BWXT COMMERCIALIZATION ACTIVITIES FOR GTRI LEU U-MO FUELS

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ABSTRACT

BWX Technologies (BWXT), the United States' research reactor fuel supplier for plate type fuel, has been contracted to provide commercialization support activities under the Global Threat Reduction Initiative (GTRI) program to develop and qualify low enrichment uranium (LEU), high density fuels suitable for most of the world's research reactors by the end of 2010. The program's main effort has been testing of uranium-molybdenum alloy fuels (U-Mo), and in light of recent fuel failures with dispersion type fuels, emphasis has now been placed on developing modified and alternative fuels.

BWXT's contract scope entails identifying requirements and planning the transition to the new LEU fuels. As there is no clearly preferred fuel technology at this point, multiple commercialization paths must be evaluated. Our baseline approach assumes the fuel is monolithic U-10Mo, and the fuel meat and aluminum alloy plate are hot isostatic pressed (HIP) together. Preliminary results are supportive of this method, however, there is potential for significant interaction between the fuel meat and aluminum alloy plate during the HIP process. Alternative bonding methods, e.g. friction stir welding are being evaluated, as well as modifying the baseline HIP parameters. Additionally, modified dispersed fuel systems are considered.

Aspects of each fuel technology and their manufacturing impact are presented and discussed.

1. Introduction

The high density U-Mo fuel system is quite unlike traditional U-Si, U-Al or U-0 fuels used currently in plate type fuel elements; it being a solid solution alloy compared to the compound intermetallics. Recent, unexpected testing failures, due to a uranium-aluminum interaction during irradiation, reinforce this issue. Further development testing is underway worldwide to evaluate features of this interaction and to determine the suitability of alternative plate alloys, matrix additions or process changes to mitigate the observed behavior.

BWXT is providing support, under funding from the Global Threat Reduction Initiative (GTRI), for commercializing technology developments relevant to the U-Mo system. In this paper, we discuss technology considerations associated with fuel plate manufacturing and what impacts might be seen with the U-Mo fuel compared with currently qualified research reactor fuel systems.

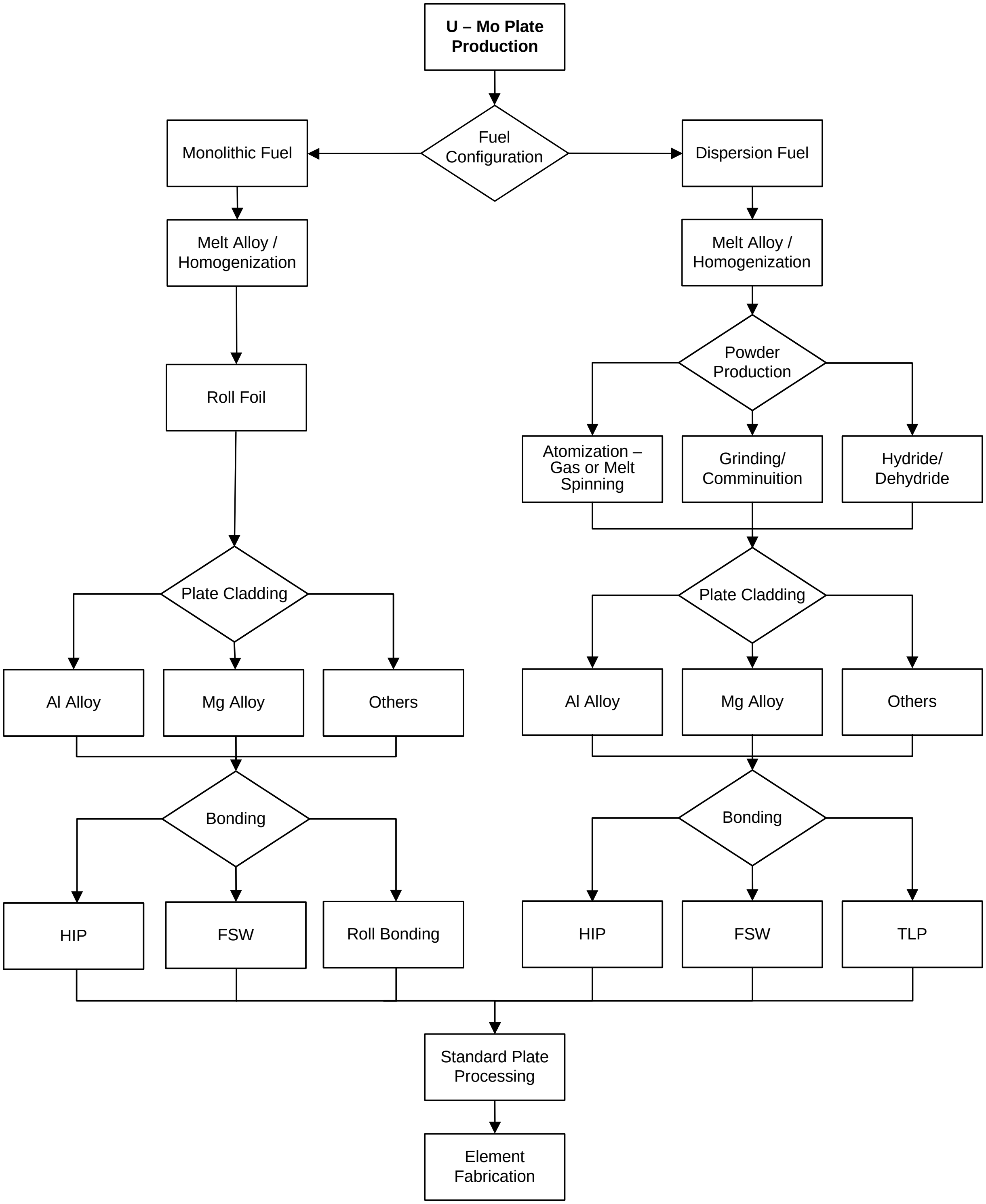

Figure 1. Process Outline & Decision Tree for U-Mo Fuel Plate Fabrication

Shown above in Figure 1, is a flow chart illustrating the manufacturing steps and options available for U-Mo plate fuel production. The figure is not intended to be totally inclusive of all possible manufacturing options or technologies. It is presented as a guide and shows what we believe to be the more promising options. We first present the options associated with making U-Mo strip, followed by a discussion of dispersion fuel. Alloy melting is addressed in both the monolithic and dispersion discussions because, while the same alloy may be used, different melting methods may be preferred due to processing and cost considerations.

2. Monolithic Fuel

2.1 Ingot Sizing

As a rule, one would prefer larger ingot volumes for rolling strip to minimize handling and roll set-ups, with a maximum melt size be determined by criticality safety and licensing requirements. One also needs to maximize the number of fuel meat foils from an ingot.

To determine the sensitivity of fuel meat yield versus ingot size, we looked at the number of foils potentially obtainable from a particular sized ingot for all dispersion-fuel plates that BWXT has produced historically. The average material waste (averaged over all plate types) versus ingot aspect ratio is shown in Figure 2. As can be seen in the figure, the loss curve exhibits a “knee” around L/L_{max} of 0.2. The yield loss continues to decrease for L/L_{max} > 0.2, but it is not very sensitive. Losses are higher for wider aspect ratio ingots, because the ingot width is wider than some fuel plates. Narrower starting ingot widths can be cross-rolled to the needed width, thereby resulting in lower losses.

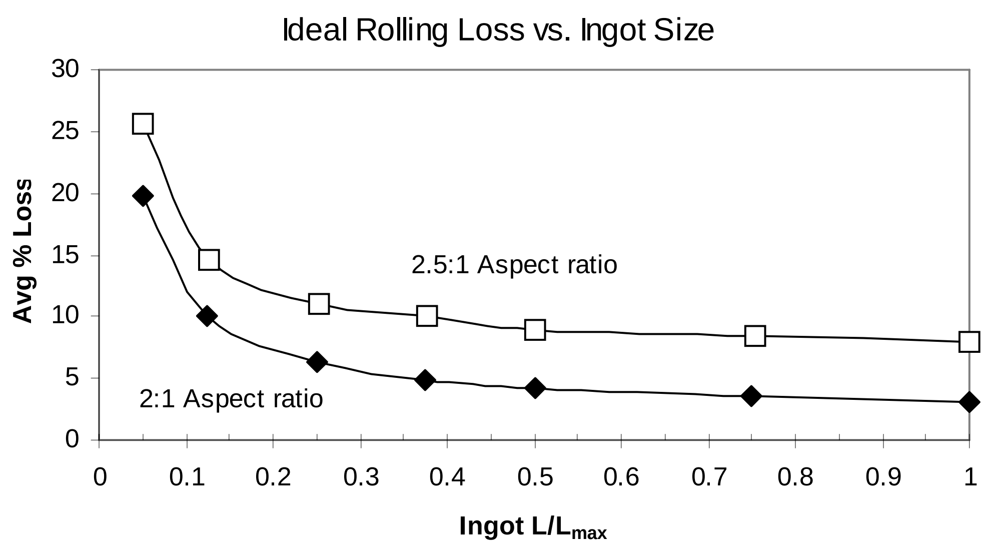

Figure 2. Average Ideal Material Loss versus Normalized Ingot Size

2.2 Melting

Because of the significant melting point (m.p.) difference between uranium (m.p. = 1405 K) and molybdenum (m.p. = 2890 K), either a significant superheat must be applied to the crucible or the molybdenum component must be selectively melted. The melt must be thoroughly mixed to ensure ingot homogeneity and uniform properties. If not, a long term, high temperature heat treatment may be necessary for diffusion to homogenize the ingot. Finally, as liquid uranium is extremely reactive, the melting must be done under a protective atmosphere (or in vacuum) and the melting crucible must be resistant to uranium attack.

Briefly summarized below are potential melting technologies and their relative merits:

Arc-melting – Suitable for small melt charges (roughly, < 1 kg), can be used to make small alloy buttons as feed for the larger melt charges. The molybdenum pieces will float to the top in the molten uranium pool and the arc can be selectively applied to them for melting. Several remelts are typically done to ensure a well-mixed button. Water cooled copper hearth results in minimal contamination. Least expensive equipment costs.

Induction melting – Induced eddy currents in the melt charge heat it and result in melting. The crucible must be compatible with liquid uranium, generally graphite with a yttria or zirconia coating to prevent carbon contamination. Coating durability is an issue, particularly for high temperatures, and high temperature needed to ensure the molybdenum melts. Significant mixing and stirring of melt pool from induced eddy currents. High equipment costs.

Skull melting – Similar to induction melting, however the process utilizes a segmented water-cooled copper crucible. Induced eddy currents in the melt charge cause the melt to move away from the crucible. Melting in a water-cooled copper crucible eliminates the possibility of reactions with refractory crucibles. Significant equipment costs.

E-beam melting – Capable of producing high purity melts, equipment costs are significant. While readily capable of melting uranium-molybdenum alloys, the required specialized equipment adds a significant overhead burden.

2.3 Casting/Slab Conditioning

For larger melt charges, i.e. > 2 kg, the mold design can play an important role in the surface quality of the casting. Minimal surface conditioning is required, not just from a cost standpoint, but also to minimize contamination and waste. Ingots should be cast to the desired fuel meat width, as minimal width increase occurs during rolling. Long, thin castings are preferable to thicker castings to ensure uniform microstructural properties through the ingot thickness and take advantage of reduced processing needed to reach final thickness.

2.4 Foil Rolling

Molybdenum acts to retain the γ-uranium phase, the preferred phase to perform mechanical processing. Ideally, the alloy would be processed at high temperature, e.g. > 790 C, allowing dynamic recrystallization. However, extensive oxidation will occur, with concomitant particulate generation during rolling, presenting a serious contamination concern.

One alternative method, developed by Kim et al. [1], directly casts a thin (approximately 100 – 150 μm) U-Mo ribbon by pouring the molten alloy onto a rapidly spinning wheel. No details on the suitability of this material to further roll reduction were presented.

Development work is necessary to determine the ingot rolling schedule. These details will be sensitive to the ingot thermal history, i.e., cast slab or melt spun ribbon. Oxidation is a concern from radiation contamination considerations, and the material is very stress-corrosion sensitive [2]. Intermediate anneals may be necessary to prevent cracking due to stress-corrosion, regardless of the work hardening levels and will certainly be required after processing to final size.

2.5 Storage

Criticality and safety requirements will limit the number of foils in a container and their relative spacing. Foils could be stored after being cut to final size for a particular refuel order, or could be stored at an intermediate size for future orders. Annealed foils will have to be stored under an inert atmosphere because of oxidation concerns.

2.6 Cladding Material

One solution to the U-Mo-Al interaction is to modify or replace the aluminum alloy used in conventional fuel plates. The standard aluminum alloy BWXT employs is 6061. There is significant experience base with this cladding material, it is well understood, is cost-effective and has proven reliability in research reactor cores.

As the recently observed in-core failures apparently arise from an interaction that develops under irradiation among the U-Mo and aluminum matrix, there is interest in evaluating the effects of different claddings and matrix additions.

2.7 Interlayers

An alternative to changing the cladding material is to add a coating or barrier layer between the fuel meat-cladding interface. This interlayer needs to be metallurgically compatible with the fuel meat and cladding and exhibit acceptable corrosion and radiation behavior. It could be applied as a separate foil, surrounding the fuel meat, or coated onto the fuel meat or plate by any number of techniques, e.g. sputtering, flame spraying, electroplating. A coating applied to the U-Mo foil could provide an additional benefit of oxidation protection. The layer(s) must be compatible with how the fuel plate is assembled and bonded together.

2.8 Plate Assembly

Final assembly of conventional fuel plates is by roll bonding. Significant elongations are needed to disrupt sufficiently the oxide layer and bond the plate components together. It has been demonstrated that U-Mo severely cracks under similar amounts of deformations [3], so alternate assembly methods need to be developed.

Hot Isostatic Pressing – BWXT is evaluating the suitability of hot isostatic pressing (HIP) to meet these requirements. The application of heat and pressure serves to bond the fuel plate components together. The elevated temperature will result in a reaction layer forming between the fuel and cladding. Mock-ups with stainless steel and aluminum have shown adequate bonding, i.e. grain growth, across the Al-Al interface. HIP is also ideal for bonding flat surfaces together, because the high process pressures will close any interfacial gaps and is especially compatible for assembling fuel plates with interlayers.

Friction Stir Welding – Idaho National Laboratory (INL) is developing a Friction Stir Welding (FSW) process. The method has been shown to bond the fuel meat and cladding, without gross mixing of the fuel and cladding. Demonstration production rates appear reasonable on model plate material. The bond is quickly formed at temperatures below aluminum's melting point, resulting in little reaction layer at the cladding-fuel interface. Scale-up to full size plates and the potentially significant surface clean-up necessary to remove flashing and produce acceptable plate flatness and surface finish are still to be evaluated.

Transient Phase Liquid Bonding – TPLB has been evaluated on a preliminary basis for assembling U-Mo fuels and aluminum alloy plates together. Some success has been seen, but more development is needed to adequately determine the process parameters [3].

3.0 DISPERSION FUEL

Failures observed to date in the U-Mo fuel system have been in dispersion type plates arising from an interaction among U, Mo and Al. With a large surface area, dispersion fuels may be extremely sensitive to this interaction. One hope for monolithic fuels is, with their significantly smaller surface area, this interaction, which will still be present, but not to the same degree, will give acceptable performance. However, changes to the dispersion fuel system are being considered as the interaction becomes better understood and these are addressed below.

3.1 Alloy Melting

Many of the considerations involved with melting for monolithic fuel also apply to production of dispersion fuel, particularly alloy homogeneity and consistency. Pre-alloying the melt charges will be needed. In cases where the powder production is directly from the melt, ensuring the melt is homogeneous is vital.

3.2 Powder Production

The U-Mo fuel system is a ductile, metallic alloy. Simple crushing operations, as used for currently qualified fuels, e.g. U-Si, are not suitable for making powder out of the U-Mo fuels. Different approaches are needed.

Grinding/Communiution – Mechanically abrading an ingot or button can generate particulates. While the generated powder has a rough, irregular shape, it can be used in dispersion fuel plates.

Hydride/Dehydride – Heated metal chips are exposed to hydrogen gas. The brittle hydrides are then milled into powder. The powder is then dehydrided by heating under vacuum at elevated temperatures.

Inert Gas Atomization – In gas atomization, a high velocity inert gas jet is directed at a stream of molten metal. The jet breaks up the stream into droplets, which then solidify. Capable of processing large melts, albeit at the expense of huge gas volumes. Powders are generally spherical, although there may be small "satellite" spheres attached to larger ones.

Rotating Electrode – A rapidly spinning electrode, from which an arc is struck, will throw off molten droplets due to centrifugal forces. Droplet size is primarily a function of rotational speed. Solidified particles have a smooth, regular spherical appearance.

3.7 Cladding Material

As for monolithic fuel meats, the same options are being evaluated for dispersion fuel meats. With a higher surface area, there is more incentive to consider alternatives to the standard 6061 cladding.

3.8 Interlayers

Application of interlayers to dispersion fuels is not exactly comparable to monolithic fuels. Coatings can be applied to the cladding and is preferable to coating the fuel powder. While powder coating technologies are available, e.g. chemical vapor deposition via fluidized bed reactor, the particle size distribution within the powder, not normally a serious issue, complicates the coating application. Coated dispersion fuels will have lowered uranium densities, compared to the uncoated fuels.

3.9 Plate Assembly

Roll bonding remains the favored method for assembling dispersion fuel plates. It is the current, standard practice and can be readily applied to the U-Mo system and has been demonstrated. Alternate methods will be evaluated, however, they have significant associated equipment and development costs.

4.0 FACILITY IMPACT

Implementation of a new fuel production line impacts the BWXT facility in a number of areas: licensing, safety, building layout, material storage. The principal driver for many decisions is the overall economics – capital equipment, processing and plant modifications. For example:

Licensing – BWXT maintains a Nuclear Regulatory Commission (NRC) license to handle and process radioactive materials. The introduction of new radioactive materials may involve a modification to our license and subsequent review and approval by the NRC before actual production can begin. Nominally, this process can take six months for routine requests.

Physical Plant – New tooling, storage containers and racks, production equipment need to be integrated into the existing factory. Potentially, new space may be required, involving expansion of manufacturing areas.

Planning – To ensure an uninterrupted supply of research reactor fuel during the changeover to U-Mo fuel production, it will be necessary to maintain existing fabrication lines. If new building space is not available, the installation of the U-Mo line will have to be fit in around existing production orders at that time. The overall impact is more severe if we change over to a monolithic fuel, as the rolling mill and melting equipment take significant floor space. Existing equipment will have to be removed; possibly involving decontamination and decommissioning, and the sequence of events must be carefully managed.

5.0 ECONOMICS

The technical feasibility to fabricate dispersion type or monolithic type fuel plates is not in question. Likely, with some development, either type plate may be shown to be technically acceptable. The ultimate choice will thus be driven by economics, or the "most number of neutrons per dollar".

We will be estimating the productivity of the identified fabrication options. Start-up costs, including facility modifications, capital equipment requirements, licensing and safety reviews will be estimated. How the "cost per neutron" compares is yet to be determined.

6.0 SUMMARY

BWXT is evaluating the issues and technical prospects involved in setting up a commercial production line for U-Mo fuels. Near term in-core radiation testing should provide guidance in which fuel configurations give acceptable behavior. Down-selecting from the many options currently being evaluated can be done. We see no technical issues that preclude the change-over. But significant planning and evaluations need to be carried out to support the change-over with minimal disruption in plate fuel supply to the research reactor community.

7.0 ACKNOWLEDGMENTS

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8.0 REFERENCES

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