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A test loop made of stainless steel (SS) was fabricated and tested in the vacuum chamber to establish the test procedures, condition the refractory metal furnaces and identify potential problems. The vacuum system, furnaces and cold-leg preheating system performed well. At ~550°C peak temperature, a thermal gradient of ~175°C was achieved with a Li velocity of ~4cm/s. The major problem identified was temperature measurement. This issue is being addressed by increasing the number of thermal wells from one to four in the V-4Cr-4Ti loop. Fabrication of the V-4Cr-4Ti loop has begun. Two-layer (Y2O3/V) coatings on V-4Cr-4Ti substrates have been fabricated and will be placed in the hot and cold legs of the loop along with uncoated specimens.

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2.1 ANALYZING IRRADIATION-INDUCED CREEP OF SILICON CARBIDE—Y. Katoh, L. L. Snead, and S. Golubov (Oak Ridge National Laboratory) ***8***

Irradiation creep, which is among the major lifetime-limiting mechanisms for nuclear structural materials, is stress-driven anisotropic plastic deformation occurring in excess of thermal creep deformation in radiation environments. In this work, experimental irradiation creep data for beta-phase silicon carbide (SiC) irradiated at intermediate temperatures is analyzed using a rate theory model with an assumed linear-coupling of creep strain rate with the rate of self interstitial atom (SIA) absorption at SIA clusters. The model reasonably explains the experimentally observed time-dependent creep rate of ion-irradiated SiC and swelling evolution of ion- and neutron-irradiated SiC. Bend stress relaxation behavior during irradiation was then simulated using the developed model to confirm agreement with the experimental data obtained by neutron irradiation experiments. Recommended directions of future experiment are provided to further verify and improve the models and assumptions in this work.

2.2 ANISOTROPY IN TENSILE PROPERTIES OF ADVANCED SILICON CARBIDE COMPOSITES—T. Nozawa, Y. Katoh (Oak Ridge National Laboratory), and R. J. Shinavski (Hyper-Therm High-Temperature Composites, Inc.) **17**

This study evaluates the anisotropy in tensile properties of satin-woven (S/W) or biaxially braided Hi- Nicalon™ Type-S fiber reinforced chemical-vapor-infiltrated (CVI) SiC matrix composites with multilayered interphase. Results indicate excellent axial and off-axis tensile fracture behaviors for the S/W composites. In contrast, the braided composites failed at unexpectedly lower stresses. The primary cause for this difference was the varied in-plane shear properties, on which off-axis tensile properties significantly depend. Superior in-plane shear

properties for the S/W composites were achieved by increasing the volume fraction of transverse fibers normal to the fracture plane. Considering the failure modes depend on the off-axis angle, the anisotropy in proportional limit tensile stress and fracture strength were satisfactorily predicted by a simple stress criterion model. The anisotropy in Young's modulus was well-described by a conventional rule of mixtures for laminates. It is worth noting that specimen size effect on axial and off-axis tensile properties seems very minor for nuclear-grade SiC/SiC composites with rigid CVI-SiC matrix.

2.3 FRACTURE STRENGTH AND TIME DEPENDENT PROPERTIES OF 0/90 AND ±55-BRAIDED WEAVE SIC/SIC TYPE-S FIBER COMPOSITES—C. H. Henager, Jr. (Pacific Northwest National Laboratory) **26**

The use of SiC-reinforced composites for fusion or other nuclear applications will not be restricted to 0/90 aligned fiber applications in all cases. Therefore, it is important to understand the role of fiber orientation in the strength, toughness, and time-dependent strength properties for such materials. The use of high-strength ceramic fibers for composites is predicated on optimizing the strength, fracture resistance, and retained strength in aggressive environments, which argues for the best use of fiber strengths, namely on-axis loading for full load transfer to the high-strength fibers. Evans et al. have developed extensive theoretical treatment of such composites loaded in on-axis orientations [1-3] but relatively few researchers have systematically studied the effects of fiber orientation on composite properties, and none have, to the best of our knowledge, performed any time-dependent testing of off-axis composites.

2.4 ELECTRICAL CONDUCTIVITY MEASUREMENTS OF SIC-BASED MATERIALS—G. E. Youngblood, E. Thomsen, and G. Coffey (Pacific Northwest National Laboratory) **44**

We have made electrical conductivity (EC) measurements of several types of 2-dimensional (2D) silicon carbide (SiC) composites using either 2- or 4-probe potentiometric methods. To assess the uncertainty in our transverse EC-measurements for thin disc-shaped composite samples when using a 2-probe method, we have developed a more reliable 4-probe method. At the same time, by comparing 2- and 4-probe measurements, we were able to estimate the error due to contact resistance and assess its effect on previous 2-probe EC measurements. From this analysis, it appears prudent to routinely use the new 4-probe set-up for all transverse EC-measurements of thin SiC-based samples.

2.5 SWELLING OF NUCLEAR GRAPHITE AND HIGH QUALITY CARBON FIBER COMPOSITE UNDER VERY HIGH IRRADIATION TEMPERATURE—L. L. Snead, T. D. Burchell, and Y Katoh (Oak Ridge National Laboratory) **51**

The purpose of this experiment was to evaluate the dimensional change of newly proposed nuclear graphite material following high-temperature irradiation, and to compare the measured swelling with the historic nuclear graphite H-451. Over the irradiation temperature range studied (~850-1475°C) and neutron dose range (~1.78, ~5.25 and 8.73 x 10^{25} n/m^2 (E>0.1 MeV)) the UCAR PCEA and SGL NBG-10 candidate nuclear graphite had similar densification to that of Great Lakes Carbon nuclear graphite H-451. In this temperature and dose range all materials remained in the densification stage. Additionally, the effect of high-temperature irradiation on the dimensional stability of high-quality carbon fiber

composites was investigated. A high thermal conductivity three dimensional carbon fiber composite, FMI-222, and a very high thermal conductivity one dimensional carbon fiber composite MKC-1PH, were studied. Results indicate that a greater than anticipated dimensional change occurs for these composites. Moreover, the dimensional stability of the 3-D composite appears to be a strong function of the sample size chosen, raising the question of the appropriate size sample to use to determine irradiation-induced dimensional change for these materials.

2.6 ACCUMULATION OF THERMAL RESISTANCE IN NEUTRON IRRADIATED GRAPHITE MATERIALS—L. L. Snead (Oak Ridge National Laboratory) **67**

A Nuclear graphite, H451, and two high thermal conductivity graphite composites have been irradiated in the temperature range of 310-710°C in the High Flux Isotope Reactor and their thermal conductivities monitored in-situ. Data were measured continuously up to a fast neutron dose of approximately 1 x 10^{25} n/m^2 (E>0.1 MeV.) Data is interpreted in terms of the added thermal resistance and materials compared on this basis. Following this analysis it is shown that for the three materials studied, which have significantly different initial thermal conductivity values, the accumulation of thermal resistance is greater for the materials with lower initial thermal conductivity. Given that vacancies dominate phonon scattering at these irradiation temperatures and dose levels, these data clearly indicate that materials of higher perfection have a slower rate of stable vacancy accumulation during irradiation.

3.0 FERRITIC/MARTENSITIC STEELS AND ODS STEELS ***84***

3.1 APPLICATION OF THE MASTER CURVE TO INHOMOGENEOUS FERRITIC/MARTENSITIC STEEL—M. A. Sokolov (Oak Ridge National Laboratory) and H. Tanigawa (Japan Atomic Energy Agency) **85**

A total of 53 specimens of F82H steel have been tested in the transition region, 27 1T C(T), 19 0.4T C(T) and 7 0.18T DC(T). The results of this study showed that the scatter of fracture toughness for a 25 mm plate of F82H-IEA steel was larger than anticipated by the conventional master curve analysis. Several other types of analysis that are the advanced extensions to the conventional master curve method were applied to theses data. It was shown that the random inhomogeneity analysis provides a better description of the data scatter for F82H steel, than does the conventional master curve analysis or any other analyses. At the same time, the T_o values derived using the conventional and random inhomogeneity analyses are quite similar.

3.2 MECHANICAL PROPERTIES AND MICROSTRUCTURE OF THREE RUSSIAN FERRITIC/MARTENSITIC STEELS IRRADIATED IN BN-350 REACTOR TO 50 dpa AT 490°C—A. M. Dvoriashin, S. I. Porollo, Yu. V. Konobeev (State Scientific Centre of Russian Federation, The Institute for Physics and Power Engineering), N. I. Budylkin, E. G. Minonova, A. G. Ioltukhovskiy, M. V. Leonteva-Smirnova (State Scientific Centre of Russian Federation), A. A. Bochvar (All-Russia Research Institute of Inorganic Materials (VNIINM), Moscow, Russia), and F. A. Garner (Pacific Northwest National Laboratory) **98**

Ferritic/martensitic (F/M) steels are being considered for application in fusion reactors, intense neutron sources, and accelerator-driven systems. While EP-450 is traditionally used with sodium coolants in Russia, EP-823 and EI-852 steels with higher silicon levels have been developed for reactor facilities using lead-bismuth coolant. To determine the influence of silicon additions on short-term

mechanical properties and microstructure, ring specimens cut from cladding tubes of these three steels were irradiated in sodium at 490°C in the BN-350 reactor to 50 dpa.

Post-irradiation tensile testing and microstructural examination show that EI-852 steel (1.9 wt% Si) undergoes severe irradiation embrittlement. Microstructural investigation showed that the formation of near-continuous χ-phase precipitates on grain boundaries is the main cause of the embrittlement.

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No contributions

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No contributions

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6.1 INFLUENCE OF CARBON ADDITION ON NEUTRON-INDUCED VOID SWELLING OF Fe-15Cr-16Ni-0.25Ti MODEL ALLOY—N. Sekimura, T. Okita (University of Tokyo), and F. A. Garner (Pacific Northwest National Laboratory) **108**

Addition of 0.05 wt% C to a model Fe-15Cr-16Ni-0.25Ti quaternary model alloy leads to a reduction in neutron-induced swelling at 430ºC. The transient regime of swelling is prolonged by carbon addition, most strongly at lower dpa rates. Contrary to the swelling behavior observed in carbon-free Fe-15Cr-16Ni and Fe-15Cr-16Ni-0.25Ti model alloys irradiated in the same experiment, Fe-15Cr-16Ti-0.25Ti-0.05C does not exhibit a strong dependence of swelling on dpa rate. It appears that carbon's role, while not yet well-defined, operates via a solute-based or TiC complex mechanism rather than by a precipitate-based mechanism. A model is proposed whereby carbon stabilizes loop microstructures against unfaulting, where unfaulting is known to be a prerequisite to formation of the glissile dislocation network needed to establish a high swelling rate. This stabilization is proposed to counteract the tendency of loop unfaulting to occur more strongly at low dpa rates.

6.2 THE SYNERGISTIC INFLUENCE OF TEMPERATURE AND DISPLACEMENT RATE ON MICROSTRUCTURAL EVOLUTION OF ION-IRRADIATED Fe-15Cr-16Ni MODEL AUSTENITIC ALLOY—T. Okita, T. Sato, N. Sekimura (Department of Quantum Engineering and Systems Science, University of Tokyo, Japan), T. Iwai (Research Center for Nuclear Science and Technology, University of Tokyo, Japan), and F. A. Garner (Pacific Northwest National Laboratory) **117**

An experimental investigation of microstructural evolution has been conducted on Fe-15Cr-16Ni irradiated with 4.0 MeV nickel ions. Irradiations proceeded to dpa levels ranging from ~0.2 to ~17 dpa at temperatures of 300, 400, 500 and 600°C at displacement rates of 1 x 10^{-4}, 4 x 10^{-4} and 1 x 10^{-3} dpa/sec. The swelling was found to monotonically increase with decreases in dpa rate at every irradiation condition studied.

The earliest and most sensitive component of microstructure to both temperature and especially displacement rate was found to be the Frank loops. The second most sensitive component was found to be the void microstructure, which co-

evolves with the loop and dislocation microstructure.

6.3 MEASUREMENT OF HELIUM GENERATION IN AISI 304 REFLECTOR AND BLANKET ASSEMBLIES AFTER LONG-TERM IRRADIATION IN EBR-11— F. A. Garner, B. M. Oliver, L. R. Greenwood (Pacific Northwest National Laboratory),[1] D. L. Porter (Idaho National Laboratory), and T. Allen (University of Wisconsin) **125**

Five hexagonal ducts constructed from AISI 304 stainless steel in the annealed state were removed from rows 8-14 of the EBR-II fast reactor after many years of irradiation to study the effect of atomic displacement rate on void swelling. For this objective it was important to ensure that the observed differences in void swelling were not strongly influenced by variations in helium/dpa ratio. The two major contributions to helium production arise from the nickel and boron content of the steel. However, the boron content was unspecified and therefore unknown, but it was determined from an unirradiated archive duct by converting a well-defined fraction to helium and then measuring the helium content using isotopic dilution mass spectrometry. The same technique was used to measure the total helium in the irradiated duct specimens. After separating the boron contribution from the total measured helium it was possible to determine the contribution from various fast and thermal neutron interactions with the other major elements in the steel and compare the helium generation with predicted values. One important conclusion of the study is that the range of He/dpa ratios over the five subassemblies was not very large, allowing the observed changes in swelling to be attributed primarily to variations in displacement rate and temperature.

6.4 LOW-TEMPERATURE MECHANICAL PROPERTIES OF Fe-0.06C-18Cr-10Ni-0.4Ti AUSTENITIC STEEL DETERMINED USING RING-PULL TENSILE TESTS AND MICROHARDNESS MEASUREMENTS—V. S. Neustroev, E. V. Boev (Research Institute of Atomic Reactors, Dimitrovgrad, Russia), and F. A. Garner (Pacific Northwest National Laboratory) **136**

Irradiated austenitic stainless steels removed from Russian water-cooled VVERs experience irradiation temperatures and He/dpa conditions that are very similar to steels to be used in ITER. Data are presented on the radiation hardening of the Russian analog of AISI 321 at 0.2 to 15 dpa in the range of 285 to 320°C. The Russian variant of the ring-pull tensile test was used to obtain mechanical property data. Microhardness tests on the ring specimens provide useful information throughout the deformed regions, but at high hardening levels caution must be exercised before application of a widely accepted hardness-yield stress correlation to prediction of tensile properties. Low-nickel austenitic steels are very prone to form deformation martensite, a phase that increases strongly with the larger deformation levels characteristic of microhardness tests, especially when compared to the 0.2% deformation used to define yield stress.

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7.1 COMPATIBILITYISSUES FOR AHIGH TEMPERATURE DUALCOOLANT BLANKET– B. A. Pint (Oak Ridge National Laboratory, USA) **144**

Compatibility experiments are being conducted to support higher temperature Pb-Li dual coolant concepts. Based on prior work on monolithic SiC at 1100°-1200°C, SiC/SiC specimens were evaluated at 1000°C.The high O content in the

commercial PbLi led to oxide layer formation on monolithic SiC specimens and small mass changes for composite materials. Further characterization is needed to determine the degree of interaction observed for the composite specimens. Aluminum-containing alloys and aluminide coatings performed well in PbLi at 800°C compared to uncoated 316SS. Model aluminide coatings made bychemical vapor deposition reduced the dissolution rate for 316SS at 800°C by a factor of 50. The superior compatibility performance of the alloys containing Yand Zr dopants suggests that similar additions maybe beneficial for the performance of protective aluminide coatings in this temperature range. Higher resolution characterization of the thin alumina layer is needed to determine the effect of exposure to Pb-Li.

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