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# Reduced Diameter and Lined Cladding Production Status

## Nuclear Technology Research and Development

*Prepared for*
*U.S. Department of Energy*
*Advanced Fuels Campaign*
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# SUMMARY

A contract has been placed with Century Tube Inc. to produce cladding for the FAST experiment. Excess EBR-II cladding tubes will be cold drawn down to 0.115 in. diameter × 0.009 in. wall and 0.077 in. × 0.006 in. wall. Lined cladding will also be tested in the FAST experiment. Century Tube will produce several samples, varying assembly the assembly process, with solid zirconium or vanadium rods inside the HT9. Cladding/liner bonding of each will be evaluated using microscopy. The best one will be further processed to form a liner tube within the cladding. A shrink fit approach is also being developed, where a solid zirconium or vanadium bar is shrunk fit into a cladding piece. This process has shown favorable results and will be compared against the co-drawn samples when available.

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# REDUCED DIAMETER AND LINED CLADDING PRODUCTION STATUS

## 1. INTRODUCTION

The Advanced Fuels Campaign is tasked with developing fast reactor fuels for advanced reactors. As part of this work, fuel irradiation tests are ongoing and with additional future tests planned. In order to show prototypic fuel cladding chemical interaction (FCCI) and to stay as near a prototypic fuel design as possible, most of the fast reactor fuels tests under this program have used HT9 stainless steel (UNS S42100) cladding. Because this is not a commercially available stainless steel grade, excess Experimental Breeder Reactor (EBR)-II cladding have been used which necessitated using standard EBR-II Mk-IV sized fuel slugs. In order to increase the number of samples irradiated and decrease the time needed to reach desired irradiation levels, a new test design, designated as the Fission Accelerated Steady-state Test (FAST), is being developed. FAST calls for fuel assemblies to be a much smaller diameter than the original EBR-II fuel. To keep prototypic FCCI behavior, the preferred cladding is still HT9. The easiest path to produce this small diameter thin walled cladding is to take existing EBR-II cladding tubes and cold draw them down to the desired size.

During irradiation of the fuel, metallic fission products are formed within the fuel. When in contact with the cladding some of these fission products, namely the lanthanide elements, will degrade the cladding strength, otherwise known as FCCI, and limit the lifetime of the fuel. In order for the irradiation samples to reach the desired levels of burnup, a mitigation strategy to limit FCCI is necessary. One proposed strategy is to include a barrier layer between the fuel and the cladding. One possible method of barrier application is to include a thin zirconium or vanadium liner inside the cladding tube during the cladding tube reduction process. Century Tubes, Inc. has been placed under contract to manufacture both the non-lined reduced diameter cladding tubes and to produce a precursor product that will be further processed to fabricate lined cladding samples per SPC-2485, Reduced Diameter and Lined Cladding Development Work. Century. Tubes reduction will be performed using an internal solid mandrel, while the lined precursor product will co-draw the HT9 tubing with a solid zirconium or vanadium rod, which will be machined into a tube, if co-drawing is successful.

## 2. NON-LINED CLADDING PRODUCTION

The non-lined cladding will follow a straight forward reduction process based on previous EBR-II cladding tube production runs. Excess MK-IV EBR-II cladding tubes were sent to Century Tube. EBR-II cladding tubes are nominally 0.230 in. OD × 0.018 in. wall × 28.5 in. in length. These will be reduced to two sizes; 1) 0.115 in. (±0.001 in.) OD × 0.009 in. (±0.0005) wall × 24 in. (±0.1 in.) length and 2) 0.077 in. (±0.001 in.) OD × 0.006 in. (±0.0005) wall × 24 in. (±0.1 in.) length. The reduction schedule was not specified and, therefore, will be left up to the vendor to develop. Final tubing will be supplied in the final normalized and tempered condition. Prior to normalizing and tempering, the final draw pass will be a 20% (±5%) reduction in cross sectional area. Normalization treatment will be performed by heating to a minimum of 1040°C followed by air cooling or equivalent. Tempering will be done by heating to 740°C – 800°C, followed by air cooling or equivalent. Any intermediate anneals will be subcritical, 787°C – 815°C, followed by air cooling. The final surface finish of the tubing shall not exceed 20 µin., and scratches, dents, or marks of greater than 0.001 in. in depth shall be noted and marked. Any tubing with these defects will be sent to Idaho National Laboratory (INL) for further evaluation, but will not be counted towards the required 12 finished tubes specified in SPC-2485. The acceptable tubing will be able to be used directly in the FAST test after a confirmatory chemical analysis is performed on the lot of tubing.

# 3. LINED CLADDING PRODUCTION

Lined cladding production is less straightforward as it is a new process. Previous work has shown that production of thin walled tubes 0.004” in thick or less is very difficult at Century Tube. Based on these difficulties, instead of co-drawing a HT9 tube with a vanadium or zirconium tube, a HT9 tubes will instead be co-drawn with a solid vanadium or zirconium bar. The barrier material will then be removed through drilling, electro-discharge machining, and honing as necessary to produce a liner of appropriate thickness. Although both zirconium and vanadium have been proposed as barrier materials and will be fabricated, the initial FAST tests will only contain zirconium because previous tests have shown decarburization of the cladding by vanadium at elevated temperatures. Optimized parameters for co-drawing of the materials have not been established. Because of this, three different processing approaches will be attempted varying when the barrier and HT9 are assembled. These processes will be further explained in the following sections. Except as noted below, both zirconium and vanadium assemblies will be fabricated with each approach. Also, because the optimized approach has not been developed yet, only the one sample with target HT9 dimensions of 0.115 in. diameter × 0.009 in. wall × 24 in. in length size will be fabricated. After the best approach is identified, additional material may be procured.

## 3.1 Co-Draw Processing Approach-1

The first approach will assemble the zirconium and HT9 just prior to the final 20% final reduction draw pass. Following reduction, the assembly will be normalized and tempered as outlined in Section 2.0 above. This process hopes to make use of the substantial forces needed for a 20% reduction for a mechanical bond. Additionally, the high temperature treatment of normalization will promote diffusion bonding between the HT9 and zirconium. Due to the high temperature of the normalization process, excessive interaction may occur between the two materials. This will be evaluated during the characterization of the produced assemblies. Because earlier testing using vanadium showed extreme decarburization at high temperatures, a vanadium containing counterpart will not be fabricated using this approach.

## 3.2 Co-Draw Processing Approach-2

The second approach attempts to avoid the high temperatures of normalization, but still provide some measure of mechanical and diffusion bonding. In this approach, the last 20% cold work is divided into two separate steps. The HT9 will undergo a 15% reduction in cross section area followed by normalization. After normalization, the zirconium will be assembled with the HT9, reduced approximately 5% more through co-drawing, followed by the tempering process outline above. Whether the HT9 can be further reduced while in the normalized but not tempered condition is not known; however, if successful, this will likely provide some level of mechanical bonding. Previous HT9/Zr interaction studies have shown that decarburization of the HT9 by the zirconium at tempering temperatures is negligible, but it is hoped that some diffusion will occur to create a metallurgical bond. A vanadium counterpart will be produced using this approach. It is assumed that some small amount of decarburization may occur; however, because tempering times and temperatures are low, the amount should be small.

## 3.3 Co-Draw Processing Approach-3

The final production scheme involving drawing relies on only a mechanical bond. In this approach, the HT9 will be reduced as in Approach-2,; however, after the 15% reduction, the HT9 will be normalized and tempered. After the heat treatment, the zirconium rod will be inserted into the cladding, and the final small reduction will take place, providing a mechanical bond.

## 3.4 Shrink Fit Processing

Shrink fit processing is a second process also being investigated to produce short cladding pieces suitable for the FAST assembly. By taking advantage of the coefficient of thermal expansion of the two materials, an interference fit can be produced that still allows assembly. Surrogate testing of these methods has begun using a 300 series stainless steel as a surrogate for the HT9. A stainless tube was machined along with a vanadium rod. The rod tube was designed to have a 0.0003 in. interference fit at room temperature. The stainless steel tube was heated to 525°C, while the vanadium rod was cooled in liquid nitrogen. The two pieces were quickly assembled with minimal force, before temperatures could equilibrate. This produced a successful mechanical bond between the two pieces. After assembly, the center portion of the vanadium rod was removed through electro discharge machining, followed by honing, producing a tube. Figure 1 shows a cross section of the top portion of the tube. Some variation in thickness is seen on the outer tube; however, this is due to laser etching on the outer diameter, and is not an artifact of the shrink fit process. Some slight thickness variations are also seen on the liner material as well, due to the machining process. Figure 2-3 show higher magnification images of the top and bottom portion of the lined tube. A small gap is present in some locations between the stainless steel and vanadium, with a small amount of debris also found in the gap. Energy dispersive x-ray spectroscopy (EDS) was used to identify both stainless steel and vanadium as part of the observed debris. The gap size varied from location but was smaller than 10 µm wide. Figure 4 also shows a location where the outer surface of the vanadium tube has been removed in one location. This was likely caused by a slight misalignment during the assembly process.

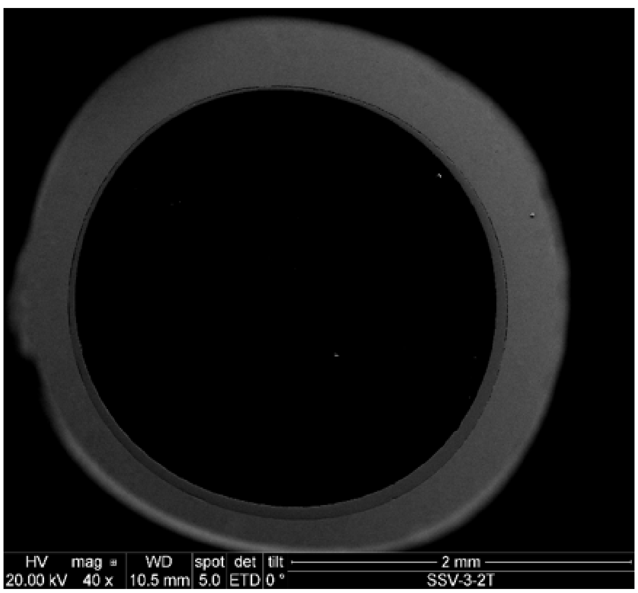


Figure 1. Stainless steel with V liner produced through shink fit processing

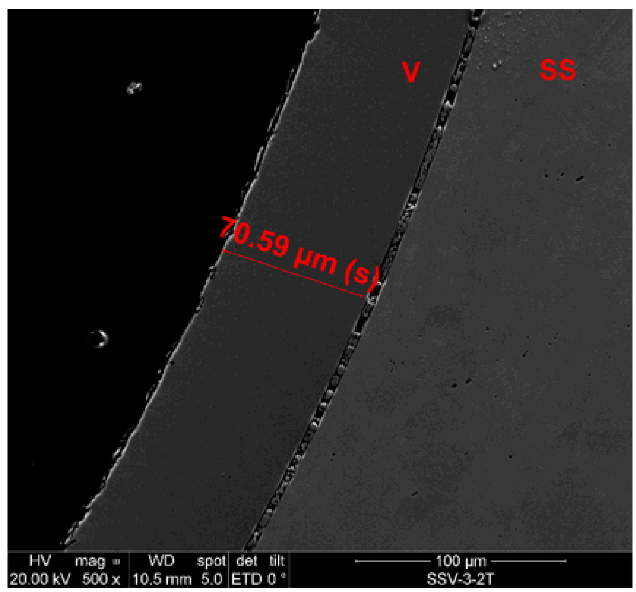


Figure 2. Typical bond area from upper region of sample showing typical gap with stainless steel with V debris.

Based on the promising results of 300 series stainless steel and vanadium, development of the shrink fit process will continue. Programmatic focus has shifted from vanadium to zirconium as the primary liner material. Therefore, continued process development will include fabrication of of zirocnium liners with 300 stainless steel. Following fabrication of lined 300 series stainless steel, lined HT9 stainless steel will be fabricated as HT9 becomes avaialable. It is expected that there will be little difference between the two stainless steel grades in fabrication.

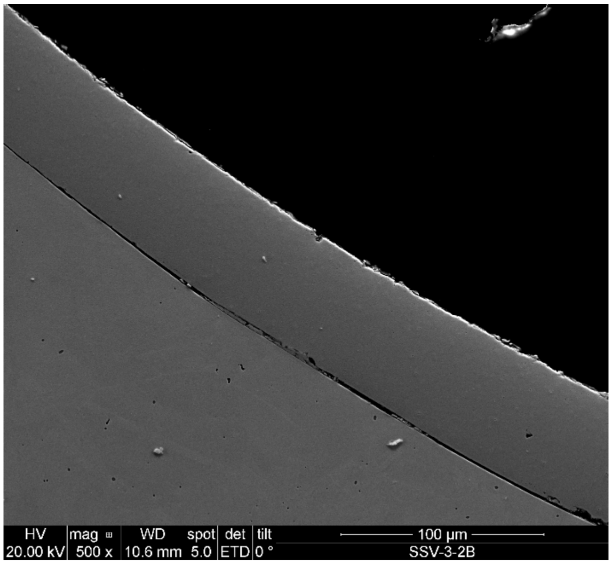


Figure 3. Typical bond area from lower region of sample showing typical gap with stainless steel with V debris.

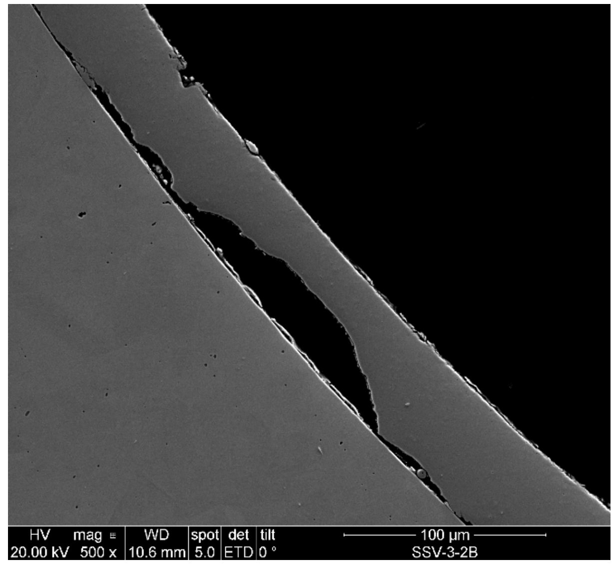


Figure 4. Typical bond area from lower region, showing typical gap and area of possible galling during assembly.

## 3.5 Characterization Plans

Characterization of the surrogate shrink fit samples will be similar to what will be done as the co-drawn samples are produced. A liner must have minimal effect on heat dissipation from the fuel to the reactor coolant. Although it is not clear how much of a metallurgical/mechanical bond is necessary for acceptable thermal transfer and fuel performance, it is assumed that a metallurgical bond is better than a mechanical bond. Mechanical bonds will often have gaps, as seen above, which will lower thermal transfer. Characterization will focus on if a metallurgical bond is present, and, if so, how much interaction is present. Mechanical bonds will be evaluated by amount and size of gap between the liner and cladding. As the best bonding approach is identified, the process may be optimized for use in the FAST experiment or, if acceptable, a sample used in this study will be used in the upcoming FAST experiment.

# 4. CONCLUSION

A contract has been placed with Century Tube Inc. to produce cladding for the FAST experiment. Excess EBR-II cladding tubes will be cold drawn down to 0.115 in. diameter × 0.009 in. wall and 0.077 in. × 0.006 in. wall. Lined cladding will also be tested in the FAST experiment. Century Tube will produce several samples, varying the assembly process, with solid zirconium or vanadium rods inside the HT9. Cladding/liner bonding of each will be evaluated using microscopy. The best one will be further processed to form a liner tube within the cladding. A shrink fit approach is also being developed, where a solid zirconium or vanadium bar is shrunk fit into a cladding piece. This process has shown favorable results and will be compared against the co-drawn samples when available.