Fuel Selection and Development for Small Fission Power System J.T. Creasy[1], R.C. Robinson[1], C. Bowman[2]; [1]Oak Ridge Y-12, creasyjt@Y12.doe.gov, [2]NASA Glenn Research Center

Introduction: Previous studies have performed system level trades for power systems applicable to a wide range of NASA space mission requirements and above 1 kWe, Fission Power Systems (FPS) are technologically superior [1, 2]. This paper summarizes fuel material selection and development issues for the 1-10 kWe class of FPS technologies known as "Kilopower". The baseline Kilopower system design utilizes a solid core, which reduces the fuel, radial reflector and shadow shield mass giving the total system a higher specific power (W/kg) than other fuel forms. The solid core is enabled by the extremely low fuel burnup in this relatively simple and robust design [3].

Fuel Selection: Pure, highly enriched uranium is the fuel of choice for any theoretical reactor and fuel enrichment density is certainly an important factor for a compact reactor design. This selection process strove to maximize ^{235}U density by taking advantage of the favorable burnup while still accommodating all the practical requirements of physical properties, mechanical properties, fabrication constraints and shipping requirements. The material choices mostly closely scrutinized were pure uranium, microalloyed uranium (doped at very low levels), and uranium-molybdenum alloys (U-Mo). Uranium oxides were not seriously concerned because volume stability issues are completely precluded by the low burnup. Other uranium-refractory metal alloys were considered briefly, but the database availability for U-Mo alloys greatly exceeds that of the other alloys.

Pure uranium and uranium with alloying at the dopant levels (very small alloying concentrations) not only have the highest enrichment density, but are also less expensive to fabricate from a simple casting perspective. The disadvantages associated with pure or nearly pure uranium (1) microstructural stability and (2) elevated temperature strength.

Microstructure Uranium has an orthorhombic crystal structure at room temperature and the lattice grows non-uniformly with temperature, Figure 1. Uranium goes through two phase changes between room temperature and projected reactor operating temperatures. These phase changes can lead to distortion and subsequent cracking as a result of thermal cycling. The low cost approach to a small core presumes casting the uranium-based core and presumes no post-casting deformation processes. A core with an as-cast microstructure will have crystallographic texture and the texture will exacerbate non-uniform thermal expansion. These materials development issues that certainly can be resolved, but require some full scale or nearly full scale fabrication trials. However, microstructural stability issue can be circumvented by alloying.

Stabilizing the high temperature gamma phase in uranium avoids both the distortion associated with the phase changes and thermal distortion of the non-isotropic crystal structures. U-Mo alloys with weight fractions of molybdenum greater than six percent can be quenched from temperatures above 802 K (565 C), to preserve the gamma phase at room temperature indefinitely. Alloys with various molybdenum weight fractions have been explored [4]. The US terrestrial reactor program has focused on the U-10Mo (ten weight percent) alloy for numerous reasons. Higher concentrations of Mo increase the low temperature stability of the gamma phase . The higher concentration of Mo also reduces irradiation induced swelling issues in the fuel under low life/high burnup conditions. But ductility of the U-Mo alloys decrease with molybdenum content. In general, higher molybdenum concentrations require more effort to obtain a good, homogenous molybdenum distribution in the product, relative to lower molybdenum concentrations.

Elevated Temperature Strength As with all alloys, the mechanical properties of uranium and U-Mo alloys vary as a function of chemistry, processing history, and test temperature. In general, uranium strength drops markedly with temperature. The ultimate tensile strength of as-cast uranium drops from nominally 400 MPa at 200C to 125 MPa at 700C [5]. Alloying with molybdenum can improve strength, but the results are highly dependent on the microstructure (heat treatment, quench rate, aging). The results of Waldron et al., suggest that there is a distinct strength advantage for properly U-Mo alloys with stabilized gamma phase in up to 500C and a slight strength advantage up to 800C [6].

Recommendation U-7Mo (seven weight percent) is recommended as the baseline alloy composition for the Kilopower solid core design. The weight percentage of molybdenum is above that need for gamma phase stability and includes a small margin. The larger property database and higher burnup stability associated with U-10Mo is not required for this application. The important factor of fuel density is maximized by minimizing molybdenum concentration, ductility is higher, and there may be a concomitant benefit in fabrication cost.

Material Development: Uranium metal alloy is well suited for the Kilopower, compact core with very low burnup. Alloying with molybdenum will improve the phase stability and may also improve the mechanical strength at operating temperature. A structural can/cladding around the core will still be required around the fuel. The chemical compatibility between uranium and many structural alloys is poor due to the formation of low melting point eutectics between uranium and common elements such as Fe, Ni, and Cr. There are no such low temperature eutectics in the U-refractory alloy combinations and molybdenum is suggested for the baseline cladding in this application. The potential for eutectic formation suggests that the fuel-heat pipe joints must be scrutinized. Alloy 230, a Ni-Cr-W-Mo solid solution strengthened superalloy, is the baseline heat pipe envelope material. Bonding the heat pipes outside of the Mo structural can/clad adds an additional thermal drop to the system, but employs the molybdenum as a diffusion barrier between heat pipe and fuel. Enough is known about the diffusion kinetics of the system to ensure safe operation for near-term terrestrial system demonstrations.

The driving principals of the materials selection for the Kilopower baseline design was to identify sound, conservative choices that would allow safe, proof-of-concept testing in the near term. System benefits can be realized in the longer term by generating project specific materials data in the areas of

- Increasing ^{235}U density of the core by reducing Mo content in fuel
- Optimizing structural design through increasing mechanical property data
- Minimizing or eliminating diffusion barrier between fuel and heat pipe by diffusion couple investigation

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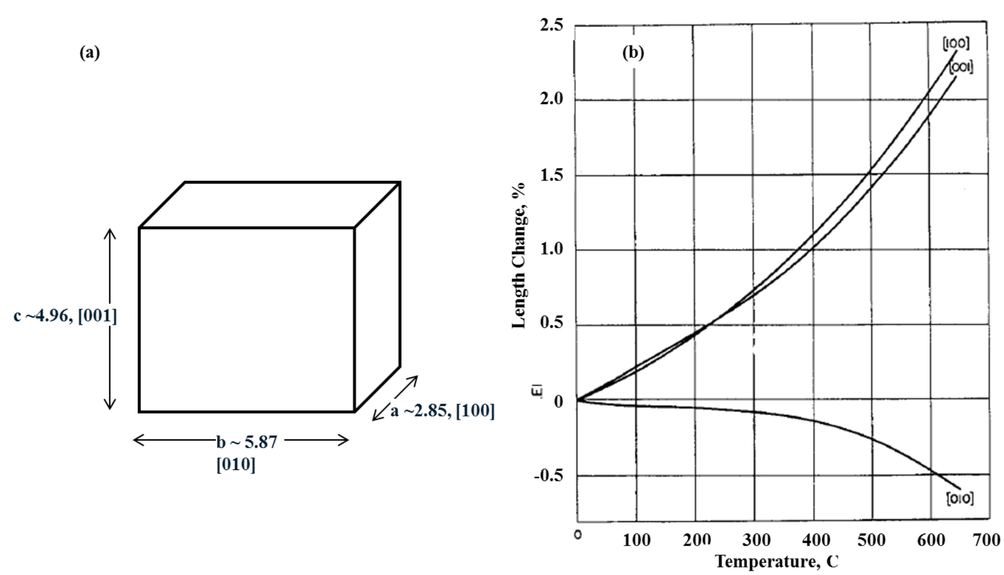

Figure 1. (a) Graphic representation of the orthorhombic crystal structure of the uranium alpha phase showing standard principal direction lattice parameter notation. (b) Percent length change of alpha uranium principal directions relative to temperature [4]