INL/CON-14-32234
PREPRINT

Application of U10Mo Fuel for Space Fission Power Applications

55th Annual Meeting of the Institute of Nuclear Materials Management

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July 2014

White Paper
Application of U10Mo Fuel for Space Fission Power Applications
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A novel reactor design has been proposed for space applications to provide hundreds of watts to one or two kilowatts of electrical power. The reactor concept proposed uses the alloy U10Mo (uranium with 10 weight percent molybdenum) as the fuel. This fuel was selected for its high uranium density, high thermal conductivity, and excellent neutronic characteristics for this application. The core is surrounded by a BeO reflector. Heat is carried from the reactor by liquid metal heat pipes. A shadow shield of LiH tungsten is also utilized to reduce the neutron and gamma radiation dose to the rest of the spacecraft. This design represents a best effort at minimizing the complexity of the fission system and reducing the mass of the system. The compact nature of the block UMo core and BeO radial reflector allows the reactor diameter to be as small as practical while still meeting the neutronic and thermal power demands. This directly results in a reduced shield mass since the reactor diameter dictates the footprint of the radiation shield. The use of heat pipes offers a straightforward primary heat transport approach using proven liquid-metal heat pipe technology. Further, the elimination of a liquid core coolant system heat transport components, both at the reactor side and radiator side, contributes to reducing the total part-count and lowering system mass. The proposed reactor is using a fuel that is being developed by DOE, but there are significant differences in the fuels enrichment, operating conditions and the physical shape of the fuel itself.[1]

This paper attempts to highlight some of the basic consideration and needs that would be expected to be met in developing this fuel and qualifying it for use.

Background

The Global Threat Reduction Initiative U.S. High Performance Research Reactor Fuel Development program has been tasked with the development of U-Mo fuel which includes development of an appropriate fuel system and design, establishing the fuel behavior and performance parameters, conducting fabrication technology development and demonstration, supporting the scale-up and transfer of fabrication technology and the supply of lead test assemblies (LTAs), and providing fuel design and licensing support for conversion.

The program has executed a wide array of fuel tests over the last decade that clearly established the viability of research reactor fuels based on uranium-molybdenum (U-Mo) alloys. Two fuel designs were initially being developed, dispersion and monolithic, which were capable of providing uranium (U) densities of approximately 8.5 g U/cc and 15.5 g U/cc, respectively. The monolithic fuel design represents a more significant departure from existing technology in that the entire fuel meat zone is replaced by the U-Mo alloy. This modification poses some unique fabrication challenges that must be resolved as part of the development effort.[2]

In late 2003, it became evident that the first generation U-Mo-based dispersion fuel design exhibited significant fuel performance problems at high power and burnup. These issues were the result of formation of a (U-Mo)Al_x reaction product that exhibited breakaway swelling. Subsequent testing has shown that small additions of Si to the aluminum (Al) matrix extends the envelope of stable the fuel behavior.[3]

In 2009, a decision was made to focus on the U–Mo monolithic fuel design as the single fuel for conversion of all remaing U.S. reactors, and qualification efforts began. This fuel design consists of a U–10Mo (wt.%) monolithic fuel with a zirconium diffusion barrier, clad in aluminum alloy 6061. This fuel has been demonstrated to meet requirements for conversion of U.S. Reactors over the range of conditions and geometries tested to date.

Development of U-Mo dispersion fuels continues for European reactors (e.g., BR2 in Mol, Belgium and RHF in Grenoble, France). While the program has seen some success in development of a U-Mo dispersion fuel capable of operation to intermediate burnup at high power, this fuel requires further development in order to meet the fuel performance requirements for European high power reactors.

REQUIREMENTS FOR FUEL QUALIFICATION

The DOE does not have a prescribed regulatory framework for the qualification of fuel for space or research reactors. Consequently, any fuel qualification process must rely on information from previous qualification campaigns (historical precedents) along with the individual reactor requirements. The IAEA provides some guidance, from which both high-level and more specific lower-level requirements can be formulated that must be satisfied for fuel “qualification”.

The general steps in the fuel qualification process are shown schematically in Figure 1. In support of these general fuel qualification processes it would be expected that that a fuel development plan contain the analysis of data integrated across fuel and reactor design and provide the documentation that the proposed fuel design and the fabrication process meet all applicable requirements.

Eventually a manufacturer-specific qualification program would need to be established. Qualification of the manufacturer is through adherence to a manufacturing and quality plan and fuel specification accepted by the DOE. The plan and specification would ensure that the fuel product is produced within the bounds of the originally qualified fuel. Fabrication process specifications used during fuel qualification must be scalable to full production process capabilities and capable of meeting quality-assurance requirements.[2]

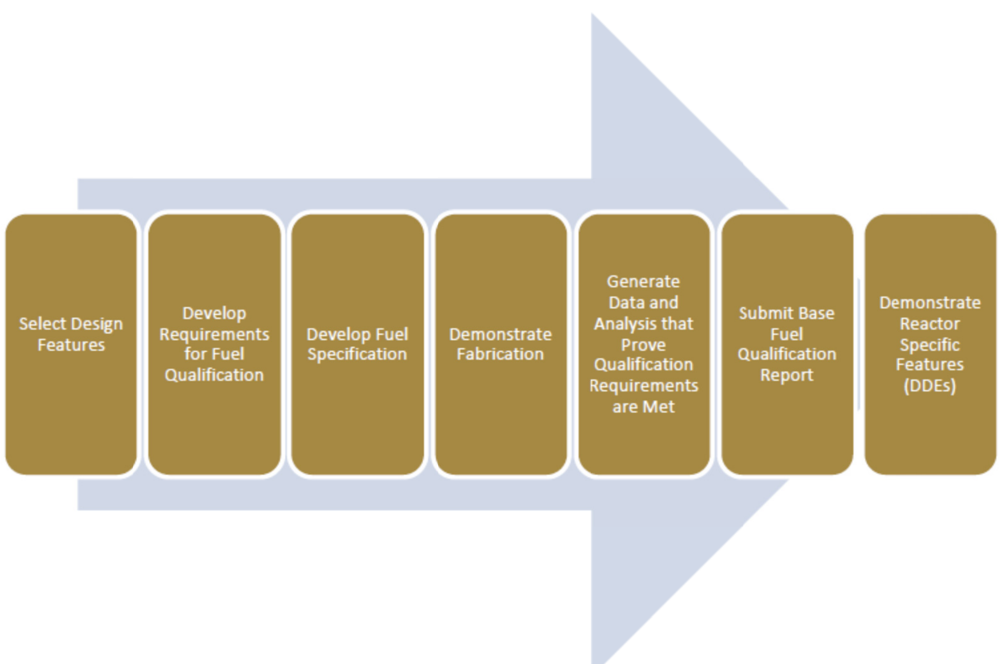

Figure 1 Schematic flowchart showing basic steps for fuel qualification.[2]

For this proposed reactor design, the design features of the reactor and fuel are conceptual in nature. The conceptual design indicates operating temperatures of 900 C, a fission power of 400 W/cm^3, and fission densities of 1.0E19 $fissions/cm^3$. Typical research reactor fuel operating temperatures range from 100 - 250C, fission power exceeding 50,000 W/cm3, fission densities to 7.2E21 $fissions/cm^3$. Because of these large differences in operating conditions, key fuel behaviors such as fission gas mobility, volatile fission product mobility, irradiation and thermal creep rates, grain growth and refinement, and phase reversion will differ, leading to new and unrelated failure modes. Fuel system material interfaces also differ and require assessment. The significant amount of testing conducted in the development of a very high-density fuel based on a U–Mo alloy is of limited application to this design. Most applicable are material property data, including mechanical and thermal properties.

While lessons can be learned from the testing and development activities completed under the the GTRI program,[5] it must be understood that the current fuel concept operates in a much different regime, using different materials in contact with the fuel, and will exhibit very different bevaviors and fuel failure modes. It us therefore essential that the core designers understand the performance of the fuel system in a relevant environment, that a fuel specification be developed that supports the required level of performance, and that the fuel manufacturing process be qualified. The performance of the fuel must be demonstrated by testing in conditions that provide adequate margin relative to normal operation and anticipated transient conditions and fuel models developed that effectively characterize fuel performance in the anticipated operating range, including uncertainties in fuel and material properties, fuel system behavior, and operating conditions.

Provided below are some basic aspects of what should be considered in a fuel “qualification” process. These characteristics must be understood and documented.[5]

Maintaining Mechanical Integrity

For purposes of fuel system and anticipated performance in the specific reactor configuration, ensuring that mechanical integrity is maintained requires that:

- The mechanical response of the fuel meat, cladding, and interlayers during normal operations and anticipated transients be established
- Diffusion layer performance limits of the fuel and the effect that the manufacturing processes have on this characteristic are established.
- Fuel mechanical modeling does not reveal inherent structural issues in the fuel system
- Physical properties related to fuel integrity are established

Irradiation tests (under prototypic conditions) and associated post-irradiation examination data must demonstrate that:

- The mechanical response and integrity of the fuel ~~plate(s)~~
- The diffusional characteristics of the fuel system
- Resistance to delamination to fuel segments, cladding or bonding between the fuel and the heat pipes during normal operation or anticipated transients.

Maintaining Geometric Stability

Ensuring that geometric stability is maintained requires that:

- The geometry of the fuel be maintained during normal operation and anticipated transients
- Changes in the geometry not compromise the ability to cool the fuel.

Irradiation tests (under prototypic conditions) and associated post-irradiation examination data must demonstrate that:

- The geometry of the fuel is maintained and is verified
- Fuel swelling behavior is evaluated to ensure the fuel does not compromise the ability to cool the fuel.

Stable and Predictable Behavior

Ensuring stable and predictable fuel behavior requires that:

- Fuel performance shall be known and predictable for the expected range of fuel composition and impurities, processing parameters, and microstructure for all credible environmental and irradiation conditions
- Fuel swelling behavior shall be within the stable swelling regime (linear and predictable)
- Uranium-molybdenum corrosion behavior with the cladding is characterized and acceptable, and does not result in formation of phases that are unstable during irradiation
- Irradiation behavior is scalable and variations with scale are predictable.

Irradiation tests (under prototypic conditions) and associated post-irradiation examination data must demonstrate that:

- Sufficient number of fuel tests are performed to demonstrate acceptable performance for fabrication conditions and the range of specification requirements for composition and impurities anticipated for commercial fabrication
- The effect of the initial fuel microstructural and evolution of the microstructure during irradiation on fuel performance is understood sufficiently to ensure that unstable behavior does not occur for the anticipated range of fuel operating conditions
- The presence of microstructural precursors to fuel failure is documented, and the impact of these precursors on fuel stability is evaluated

Some variations in the fuel properties are expected as a result of variations introduced during the fabrication process of the fuel meat or fuel element. These variations must be well documented and demonstrated to show that they do not have a significant impact on fuel performance. Fuel failure modes must be identified and margin included in the testing program to ensure that fuel operation is begnign under the range of potential operating conditions (uncertainty). Because of the range of operating conditions of the FPS concept, it is likely that many test aspects can be conducted out-of-pile, however in-pile testing is required to validate the performance of the fuel system.

Status of U–Mo Alloy Based 'Monolithic' Plate Development Program

The program has performed a series of fuel tests since 2005 that have established the viability of monolithic research-reactor fuels based on uranium-molybdenum (U–Mo) alloys.[4,6]

Based on data available in 2009, a decision was made to focus U–Mo monolithic fuel development and qualification efforts on a single fuel design. This fuel design consists of a U–10Mo (wt.%) monolithic fuel foil, a zirconium barrier layer applied to the faces of the foil, and 6061 aluminum cladding bonded to itself and to the fuel foil by a HIP process.

Because of inherently better gamma-phase stability and qualitatively better rolling behavior, U–10Mo was selected as the fuel alloy of choice, exhibiting reasonable uranium density and good irradiation performance. A zirconium foil barrier between the fuel and cladding was chosen to provide a predictable, well-bonded, fuel-cladding interface, greatly reducing fuel-cladding chemical interaction. The fuel plate testing conducted to inform this selection was based on the use of U–10Mo foils fabricated by hot and cold co-rolling with a Zr foil. The foils were subsequently bonded to the Al–6061 cladding by hot isostatic press or friction stir bonding.

Fuel plates fabricated with a zirconium barrier layer exhibited no failures within the peak United State High Performance Research Reactors operating envelope, regardless of the fabrication method (HIP or friction bonding). Recent information on ATR and HFIR fuel-operating conditions indicates that an expanded testing envelope is required to ensure that the selected fuel performs under this extended range of conditions.

The development of a commercial-scale fabrication line and associated fabrication processes is ongoing, with the goal of selecting an optimized process that provides a product that meets fuel performance requirements at an acceptable cost. The results of this research and development will be used to establish an improved baseline process that is designed to accommodate full-scale production requirements. Fabrication development work has been identified that may result in significant process changes targeted at reducing fuel cost, for example, by reducing the number of process steps required, increasing yield, and eliminating or reducing difficult-to-recover scrap material. [6]

Status of U–Mo Alloy Based Fission Power System (FPS)

The FPS is novel in that it is using a solid core of U10Mo surrounded by a BeO reflector to achieve nuclear criticality (and power) and then conducts the heat to the heat pipes. The U10Mo fuel being developed by DOE is being designed to operate at energy densities of 300-400 W /cm3 and maximum core temperatures of 1400K. The small fission power system will have a max energy density of 3.5 W/cm3 and a max fuel temperature of 1200K. So it is well within the planned operating envelope of the operating envelope of the U10Mo fuel. In addition the FPS will not be subject to continual temperature cycles from operating temperature to ambient temperatures as it is planned that once the FPS is turned on it will remain at the operating temperature for the life of the mission.

Note: It is critically important that the fuel interfaces be understood from both material compatibility and structural perspectives. The materials of construction for the FPS will need to be identified and tested for compatibility and structural aspects of the design misison.

With that being said numerous questions regarding fabrication techniques and cladding of the fuel elements remain. This has been a principle point of the DOE U10Mo program to date and so it would be expected to require significant fuel development efforts to achieve confidence in the fuel design for a space flight system. So while much of the fabrication, irradiation and PIE information from the U10Mo program is of value, it is not sufficient to qualify the fuel for the FPS in itself. Additional fuel system testing is needed.

It would also be expected that some "system" test of the fuel, heat pipes and reflector/control system would be needed to qualify the design of the reactor and provide some evaluation of the integrated system. Some of this may be accomplished by non-reactor testing and others through the use of a zero or low power critical test. A plan proposing the extent of the system qualification and proposed test program is required to define system specific requirements and how those requirements will be met, resulting in a qualified fuel.

Estimates and information from Mitch Meyer (INL)[7]:

The life cycle cost U-Mo monolithic fuel qualification is about $375 M. This includes an in-depth downselect test on the front end, and specific testing for each of the 5 reactors. That number doesn't include fabrication development and scale up. It does include property measurements, development of specialized PIE equipment, post irradiation accident testing, QA, planning and PM, etc. This fuel is difficult because it has to operate at both very high power density and very high burn up and it has to work for 5 very different reactors.

If you were to qualify the fuel for one reactor, the operating envelope is not a stretch, the fuel has been selected based on some existing performance data, and 'standard' PIE is all you need, you might see the cost reduced by $100 - $200 M. This gets you a small sample test over a wide range of variables, a scale up test, and an integral demonstration of several fuel elements (depending on the size of the elements). The cost can swing by $10's M based on irradiation testing requirements.

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