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Low-Enriched Uranium-Molybdenum Fuel Plate Development

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T. C. Wiencek and I. G. Prokofiev

Argonne National Laboratory

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Abstract-

In order to examine the fabricability of low-enriched uranium-molybdenum powders, full-sized (450 x 60 x 0.5-mm fuel zone) fuel plates loaded to 6 gU/cm³ were produced. U-10wt.%Mo powders produced by gas atomization and conventional machining and grinding were tested. These powders were supplied to Argonne national Laboratory (ANL) by the Korean Atomic Energy Research Institute (KAERI) and Atomic Energy of Canada Limited (AECL) respectively. Both of the powders produced acceptable fuel plates based on fuel homogeneity. Operator skill during loading of the powder into the

compacting die and fuel powder morphology were found to be important factors for production of a homogenous fuel distribution.

Smaller (94 x 22 x 0.6-mm) test plates were fabricated at a loading of 8gU/cm^3 using U-10wt.%Mo (U-10Mo) foil disks instead of a conventional powder metallurgy compact. Two of this type of fuel plate are currently undergoing irradiation in the RERTR-5 high-density fuel experiment in the Advanced Test Reactor (ATR).

Introduction

Recent irradiations have shown that low-enriched uranium-molybdenum (U-Mo) fuel is a very stable fuel at low temperatures and high burn-up[1]. A workshop was held in early 2000 at Argonne National Laboratory (ANL) to discuss and begin implementation of Full-sized element irradiations for intermediate-density U-Mo qualification[2]. The proposed loading was set at 6.0gU/cm^3. To quickly determine the rolling properties of the fuel, full-sized fuel plates at this loading were to be fabricated at ANL using 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) respectively.

The U-Mo fuels exhibit a high degree of ductility and are readily reduced to foil. Fuel plates using thin slices cut from $U_6(Ni_{0.6}Fe_{0.4})$ and $U_3(Si_{0.8}Ge_{0.2})$ have been successfully produced and irradiated[3]. Similar plates could be produced using U-10Mo foil disks instead of a sliced sample or a conventional powder metallurgy compact. Irradiation properties of bulk U-Mo in foil form would be very useful to understand and model the response of conventional powdered U-Mo fuels. In addition, overall fuel plate loading using U-Mo foils could easily exceed 9.0gU/cm^3 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 using spherical tungsten powder and pure aluminum powder. The powders were loaded into a simulated die cavity and radiographs were taken of the powder as loaded. After uniform loose powder filling techniques were developed, compacts were made and radiographed to measure homogeneity.

Spherical U-10Mo powder produced by gas atomization[4] was obtained from KAERI and conventionally ground U-10Mo powder was obtained from AECL. The refined die loading techniques developed were applied to fabricate green 40 vol. % fuel/ 60 vol. % pure Al compacts with a target uranium loading of 6gU/cm^3. Two fuel powder distributions were used, 30% - 125-88μm (120+170 mesh), 40% 88-63μm (-170+230 mesh) and 30% -63-44μm (-230+325 mesh) and 20% -

125-88μm (120+170 mesh), 60% 88-63μm (-170+230 mesh) and 20% -63-44μm (-230+325 mesh). The compacts were assembled into cleaned 6061 aluminum alloy cladding, welded, and hot-rolled into full-sized U-10Mo plates. An 87% reduction, (7.7 times increase in length) was used to produce a final thickness of 0.060 in. (1.5mm). The procedures are cover in detail elsewhere[5]. The fuel plates were then tested for blisters, density by the Archimedes method, radiographed, and studied metallographically.

Depleted U-10Mo alloy was cast and rolled at 650 °C into 0.5-mm (0.020-in.) foil. Discs 12.5 mm (0.5 in.) were punched out of the foil and roll bonded in 6061 aluminum alloy at 500 °C. Blister testing checked 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.) discs, 6 LEU plates with dimensions of 101.6 x 25.4 x 1.4 mm (4 x 1 x 0.055 in.) were produced.

Results and Discussion

Powder Metallurgy Loose Powder and Compact Homogeneity Tests

Initial loose 60 v/o U-10 Mo - 40 v/o Al powder loading experiments showed the importance of operator technique on the homogeneity of the powder as loaded. Fig. 1 shows a positive print (lighter areas are Al rich) of a poorly loaded compact made by an inexperienced operator. Fig. 2 shows a compact made by the same operator after refinements to his loading techniques.

Fig 1. Improperly Loaded Fuel Powder

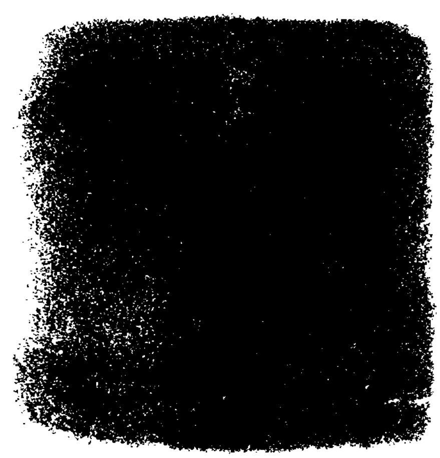

Fig 2. Properly Loaded Fuel Powder

Full-Size Fuel Plate Fabrication Tests

Spherical U-10 Mo Powder Fuel Plates

Overall the fuel rolled quite well and radiographic inspection indicated that the fuel distribution in the four plates produced was very uniform. A typical radiograph is given in Fig 3. Densitometer readings were taken and the results are given in Table 1. A minor dog-bone region is visible (left side) on the trailing end of the plate, however, the maximum flue loading variation of +15%, which includes the dog-bone area, is within normal plate specifications. It should be noted that no correction was made for non-uniformities in the x-ray beam. Radiographs of a Tantalum plate with uniform thickness showed that the x-ray beam varies +- 5% in the area. Also the standard used was an 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%.

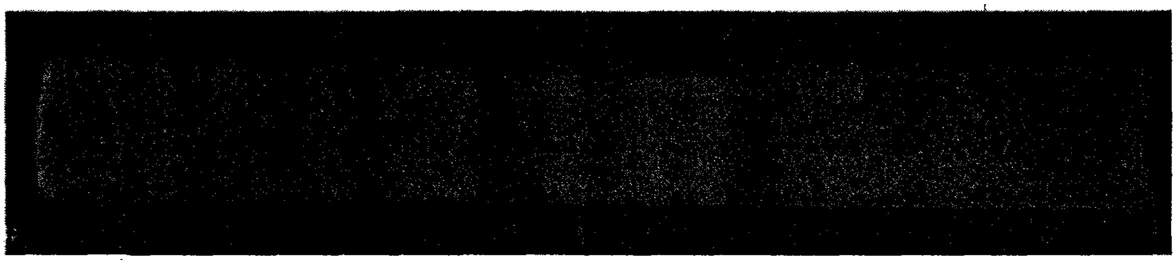

Fig 3. Typical Radiograph of Spherical U-10Mo Fuel Plate

Table 1. Spherical U-10Mo Fuel Plate Loadings Measured by Radiography

Plate Identification	Average Density	Minimum Loading Varience Percent gU/cm3	Maximun Loading Varience 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 (Fig 4.) of one of the spherical powder fuel plates showed the minimum cladding thickness was 0.45 mm (0.018 in) for the nominal 0.5 mm (0.02 in.) cladding thickness. The maximum fuel thickness over the standard radiography spot size of 3-mm (0.12-in.) was found to be +15% in the dog-bone region. Fuel thickness variation over the rest of the plate was < ±5. All of these values are quite good and it is anticipated that there should be no major fuel fabrication problems due to the spherical U-10Mo powder when the full-size 6.0gU/cm^3 test elements are manufactured. It most likely that acceptable fuel plates can be fabricated with loadings up to 8gU/cm^3 will be possible with the spherical fuel.

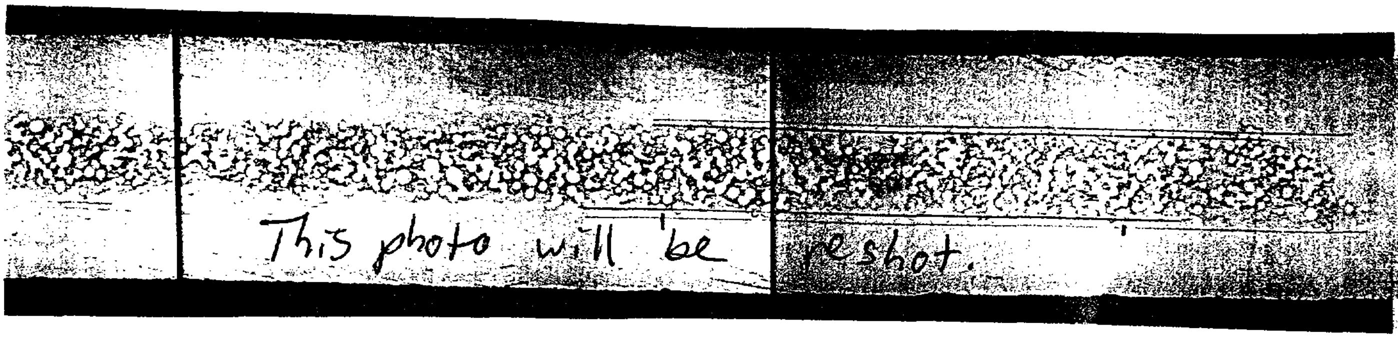

Fig. 4 Cross Section of Spherical U-10Mo Fuel Plate Containing the Maximum Dog-Bone (~20 X)

Ground U-10 Mo Powder

The ground U-10Mo powder also rolled well and radiographic inspection showed that the fuel distribution in the four plates produced was very uniform except for the dog-bone ends of the fuel zone. Densitometer readings were taken and the results are given in Table 2. A typical radiograph is given in Fig 5. A cross section taken of one of the fuel plates (Fig 6.) showed that the minimum cladding thickness was 0.3-mm (0.012-in) for the nominal 0.5-mm (0.02-in.) cladding thickness. The maximum fuel thickness over the standard radiography spot size of

3-mm (0.12-in.) was found to be +30% in the dog-bone region. Fuel thickness variation over the rest of the plate was < ±10. There should be no major fuel fabrication problems due to the ground U-10Mo powder when the full-size 6.0gU/cm^3 test elements are manufactured. However, the homogenity values are approaching the maximum specifications allowed and most likely the rejection rate of plates >6gU/cm^3 will be unacceptably high.

Table 2. Ground U-10Mo Fuel Plate Loadings Measured by Radiography

Plate Identification	Average Density	Minimum Loading Varience Percent gU/cm3	Maximun Loading Varience 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

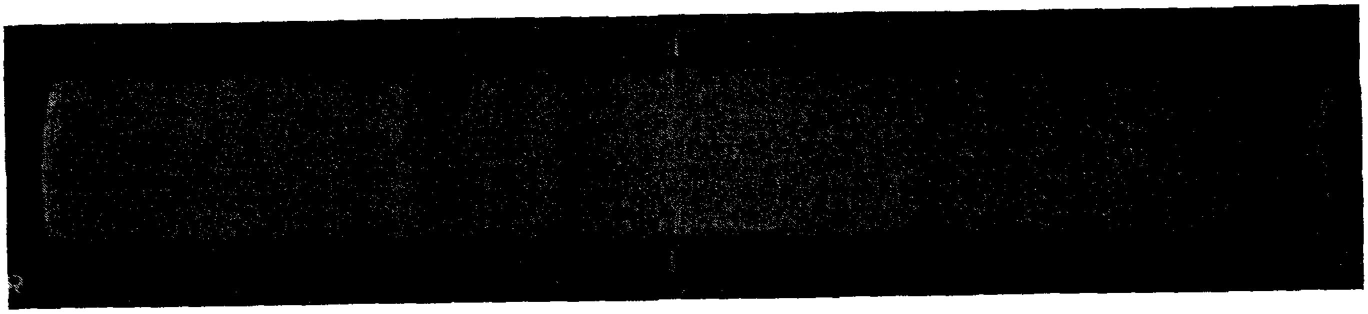

Fig 5. Typical Radiograph of Ground U-10Mo Fuel Plate

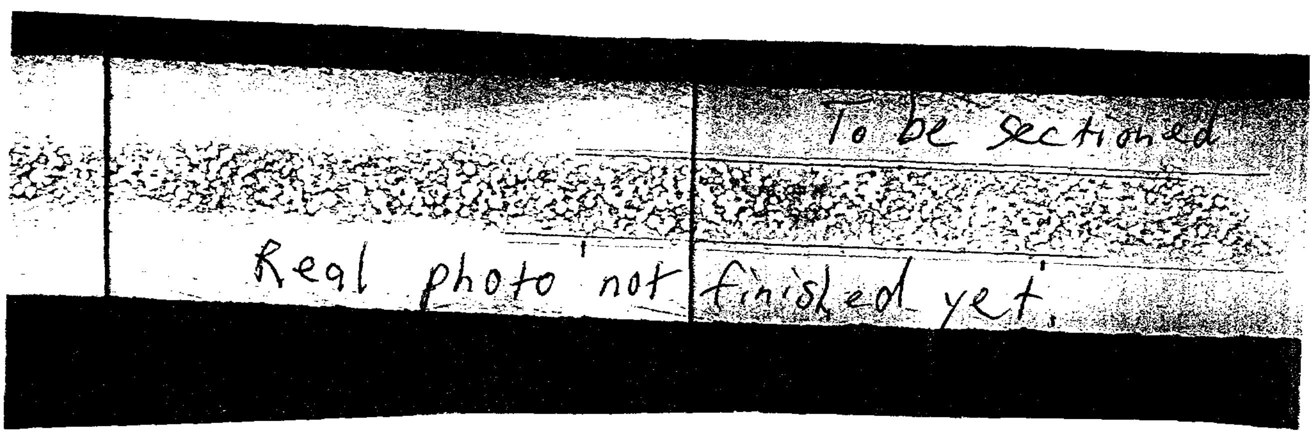

Fig. 6. Cross Section of Ground U-10Mo Fuel Plate Containing the Maximum Dog-Bone (~20X)

Comparison of Spherical and Ground U-10 Mo Powder Fuel Plates

A comparison of the two types of U-10Mo powder is given in Table 3. A higher resistance to flow during fabrication of the ground powder into plates can be seen in the higher pressures required to produce the green compacts, the higher porosities in 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. There was no significant difference in homogeneity for the two fuel distributions used. 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	Compacting Pressure MPa (ksi) At 85% Dense	Average Fuel Zone Porosity	Average Fuel Loading gU/cm3 by Archimedes method	Average Fuel Loading gU/cm3 By radiography	Average Maximum Fuel Loading gU/cm3 By radiography	Average Minimum Fuel Loading gU/cm3 By radiography
Spherical	207 (30)	< 1%	6.38	6.58	+ 13.44	- 7.61
Ground	462 (67)	5 %	6.08	6.17	+ 23.20	- 19.92

Amount of Fuel Out of Zone
Significant
Minimal

Foil Type Fuel Plates

Radiographic inspection of the six LEU foil type fuel plates indicated that the U-10Mo foil had insufficient ductility at the rolling temperature to elongate the same amount as the 6061 Al alloy cladding and fractured into pieces. (Fig. 7) A small amount of elongation for the fuel, ~15%, was estimated from the radiographs. 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 given in Fig. 8. The cladding thickness ranged from 0.45-0.72-mm (0.018- 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 0.27-0.32-mm (0.011-0.013-in) which agrees with the amount of elongation measured by radiography. These fuel plates were far from being optimized because there was insufficient time to improve the final plate geometry and meet the irradiation insertion date. The remaining five plates were shipped to

ANL-W and two were chosen for insertion into the RERTR-4/5 irradiation test matrix.

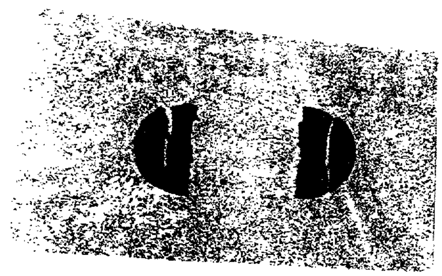

Fig. 7 Radiograph of Foil U-10Mo Fuel after Hot Rolling

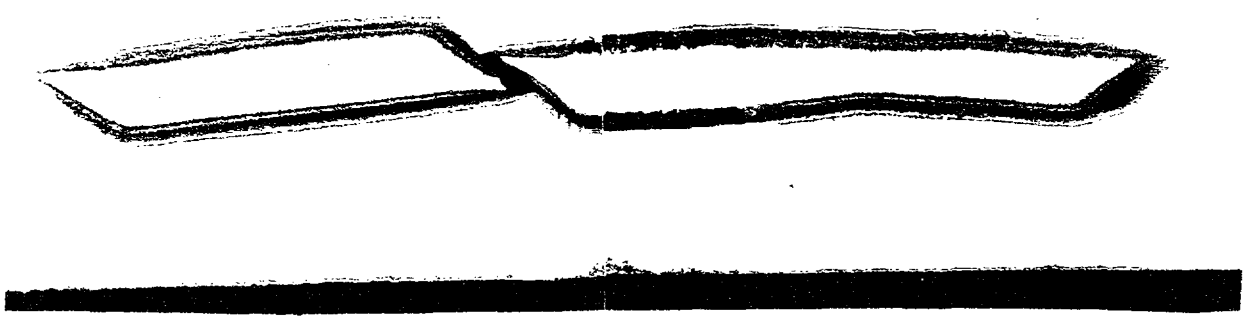

Fig. 8. Cross Section of Foil U-10Mo Fuel Plate (~25X)

Summary and Conclusions

U-10Mo powder can be fabricated into 6 gU/cm^3 full-sized fuel plates using conventional production methods. At 6 gU/cm^3 either spherical gas atomized or conventionally ground powder will produce acceptable fuel plates. Higher loadings will favor using the spherical powder.

Bulk U-10Mo foil type plates were sucessfully fabricated. Further development will depend on the results of the RERTR- 4/5 irradiation tests.

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