Low-Enriched Uranium-Molybdenum Fuel Plate Development*

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ABSTRACT

To examine the fabricability of low-enriched uranium-molybdenum powders, full-size 450 x 60 x 0.5-mm (17.7 x 2.4 x 0.020-in.) fuel zone test plates loaded to 6 g U/cm^3 were produced. U-10 wt.% Mo powders produced by two methods, centrifugal atomization and grinding, were tested. These powders were supplied at no cost to Argonne National Laboratory by the Korean Atomic Energy Research Institute and Atomic Energy of Canada Limited, respectively. Fuel homogeneity indicated that both of the powders produced acceptable fuel plates. Operator skill during loading of the powder into the compacting die and fuel powder morphology were found to be important when striving to achieve homogeneous fuel distribution.

Smaller, 94 x 22 x 0.6-mm (3.7 x 0.87 x 0.025-in.) fuel zone, test plates were fabricated using U-10 wt.% Mo foil disks instead of a conventional powder metallurgy compact. Two fuel plates of this type are currently undergoing irradiation in the RERTR-4 high-density fuel experiment in the Advanced Test Reactor.

INTRODUCTION

Recent irradiation studies have shown that low-enriched uranium-molybdenum (U-Mo) fuel is very stable at low temperatures and high burnup.[1] The US RERTR program has developed an intermediate goal[2] of qualifying U-Mo fuel in full-size plates loaded to 6 g U/cm^3. To quickly determine the rolling properties of the fuel, full-size fuel plates at this loading were fabricated at ANL from U-10 wt. % Mo (U-10Mo) powder provided to ANL by the Korean Atomic Energy Research Institute (KAERI) and the Atomic Energy of Canada Limited (AECL).

The U-Mo fuels are highly ductile and readily reduced to foil. Ugajin et al. have successfully produced and irradiated fuel plates cut from thin slices of $U_6(Ni_{0.6}Fe_{0.4})$ and $U_3(Si_{0.8}Ge_{0.2})$.[3] Similar plates could be produced from U-10Mo foil disks instead of sliced samples or conventional powder metallurgy compacts. Information about the irradiation properties of bulk U-Mo in foil form would be very useful as investigators seek to understand and model the response of powdered U-Mo fuels. In addition, overall equivalent fuel plate loadings of up to 15.2 g U/cm^3 are obtainable using U-Mo foils and may form the basis of a new design for a high-powered research reactor.

EQUIPMENT AND EXPERIMENTAL PROCEDURES

Special die cavity loading techniques were developed during which spherical tungsten powder and pure aluminum powder were loaded into a simulated die cavity. Radiographs were taken of the as-loaded powders. After uniform loose-powder filling was achieved, compacts were made and radiographed to measure homogeneity.

Spherical U-10Mo powder produced by centrifugal atomization[4] was obtained from KAERI, and ground U-10Mo powder was obtained from AECL. The developed and refined die-loading techniques were used to fabricate green 40 vol.% fuel/60 vol.% pure aluminum compacts with a target uranium loading of 6 g U/cm^3. Two fuel powder distributions were used: 30% 125-88 μm (-120+170 mesh), 40% 88-63 μm (-170+230 mesh), and 30% 63-44 μm (-230+325 mesh); and 20% 125-88 μm (-120+170 mesh), 60% 88-63 μm (-170+230 mesh), and 20% 63-44 μm (-230+325 mesh). The compacts were assembled into clean 6061 aluminum alloy cladding, welded, and hot-rolled into full-size U-10Mo plates. An 87% reduction, (7.7 times increase in length) achieved a final thickness of 1.5-mm (0.060-in.). The reduction procedures are reported in detail elsewhere.[5] After reduction, the fuel plates were tested for blisters, measured for density by the Archimedes method, radiographed, and studied metallographically.

Depleted U-10Mo (DU-10Mo) alloy was cast and rolled at 650°C into 0.5-mm (0.020-in.) foil. Discs, 12.5-mm dia. (0.5-in.), were punched out of the foil and roll-bonded in 6061 aluminum alloy at 500°C. Blister testing was performed to check the bonding, and metallographic sections were taken. A low-enriched uranium (LEU) U-10Mo ingot was then cast and rolled to foil at 650°C. Using 12.5-mm dia. x 0.36-mm (0.5 x 0.014-in.) thick discs, six 101.6 x 25.4 x 1.4-mm (4 x 1 x 0.055-in.) LEU plates were produced.

RESULTS AND DISCUSSION

Powder Metallurgy Homogeneity Tests of Loose Powder and Compacts

Initial loose 60 v/o U-10Mo - 40 v/o Al powder loading experiments revealed the importance of operator technique on the homogeneity of the as-loaded powder. Figure 1 shows a radiograph (darker areas are aluminum rich) of an inhomogeneous compact loaded by an inexperienced operator. Figure 2 shows a compact loaded by the same operator after his loading technique was refined.

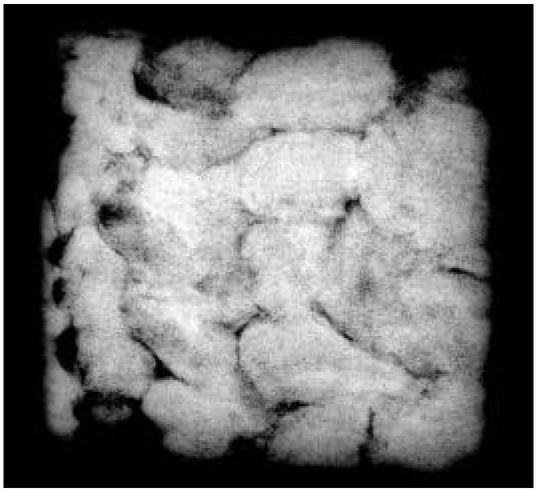

Fig. 1. Compact made from improperly loaded fuel powder

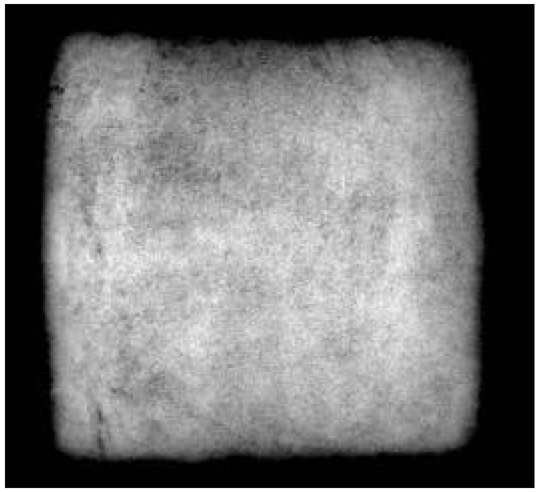

Fig. 2. Compact made from properly loaded fuel powder

Full-Size Fuel Plate Fabrication Tests

Spherical U-10Mo Powder Fuel Plates. Overall, the spherical U-10Mo powder fuel rolled quite well, and radiographic inspection indicated that fuel distribution in the four plates produced was very uniform. Nominal fuel plate thickness was 1.5 mm (0.060 in.) with a nominal 0.5-mm (0.020) fuel zone thickness. A typical radiograph is presented in Figure 3. Densitometer readings were taken and the results are listed in Table 1. Although a minor dog-bone region is visible on the left side, i.e., on the trailing end, of the plate, the maximum fuel loading variation of +15%, which includes the dog-bone area, is within normal plate specifications. No correction was made for nonuniformities in the X-ray beam. Radiographs of a tantalum plate with uniform thickness showed that the X-ray beam varies ±5% in the area used to measure fuel zone loadings. Also, the standard used was a uranium aluminum alloy, and no corrections were made for the contribution of the molybdenum to the density readings. Therefore, the true loading variance is most likely <15%.

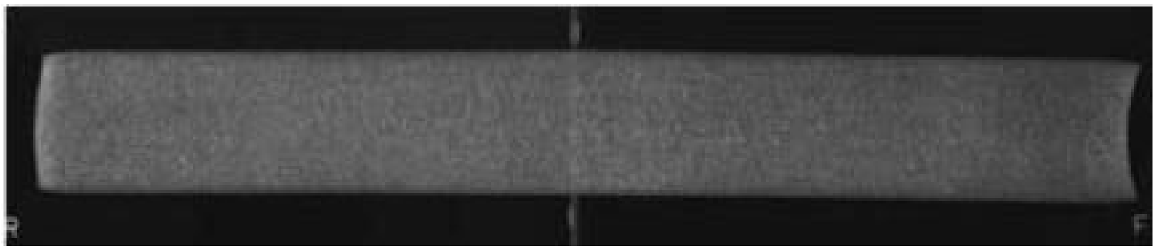

Fig. 3. Typical radiograph of spherical U-10Mo fuel plate (~1/3 X)

Table 1. Spherical U-10Mo fuel plate loadings measured by radiography

Plate Identification	Average Density g U/cm^3	Minimum Loading Variance Percent	Maximum Loading Variance Percent
MoS-1	6.45	-9.01	12.96
MoS-2	6.41	-7.69	10.41
MoS-3	6.71	-5.13	15.38
MoS-4	6.76	-8.62	15

A full metallographic section (Figure 4) of one of the spherical-powder fuel plates showed that the minimum cladding thickness was 0.45 mm (0.018 in.) for the nominal 0.5-mm (0.020-in.) cladding thickness. The maximum variation of fuel thickness over the standard 3-mm (0.12-in.) radiography spot was +15% in the dog-bone region. The variation in fuel thickness over the rest of the plate was <±5. All of these values are quite good and it is anticipated that no major fuel fabrication problems should arise from the spherical U-10Mo powder if full-size 6 g U/cm^3 elements are manufactured.

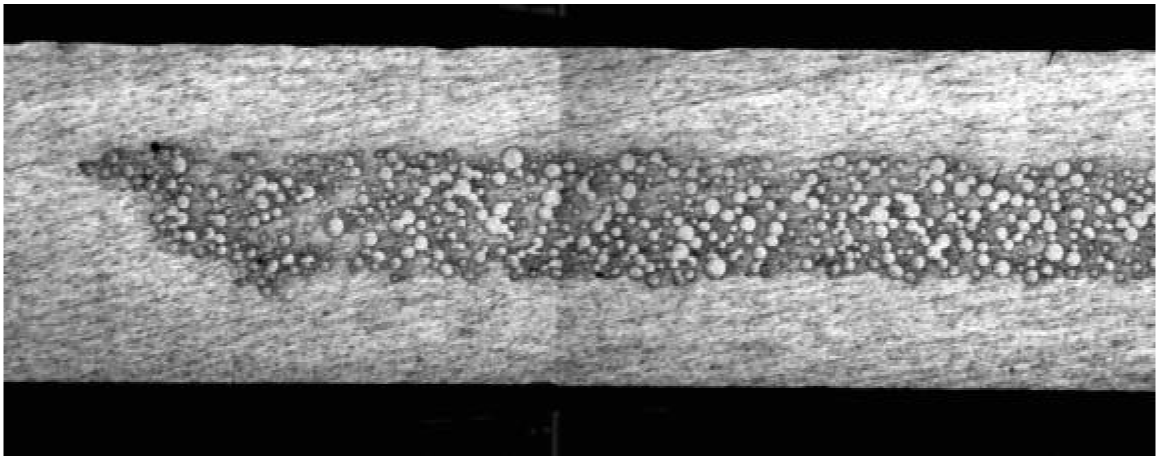

Fig. 4. Cross section of spherical U-10Mo fuel plate containing maximum dog-bone (≈30 X)

Ground U-10Mo Powder. The ground U-10 Mo powder also rolled well, and radiographic inspection showed that the fuel distribution in the four plates that were produced was very uniform, except in the dog-bone ends of the fuel zone. Densitometer readings were taken and the results are listed in Table 2. A typical radiograph is shown in Figure 5. A cross section of one fuel plate (Figure 6) showed that the minimum cladding thickness was 0.3 mm (0.012 in.) for the nominal 0.5-mm (0.020-in.) cladding thickness. The variation in maximum fuel thickness over the standard 3-mm (0.12-in.) radiography spot was +30% in the dog-bone region. Fuel thickness variation over the rest of the plate was <±10. No major fuel fabrication problems due to the ground U-10Mo powder should be encountered if full-size 6 g U/cm^3 elements are manufactured.

Table 2. Ground U-10 Mo fuel plate loadings measured by radiography

Plate Identification	Average Density g U/cm^3	Minimum Loading Variance Percent	Maximum Loading Variance Percent
MoG-1	6.31	-19.64	17.86
MoG-2	6.16	-33.9	18.64
MoG-3	6.17	-15.79	21.82
MoG-4	6.07	-10.34	34.48

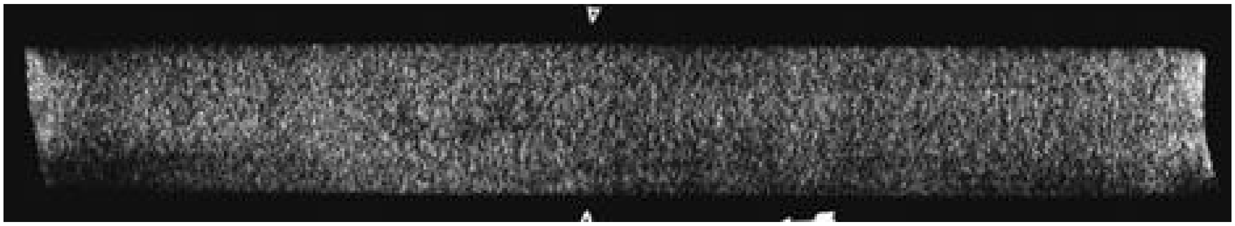

Fig. 5. Typical radiograph of ground U-10Mo fuel plate (≈1/3 X)

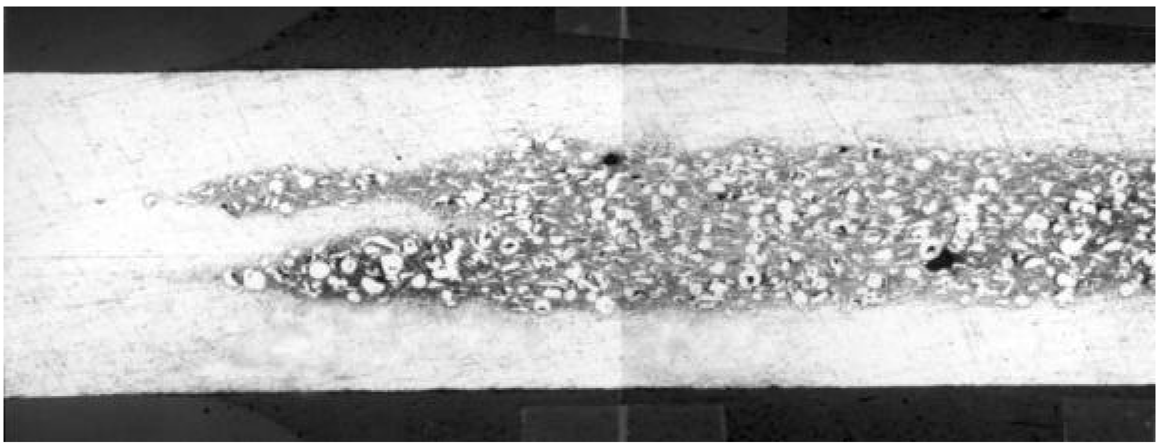

Fig. 6. Cross section of ground U-10Mo fuel plate containing the maximum dog-bone (≈30X)

Comparison of Spherical and Ground U-10 Mo Powder Fuel Plates. Properties of the two types of U-10Mo powder are presented in Table 3. Higher resistance to flow during fabrication of the ground powder into plates is reflected in the higher pressures required to produce the green compacts, the higher porosities of the final plates, and the lower homogeneity as measured by the maximum and minimum fuel loading variation. The increased porosity caused the lower loading at the same charged amount of fuel. No significant difference in homogeneity was observed for the two tested fuel distributions. Finally, resistance to flow is reflected by the minimal amount of fuel out-of-zone in the ground powder plates.

Table 3. Comparison of Fabrication Properties for Spherical and Ground U-10Mo powder

U-10Mo Powder Type	Spherical	Ground
Compacting Pressure, MPa (ksi) at 85% Dense	207 (30)	462 (67)
Average Fuel Zone Porosity, (%)	< 1	5
Average Fuel Loading, g U/cm^3 by Archimedes Method	6.38	6.08
Average Fuel Loading g U/cm^3 by Radiography	6.58	6.17
Average Maximum Fuel Loading Variance by Radiography (%)	+ 13.44	+ 23.20
Average Minimum Fuel Loading Variance by Radiography (%)	- 7.61	- 19.92
Amount of Fuel Out-of-Zone	Significant	Minimal

Figures 7 and 8 are higher magnification views of typical spherical and ground powder fuel zones. The smooth curved surfaces of the spherical powder allow the Al matrix to flow with lower resistance during fabrication resulting in a very uniform fuel zone thickness and in the lack of any significant measured or visible porosity. The ground powder consists of somewhat round large particles and many small angular particles. The sharp edges produce higher resistance to matrix flow and result in a less uniform fuel zone thickness and a visible amount of porosity.

It most likely that acceptable fuel plates can be fabricated with loadings up to 8 g U/cm^3 with the spherical fuel. Modifications to compact production techniques can be easily made to minimize the amount of fuel out-of-zone. However, the homogeneity values for the ground powder fuel plates are approaching the maximum specifications allowed and most likely the rejection rate of plates using ground powder and loadings >6 g U/cm^3 will be unacceptably high.

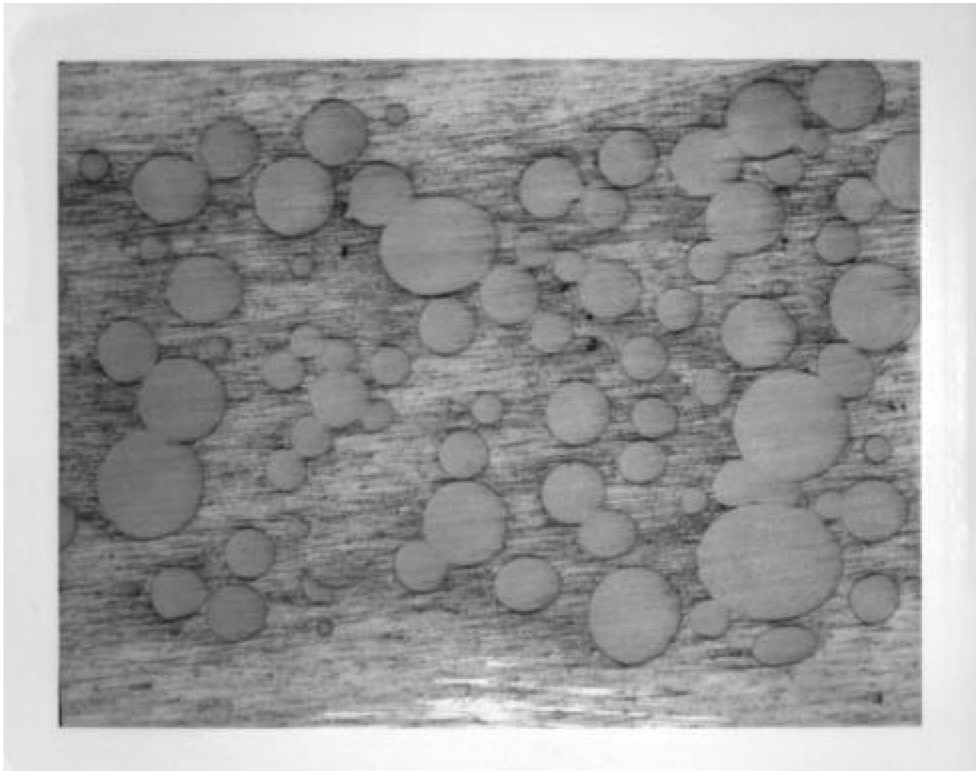

Fig. 7 Cross section of spherical U-10Mo fuel plate (≈150X)

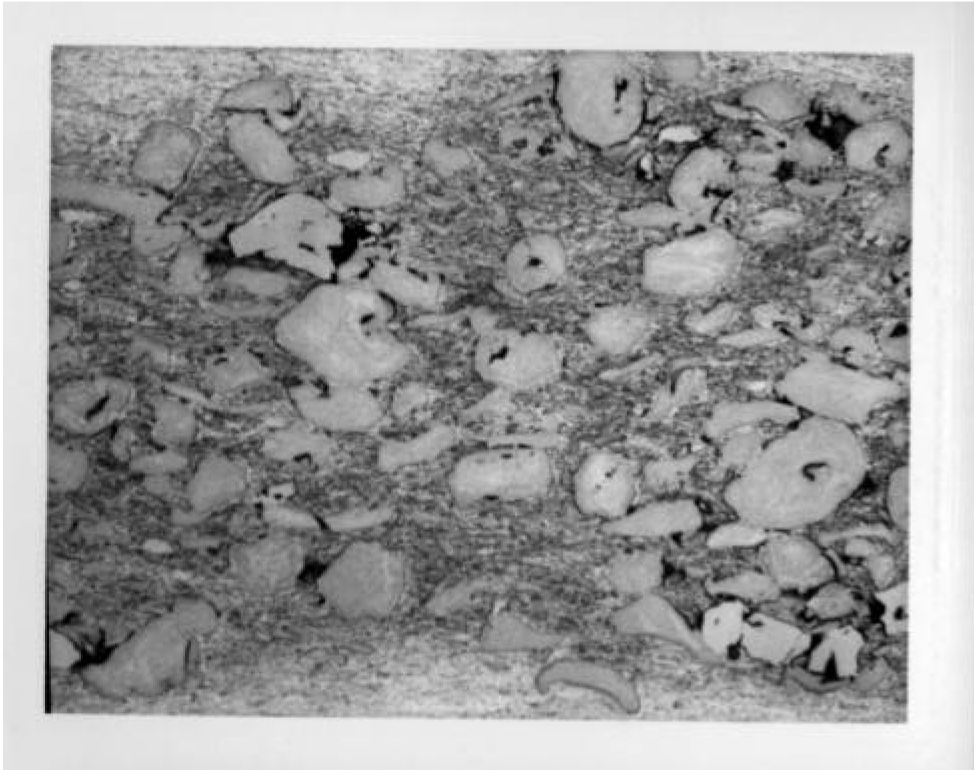

Fig. 8 Cross section of ground U-10Mo fuel plate (≈150X)

Foil Type Fuel Plates

Initial foil thickness for the experiments with the DU-10Mo was based on achieving an estimated 30% reduction in thickness after an 86% reduction in fuel plate thickness.   An equivalent target fuel loading of 8 gU/cm^3, based on a 0.62-mm (0.025-in.) thick fuel zone, would require an initial foil thickness of 0.5-mm (0.020-in.). Radiographic inspection of the DU foil-type fuel plates indicated that the U-10Mo foil was insufficiently ductile at the rolling temperature to elongate the same amount as the 6061 Al alloy cladding, and fractured into pieces after hot rolling. (Figure 9) From the radiographs, the amount of elongation for the fuel was estimated to be ≈15%. Final average thickness was 0.43 mm (0.017 in.) which gave an equivalent loading of 10.3 g U/cm^3.

To take into account the lower reduction in thickness, the LEU foils for the second experiment were cold rolled to an initial thickness of 0.36-mm (0.014-in.).   This would produce a loading closer to 8 g U/cm^3 after a 15% reduction in thickness during the cladding process.

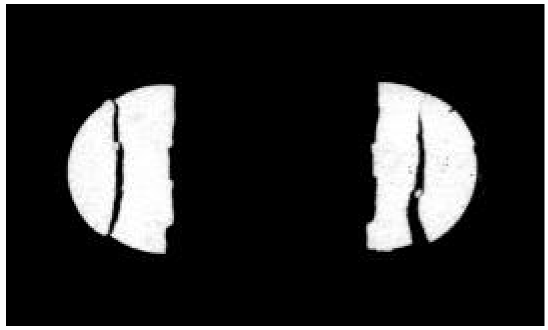

Fig. 9 Radiograph of foil U-10Mo fuel after hot rolling (≈2X)

Results of the bonding tests were good and metallographic examination of one of the plates showed acceptable fuel/cladding contact. A typical cross section of one of the LEU plates is presented in Figure 10. The cladding thickness ranged from 0.45 to 0.72 mm (0.018 to 0.029 in.) The large variation in cladding thickness is due to fuel moving in the short transverse (thickness) direction during rolling. The fuel thickness ranged from 0.27 to 0.32-mm (0.011 to 0.013-in.), which agrees with the amount of elongation measured by radiography. Final average fuel loading was 7.3 g U/cm^3.

These fuel plates were far from optimized because time was insufficient to improve the final plate geometry and meet the irradiation date. The remaining five plates were shipped to ANL-W, and two of those were chosen for insertion into the RERTR-4 irradiation test matrix.

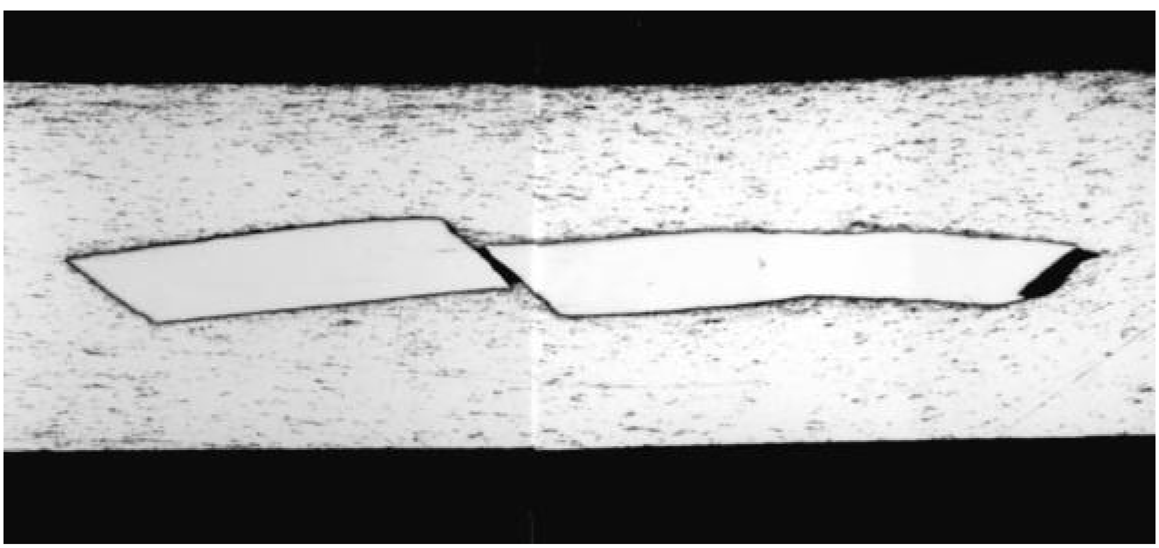

Fig. 10. Cross section of foil U-10Mo fuel plate (≈30X)

SUMMARY AND CONCLUSIONS

U-10Mo powder can be fabricated into 6 g U/cm^3 full-size fuel plates by conventional production methods. At 6 g U/cm^3, either centrifugal atomized or ground powder will produce acceptable fuel plates. Higher loadings favor the use of spherical powder.

Bulk U-10Mo foil-type irradiation specimens were successfully fabricated. Considerable development of fabrication techniques will be required before acceptable full-size foil type fuel plates are produced. The extent to which we will pursue this goal will depend on the results of the RERTR- 4 irradiation tests.

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REFERENCES

1. M. K. Meyer, et al., Irradiation Behavior of Uranium-Molybdenum Dispersion Fuel: Fuel Performance Data from RERTR-1 and RERTR-2, Proc. of the 1999 International Meeting on Reduced Enrichment for Research and Test Reactors, Budapest, Hungary, (1999)

2. J. L. Snelgrove and A. Languille, "Qualification of Uranium-Molybdenum Alloy Fuel--Conclusions of an International Workshop," Transactions of the 4th International Topical Meeting on Research Reactor Fuel Management, Colmar, France, March 19-21, 2000,
pp. 104-109 (March 2000).

3. M. Ugajin, et al, Irradiation Behavior of High Uranium-Density Alloys in Plate Fuels, Journal of Nuclear Materials, 245 (1998) pp. 78-83

4. K. H. Kim, et al., Development of High Loading U-Mo Alloy Fuel by Centrifugal Atomization, Proc. of the 1996 International Meeting on Reduced Enrichment for Research and Test Reactors, Seoul, Korea, (1996)

5. T. C. Wiencek, Summary Report on Fuel Development and Miniplate Fabrication for the RERTR Program, 1978-1990, Argonne National Laboratory Report ANL/RERTR/TM-15 (1995)