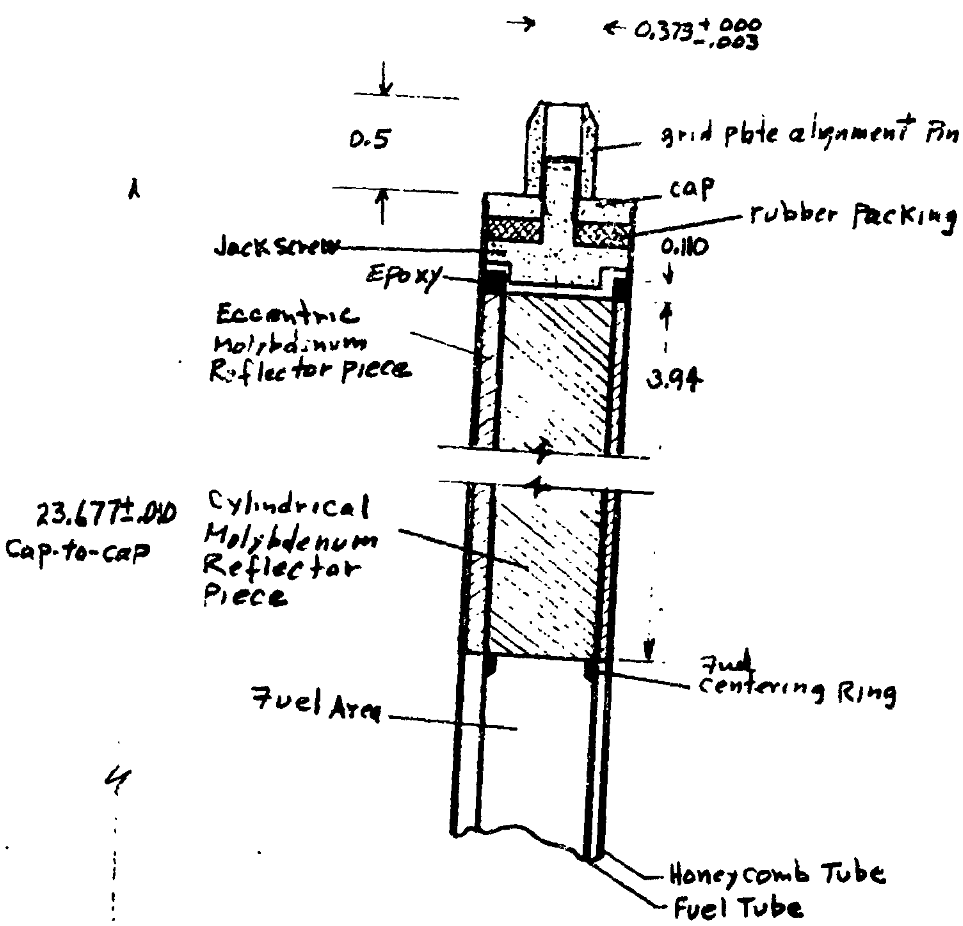



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Fig. 3 Fuel Element Closure Method And END REFLECTOR DESIGN
ALL DIMENSIONS IN INCHES

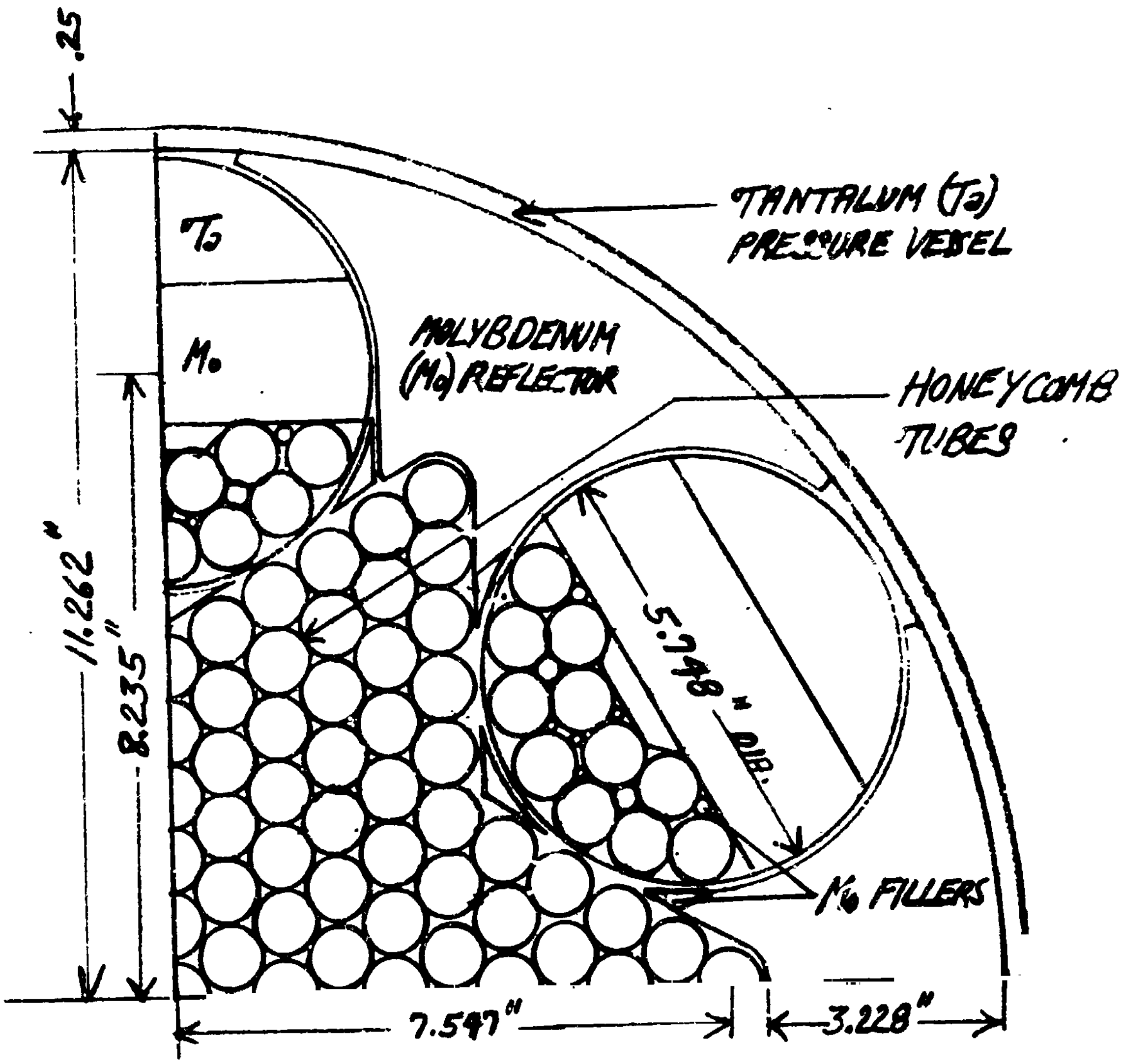
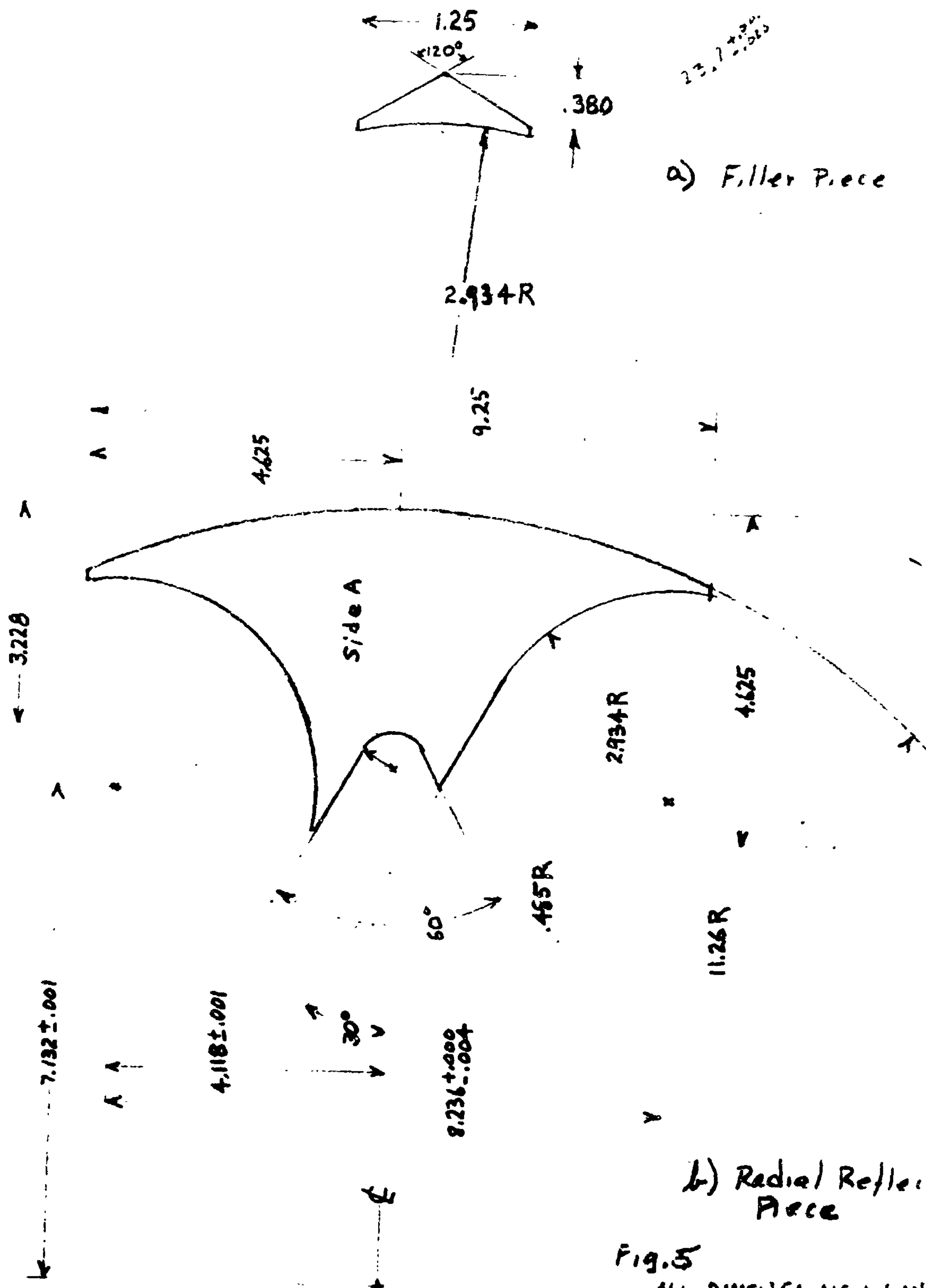


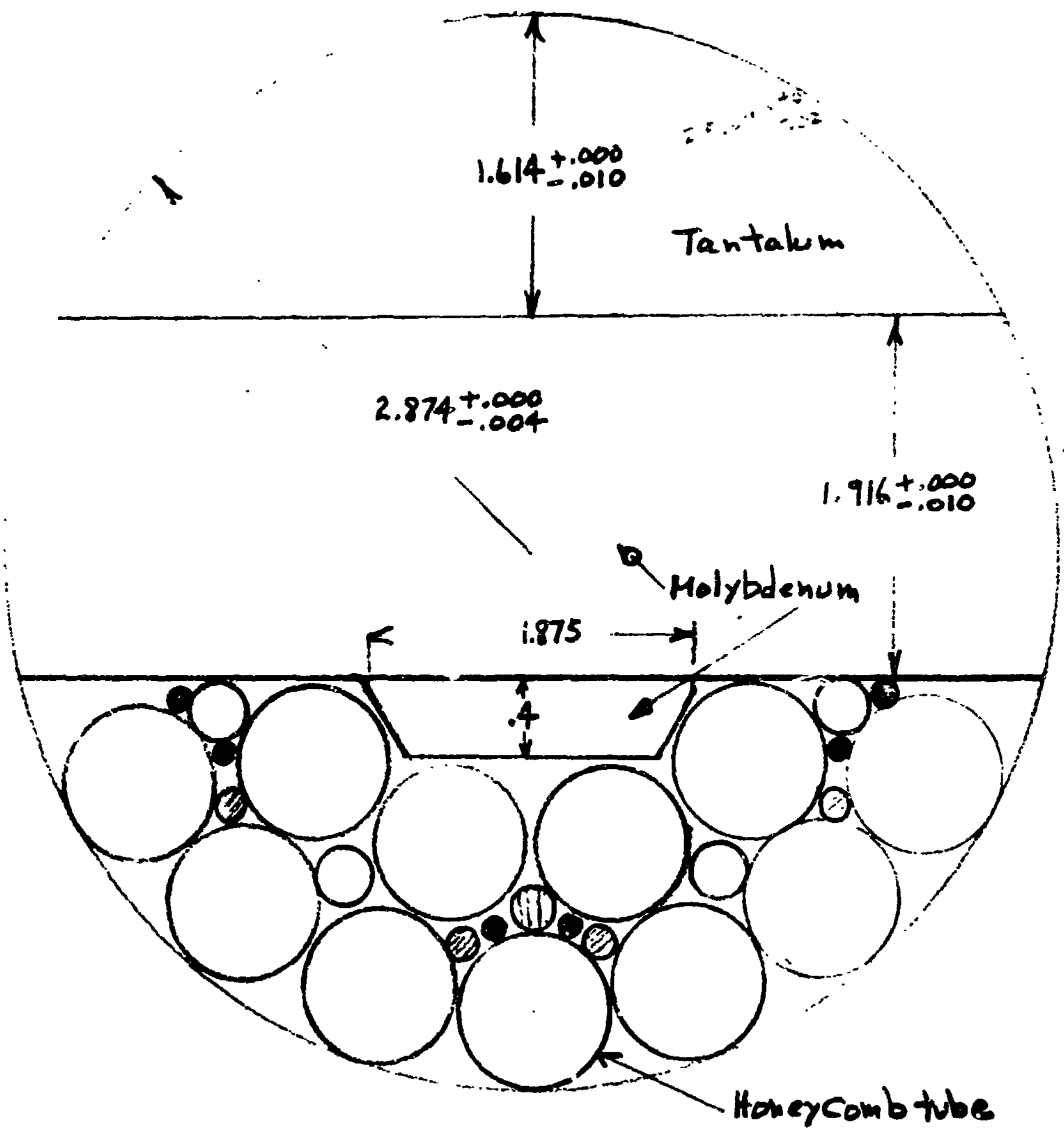

Fig. 4 CROSS SECTION OF A REACTOR QUADRANT




a) Filler Piece

b) Radial Reflector Piece

Fig.5
ALL DIMENSIONS IN INCHES




Molybdenum Rods

- 1/8 Dia
- 3/16
- 1/4
- 5/16

Use fuel [illegible] drawing for [illegible]

Fig. 6 Control Drum Geometry
Dimensions in inches.

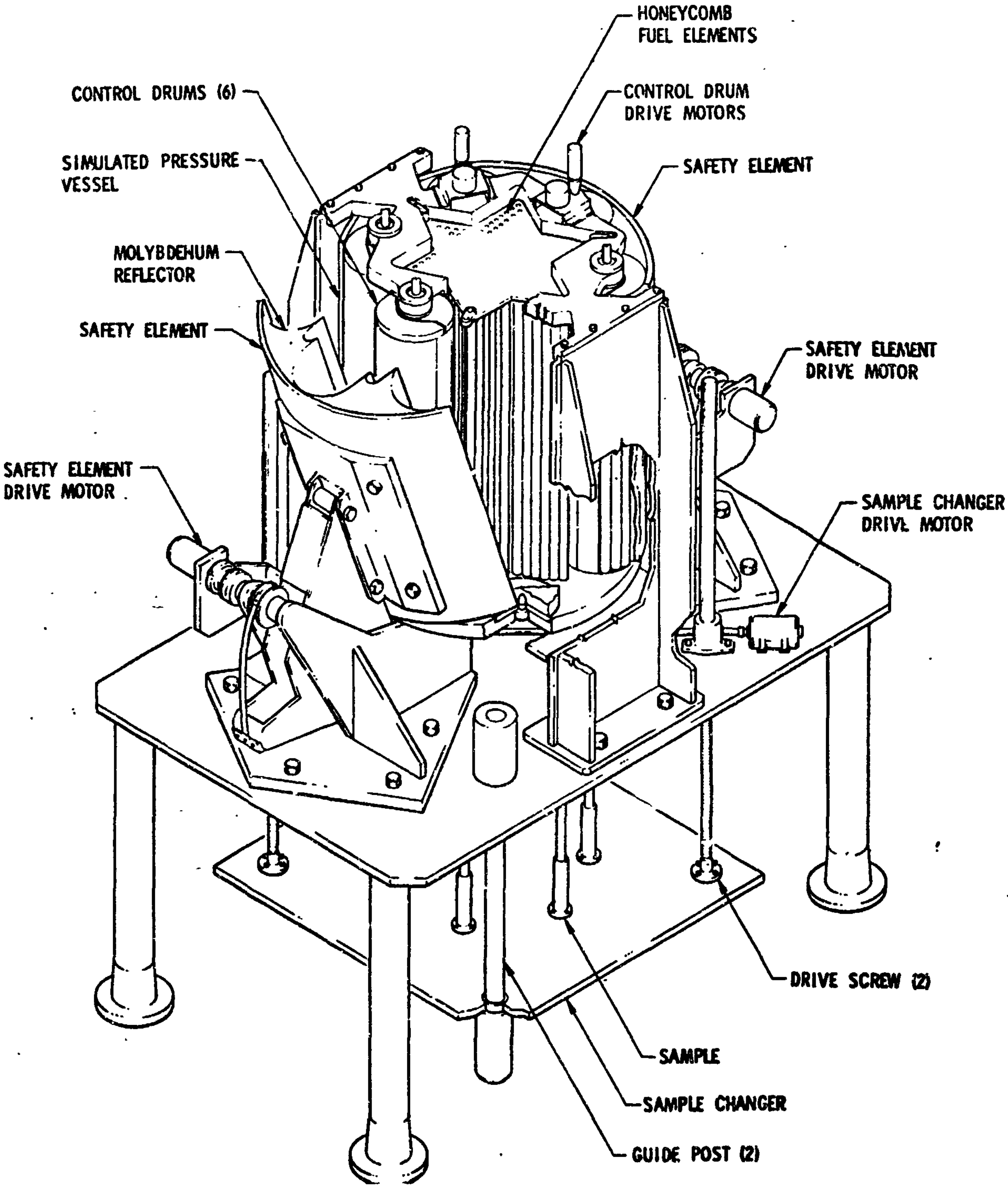
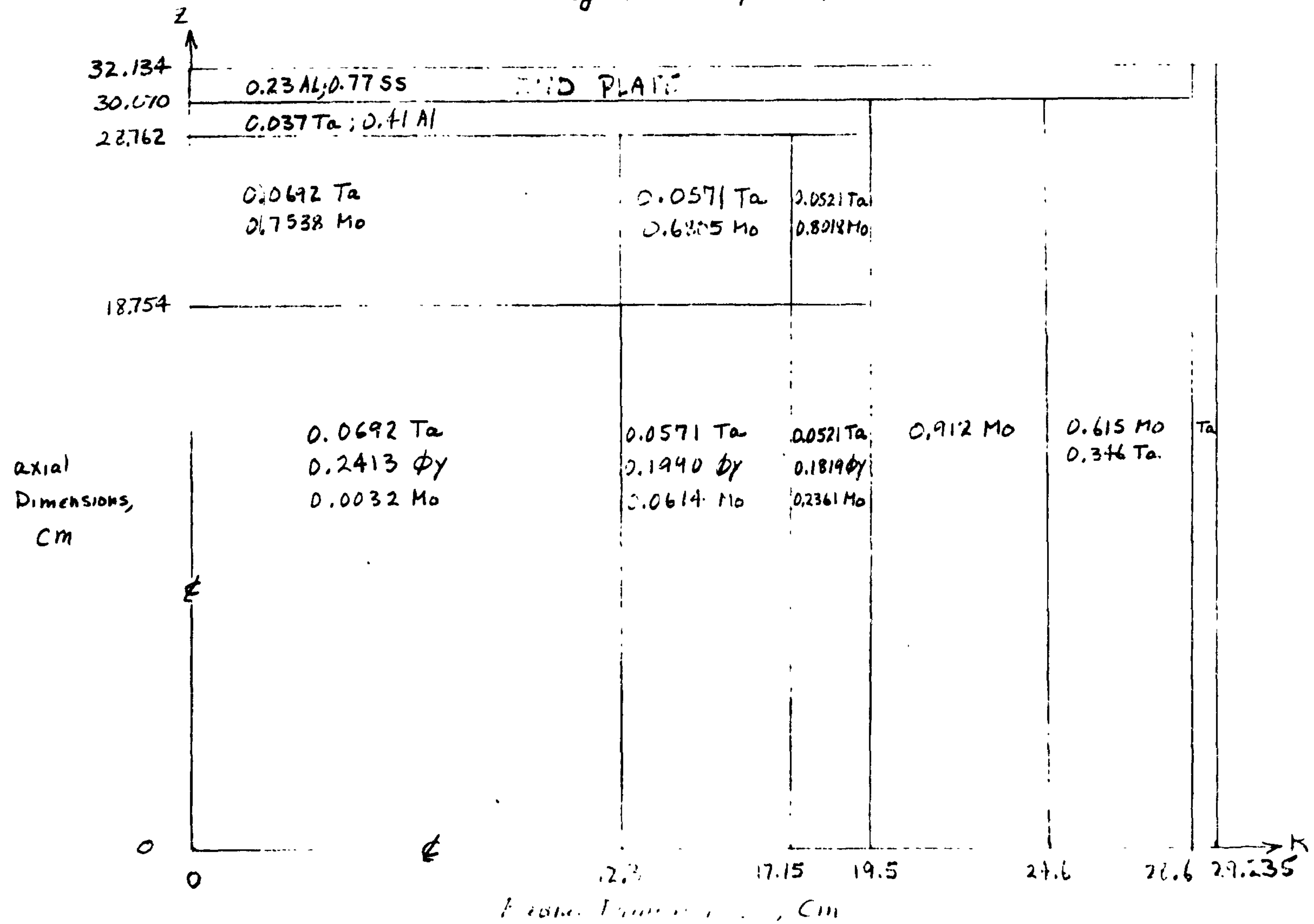



Figure 7. - Critical machine.

Fig. 8.- R,Z Calculation Geometry showing Volume Fractions of Materials in each region. ... 179.49 kg of Oralloy (Oy).



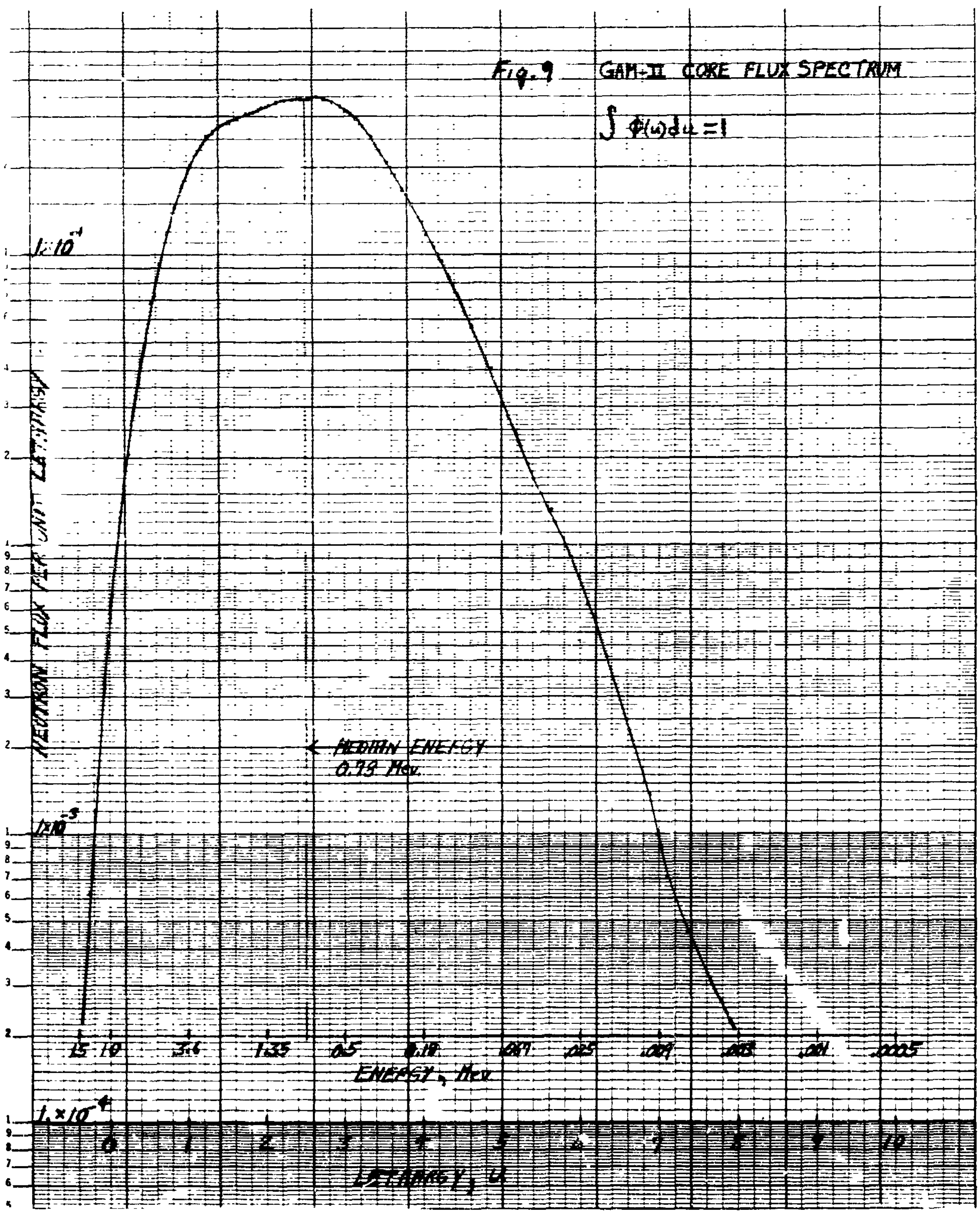
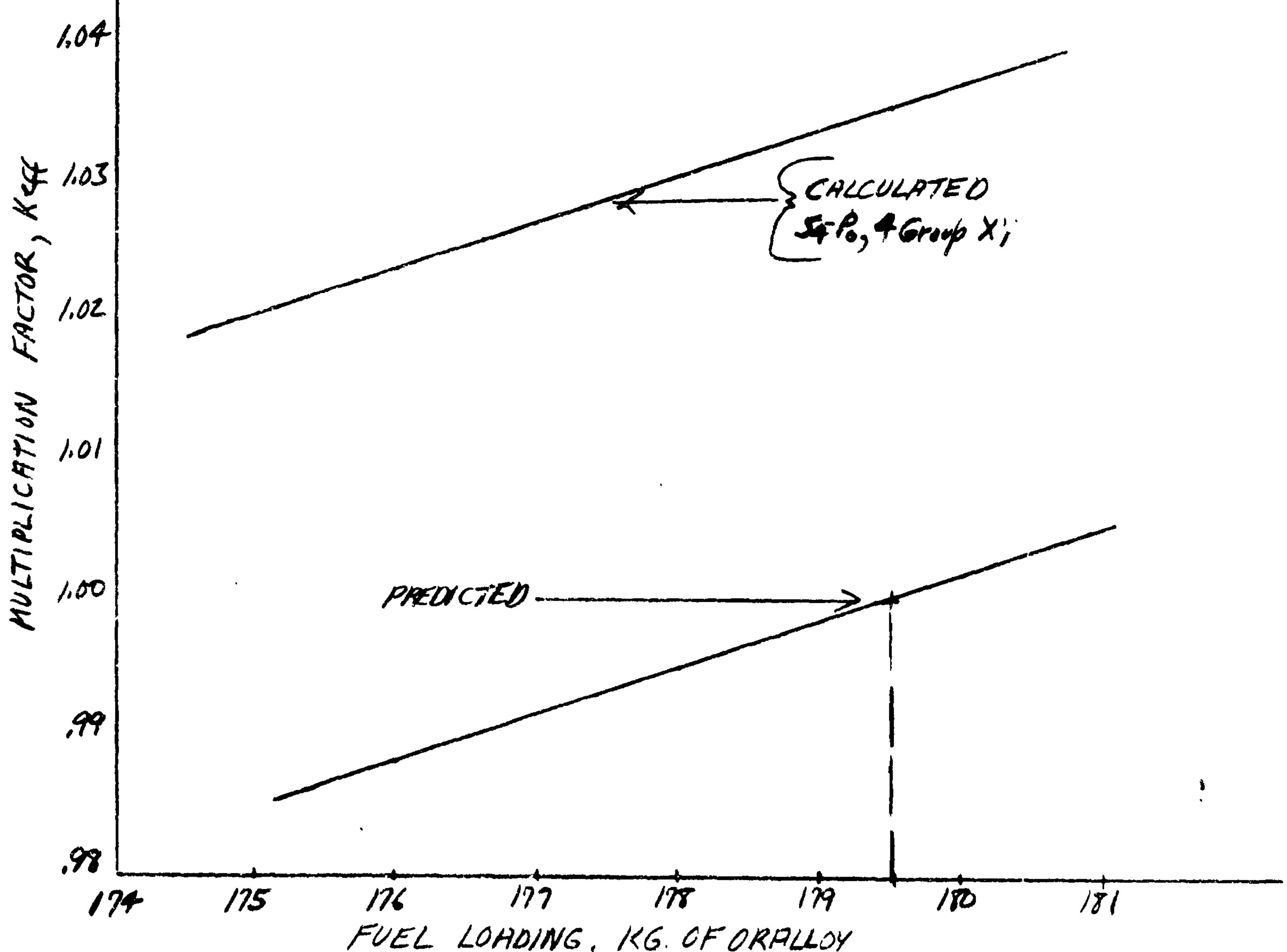


Fig. 9 GAM-II CORE FLUX SPECTRUM
$\int \Phi(u)du = 1$
1×10⁻⁴
1×10⁻³
1.×10⁻⁴
NEUTRON FLUX PER UNIT LETHARGY
← MEDIAN ENERGY
0.79 Mev.
15 10 3.6 1.35 0.5 0.18 .067 .025 .009 .003 .001 .0005
ENERGY, Mev
0 1 2 3 4 5 6 7 8 9 10
LETHARGY, u

FIG. 10 MULTIPLICATION FACTORS FOR CRITICAL ASSEMBLY

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