Development of Technology of High Density LEU Dispersion Fuel Fabrication

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ABSTRACT

Advanced Materials Fabrication Facilities at Argonne National Laboratory have been involved in development of LEU dispersion fuel for research and test reactors from the beginning of RERTR program. This paper presents development of technology of high density LEU dispersion fuel fabrication for full size plate type fuel elements. A brief description of Advanced Materials Fabrication Facilities where development of the technology was carried out is given. A flow diagram of the manufacturing process is presented. U-Mo powder was manufactured by the rotating electrode process. The atomization produced a U-Mo alloy powder with a relatively uniform size distribution and a nearly spherical shape. Test plates were fabricated using tungsten and depleted U-7 wt.% Mo alloy, 4043 Al and Al—2 wt% Si matrices with Al 6061 aluminum alloy for the cladding. During the development of the technology of manufacturing of full size high density LEU dispersion fuel plates special attention was paid to meet the required homogeneity, bonding, dimensions, fuel out of zone and other mechanical characteristics of the plates.

Introduction

Since late 70's, the Reduced Enrichment for Research and Test Reactors (RERTR) Program has pursued the development of high-density dispersion fuels, making feasible the conversion of research and test reactors to low enriched uranium (LEU) fuel. Advanced Materials Fabrication Facilities (AMFF) at Argonne National Laboratory have been involved in development of LEU dispersion fuel for research and test reactors from the beginning of RERTR program (see Figure 1). Fabrication of LEU miniature and full size nuclear fuel plates is utilized in the AMFF, which is a radiological facility. AMFF is

an integrated 20,000 square foot research facility, which contains numerous types of fabrication equipment for manufacturing of advanced materials and nuclear fuels.

Full size fuel plate manufacturing process involves starting with Uranium alloys powder as required mixed with commercial aluminum powder, compacted and clad with aluminum alloy by a hot rolling process, followed by cold rolling. Well known fuel plate fabrication diagram is presented on Figure 2. RERTR dispersion fuel plates (miniature or full-size) are produced from the following materials: Al 6061/4043 or other Al alloy, Alcan MD101 Al powder (or equal) or aluminum alloy powder, alloyed uranium (depleted or enriched), either binary (U + Si, U + Mo) or ternary (U + Si + Al, U + Mo + Ti), pure Al/Si/Mo/Ti. The fuel plates are then inspected, machined to size, and shipped to a reactor for irradiation (see Figure 2). The main fabrication task for the RERTR program is to develop fabrication technology for miniature and full size LEU dispersion fuel plates.

Figure 1. Advanced Materials Fabrication Facilities

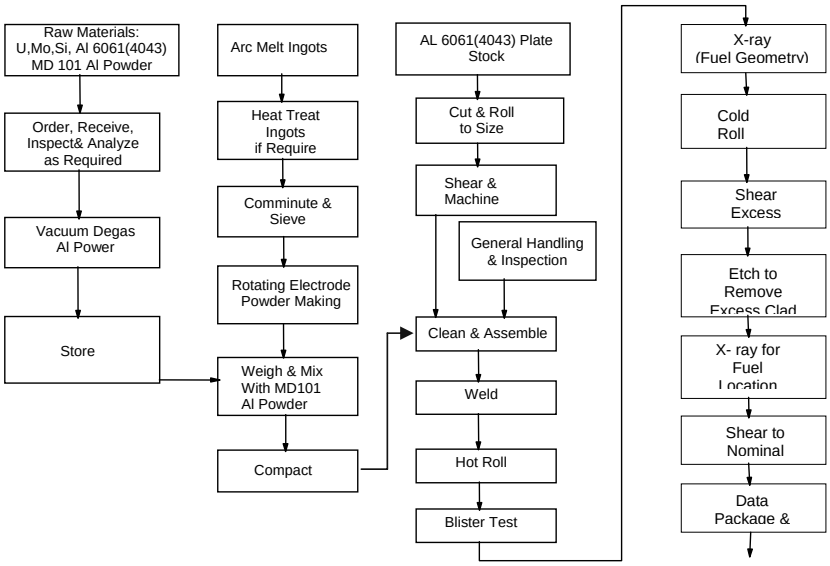

Figure 2. Flow chart of RERTR Fuel Plate Fabrication Process

It is well know that development of new fuel is complex process. Some of the failures of the research reactors fuels prove that there are still problems with our understanding of fuel development process and qualification of the fuel for research reactors. Large volume of work on LEU dispersion fuel development has been done, which is a good base for qualification of dispersion fuel and to avoid fuel failures in the future. Increasing of the density of dispersion U-Mo based fuel beyond 6.0 gU/cm3 requires a substantial amount of time and funding.

Currently developed LEU dispersion fuel, which was in the core of research reactor fuel operation for many years has several advantages compare to the alternative high density LEU fuels:

- Dispersion fuel shows better strength and irradiation characteristics compare to other alternative fuels.
- Dispersion fuel up to now has shown very good performance.
- Development of the high density dispersion fuel is far ahead compared to the development of other alternative LEU fuels.
- Blister temperature of dispersion fuel is up to 38 % higher compare to the other alternative LEU fuels, which will substantially increase the safety and operational margins. Major parts of the reactor feasibility studies are performed using dispersion fuel blistering temperature.

Dispersion fuel is technologically well developed for density up to 6.0 g/cc. Currently even higher density fuels above 6 gU/cc are needed in order to meet the LEU fuel requirements for the high performance research and test reactors. Current efforts will extend this limit to density 8.0 g/cc. The RERTR program has been making an effort to

develop dispersion fuels with uranium densities of 8 to 9 g U/cc for research and test reactors. Using atomized U-Mo powder, mini fuel plates have been successfully fabricated (Ref.1). In this paper further fabrication technology development of full size fuel plate with high density of dispersion fuel is presented.

In order to support high density fuel plate technology development existing equipment was modified and new one was developed at ANL AMFF. A large glovebox has been installed to handle the fuel powder fabrication. Equipment and appropriate procedures for U-Mo powder fabrication were developed. Rolling equipment and procedures were updated in order to make possible fuel manufacturing development at high temperatures. In parallel with fuel development activities AMFF successfully underwent major health and safety assessments, satisfying the increased US DOE health and safety requirements.

Improvement of the quality of fabricated fuel plates was achieved through:

- Improvement of homogeneity of the fuel meat through enhancement of the mixing of the U-Mo and Al powder. The mixture was well blended in a modified V-type mixer to enhance the blending homogeneity.
- Improvement of the ingot melting procedure.
- Selection of appropriate rolling parameters, based on experimental techniques and results of the testing.
- Meeting the design specification requirements.
- Decreasing of the fuel out-of-zone (FOZ).
- Improvement of the bonding

Fuel meat homogeneity is important characteristics of uncertainties of the power distribution of the fuel plate. Uncontrolled deviations of the uranium density could lead to ‘hot spots’, increasing of the values of ‘hot channel factors’ and as a consequence of this to decreasing of the maximum allowable reactor power. Therefore homogeneity of fuel meat shall be controlled well in the scope of the technical specification. By increasing f the fuel density, control of the fuel meat homogeneity become more difficult.

An Important characteristic of the quality of the fuel plates is the condition of the dog bone area at the end of the fuel meat, which should be also very well controlled. Uncontrolled increasing of the fuel thickness, beyond design specification could lead to decrease of the cladding thickness and as a consequence of this to decrease of the strength of the cladding.

The developed full size fuel plate manufacturing technology was successfully improved. The problems with the fuel meat homogeneity, FOZ distribution, bonding and meeting the design specification requirements for U-Mo high density fuel (8.0 gU/cc nominal loading for U-7%Mo), which we experience at the beginning were solved (see Figures 3-9).

Fuel plate characterization

The current design and fabrication process for RERTR fuel plates utilizes film radiography during the nondestructive testing and characterization. Digital radiographic methods offer a potential increases in efficiency and accuracy. The traditional and digital radiographic methods were demonstrated and analyzed in process of full size fuel plate development. Fuel loading data from each method (traditional and digital) were analyzed and compared and accuracy was assessed. The new digital method is shown to be more accurate, productive and informative (see Ref. 2).

Digital radiography may provide important three dimensional data that would be very difficult and expensive to obtain using the traditional methods. The digital information generated can be easily integrated into computer analyses and modeling programs. Due to the exclusion of radioactive materials in the digital radiography facility, tungsten was used as a surrogate fuel. Procedures for the digital radiographic method were successfully developed with tungsten as the “fuel”, but could also be applied to Uranium alloy.

Each manufactured fuel plate was examined utilizing destructive and nondestructive techniques. The aim of these examinations was the measurement of the meat and cladding thickness, homogeneity, strength and bonding assessment. The homogeneity of uranium distribution was quantitatively inspected by means of a radiographic system with an X-ray spot that scans the length of the plate and with destructive methods and micrographs. Figures 3 - 5 show the variation of the uranium density along the meat on U - Mo plates. It could be seen substantial progress in controlling of the homogeneity. It also shows the arrangement of the particles in the meat. As it can be seen nearly all the space of the fuel meat is occupied by U-Mo particles.

The traditional method of nondestructive analysis has consisted of taking various radiographs of fuel plates and measuring the volume through the Archimedes water displacement method. These methods along with known parameters of the materials used to construct the fuel plate allow for numerous key attributes to be calculated, most importantly, the fuel loading density. The radiographic component of this process is the most time consuming and is the greatest potential source of uncertainty. X-ray films were used to check the meat dimensions. The results confirm meeting the design specifications.

Two types of radiographic exposures are used for each fuel plate, a shorter duration “location” exposure and the more extended “density” exposure. The location x-ray is used for qualitative analysis of the location of the fuel and is used to detect any fuel in the non-fuel zone areas, the rails and ends of the plate (see Figures 6 and 7). Fuel located in these areas is referred to as fuel out of zone (FOZ).

For overall general trends the radiographs were scanned and digitized. This allows colorization of the images with photo editing software. Colorization enables easy visualization of general and gross trends in the fuel loading (see Figure 8-9).

Future utilization of the digital radiographic method will require development of a computer program which would automatically analyze the images once they are taken. This could further increase the speed and efficiency of the nondestructive testing of RERTR fuel plates. The three dimensional capabilities of the digital method will offer an opportunity to examine compacts before they are rolled into plates. It may be possible to characterize compacts in this way, and then determine if they will perform adequately when rolled. The ability to eliminate defective or low quality compacts through three dimensional radiography could save the time and cost of replacing an out of specification plate.

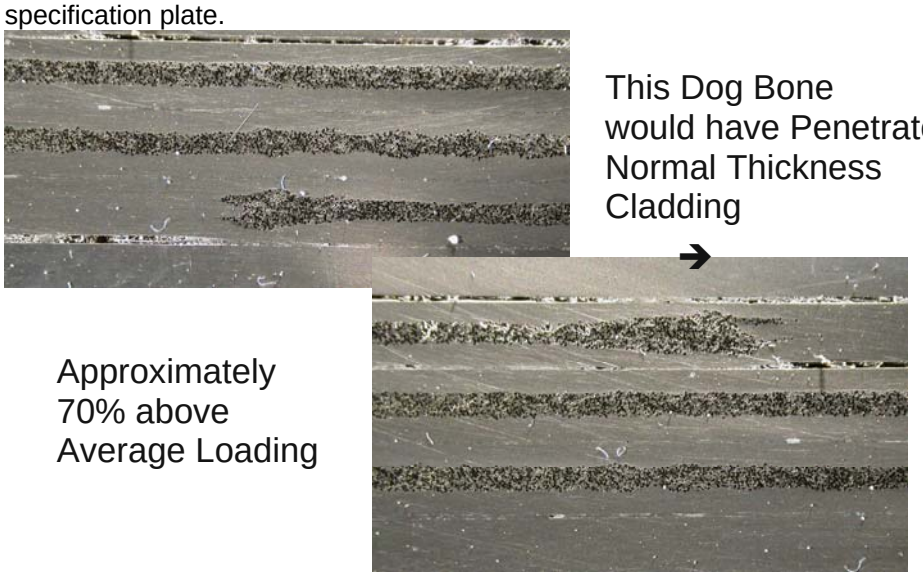

Figure 3. Homogeneity Using Standard Method

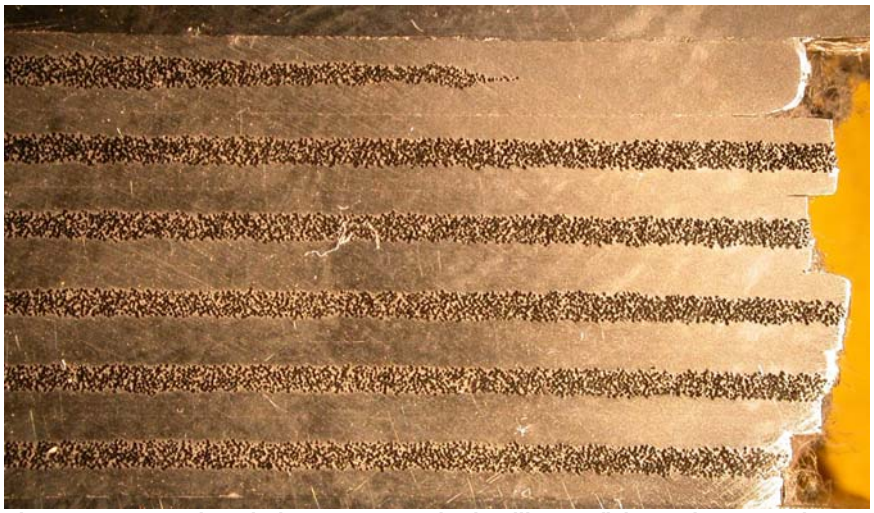

Figure 4. Improved Fuel Plate Homogeneity (Trailing End) (Less than 20% above Average Loading in Dog Bone Area)

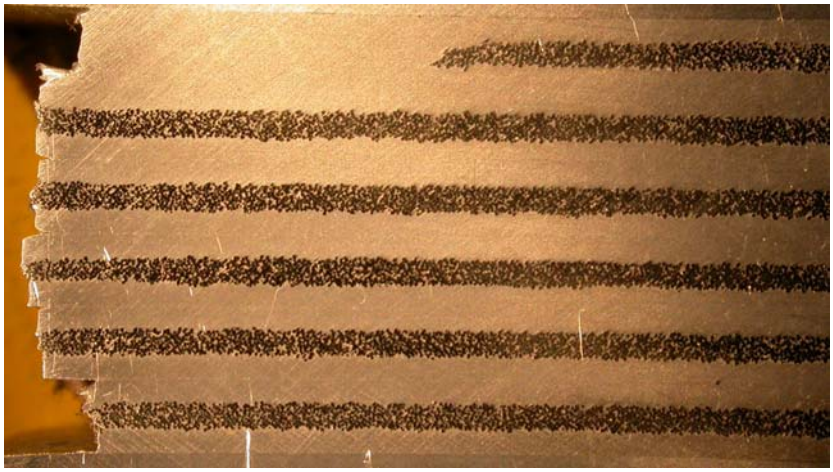

Figure 5. Improved Fuel Plate Homogeneity (Lead End) (Less than 15% above Average Loading in Dog Bone Area)

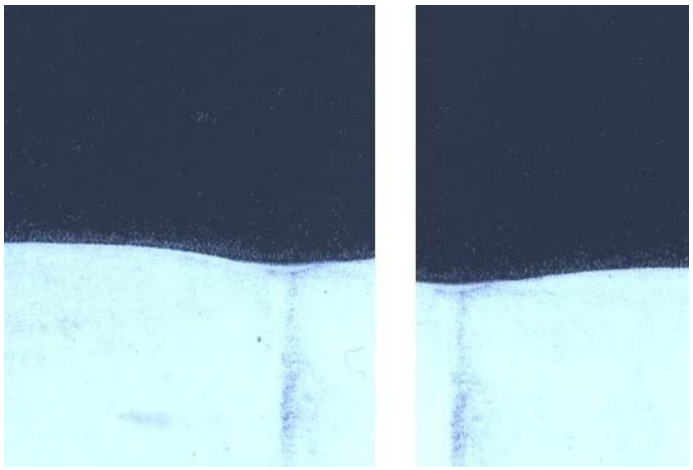

Figure 6. Excessive Fuel Out-of-Zone using Standard Method

Figure 7. Minimal Fuel Out-of-Zone (Improved)

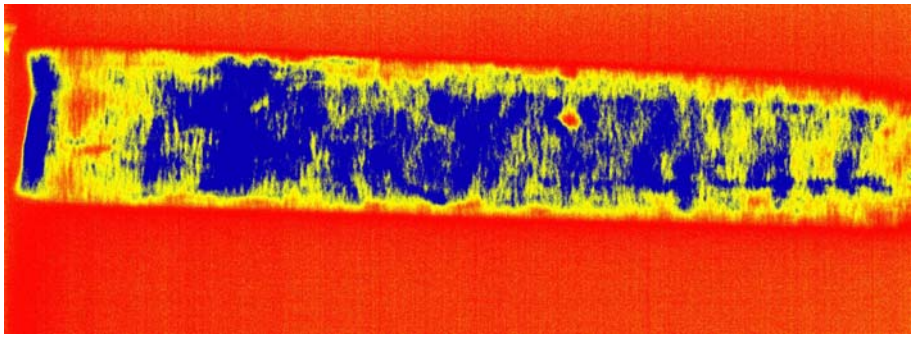

Figure 8. Standard Methods Fuel Plate Homogeneity 8g/cm3

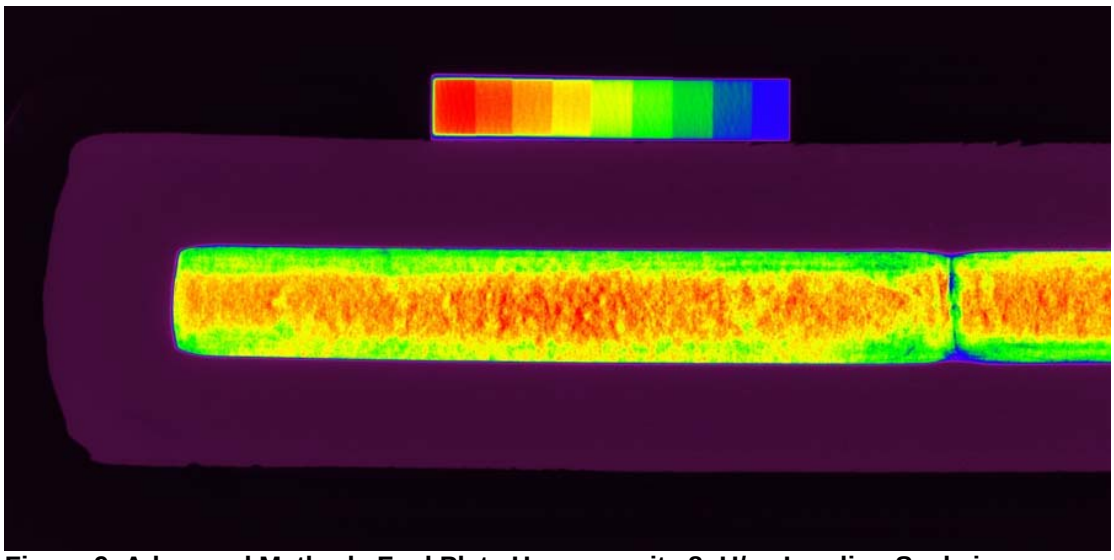

Figure 9. Advanced Methods Fuel Plate Homogeneity 8gU/cc Loading Scale is Highly Expanded. Actual Maximum Loading Variation is < ±20%

Conclusions

The carried out analysis shows the advantages of the LEU dispersion fuel compare to other alternative LEU fuels. The technological development presented in this paper shows that LEU U-Mo fuel density 8.0 g/cc is achievable. Special attention was paid to improvement of homogeneity, bonding and out of zone fuel distribution. Introduction of prospective non destructive digital characterization techniques will improve the characterization of the fuel and speed up the development process. It is believed that fuel load 9.0 gU/cc could be reach with 'standard' fabrication methods. Higher loading (9.0 to 10.0 g/cc)

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will require more efforts and optimization of the fuel design. Current results suggest that that the upper limit of fuel loading will be approximately 10.0 gU/cc. At this loading will contain 63 v/o fuel, 22 v/o Al and 15 v/o voids. It is currently believed that it will not be possible to roll a bonded plate with less than 20 v/o Al.

Completion of the qualification program for dispersion fuels will be an important backup for the conversion to LEU of major part of existing research reactors. Future success and wide utilization of the dispersion fuel is limited by the density requirements beyond the current value of 8.0 gU/cc. The combination of very high density dispersion fuel with small increase in the standard design fuel zone thickness or a small increase of the enrichment above the currently allowed value of 20 wt% U-235 could be the path to LEU fuel conversion of all research and test reactors.

Acknowledgments.
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2. T. Davidsmeier, R. Koehl, R. Lanham, E. O'Hare and T. Wiencek, Comparison of Traditional Nondestructive Analysis of RERTR Fuel Plates with Digital Radiographic Techniques, ANL, to be published.