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# CASTING DEVELOPMENT FOR URANIUM-MOLYBDENUM ALLOY SHAPES

By

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## ABSTRACT

The casting of shapes of uranium-molybdenum metal of varying sizes and thicknesses from a molten charge has been successfully accomplished with specifically designed graphite distributors and molds. Solid cylinders, hollow cylinders, and flat plate shapes were cast in gang molds. As many as 35 solid cylinders have been cast simultaneously. All castings had smooth surfaces, and solid shapes were cast to 0.006-in. tolerance on all dimensions except length.

# I. INTRODUCTION

One of the final steps in the processing of a metal is its fabrication into a shape of specified geometry and close dimensional tolerance. Fabrication of uranium-molybdenum alloys, particularly in the ranges of 2.5 to 10.0 wt % molybdenum, by conventional methods, to close tolerances is time consuming, difficult, and costly. Because of these considerations, and the added incentive of reducing nonrecoverable scrap because of the high value of $U^{235}$ present in enriched fuels, the problem of developing a casting technique was undertaken.

# II. EXPERIMENTAL WORK

Methods investigated for casting shapes to close tolerances included centrifugal casting (Figures 1 and 2) and pressure casting in Vycor molds (Figures 3 and 4). However, the casting designs and procedures for these methods were found too limited in application and expensive for this investigation.

The static gravity casting method was re-evaluated, and a distributor under a bottom-pour crucible was conceived and developed to direct molten metal through predetermined gates into identical size graphite molds (Figures 5 and 6). Several trial runs were made with modified distributors and molds on cylinders (Figures 7, 8, and 9). The results obtained were encouraging enough to apply the distributor-mold concept to other shapes and sizes of uranium-molybdenum metals.

The vacuum furnace equipment used in this study consisted of a 30-in. diameter stainless steel furnace in two sections: a vacuum system, containing a 27-cfm mechanical pump, and a 6-in. diameter oil diffusion pump; plus a 100-kw, 3000-cycle induction melting source, supplying a 7-1/2-in. ID by 10-1/2-in. long induction coil (Figure 10). Supports for the coils were constructed from Supermica ceramoplastics, a material which was found to be excellent, in regard to outgassing and heat resistant characteristics for high temperature work in vacuum.

The various phases of casting investigated are discussed under the following headings.

## A. ALLOYING PROCEDURE

The addition of molybdenum pellets of 1/2-in. diameter and 3/16-in. length (approximately 12 gm/piece) gave best results for a homogeneous alloying with uranium. The use of molybdenum powder, wire, and sheet was tried, with less success than with the pellets. A typical chemical analysis of molybdenum distribution is shown in Table I.

## B. GRAPHITE PREPARATION

Any clay-free, dense graphite was suitable for molds. Graphite components were cleaned with fine emery cloth and subsequently coated with a slurry of magnesium zirconate. This combination was found superior to other methods for preventing carbon pickup during melting and casting operations. The primary solution of magnesium zirconate was poured into a 1-ℓ container and thoroughly mixed in a shaker for 10 min. The graphite components were either dip coated or brushed with the prepared magnesium zirconate wash, air dried, and then baked to drive off the moisture. Complete drying is essential. Figure 11 dramatically shows the effect of moisture remaining in the mold.

## C. MOLD DESIGN

The distributor design proved to be most critical. A typical design is shown in Figure 12. The rate of feeding material through the distributor was found to control both the surface appearance and the soundness of the casting. The feed ratio was determined by trial and error methods, and is discussed in the following paragraph. From experimental work, it was determined that this range of alloys had a shrinkage ratio of 2.0 to 2.6%. All mold design included this factor for good dimensional control.

## D. FEED RATIO

The ratio of the area of the pour hole in the crucible to the total area of openings in the distributor is the feed ratio. If this ratio was too small, cold shuts and underfeeding resulted. If the ratio was too large, mechanical problems in pouring resulted. The optimum ratio was found to be from 1.4 to 1.0 for all shapes poured.

## E. MELTING AND CASTING

The dried magnesium zirconate coated crucible, distributor, and multiple-cavity mold were assembled and placed in the vacuum furnace chamber. The crucible was charged, the furnace sealed off from the atmosphere, and then evacuated for a period of approximately 45 min, in order to obtain an internal vacuum of 100$\mu$ or less. A typical melting and casting cycle for U - 3.5 wt % Mo alloy is shown in Table II. Note that the pouring temperature of 1365 to 1405°C was found satisfactory for all molybdenum alloys from 2.5 to 10 wt %. Radiographic inspection, shown in Figure 26, reveals the soundness of castings made in this manner. Cobalt-60 was the source for all radiographic work.

## F. GRAIN SIZE

No attempt was made to control the grain size of castings. Figures 24 and 25 show the variation obtained from a U - 3 wt % Mo cast solid cylinder. This is typical of most castings poured into warm molds. This grain size will vary with the temperature profile of the mold.

## G. DENSITY

The actual densities of solid, cylindrical, cast slugs of various molybdenum content are shown in Table III. Approximately 98% or higher of the calculated density was obtained in this study. The calculated density was derived from the "Rule of Mixtures":

$$D = \frac{100\%}{\frac{\%A}{D_A} + \frac{\%B}{D_B}} \quad (\text{gm/cm}^3)$$

## H. SHAPES CAST

### 1. Solid and Hollow Cylinders

The casting of 3/4-in. diameter, 12-in. long solid cylinders was accomplished, using a distributor, as shown in Figure 7. The size of the mold, which contained 35 cavities, was limited by the size of the induction coil. This, in turn, was controlled by the size of the vacuum melting chamber. Based upon the experience gained from the use of this mold, it is believed possible to cast approximately 100 slugs simultaneously. The U-Mo slugs cast in this mold are shown in Figures 8 and 9.

An alternate design fuel piece, for use in the Sodium Graphite Reactor, is a hollow slug. Figure 18 shows these as-cast hollow slugs with the gating removed. The main difficulty in casting this shape was in maintaining concentricity and uniformity of wall thickness. To minimize this, several methods for preventing core shift during pouring were tried. The final result was attained by using an individual tight-fitting graphite insert in a core print, in both the bottom plate and the distributor. To remove the graphite core rod, it was necessary to drill a small hole through the center of the rod and then remove it with a hydraulic press. Several other hollow cylindrical shapes are shown in Figures 19, 20, and 21.

2. Flat Plates

During the fuel element development work for the Organic Moderated Reactor, it was advantageous to use as-cast flat plates. The mold and distributor for producing 1/8-in. thick, 3-in. wide, and 15-in. long U-Mo flat plates are shown in Figure 14. During this development program, the effect of moisture in the graphite mold became apparent. The effect was more pronounced because of the smaller cross section, which increased the probability of entrapping moisture in the mold cavity. The effect of entrapping moisture in the mold is shown in Figure 11.

Several other fuel plates of various dimensions were cast during this investigation. The thinnest plate was 1/32 in. thick (Figure 13), while the thickest was 3/4 in. thick (Figure 16). The 1/4-in. thick plate of U-Mo cast in a gang mold is shown in Figure 15.

3. Large Hollow Tubes

Another fuel element shape, desirable for the organic reactor concept, is a large, hollow, concentric cylinder, composed of two aluminum-clad U-Mo alloy tubes. Figure 22 shows the top view of the duplex castings. The larger has a 5-in. OD and a 4-1/2-in. ID, while the smaller has a 3-1/2-in. OD and a

3-in. ID; both are 15 in. long. Figure 23 shows the pour holes in the distributor, through which castings are poured. The distributor is shown in Figure 12. The development work for producing sound castings of this shape was concerned mainly with the gating through the distributor. The rate of metal flow and the amount of metal maintained in the distributor had to be controlled very closely to insure good casting surface, and sound, homogeneous castings. A complete set of castings for one element is shown in Figure 23, in the as-cast condition. Note that the surfaces are smooth and no evidence of cold shuts is apparent.

## III. CONCLUSIONS

The results indicate that sound, dense U-Mo castings with smooth surfaces can be vacuum cast by a simple bottom-pour technique into a properly gated distributor and graphite mold. The yield from charged weight of metal to semifinished casting was approximately 85%. By recycling recoverable metal, a yield of 95% was obtained throughout this investigation. A possible heat treatment of alloy castings may be required to insure grain size homogeneity.

## TABLE I

## TYPICAL MOLYBDENUM CONTENT IN URANIUM CASTINGS

| Sample | | Mo Present (wt %) | Mo Required (wt %) |
|---|---|---|---|
| H-312 | Top | 2.75 | |
| | Bottom | 2.79 | |
| H-323 | Top | 2.89 | 3.0 |
| | Bottom | 2.80 | |
| H-317 | Top | 2.89 | |
| | Bottom | 2.96 | |
| H-305 | Top | 3.65 | |
| | Bottom | 3.68 | |
| H-283 | Top | 3.69 | 3.5 |
| | Bottom | 3.70 | |
| H-519 | Top | 3.70 | |
| | Bottom | 3.64 | |
| H-432 | Top | 5.20 | |
| | Bottom | 5.28 | 5.0 |
| H-4321 | Top | 5.11 | |
| | Bottom | 5.13 | |
| H-405 | Top | 7.53 | |
| | Bottom | 7.51 | 7.5 |
| H-377 | Top | 7.65 | |
| | Bottom | 7.85 | |
| H-403 | Top | 9.95 | |
| | Bottom | 9.77 | |
| H-438 | Top | 9.77 | 10.0 |
| | Bottom | 9.81 | |
| H-019 | Top | 10.42 | |
| | Bottom | 10.30 | |

## TABLE II

## TYPICAL CYCLE FOR STATIC MELTING AND CASTING U - 3 WT % MO ALLOY

| Time | Remarks | Power Input (kw) | Capacitance (kva) | Pressure ($\mu$) | Cruc. Temp. (°C) | Mold Temp. (°C) |
|---|---|---|---|---|---|---|
| 11:20 | Out gas | 12 | 0 | 200 | - | - |
| 11:40 | Power off | 12 | 0 | 190 | 985 | - |
| 12:10 | Power on | 16 | +3 | 80 | - | - |
| 12:25 | Melting | 16 | +2 | 120 | 1175 | 271 |
| 12:45 | - | 16 | +2 | 78 | 1310 | 360 |
| 1:00 | Molten | 16 | +2 | 88 | 1345 | 416 |
| 1:15 | - | - | - | 70 | 1365 | 462 |
| 1:30 | - | - | - | 60 | 1372 | 495 |
| 1:45 | Hold | - | - | 50 | 1385 | 516 |
| 2:00 | Raise | 17 | +2 | 44 | 1375 | 532 |
| 2:10 | - | - | - | 43 | 1405 | 537 |
| 2:14 | Poured with Power on | - | - | 43 | 1405 | 539 |
| 2:18 | Power off | - | - | 43 | - | - |
| 2:50 | Cool with helium to room temperature | - | - | - | - | - |

## TABLE III

## DENSITY OF U-MO CAST ALLOYS

| Sample No. | Molybdenum (wt %) | Actual Density (gm/cm$^3$) | Calculated Density (gm/cm$^3$) |
|---|---|---|---|
| 100 | | 18.33 | |
| 102 | | 18.35 | |
| 104 | 3.0 | 18.35 | 18.30 |
| 105 | | 18.35 | |
| 111 | | 18.35 | |
| 151 | | 17.74 | |
| 152 | | 17.75 | |
| 153 | 5.0 | 17.75 | 18.08 |
| 154 | | 17.75 | |
| 155 | | 17.75 | |
| 201 | | 17.35 | |
| 202 | | 17.35 | |
| 203 | 7.5 | 17.36 | 17.70 |
| 204 | | 17.35 | |
| 205 | | 17.35 | |
| 250 | | 17.10 | |
| 251 | | 17.10 | |
| 252 | 10.0 | 17.11 | 17.15 |
| 253 | | 17.10 | |
| 255 | | 17.13 | |

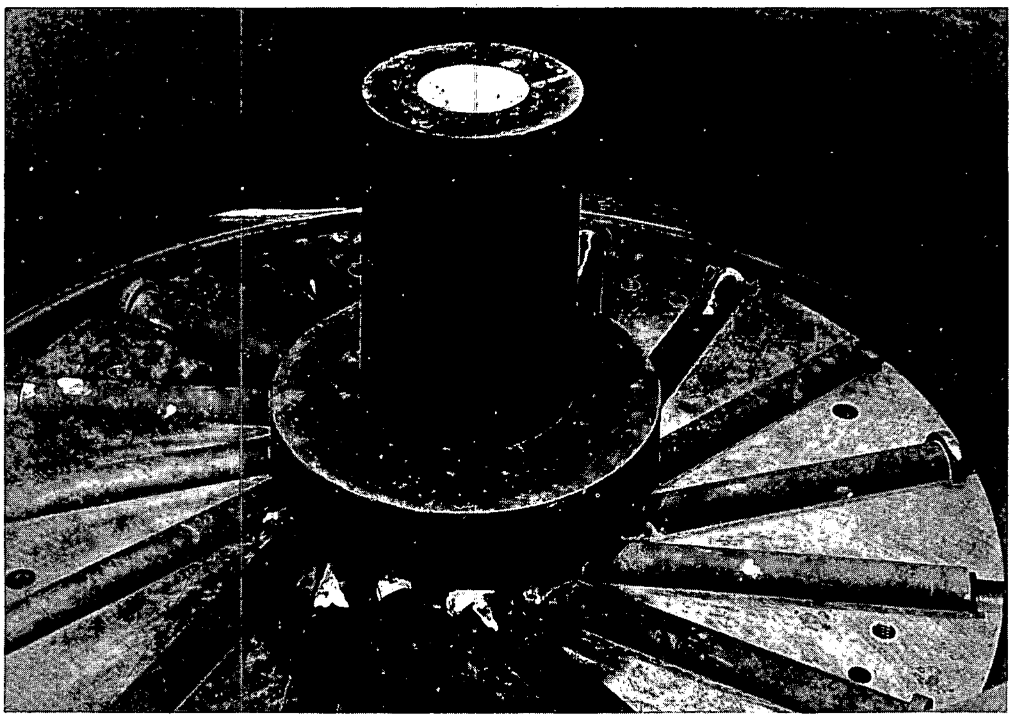

Figure 1. Centrifugal Casting Design for 3/4-in. Diameter by 10 in. Solid Cylinders

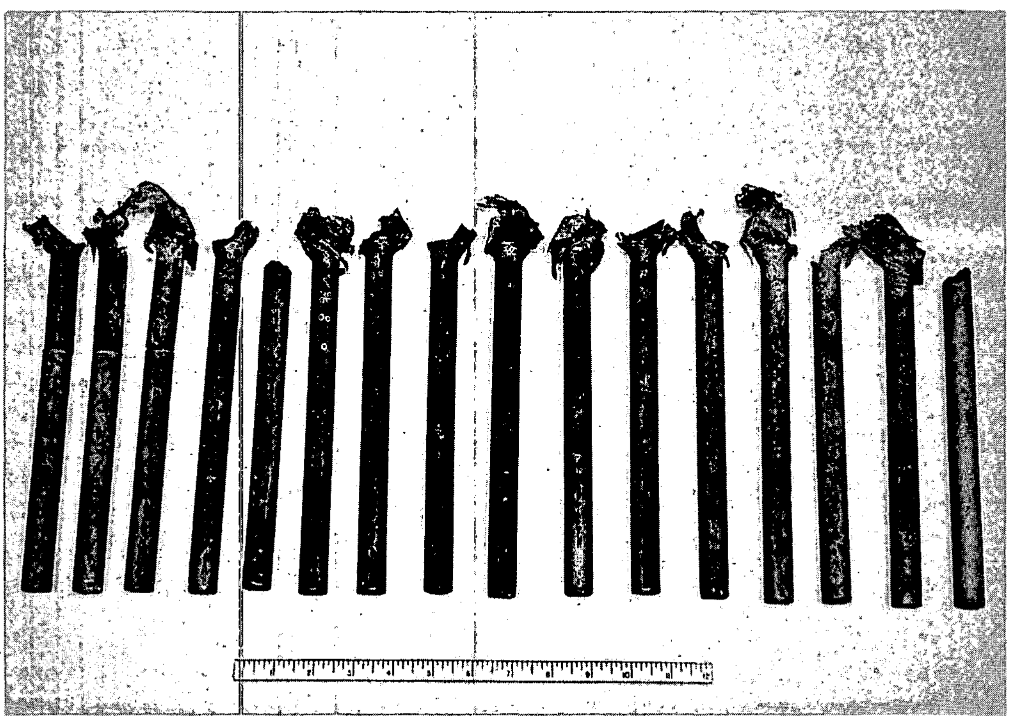

Figure 2. Centrifugal Cast 3/4-in. Diameter by 10 in. Solid Cylinders (3% Mo)

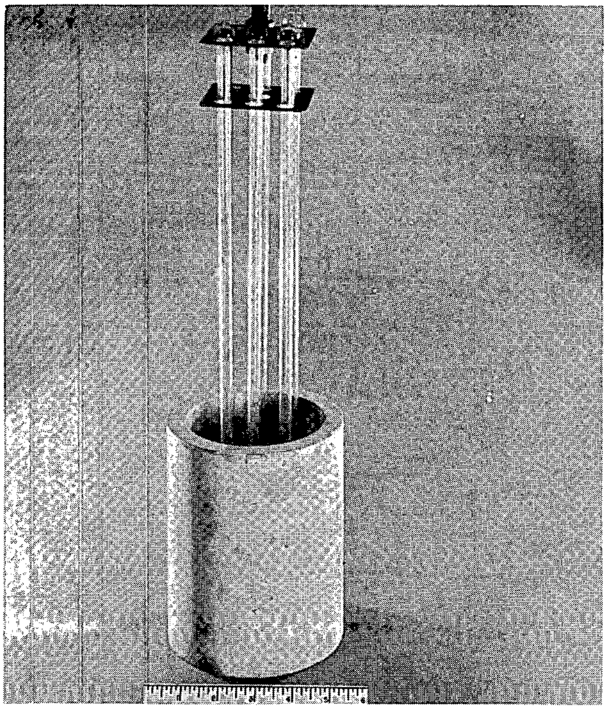

Figure 3. Pressure Casting Design for 5/16-in. Diameter by 14 in. Rod

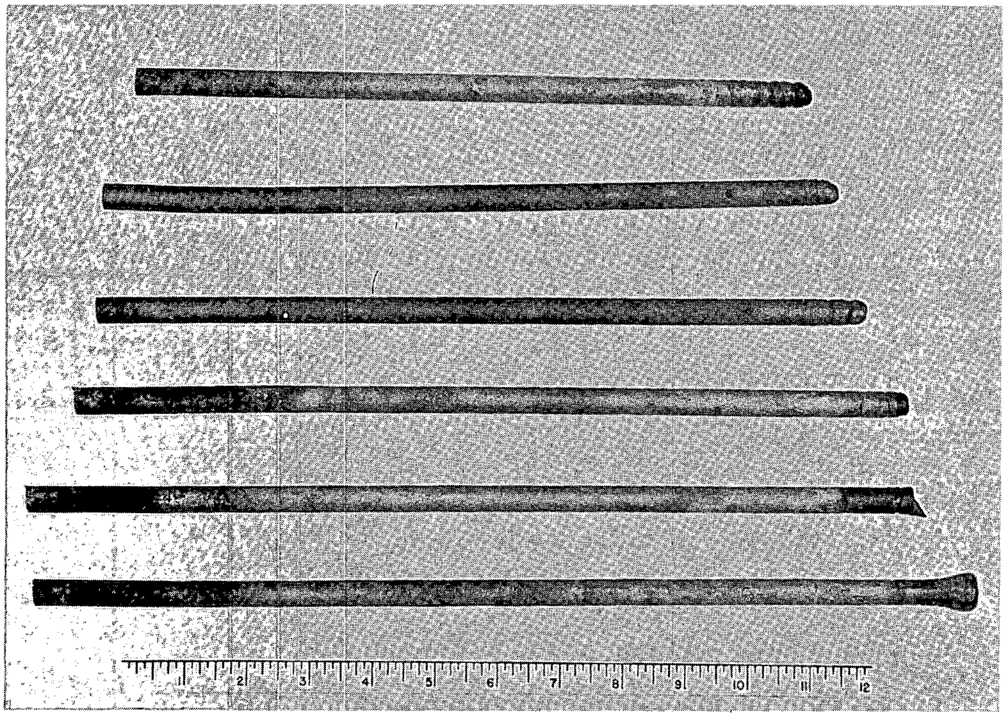

Figure 4. Pressure Cast 5/16-in. Diameter Uranium Rods

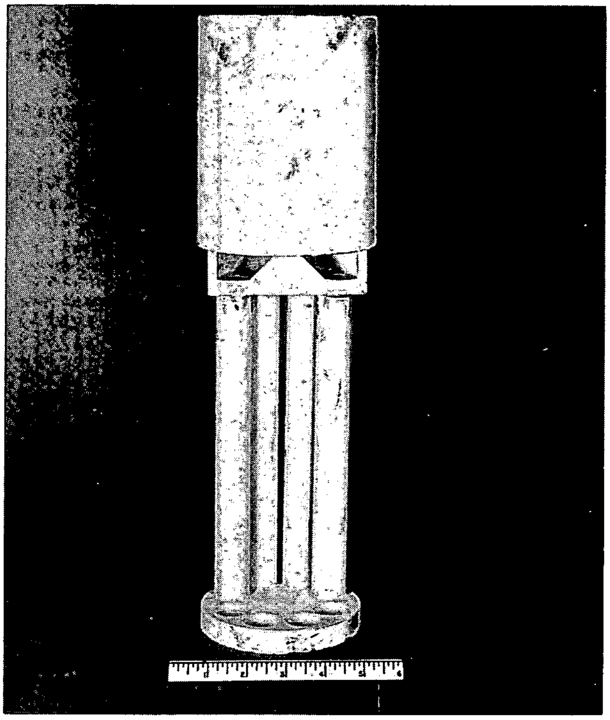


Figure 5. Melting and Casting Assembly for 3/4-in. Diameter by 10 in. Solid Cylinders (8 per Mold)

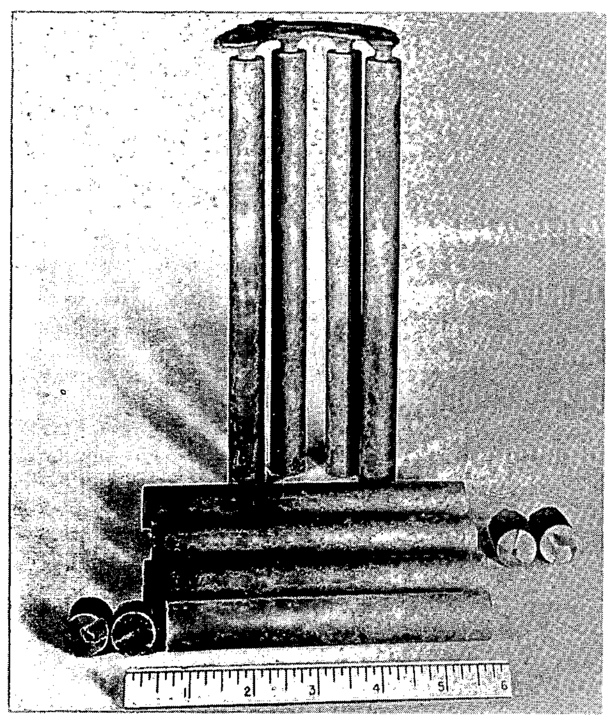


Figure 6. Casting of 3/4-in. Diameter U-Mo Solids, Using Mold Shown in Figure 5

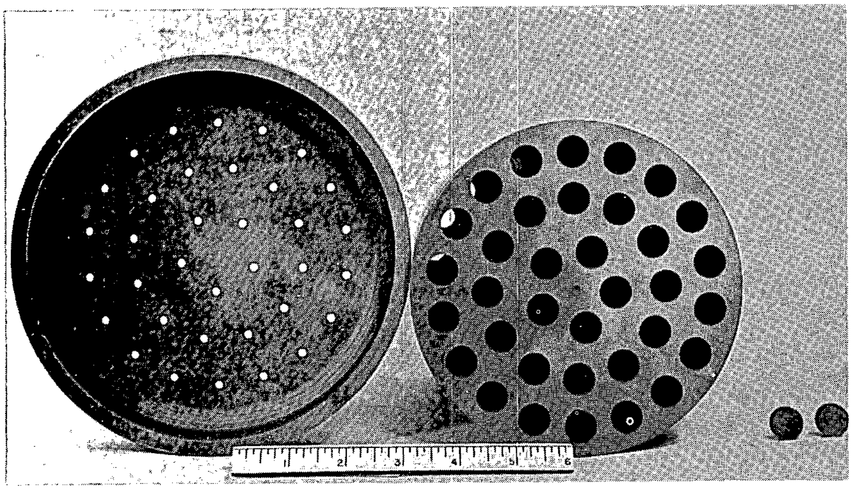

Figure 7. Modified Distributor and Casting Mold for 5/8-in. Diameter by 15 in. Solid Cylinders (35 per Mold)

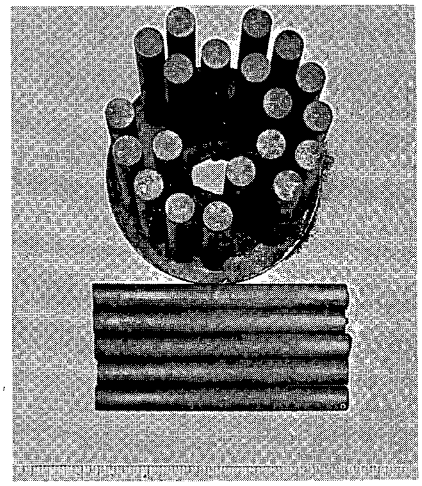

Figure 8. Typical 3/4-in. Diameter Solid Cylinders from Improved Distributor and Mold Based on Design Shown in Figure 7

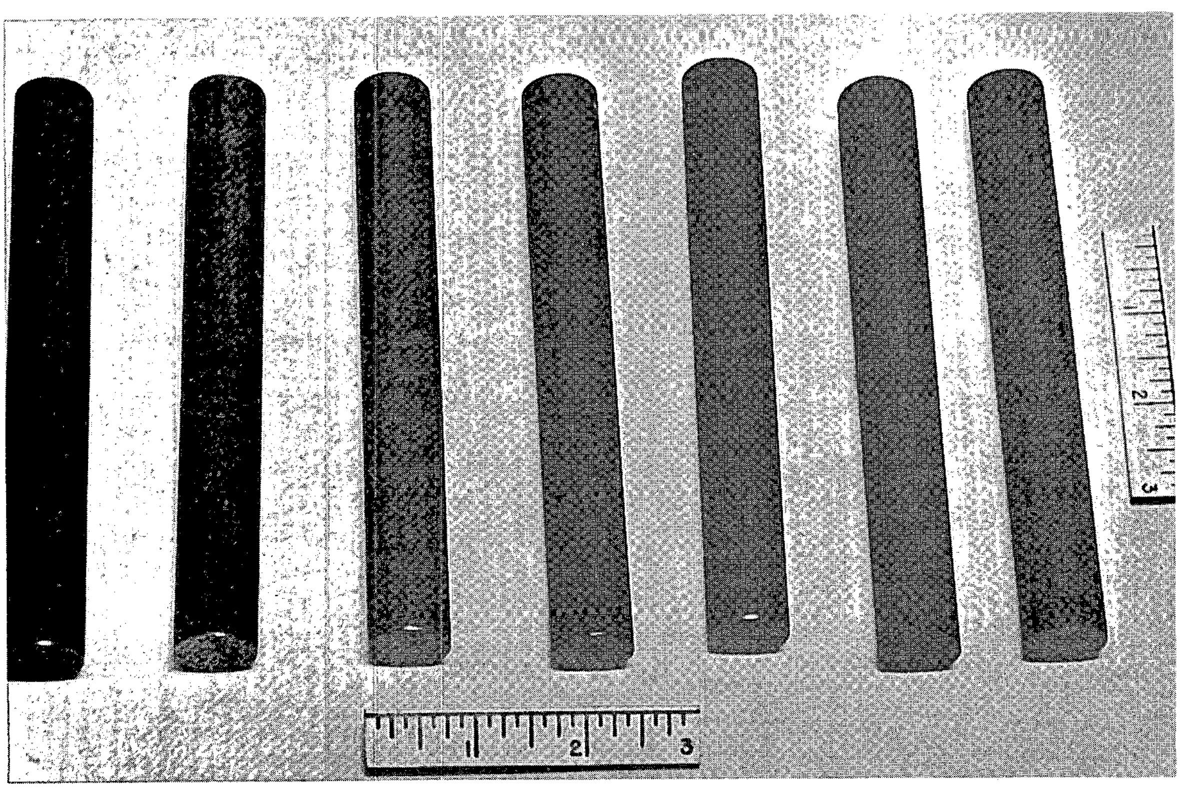

Figure 9. Sand Blasted 3/4-in. Diameter U-Mo Slugs, End Faced Only, Cast in Molds Shown in Figure 8

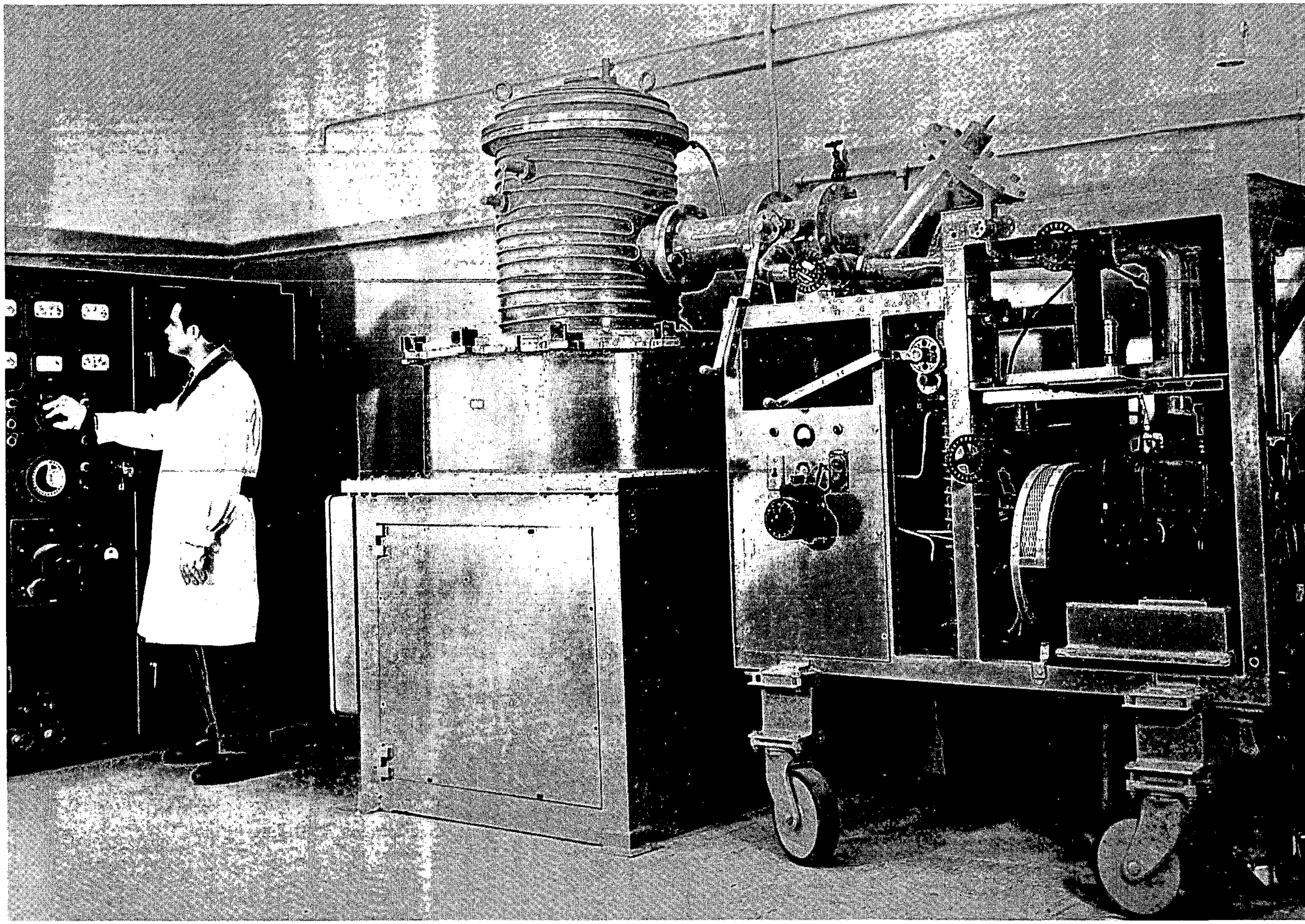

Figure 10. Melting, Casting, and Vacuum Unit

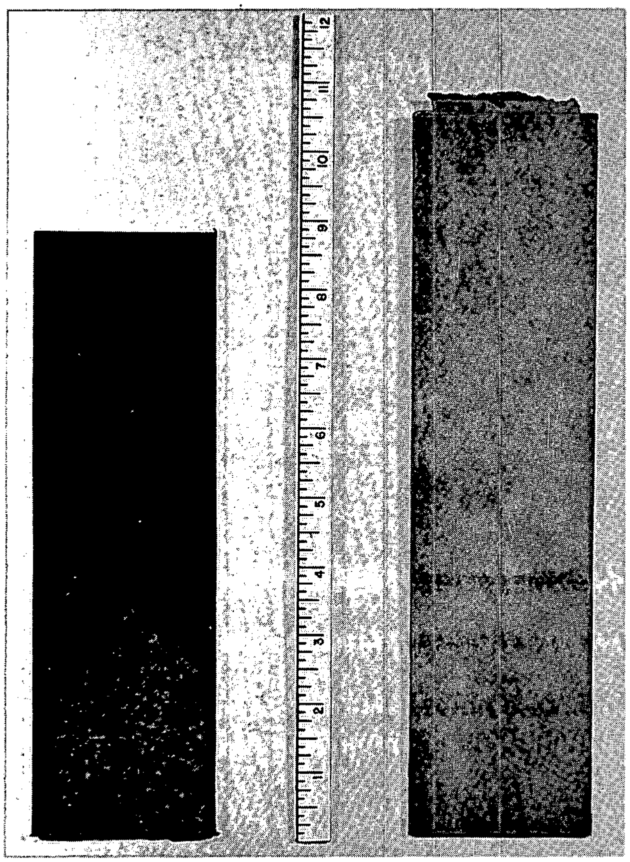

Figure 11. Plate on Left - Cast into Mold Not Completely Dried
Plate on Right - Cast into Mold Completely Dried

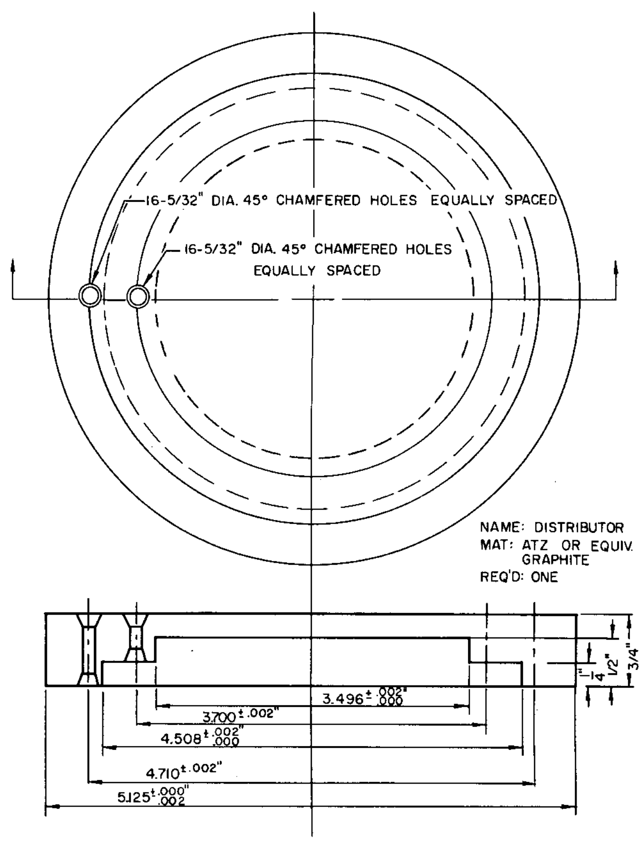


Figure 12. Distributor and Gating for Duplex

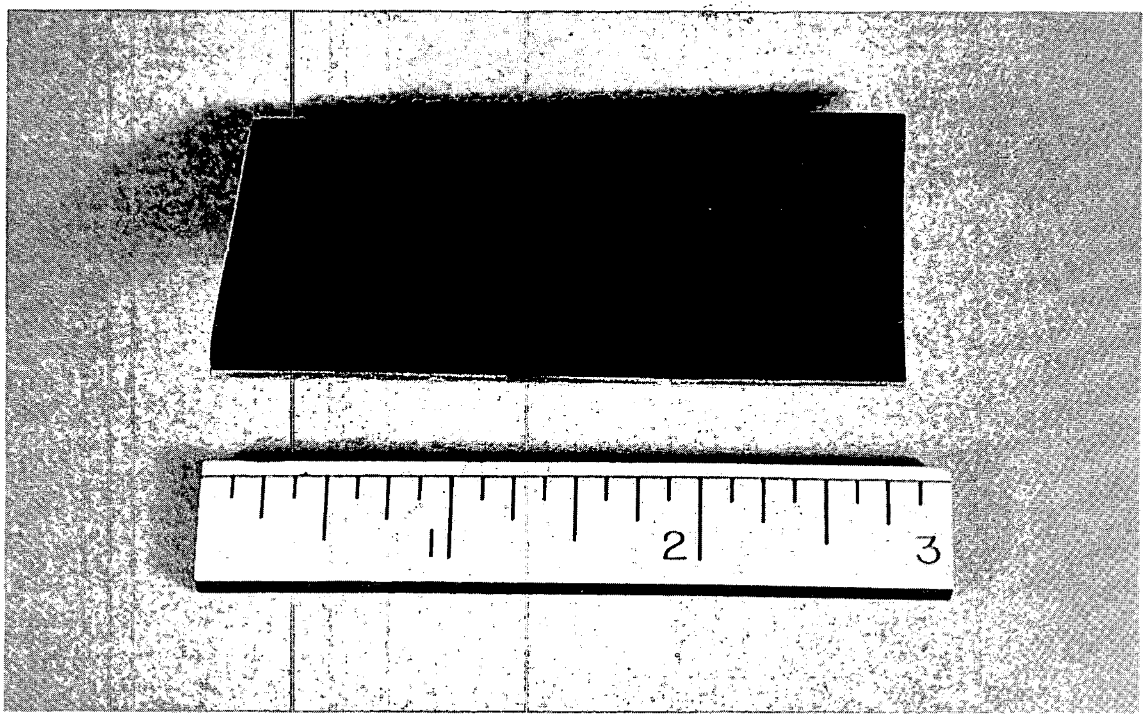


Figure 13. Uranium Casting, 1/32-in. Thick

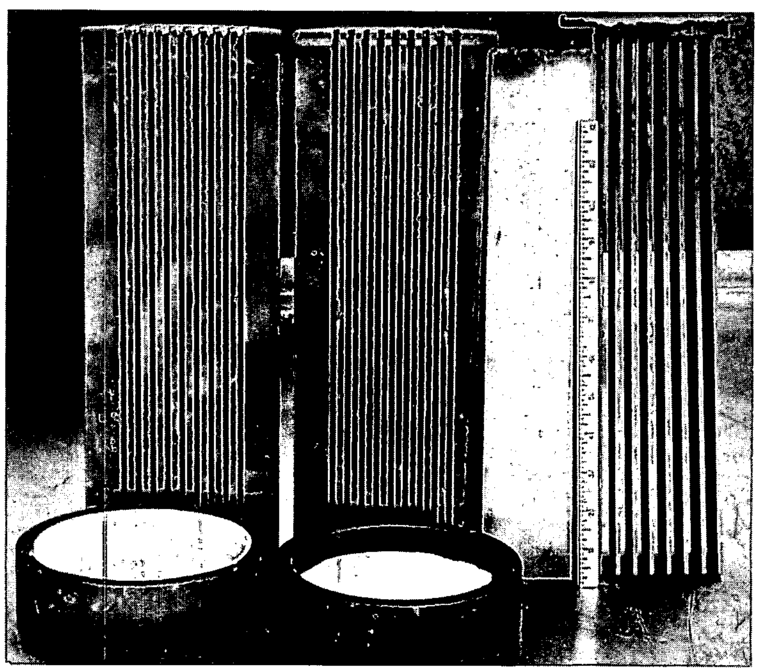

Figure 14. Graphite Mold and Distributor for U - 3.5 wt % Mo Plates, 1/8-in. Thick by 3-in. Wide by 15-in. Long (9 per Casting)

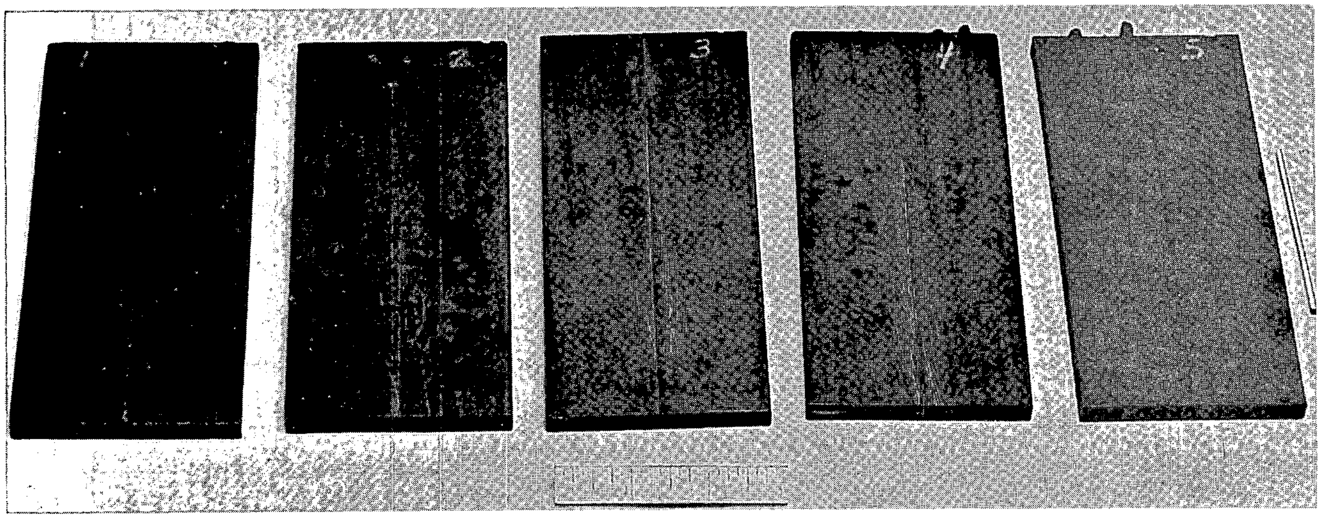

Figure 15. Typical 1/4-in. Thick U - 3.5 wt % Mo Plate Castings (5 per Casting)

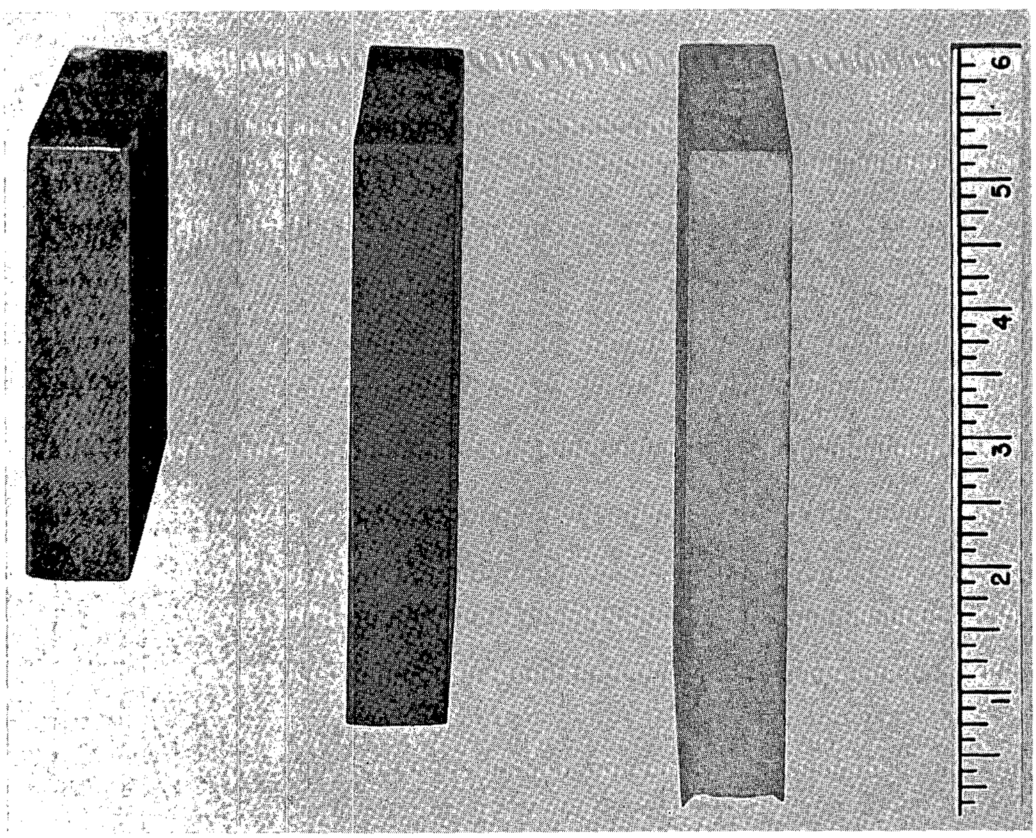

Figure 16. U-Mo Slabs, 3/4-in. Thick

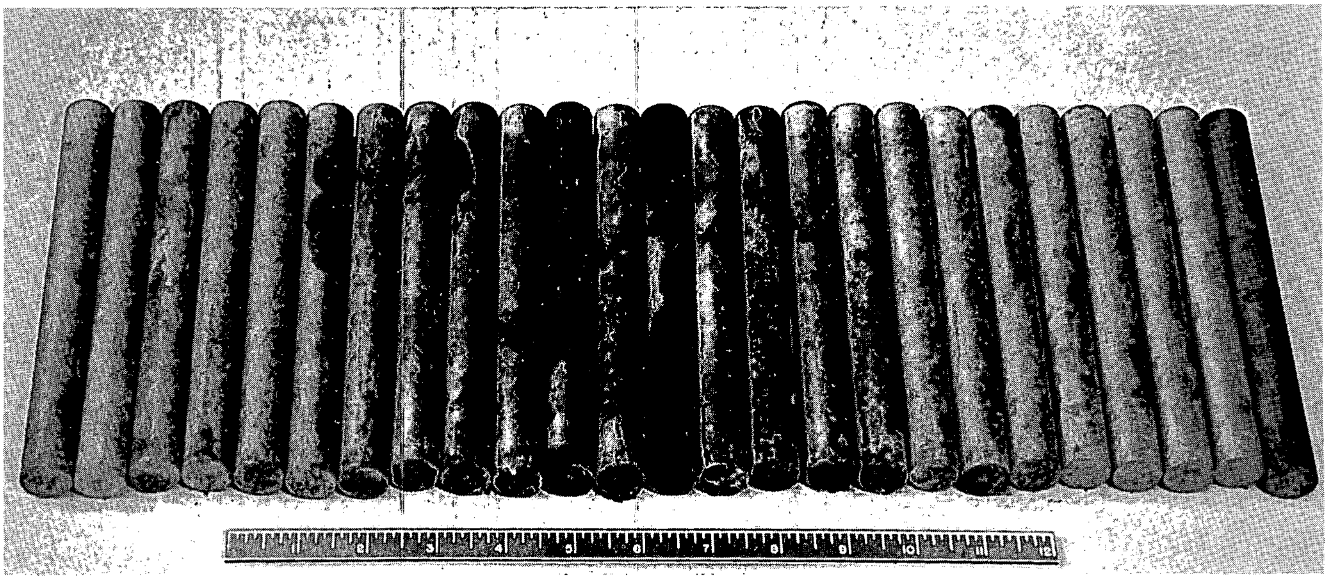

Figure 17. U - 10 wt % Mo Solid Cylinders, 3/4-in. Diameter (25 per Casting)

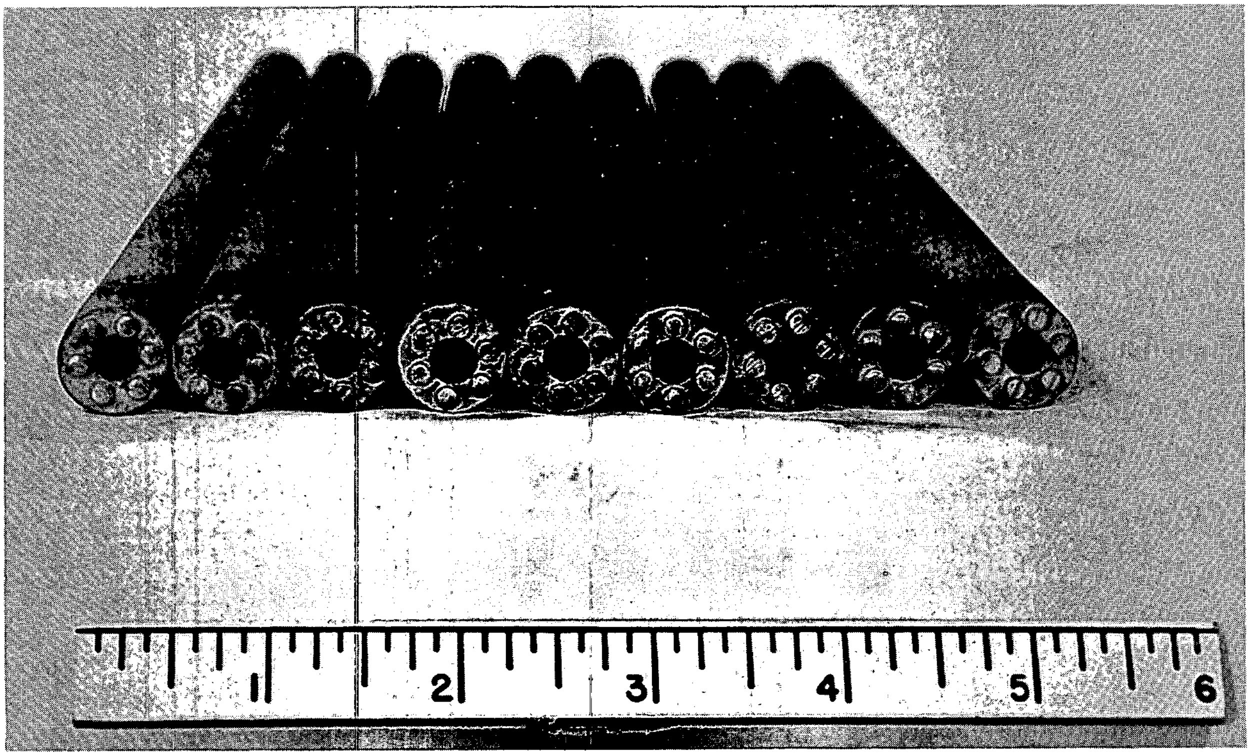

Figure 18. U - 10 wt % Mo Hollow Cylinders, 0.633-in. OD, 1/4-in. ID (10 per Pour)

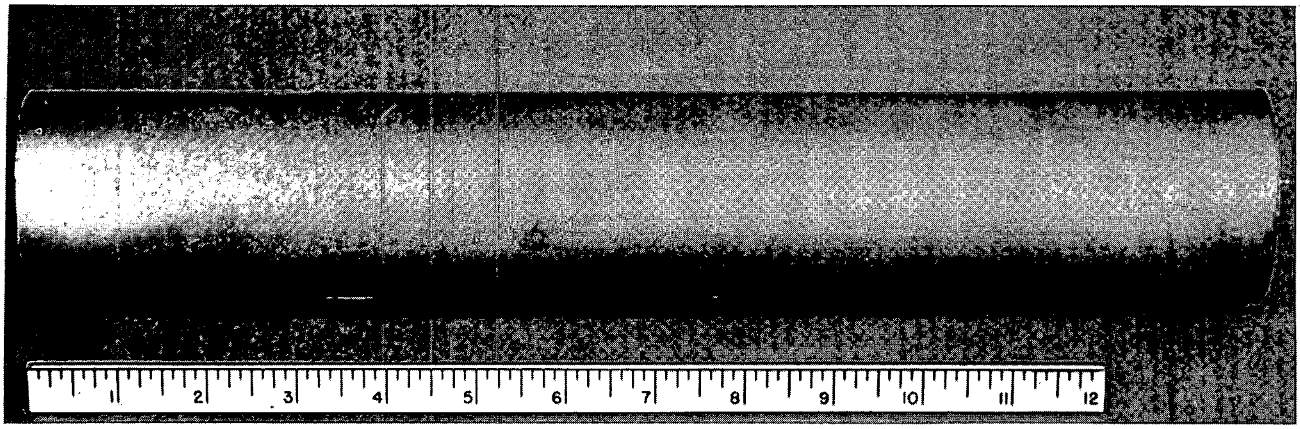

Figure 19. U - 3.5 wt % Mo Tube Casting, 2-3/8-in. OD, 2-in. ID

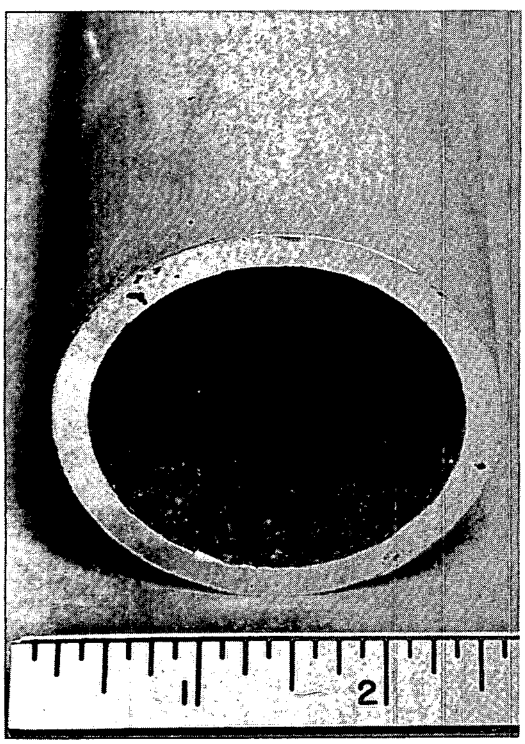

Figure 20. U-Mo Tube Casting' (Front View of Figure 19)

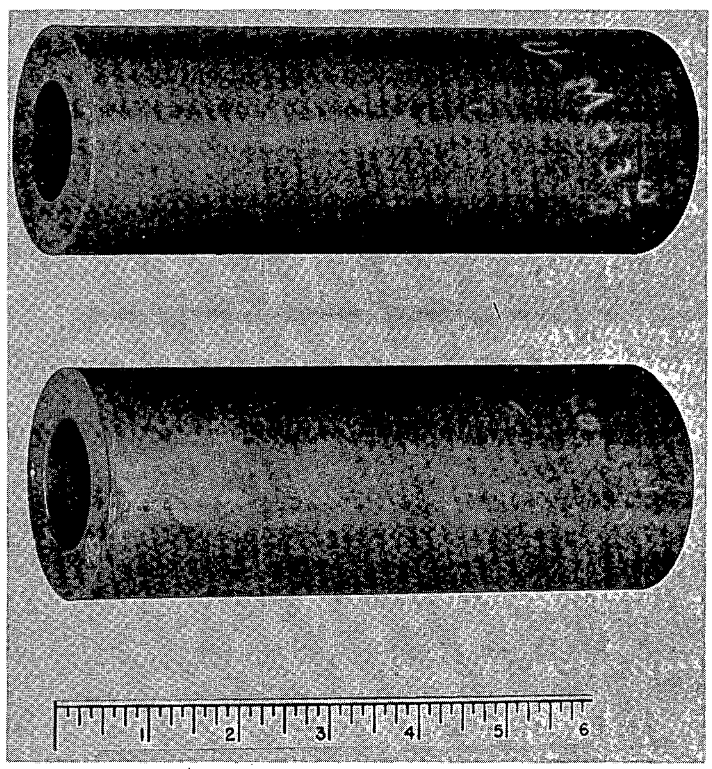

Figure 21. Thick Walled Tube Casting of U - 3 wt % Mo, 2-3/8-in. OD, 1-3/8-in. ID

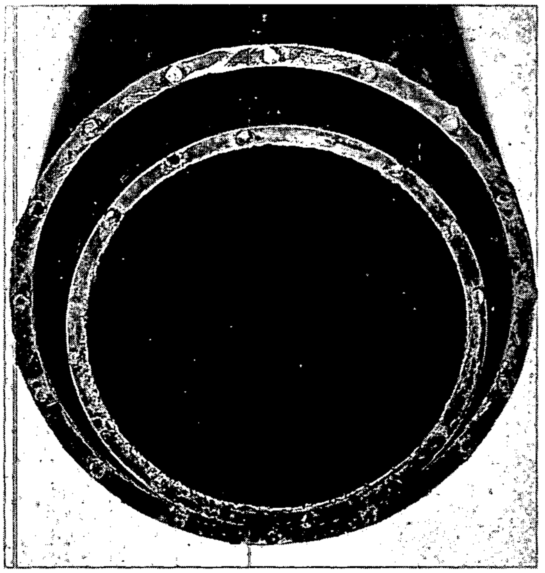

Figure 22. Duplex Casting of U - 3.5 wt % Mo, Cast Simultaneously (Outer Tube: 5-in. OD, 4-1/2-in. ID; Inner Tube: 3-1/2-in. OD, 3-in. ID; 15-in. Long)

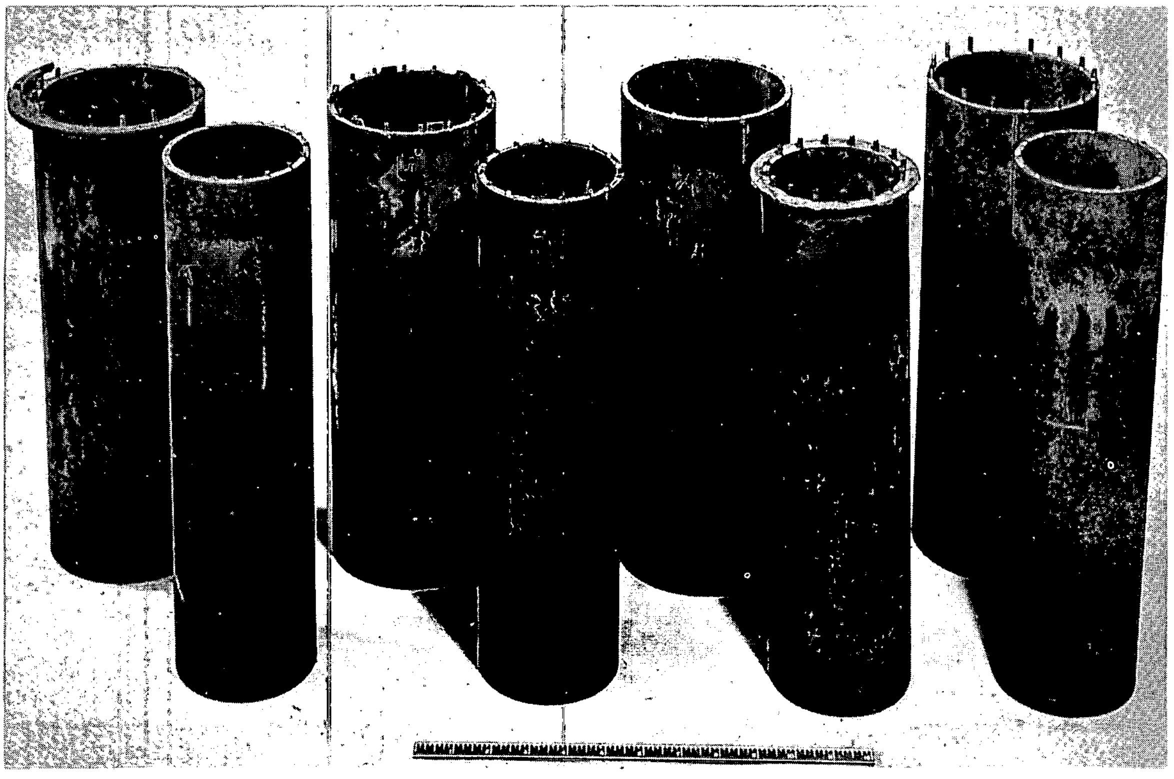

Figure 23. Typical U - 3.5 wt % Mo Castings

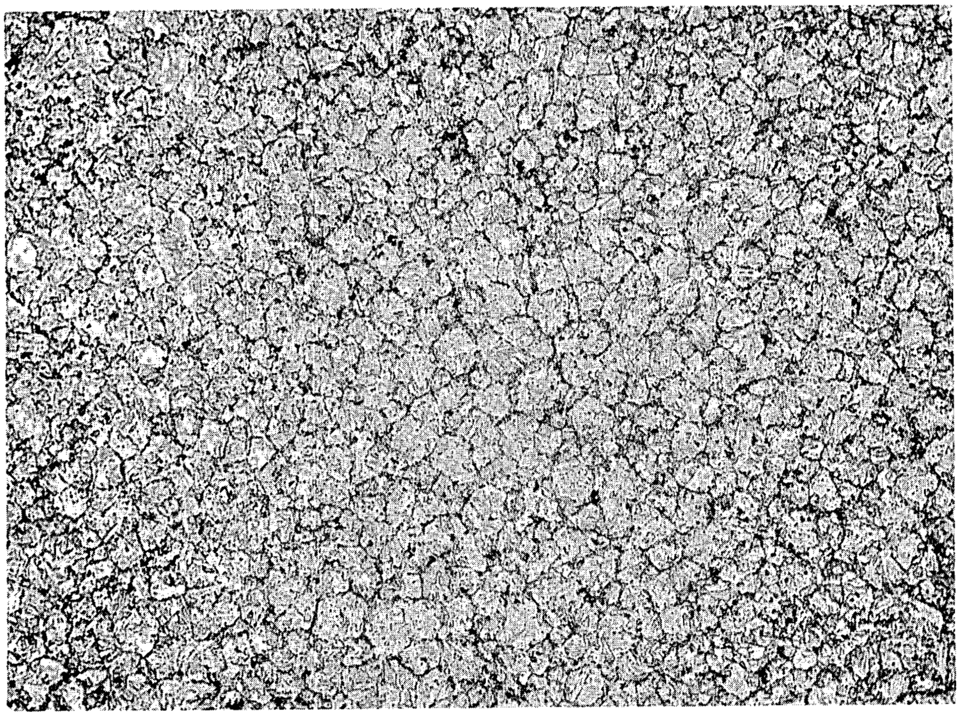

Figure 24. Microstructure of Top of U - 3 wt % Mo Alloyed Slug

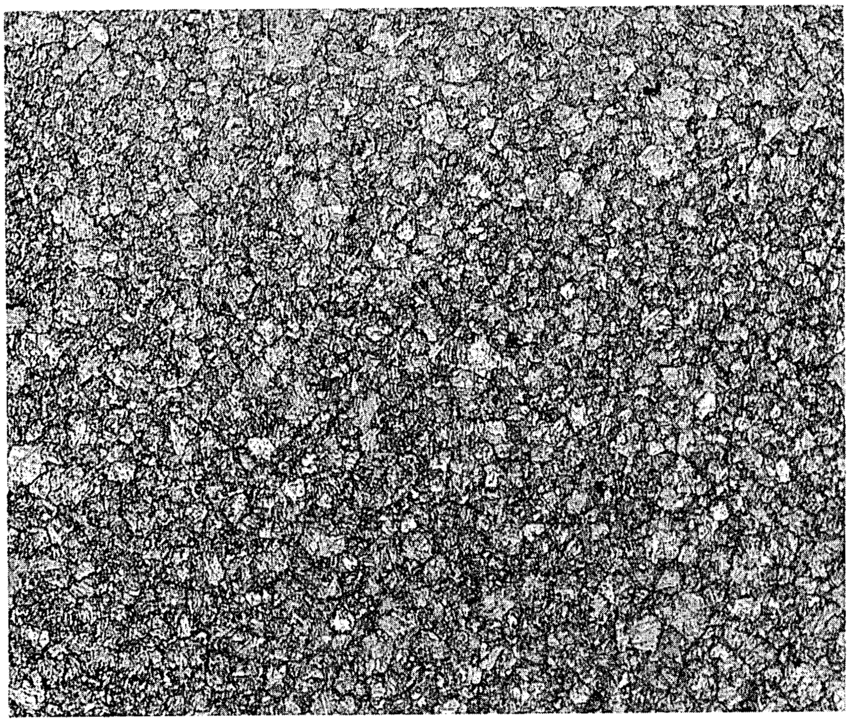

Figure 25. Microstructure of Bottom of U - 3 wt % Mo Alloyed Slug

Figure 26. (a) Radiograph of As-Cast Slugs of U - 10 wt % Mo

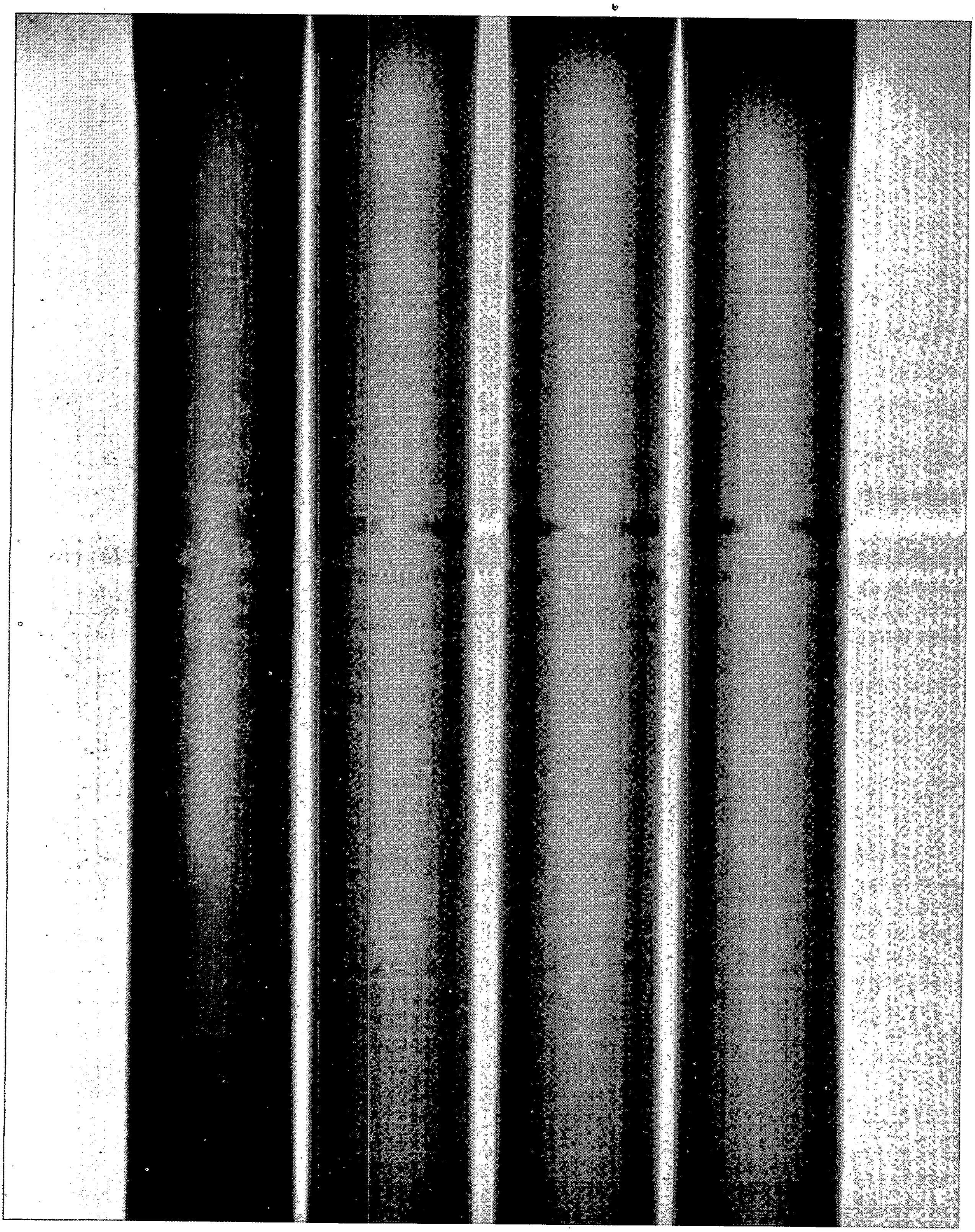

Figure 26. (b) Radiograph of U Alloy Tubes, As Cast

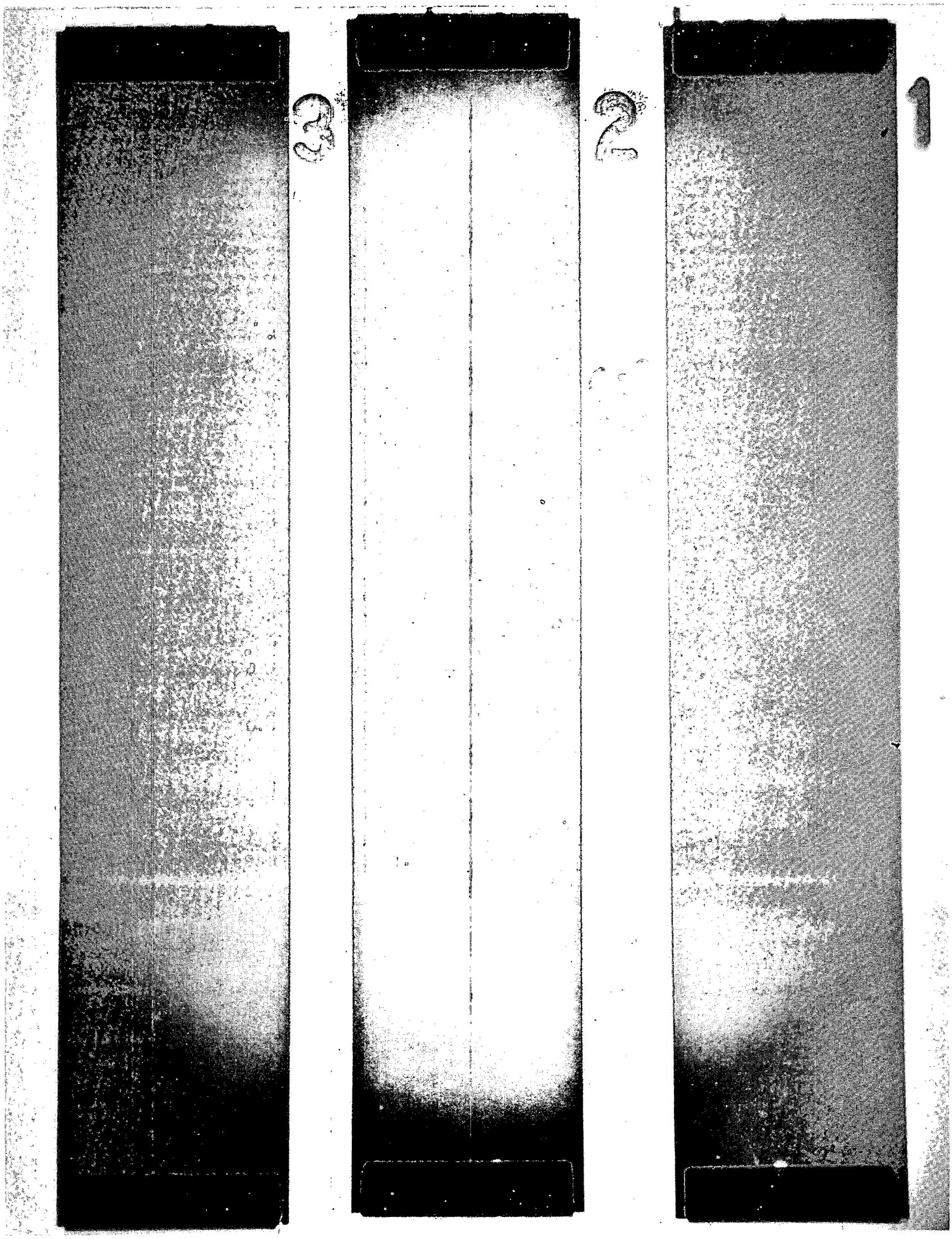


Figure 26. (c) Radiograph of U - 3.5 wt % Mo Flat Plates