DESIGN EVOLUTION OF HOT ISOSTATIC PRESS CANS FOR NTP CERMET FUEL FABRICATION.
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Introduction: Nuclear Thermal Propulsion (NTP) is under consideration for potential use in deep space exploration missions due to desirable performance properties such as a high specific impulse (> 850 seconds). Tungsten (W)-60vol%UO_2 cermet fuel elements are under development, with efforts emphasizing fabrication, performance testing and process optimization to meet NTP service life requirements [1]. Fuel elements incorporate design features that provide redundant protection from crack initiation, crack propagation potentially resulting in hot hydrogen (H_2) reduction of UO_2 kernels. Fuel erosion and fission product retention barriers include W coated UO_2 fuel kernels, W clad internal flow channels and fuel element external W clad resulting in a fully encapsulated fuel element design as shown in Figure 1.

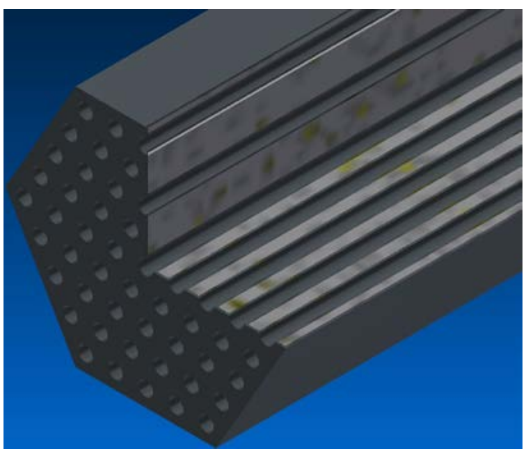

Figure 1. 61channel cermet fuel element concept.

Problem Statement & Objectives: Reactor core fuel elements must survive the aggressive NTP environment, which includes operation in temperatures of 2850 to 3000 K while subjected to flowing hot H_2, vibration, acoustic, and mixed neutron and γ-ray environments [2]. Fuel element performance is a direct consequence of the fabrication process and corresponding structure property relations. Powder metallurgy is used to manufacture W-60vol%UO_2 cermet fuel elements in which W coated UO_2 powder is packed into a can and undergo consolidation through Hot Isostatic Press (HIP) [3]. The objective of this effort is to design HIP cans that can be cost effectively manufactured, facilitate ease of powder fill, endure HIP conditions with minimal/uniform geometric deformation and be readily removed after consolidation.

Design: HIP can design has proven to be a highly iterative process thorough component manufacture, can/mandrel assembly, can welding, powder fill, can/mandrel removal and resulting fuel element properties are evaluated for numerous prototypes. Innovative lessons learned are implemented into subsequent design generations as soon as possible to decrease development time. The current HIP can design consists of 61 W cladded Molybdenum (Mo) channel rods, top and bottom Niobium (Nb) spacer grids, top and bottom Nb can plates, external W clad, can Nb wall and powder fill tube as illustrated in Figure 2.

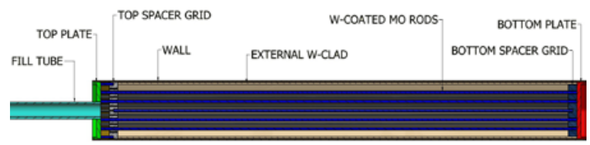

Figure 2. 61 channel HIP can design.

Designs are complex in that they provide rigid mechanical support of internal mandrel components without the use of fasteners, adhesive, brazes or internal welds. Slip-fit tolerances provide a degree of component repeatability yet are flexible enough to allow for relative ease of assembly and provide sufficient internal space for powder infiltration. Powder flow must occur evenly within the can in order to uniformly fill the interstitial void space and provide a high green packing density to minimize deformation during HIP.

Manufacture: HIP cans are fabricated from the refractory alloys due to strength at high temperature, which is required to maintain structural integrity during HIP. CNC milling was initially used to manufacture can components for the first two years of development. However, milling proved to be time consuming and expensive since machining small and complex Nb parts can be difficult and successful results require very specific machining variables (e.g. cutting speeds, feed rates, cutting fluids, bit type). Several alternate methods were investigated and abrasive water jet cutting proved excellent to rapidly manufacture complex components with required tolerances, minimize material waste and significantly reduce cost. After three iterative attempts the water jet process decreased machining time from several hours per component with traditional milling to less than 45 minutes for all four major internal components as shown in Figure 3. An additional hour of milling adds blind holes, pockets, and threads to these parts.

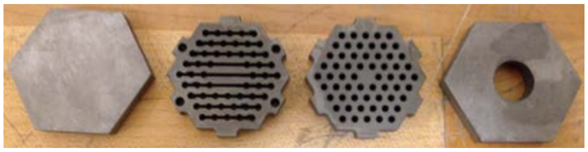

Figure 3. Water-jet machined niobium HIP can parts.

Two Nb sheets are bent into a half-hexagonal shape, assembled as a clam-shell then welded to one another and then welded to the can bottom plate. Flow channel mandrels are made from 1.7 mm (0.067 in.) diameter Mo rods coated with a 0.25 mm (0.01 in) thick layer of W by either a vacuum plasma spray (VPS) or electro (EL)-forming deposition process carried out by Plasma Processes Inc. VPS and EL-forming are also used to fabricate 1 mm (0.04 in) thick external W hex clads and initial results are promising.

Assembly: HIP can components are thoroughly cleaned to remove oxide scales before assembly. The 61 W-coated Mo rods are stacked in the appropriate arrangement using top and bottom spacer grids held in place by a stacking jig. The W exterior clad and Nb can are slid onto the rod assembly, inverted, jig removed, standoff channels added, then the can top plate/fill-tube assembly is welded in place. Fusion welds are made in a low oxygen, low moisture atmosphere glove box to prevent oxidizing the weld joints that can lead to failure during HIP. After welding the cans are helium leaked checked to ensure hermeticity.

Fill, Close-out and HIP: The cans are held in the vertical position by a fixture that is attached to a vibration generator. The appropriate quantity of W-UO_2 powder is fed into a vibratory feeder that flows the powder into the can at a very slow feed rate in order to allow the powders to reach maximum green packing density during the fill process (nominal is between 70-80%TD). Achieving the maximum packing density is critical to minimize can deformation during HIP and to attain the desired net-shape geometry established by fuel design requirements. After powder fill the can is evacuated for several hours to remove trace gases then the fill tube is crimped with a pneumatic press. A weld is placed on the crimped surface to seal the can then the excess fill stem is cut off using the weld torch in preparation for HIP as shown in Figure 4.

Figure 4. Filled 61 channel can ready for HIP.

HIP: The filled cans undergo a HIP schedule that is still under development but can be approximated to be 28,000 psig at 1,700 °C for several hours in order to force liquid phase sintering between the powders that result in consolidation into one solid part. Great care is taken to ensure that temperature and pressure ramp rates are within acceptable limits to produce fuel elements with the desired material and geometric properties. Final fuel density is highly dependent on green packing density and HIP schedule.

Post-HIP Processing: Once a consolidated can is formed several post-HIP processing steps are require to produce a net-shape fuel element. The can ends are cut-off below top spacer grid and above the bottom spacer grid using an abrasive saw. The optimal process to remove the can walls are still under investigation but the most promising options include abrasive grinding or water jet machining. The internal Mo mandrels are removed through an active chemical etch process. The final W-UO_2 fuel element is fully encapsulated with W that provides multiple barriers of protection from the NTP operating environment.

Conclusions: HIP can designs have demonstrated the ability form sub and full-scale net-shape fuel element using traditional powder metallurgy techniques to form W-UO_2 cermet fuel elements for NTP service. Several more iterations will be required to optimize design and process variables based on shrinkage values that result from HIP and to incorporate additional lessons learned through the development process.

Recommendation for Future Work: Follow-on efforts should focus on developing methods to reduce the cost of can production through either materials selection or novel designs and manufacture methods. For example, fabricating the top and bottom spacer grids from W to minimize the amount of material to be removed prior to chemical etching. Optimizing spacer grid pitch as a function of HIP shrinkage values, green packing density and non-destructive evaluation (NDE) methods require maturation to decrease the variation in dimensional tolerance, properties and ultimately fuel element performance during testing and operation.

Acknowledgments: The authors would like to thank Daniel Cavender, Ronnie Renfroe and Jim Martin at NASA Marshall Space Flight Center and Hoss Burtts of YetiSpace. The NASA Nuclear Cryogenic Propulsion Stage (NCPS) project supported the work described as part of technology development activities. Any options expressed are those of the author and do not necessarily reflect those of NASA.

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