Availability of well-characterized, highly irradiated 304 stainless steel for NSUF-supported studies

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It was successfully demonstrated that ultrasonic measurements were in full agreement with density-change and microscopy measurements.

Stainless steels serve as the major structural components in both fast reactors and thermal power reactors, not only in the U.S., but in Russia, China, Japan, most European countries and other nations. Therefore, intense international interest is growing in the response of these steels to increasing radiation exposure, especially in the light-water reactor (LWR) power-generation community, where government-granted operation licenses for 30 years (Russia, Japan) or 40 years (U.S.) are approaching or exceeding these lifetime limits. Requests in the U.S. for life extension to 60 years are now being considered and, in many cases, granted, generating new interest in research on radiation response of these steels.

In the U.S., Western Europe and Asia, the major construction steel employed in reactor construction was AISI 304, produced 45–60 years ago, but with then-current technology, which produced steels with less stringent specifications than currently required, especially with respect to minor deleterious elements such as sulphur and phosphorous—important in corrosion and welding—or with respect to gases such as oxygen and nitrogen, which are important initiators of void swelling.

Studies to support plant life extension require sufficient material of the 60-year-old vintage, subjected to well-characterized neutron irradiation at high enough exposures to enter material-degradation regimes involving transmutation, segregation, precipitation, helium generation, void swelling, irradiation creep, embrittlement, etc. Most currently available specimens in the NSUF Nuclear Fuels and Materials Library (NFML) are relatively small in size with the exception of a few specimens produced from AISI 304.

Project Description

For activities such as training of students, development of new microstructural and microchemical interrogation techniques, or exploration of various degradation mechanisms on LWR-relevant material, the NSUF NFML contains rather large single-heat volumes of AISI 304 stainless steel of the appropriate vintage and technology. These cover a wide, well-characterized range of temperature, dose, dose rate and helium levels. Specimens range from forearm-sized blocks and fist-sized chunks, inch-thick plates, cm-size cubes, mm-thick plates to smaller sizes such as 3 mm-diameter microscopy disks. Most importantly, a number of published studies have been conducted on these materials so that, in new studies, the researchers will know in advance the microstructural and microchemical characteristics of their specimens, as well as their exposure doses, temperatures, helium content, radioactivity levels and radioisotope content.

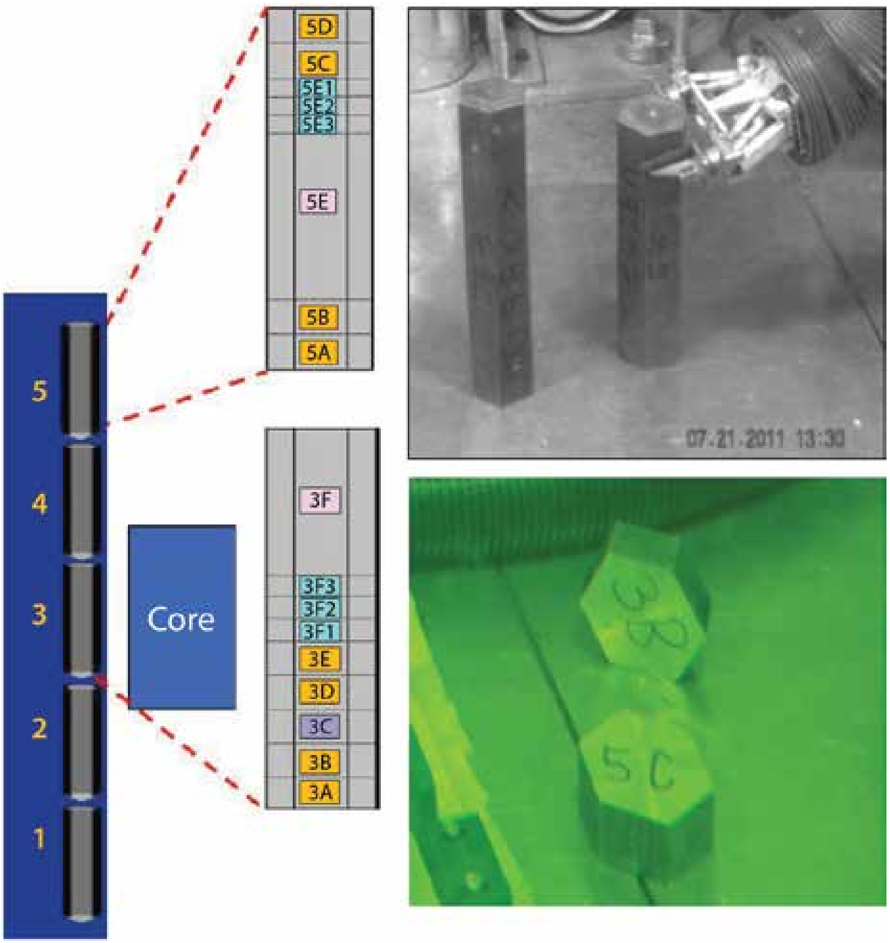

Figure 1. Schematic diagram of the U9807 assembly and its relationship to the EBR-II fueled core. The core is 30 cm tall so Block 3 is the only one fully within the elevation range of the core. Also shown are the two blocks chosen for extensive evaluation at Westinghouse—Block 3 below and above—with the first stage of destructive examination being the production of hex-coins with thicknesses of either 1.2 or 2.5 cm. The mid-block exposures of 3 and 5 were ~30 dpa and ~2.5 dpa, respectively.

These AISI 304 materials were retrieved from the Idaho National Laboratory (INL) Experimental Breeder Reactor II (EBR-II) near Idaho Falls. As shown in Figure 1, the EBR-II fast reactor Row 8 reflector assembly designated U9807 comprised a stack of six hexagonal cross-section blocks (hex-blocks), with sodium flowing outside the wrapper duct (hex-can) and also flowing in the gaps between the outer surface of the hex-blocks and the inner surfaces of the hex-can. There are both radial and axial variations in temperature and neutron exposure in these blocks, determined by ambient coolant temperature and gradients in gamma heating within the block.

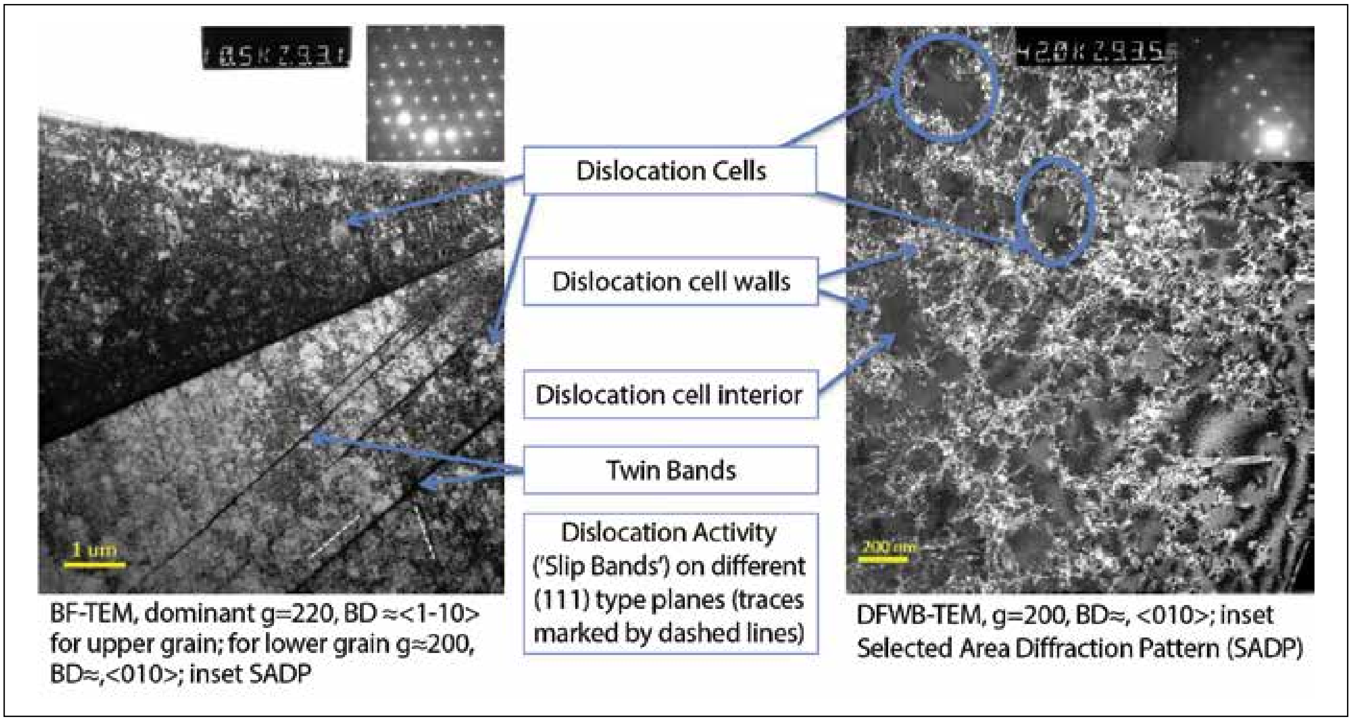

Figure 2. Cold-worked microstructure of an archive block, showing deformation-induced twin bands and dislocation cells existing prior to irradiation.

As shown in Figure 2 the as-produced microstructure of the blocks is typical of ~5% cold-working, all traces of which disappear during irradiation. Most importantly, this Row 8 reflector assembly operated over the range of dpa rates that are characteristic of the baffle-former assembly of pressurized water reactors (PWRs).

With the exception of the discarded, much longer (395.3 mm) Block 1, located far below the core, each of the four hex-blocks in the NSUF NFML had initial dimensions of 52.2 mm flat-to-flat cross-sectional thickness and a length of either 217.5 (for Blocks 5 and 6) or 243.3 mm (Blocks 2,3,and 4). Block 6 was also discarded and is not in the NFML. Blocks 2–5 are currently maintained in the NSUF NFML, with Blocks 2 and 4 located at INL in fully intact form, with profilometry data available to describe their dimensional changes.

Blocks 3 (mid-core) and 5 (far above-core) were shipped to the Westinghouse hot cells in Pittsburgh and have since been extensively sectioned into smaller segments with a wide range of sizes and geometries. Large portions of both blocks still remain in Pittsburgh, but various subsets of smaller specimens have been shipped to several national laboratories, to the Center for Advanced Energy Studies (CAES) and a number of universities. Some of these previously shipped specimens have been tested to destruction, but others remain intact at Westinghouse or their current location for further use or for shipment to other laboratories.

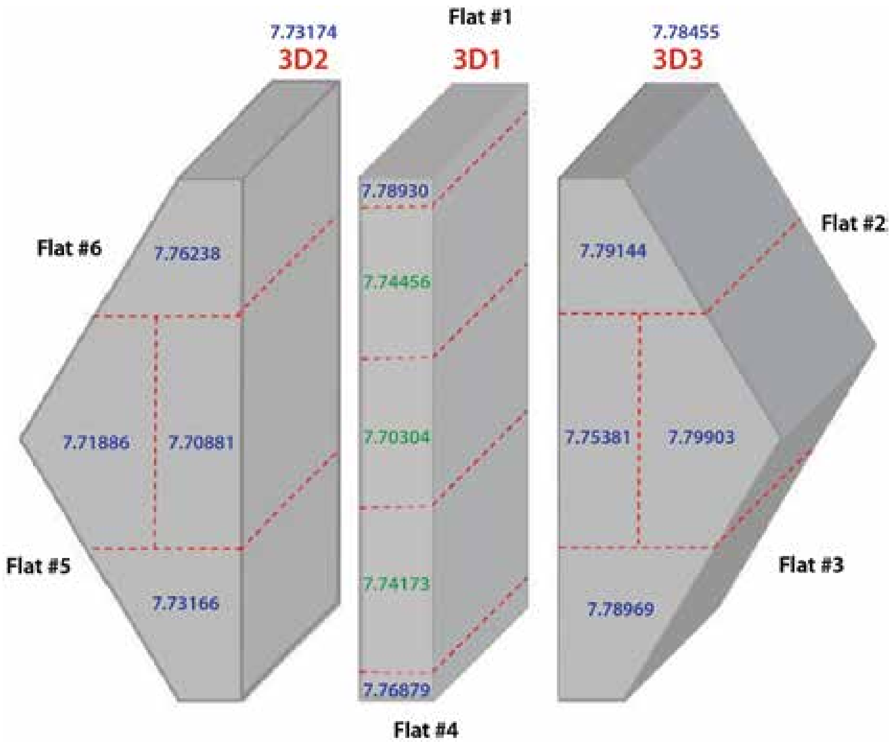

Figure 3. Second stage of cutting after ultrasonic and density measurements were completed on the three-dimensional hex-coin, with measured densities of each piece shown. Slice 3D1 is an iso-dose (28 dpa) strip such that the only variable is the temperature which peaks near the center. Both microscopy and density measurements confirm that void swelling peaks in the center of the strip. The NSUF inventory contains a number of intact, uncut coins.

Previous studies on hex blocks have involved the University of Wisconsin, University of Michigan, Boise State University, University of Pittsburg, Massachusetts Institute of Technology, Texas A&M, Purdue University, CAES, Electric Power Research Institute, MicroXact Inc., Radiation Effects Consulting, LLC, INL, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, as well as two Japanese entities, the University of Tokyo and Nuclear Fuel Industries-Osaka. A wide range of mechanical, microstructural, microchemical, and dimensional studies have been conducted by these groups. Results of these studies are available to guide the definition and interpretation of new studies, and are listed below. Other publications are in preparation. Currently ongoing studies include welding-induced crack formation, scanning electron microscopy of deformation-induced phase stability, laser and acoustic interrogation of radiation-induced microstructure, non-linear ultrasonic testing of microstructure, and subsequent ion irradiation on neutron-preconditioned specimens. A full description of the available specimen inventory and current location of each specimen can be found on the NSUF website.

Accomplishments

In typical PWRs, the structural components range from ~2–4 cm in thickness and experience significant gradients in neutron-flux spectra, dpa, temperature, and helium generation, potentially producing complex internal distributions in void swelling. The development of new experimental

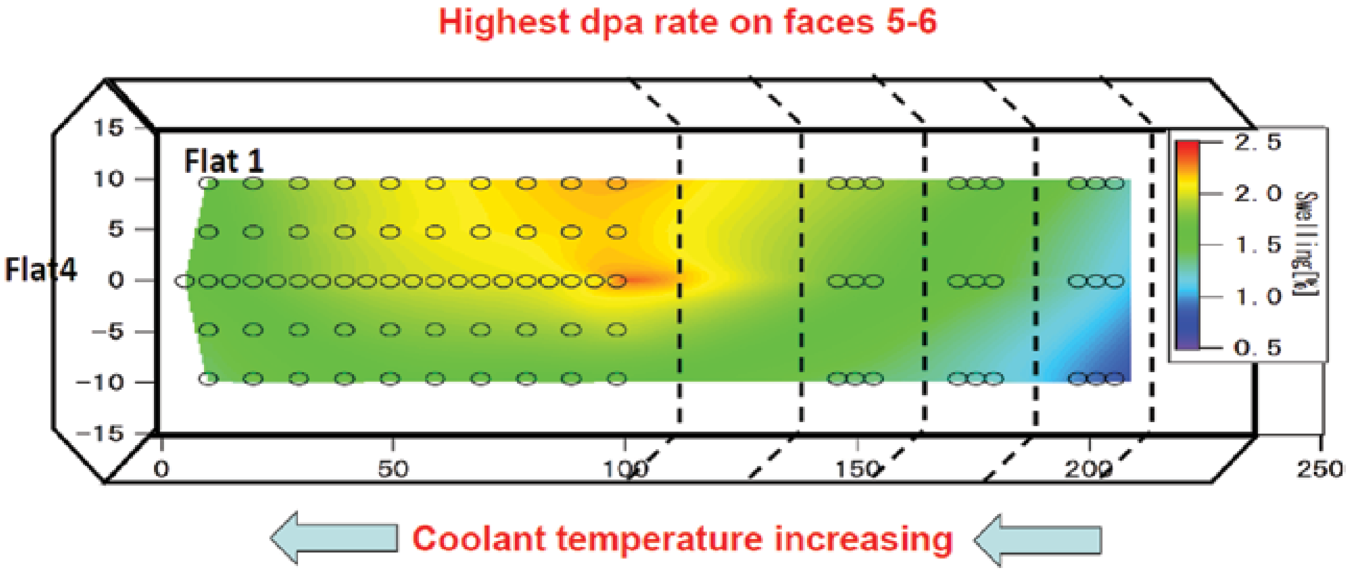

Figure 4. Average through-thickness swelling determined between flats 1 and 4 of Block 3 using time-of-flight ultrasonic measurements. Dotted lines indicate the cutting locations that will be used later to produce the 2.5-cm-thick hex coins.

techniques involving ultrasonic or laser interrogation will require similarly thick materials. Likewise studies on welding or corrosion are best conducted using thick specimens. Other studies on mechanical properties or physical properties are better studied using thinner specimens. The current hex-block specimen inventory covers this full range of sizes.

Before sectioning of the two blocks at Westinghouse, each was extensively measured using non-destructive profilometry techniques to assess carbide-induced shrinkage, void-induced swelling, and block bending. Non-destructive time-of-flight ultrasonic measurements were then used to identify the average levels of void swelling and carbide precipitation across opposing flats of the two blocks. The first round of cutting to produce 0.5 and 1.0 inch thick "hex-coins" was followed by density measurements and more ultrasonic measurements across the new cut faces. Subsequent sectioning of the hex-coins was followed by additional density measurements and the production of specimens for measurement of various mechanical and physical properties, microstructure and microchemistry. Figure 3 provides an example of the second stage of cutting of one coin, to be followed later by cutting of smaller specimens for microscopy, shear punch, and other tests.

The original major goal of the hex-block program was to demonstrate that ultrasonic measurements could be used to assess the internal distribution of void swelling and carbide densification in thick components. It was successfully demonstrated that ultrasonic measurements were in full agreement with density-change and microscopy measurements. Some examples of these results are shown in Figures 4-6.

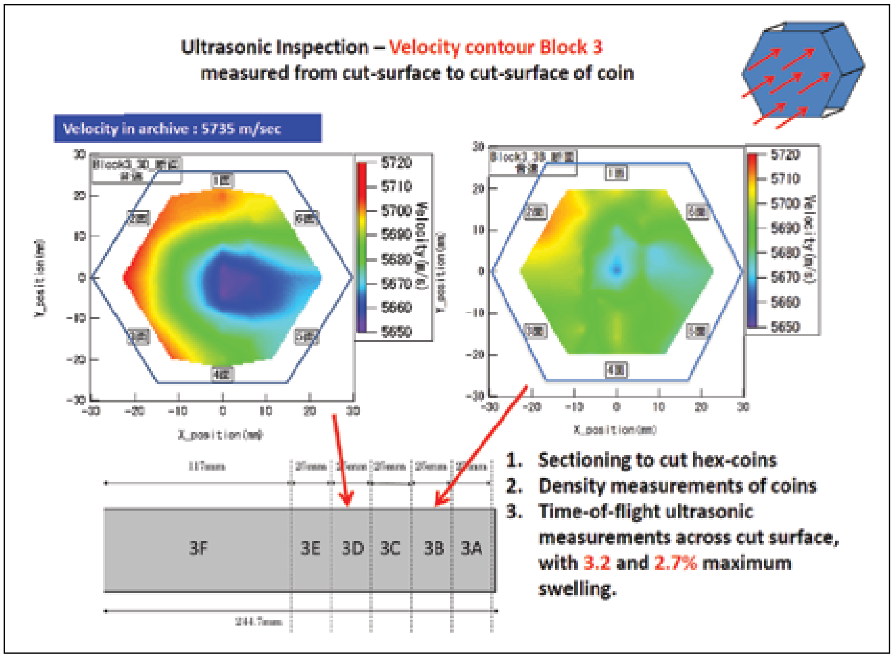

Figure 5. Time-of-flight measurements of internal swelling distribution in two Block 3 hex-coins. Coin 3D experienced both higher dose and temperature compared to coin 3B. The asymmetry of swelling is the consequence of a gradient in gamma heating rate, moving from right to left.

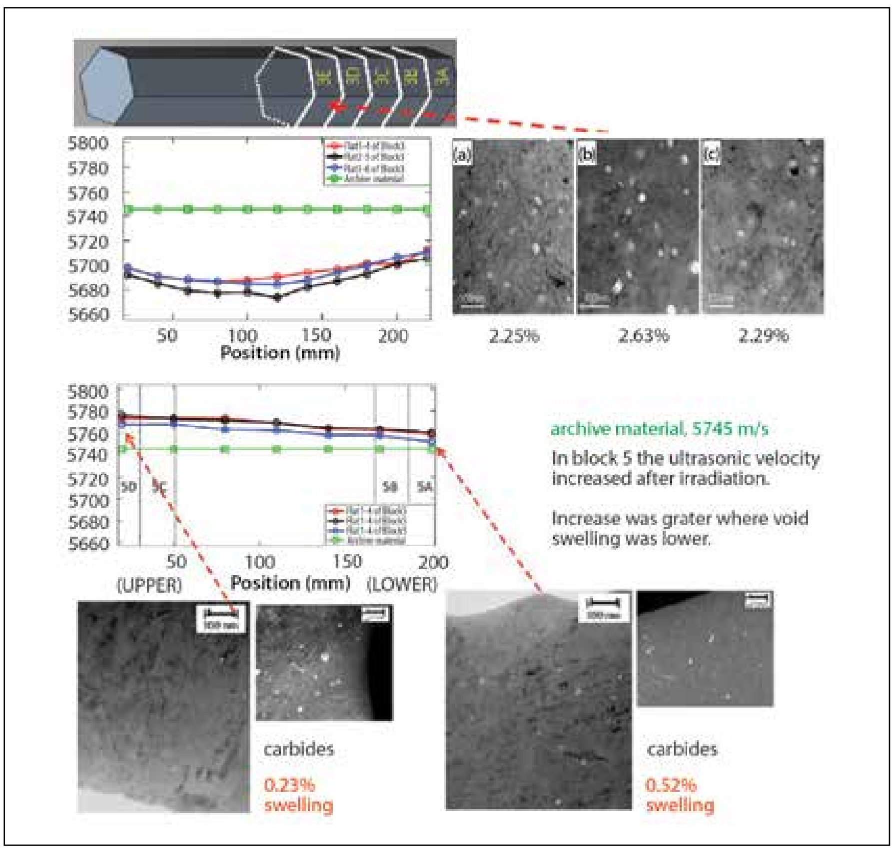

Figure 6. Time-of-flight through-thickness measurements showing the effect of competing effects of carbide densification and void swelling in high-dose Block 3 and low-dose Block 5. Carbide precipitation increases the flight time while void swelling decreases it. Swelling peaks in the hotter center of Block 3.

Publications

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Distributed Partnership at a Glance	
NSUF and Partners	**Facilities and Capabilities**
Westinghouse	Materials Center of Excellence (MCOE) Laboratories
Collaborators	
Radiation Effects Consulting	Frank Garner (principal investigator)
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