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1.1 BEAM-TARGET INTERACTION IN AN ACCELERATOR-BASED NEUTRON SOURCE FOR A FUSION MATERIALS TEST FACILITY' -- A. Hassanein and D. Smith (Argonne National Laboratory) 3

High-current linear-accelerators have increased the attractiveness of a deuterium-lithium neutron source for fusion materials testing and evaluation. Detailed beam-target interaction and the resulting energy deposited and the **jet** thermal response are analyzed. Issues relating to jet instabilities, nozzle erosion rates, and the impact of thicker jets on the neutron spectrum at the testing area need further analysis.

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A proposed high-flux high energy fusion materials irradiation facility **uses** a deuteron beam impinging on a lithium target to produce neutrons with a spectrum that peaks around 14 MeV. The lithium target consists of a jet of liquid lithium of appropriate thickness. The lithium target development activity is examining the possibility of creating a stable planar free **jet** of desirable thermal hydraulic characteristics through magnetohydrodynamic body forces created by a DC magnetic field.

1.3 CONCEPTUAL DESIGNS OF SUPERCONDUCTING ACCELERATORS FOR A FUSION MATERIALS IRRADIATION FACILITY' -- R.B. Clare, J.R. Delayen, and B.J. Micklich (Argonne National Laboratory) 7

This research has been of a theoretical and analytical nature. We have investigated the dynamics of high-current beams with the goal of identifying possible instabilities and their cures, and also the causes of emittance growth and halo formation which would lead to activation of the accelerator. **We** have also done conceptual designs of some of the critical components of the accelerator, and we have developed a model for the control and stabilization of heavily beam loaded superconducting cavities.

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Results from preliminary calculations for one beam and dual beam configurations are presented. The influence of the lithium target thickness on the neutron economy of the system has been addressed. The nuclear responses induced by the neutron source has been calculated and a brief discussion about the lack of evaluated nuclear cross section data above 20 MeV is presented.

1.5 THE INFLUENCE OF SPECIMEN SIZE ON MEASUREMENT OF THERMAL OR IRRADIATION CREEP IN PRESSURIZED TUBES -- F.A. Garner and M.L. Hamilton, (Pacific Northwest Laboratory), R.J. Puigh. C.R. Eiholzer and D.R. Duncan, (Westinghouse Hanford Company). M.B. Toloczko, (University of California) and A.S. Kumar. (University of Missouri-Rolla) 12

Thin-walled pressurized tubes have been developed for measurement of thermal creep and irradiation creep. Miniaturization of these tubes allows more tests to be conducted in the limited reactor space available and decreases the impact of displacement rate gradients and temperature gradients. Studies conducted on a variety of **tube** sizes show that, when specimen fabrication history and irradiation conditions are controlled, miniaturization can **be** successfully achieved and valid data produced

'**Inadvertantly** omitted from DOE/ER/12

1.6 STATUS OF U.S./JAPAN COLLABORATIVE PROGRAM PHASE II HFIR TARGET CAPSULES -- J.E. Pawel and R.L. Senn (Oak Ridge National Laboratory) 21

A complete description and details of the design, construction, and installation of capsules JP-9 through JP-16 has been previously reported. The capsules were installed in the High Flux Isotope Reactor **(HFIR)** target July 20, 1990 for irradiation beginning with HFIR fuel cycle 289. The capsules were removed and stored in the reactor pool during HFIR cycle 292 (11/25/90 - 12/10/90) to provide room for required isotope production. They were reinstalled for HFIR cycle 293 for continued irradiation. Of these eight target capsules, JP-10, 11, 13, and 16 completed their scheduled number of cycles (11) and were removed from the reactor in September 1991. In addition, JP-14 was removed from the reactor at the end of cycle 310 (9/18/92) after 21 cycles.

Three new capsules in this series, JP-20, 21, and 22, are currently being designed. These capsules were added to the program in order to complete the experimental matrix included in the JP-9 through JP-16 capsules. The new capsules will contain transmission electron microscope (TEM) disks and SS-3 flat tensile specimens at 300-600°C and will achieve doses of 8, 18 and 40 dpa, respectively. The preliminary experiment matrix is described in detail in a previous report.

1.7 FABRICATION AND OPERATION OF HFIR-MFE RB' SPECTRALLY TAILORED IRRADIATION CAPSULES -- A.W. Longest, D.W. Heatherly, E.D. Clemmer (Oak Ridge National Laboratory) 23

Fabrication and operation of four HFIR-MFE RB' capsules (60, 200, 330, and 400°C) to accommodate MFE specimens previously irradiated in spectrally tailored experiments in the **ORR** are proceeding satisfactorily. With the exception of the 60°C capsule, where the test specimens are in direct contact with the reactor cooling water, specimen temperatures (monitored by 21 thermocouples) are controlled by varying the thermal conductance of a thin gas gap region between the specimen holder outer sleeve and containment tube.

Irradiation of the 60 and 330°C capsules was started on July 17, 1990. As of September 30, 1992, these two capsules had completed 22 cycles of their planned 24-cycle (formerly 22-cycle) irradiation to a damage level of approximately 18.3 displacements per atom (dpa). Assembly of the 200 and 400°C capsules is scheduled for completion in November 1992; operation of these two capsules will follow the first two (60 and 330°C).

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2.1 NEUTRON DISPLACEMENT DAMAGE CROSS-SECTIONS **FOR** SiC -- Hanchen Huang and Nasr Ghoniem (University of California, Los Angeles) 29

Calculations of neutron displacement damage cross-sections for SiC are presented. We use Biersack and Haggmark's empirical formula in constructing the electronic stopping power, which combines the Lindhard's model at low PKA energies and the Bethe-Bloch's model at high PKA energies. The electronic stopping power for polyatomic materials is computed on the basis of Bragg's Additivity Rule. A continuous form of the inverse power law potential is used for nuclear scattering. Coupled intergro-differential equations for the number of displaced atoms j, caused by PKA i, are then derived. The procedure outlined above gives partial displacement cross-sections, displacement cross-sections lor each specie of the lattice, and for each PKA type. The corresponding damage rates for several fusion and fission neutron spectra are calculated. The stoichiometry of the irradiated material is investigated by finding the ratio of displacements among various atomic species. The role of each specie in displacing atoms is also investigated by calculating the fraction of displacements caused by each PKA type. The study shows that neutron displacement damage rates of *SiC* in typical magnetic fusion reactor first wall will be ~10-15 [dpa] $[MW]^{-1}[m]^2$, that in typical lead-protected inertial confinement fusion reactor first walls to be ~15-20 [dpa]$[MW]^{-1}[m]^2$. For fission spectra, we find that the neutron displacement damage rate of *SiC* is ~74 [dpa] per 10^{27} n/m^2 in FFTF. ~39 [dpa] per 10^{27} in HFIR, and 25 [dpa] per 10^{27} in NRU. Approximately 80% of displacement atoms are shown to be of the carbon-type.

2.2 TRANSMUTATION OF COPPER IN FFTF AND STARFIRE -- F.A. Garner and L.R. Greenwood (Pacific Northwest Laboratory) and F.M. Mann (Westinghouse Hanford Company) 42

Calculations of the transmutation of pure copper in the recent MOTA-2A out-of-core experiment yield somewhat different values than expected from previous calculations for earlier MOTA in-core experiments. The differences arise not only from position-dependent spectral variations but also from changes in neutron flux and spectrum associated with the placement of the CDE experiment in FFTF. In addition, there has been a re-evaluation of the cross-sections for transmutation. The resulting differences between the current and earlier predictions for the original FFTF core loading are that the zinc concentration is significantly higher and the nickel concentration is somewhat lower in the current calculation. Relative to the original core loading, however, the production rate per dpa of both nickel and zinc in the MOTA-2A experiment in the current core loading is increased due to spectral softening arising from both the new CDE core and the out-of-core location.

Although the nickel transmutation rate increases significantly in the STARFIRE first wall neutron spectrum. the nickel-to-zinc transmutation ratio is also reduced compared to that of previous calculations, with the difference arising only from the re-evaluation of the transmutation cross-sections.

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5.1 ANALYSIS OF DISPLACEMENT DAMAGE AND DEFECT PRODUCTION UNDER CASCADE DAMAGE CONDITIONS -- S.J. Zinkle (Oak Ridge National Laboratory and B.N. Singh (Riso National Laboratory) ... 55

The production, annihilation, and accumulation of point defects in metals during displacive irradiation is dependent on a variety of physical conditions. including the nature and energy of the projectile particles and the irradiation temperature. This paper briefly reviews the evolution of the defect population in an isolated displacement cascade, and outlines a proposed framework for identifying the relevant components of displacement damage and defect production under cascade damage conditions. The most significant aspect of energetic cascades is that the concepts of atomic displacements and residual defect production must be treated separately. an evaluation of experimental and computer defect production studies indicates that the overall fraction of defects surviving correlated annihilation in the displacement cascade in copper decreases from about 30% of the Norgett-Robinson-Torrens (NRT) calculated displacements at 4 K to about 10% of the NRT displacements at 300 K. Due to differences in the thermal stability of vacancy versus interstitial clusters, the fractions of freely migrating defects available for inducing microstructural changes at elevated temperates may be higher for vacancies than for interstitials. The available evidence suggests that the fraction of freely migrating vacancies at temperatures relevant for void swelling in copper *is* ~5% of the calculated NRT displacements.

5.2 THE RELATIONSHIP BETWEEN THE COLLISIONAL PHASE DEFECT DISTRIBUTION AND CASCADE COLLAPSE EFFICIENCY -- K. Morishita (U. Tokyo), H.L. Heinisch (Pacific Northwest Laboratory) and S. Ishino (U. Tokyo) **74**

Cascades produced in binary collision simulations of ion-irradiation experiments were analyzed to determine if a correlation exists between the defect distribution in the collisional phase and the number of visible clusters produced directly in cascades (caused by the so-called 'collapse" of the cascade defects). The densities of the vacancy distributions in the simulated cascades were compared to the measured cascade collapse efficiencies to obtain the minimum or "critical" vacancy densities required for collapse. The critical densities are independent of the cascade energy for self-ions and exhibit differences with ion mass that are consistent with the cascade energy dissipation characteristics

5.3 EFFECTS OF STRESS ON MICROSTRUCTURAL EVOLUTION DURING IRRADIATION -- D.S. Gelles (Pacific Northwest Laboratory) 79

Many theories have been postulated to describe irradiation creep but few have been supported with microstructural evidence. The purpose of this paper is to review microstructural studies of the effects of stress during irradiation in order to assess the validity of the available irradiation creep theories. Microstructural studies based on high voltage electron, ion, proton and neutron irradiation will be described, with major emphasis placed on interpreting behavior demonstrated in austenitic steels. Special attention will be given to work on fast neutron irradiated Nimonic PE16, a precipitation strengthened superalloy.

5.4 IRRADIATION CREEP DUE TO SIPA UNDER CASCADE DAMAGE CONDITIONS -- C.H. Woo (Whiteshell Laboratories), F.A. Garner (Pacific Northwest Laboratory) and R.A. Holt (Chalk River Laboratories) 93

This paper derives the relationships between void swelling and irradiation creep due to SIPA and SIG under cascade damage conditions in an irradiated pressurized tube. It is found that at low swelling rates irradiation creep is a major contribution to the total diametral strain rate of the tube, whereas at high swelling rates the creep becomes a minor contribution. The anisotropy of the corresponding dislocation structure is also predicted to decline as the swelling rate increases. The theoretical predictions are found to agree very well with experimental results.

5.5 SIMULATING HIGH ENERGY CASCADES IN METALS -- H.L. Heinisch (Pacific Northwest Laboratory) . . 101

The processes of radiation damage, from initial defect production to microstructure evolution, occur over a wide spectrum of time and size scales. An understanding of the fundamental aspects of these processes requires a spectrum of theoretical models, each applicable in its own time and distance scales. As elements of this multi-model approach, molecular dynamics and binary collision simulations play complementary roles in the characterization of the primary damage state of high energy collision cascades. Molecular dynamics is needed to describe the individual point defects in the primary damage state with the requisite physical reality. The binary collision approximation is needed to model the gross structure of statistically significant numbers of high energy cascades. Information provided by both models is needed for connecting the defect production in the primary damage state with the appropriate models of defect diffusion and interaction describing the microstructure evolution. Results of binary collision simulations of high energy cascade morphology are reviewed. The energy dependence of freely migrating defect fractions calculated in recent molecular dynamics simulations are compared to results obtained much earlier with a binary collision/annealing simulation approach. The favorable agreement demonstrates the viability of the multi-model approach to defect production in high energy cascades.

5.6 SWELLING OF PURE NICKEL OBSERVED IN THE SECOND DISCHARGE OF THE AA-14 EXPERIMENT -- F.A. Garner (Pacific Northwest Laboratory) 107

The swelling of neutron-irradiated pure nickel is strongly dependent on its tendency toward saturation. The factors which induce saturation also lead to a strong dependence on irradiation temperature for nickel in the annealed condition. When irradiated in the cold-worked condition, however, the temperature dependence of swelling is strongly reduced but the tendency toward saturation persists.

5.7 COMPLETION OF THE ORR/MFE-4 EXPERIMENT INVOLVING HIGH RATES OF HELIUM GENERATION IN Fe-Cr-Ni ALLOYS -- N. Sekimura (University of Tokyo) and F.A. Gamer (Pacific Northwest Laboratory) 109

Completion of the microscopy examination of the ORR/MFE-4 experiment confirms the conclusions reached earlier in this study. Helium generated at very high levels (~30 to 60 appm/dpa) does indeed strongly influence the microstructural evolution of Fe-Cr.-Ni austenitic alloys, especially when the temperature history involves a large number of low temperature excursions. Under these conditions the effect of composition and starting condition are relatively unimportant.

5.8 ^{59}Ni ISOTOPIC TAILORING EXPERIMENT: RESULTS OF TENSILE TESTS ON MOTA-1G SPECIMENS -- M.L. Hamilton and F.A. Garner (Pacific Northwest Laboratory) 115

Tensile tests have been conducted on the last two groups of isotopic tailoring specimens discharged from MOTA-1G. The results agree with those reported earlier, showing a very small impact of fusion-relevant helium/dpa levels on neutron-induced changes in tensile properties of three model austenitic alloys.

5.9 MICROSTRUCTURAL EVOLUTION IN IRRADIATED Fe-Cr-M ALLOYS; SOLUTE EFFECTS - D.S. Gelles (Pacific Northwest Laboratory) 118

A series of alloys based on Fe-10Cr with solute additions of silicon, vanadium, manganese, tungsten, tantalum, and zirconium at 0.1 and 1.0% levels, has been examined by transmission electron microscopy following fast neutron irradiation. Marked differences in dislocation evolution and void shape following neutron irradiation were found as a function of alloying. The present study extends previous examinations by investigating microstructural response following irradiation at a lower temperature (365°C) to 30 dpa and to a higher dose, 100 dpa, at 410°C. Swelling level, void shape, and dislocation configuration continued to vary as a function of the various solutes present in the same manner as seen previously. However, two additional observations were made. Irradiation at the lower temperature promotes precipitation of chromium rich a phase and reduces microstructural evolution. Also, irradiation to higher dose, reduces the effect each solute exerts by lessening the wide variation in void shape and dislocation evolution that were found at lower dose.

5.10 POSTIRRADIATION DEFORMATION BEHAVIOR IN FERRITIC Fe-Cr ALLOYS -- M.L. Hamilton and D.S. Gelles (Pacific Northwest Laboratory) and P.L. Gardner (University of Missouri-Rolla) 131

It has been demonstrated that fast neutron irradiation produces significant hardening in simple Fe (318) Dr binary alloys irradiated to about 35 dpa in the temperature range 365 to 420°C, whereas irradiation at 574°C produces hardening only for 15% or more chromium. The irradiation-induced changes in tensile properties are discussed in terms of changes in the power law work hardening exponent. The work hardening exponent of the lower chromium alloys decreased significantly after low temperature irradiation (≤ 420°C) but increased after irradiation at 574°C. The higher chromium alloys failed either in cleavage or in a mixed ductile/brittle fashion. Deformation microstructures are presented to support the tensile behavior.

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6.1.1 CHARPY IMPACT TOUGHNESS OF MARTENSITIC STEELS IRRADIATED IN FFTF: EFFECT OF HEAT TREATMENT -- R.L. Klueh and D.J. Alexander (Oak Ridge National Laboratory) 141

Plates of 9Cr-1MoVNb and 12Cr-1MoVW steels were normalized and then tempered at two different tempering conditions. One-third-size Charpy specimens from each steel were irradiated to $7.4\text{-}8 \times 10^{26}$ n/m^2 (about ~35 dpa) at 420°C in the Materials Open Test Assembly (MOTA) of the Fast Flux Test Facility. Specimens were also thermally aged to 20,000 h at 400°C to compare the effect of aging and irradiation. Previous work on the steels irradiated to 4-5 dpa at 365°C in MOTA were reexamined in light of the new results. The tests indicated that prior-austenite grain size, which was varied by different normalizing treatments, had an effect on impact behavior of the 9Cr-1MoVNb but not on the 12Cr-1MoVW. Tempering treatment had relatively little effect on the shift in DBTT for both steels. Conclusions are presented on how heat treatment can be used to optimize properties.

6.1.2 RELATIONSHIP OF BAINITIC MICROSTRUCTURE TO IMPACT TOUGHNESS IN Cr-Mo AND Cr-W STEELS -- R.L. Klueh and D.J. Alexander (Oak Ridge National Laboratory) 151

Non-classical bainite microstructures can develop during continuous cooling of low-carbon alloy steels. These differ from classical upper and lower bainite developed by isothermal transformation. Two non-classical bainite microstructures were produced in a 3 Cr-1.5Mo-0.25V-0.1C steel using different cooling rates after austenitizing-water quenching and air cooling. The carbide-free acicular bainite formed in the quenched steel had a lower ductile-brittle transition temperature (DBTT) than the granular bainite formed in the air-cooled steel. With increasing tempering parameter, the DBTT of both decreased and approached a common value, although the final value occurred at a much lower tempering parameter for the quenched steel than for the air-cooled steel. The upper-shelf energy was similarly affected by microstructure. These observations along with similar observations in two Cr-W steels indicate that control of the bainite microstructure can be used to optimize strength and toughness.

6.1.3 REDUCED ACTIVATION FERRITIC ALLOYS FOR FUSION -- D.S. **Gelles** (Pacific Northwest Laboratory) 157

Reduced activation martensitic alloys can now be developed with properties similar to commercial counterparts, and oxide dispersion strengthened alloys are under consideration. However, low chromium Bainitic alloys with vanadium additions undergo severe irradiation hardening at low irradiation temperatures and excessive softening at high temperatures, resulting in a very restricted application window. Manganese additions result in excessive embrittlement. as demonstrated by post-irradiation Charpy impact testing. The best composition range for martensitic alloys appears to be 7 to 9 Cr and 2 W, with swelling of minor concern and low temperature irradiation embrittlement perhaps eliminated. Therefore, reduced activation martensitic steels in the 7 to 9 Cr range should be considered leading contenders for structural materials applications in power-producing fusion machines.

6.1.4 MECHANICAL PROPERTIES OF MARTENSITIC ALLOY AISI 422 -- M.L. Hamilton (Pacific Northwest Laboratory) and F.H. Huang and W. Hu (Westinghouse Hanford Company). 168

Ht9 is a martensitic stainless steel that has been considered for structural applications in liquid metal reactors (LMRs) as well as in fusion reactors. AISI 422 is a commercially available martensitic stainless steel that closely resembles HT9, and was studied briefly under the auspices of the U.S. LMR program. Previously unpublished tensile, fracture toughness and charpy impact data on AISI 422 were reexamined for potential insights into the consequences of the compositional differences between the two alloys, particularly with respect to current questions concerning the origin of the radiation-induced embrittlement observed in HT9.

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No Contributions

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6.3.1 STATUS OF THE DYNAMIC HELIUM CHARGING EXPERIMENT (DHCE)' -- B.A. Loomis and D.L. Smith (Argonne National Laboratory), H. Matsui (Tohoku University), M.L. Hamilton (Pacific Northwest Laboratory), K.L. Pearce (Westinghouse Hanford Company), J.P. Kopasz and C.E. Johnson (Argonne National Laboratory), R.G. Clemmer and L.R. Greenwood (Pacific Northwest Laboratory) 179

This report summarizes the status of the DHCE in FFTF-MOTA. the preparations for retrieval of specimens from the irradiation capsules. and experimental results on procedures for the removal of tritium from the irradiated specimens.

6.3.2 HYDROGEN EMBRITTLEMENT OF NIOBIUM-BASE ALLOYS FOR APPLICATION IN THE ITER DIVERTOR' -- D.T. Peterson (Iowa State University), and A.B. Hull, B.A. Loomis (Argonne National Laboratory) 182

The corrosion rate of Nb alloys in high-purity water was demonstrated to be quite low at 300°C and only a fraction of the hydrogen (H) produced by corrosion was absorbed. The calculated H concentrations in an ITER divertor plate are below levels expected to cause embrittlement.

Corrosion, H absorption, and resistance to embrittlement of NB can be significantly improved by alloying. Alloying of Nb can increase the terminal solid solubility of H in Nb-V alloys. Consequently, alloying NB with V reduces the embrittlement caused by H. Hence, there appear to be good prospects for increasing the solubility of the hydride phase and of increasing the tolerance for H by developing appropriate NB alloys. Thermotransport of H may perturb H concentration and thus needs further evaluation.

6.3.3 TENSILE PROPERTIES OF VANADIUM-BASE ALLOYS WITH A TUNGSTEN/INERT-GAS WELD ZONE' -- B.A. Loomis, C.F. Konicek. L.J. Nowicki, and D.L. Smith (Argonne National Laboratory) 187

The tensile properties of V-(0-20)Ti and V-(O-15)Cr-5Ti alloys after butt-joining by tungsten/inert-gas (TIG) welding were determined from tests at 25°C. Tensile tests were conducted on both annealed and cold-worked materials with a TIG weld zone. The tensile properties of these materials were strongly influenced by the microstructure in the heat-affected zone adjacent to the weld zone and by the intrinsic fracture toughness of the alloys. TIG weld zones in these vanadium-base alloys had tensile properties comparable to those of recrystallized alloys without a weld zone. Least affected by the TIG welding were tensile properties of the V-5Ti and V-5Cr-5Ti alloys. Although the tensile properties of the V-5Ti and V-5Crf-5Ti alloys with a TIG weld zone were acceptable for structural material, these properties would be improved by optimization of the welding parameters for minimum grain size in the heat-affected zone.

6.3.4 EFFECTS OF IRRADIATION-INDUCED PRECIPITATION ON PROPERTIES OF VANADIUM ALLOYS -- H.M. Chung (Argonne National Laboratory) 194

Two major and two minor types of irradiation-induced precipitates were identified in V-Ti, V-Cr-Ti, and V-Ti-Si alloys after neutron irradiation in the Fast Flux Test Facility (FFTF) at 420 and 600°C to fluences up to 114 dpa. The major precipitates are Ti_5Si_3 and Ti20 phases. Effects of irradiation temperature and dose on the two major types of precipitation were examined after irradiation at 420, 600, and 600°C plus an excursion to 850°C for 50 min. Precipitation of the very fine Ti_5Si_3 particles at 420°C increases monotonically with increasing dose, whereas at 600°C the maximum precipitation occurs at –20-40 dpa. The characteristic precipitation kinetics were consistent with swelling and elongation behavior observed for the low and high irradiation temperatures. For operation at 420°C. it is important to optimize the Si level and ensure sufficient Ti "in solution" (i.e., Ti solutes not bound to thermal precipitates), and thereby optimizing the precipitation of Ti_5Si_3. For operation at 600°C, minimizing the O content. in addition to Si and Ti control, is important in minimizing Ti_2O precipitation.

6.3.5 PRELIMINARY ASSESSMENT OF CANDIDATE NIOBIUM ALLOYS FOR DIVERTOR STRUCTURES -- J.A. Todd (Illinois Institute of Technology) and I.M. Purdy (Argonne National Laboratory) 203

Corrosion rates of several Nb-base alloys that contain –2.5 at. % Zr, V, Hf, Ti, Ta, Mo, or W were determined in HP deoxygenated water at 300°C. Microstructural characteristics of the corrosion-product layers were examined by optical and scanning electron microscopy (SEM). Although the weight-gain corrosion rates were not excessive wand only a fraction (<20%) of the hydrogen liberated by the overall corrosion reaction was absorbed by the alloys, most of the alloys were deemed to be brittle, i.e., fracture occurred during a 90° bend test. The microstructural evaluations revealed numerous cracks and spalling of the oxide layers; this is characteristic of nonprotective film formation. Some of the crack surfaces in the alloys were covered by corrosion product, indicating that the cracks formed during exposure to high-temperature water. The presenl results suggest that Nb alloys with higher concentrations of alloying elements are required to improve the protective nature of the corrosion-product layers and to decrease hydrogen uptake and embrittlement. Procurement of candidate alloys is in progress and corrosion/H_2-embrittlement tests will be conducted at lower temperatures to determine material operating conditions that will lead to adequate performance of alloys as structural materials in the ITER divertor.

6.3.6 CREEP OF V-5Cr-5Ti AND V-10Cr-5Ti ALLOYS AT 600°C -- B.A. Loomis, L.J. Nowicki, and D.L. Smith (Argonne National Laboratory) 214

Creep tests were conducted on V-5Cr-5Ti and V-10Cr-5Ti alloys at 600°C. The results of these tests show that the V-10Cr-5Ti alloy has significantly higher creep strength than the V-5Cr-5Ti alloy.

6.3.7 RELATIONSHIP OF HARDNESS AND TENSILE STRENGTH OF VANADIUM AND VANADIUM-BASE ALLOYS -- B.A. Loomis, J. Gazda. L.J. Nowicki, and D.L. Smith (Argonne National Laboratory) 217

The Vickers hardness numbers (VHNs) of annealed and recrystallized vanadium and V-(0-15)Cr-(0-5)Ti-(0-1)Si alloys were determined at 25°C. The relationship between the VHN and the tensile strength of these materials previously reported by Loomis et al. are presented in this report. These results show that the VHN, yield strength (YS), and ultimate tensile strength (UTS) of V-(0-15)Cr-5Ti alloys at 25°C have a similar dependence on Cr concentration and that the VHN, YS, and UTS of V-(0-20)Ti alloys at 25°C have a similar dependence on Ti concentration. On the basis of these results and the small size of the test specimen, it is recommended that the Vickers hardness test be utilized in the vanadium alloy development program to determine the effects of thermal-mechanical treatment, impurities (i.e., O, N, C, H, and Si), and irradiation on tensile properties of vanadium-base alloys.

6.3.8 CORRELATION OF MICRO STRUCTURE AND MECHANICAL PROPERTIES OF VANADIUM-BASE ALLOYS -- J. Gazda and S. Danyluk (University of Illinois at Chicago) and B.A. Loomis and D.L. Smith (Argonne National Laboratory) 222

The mechanical properties and microstructure of V, V-3Ti-1Si, and V-5Ti alloys were investigated by microhardness testing, optical microscopy, and transmission electron microscopy (TEM). The microhardness data were related to tensile test data reponed by Loomis et al. The microhardness and tensile strength of these materials were related to the number density of precipitates. The most common precipitates were identified as: V6O13 and VS4 for vanadium; Ti(C,N,O) and various forms of Ti-S for V-3Ti-1Si; Ti(C,N,O) and TiN for V-5Ti. The crystallographic lattice parameters for these alloys were determined by X-ray diffraction.

6.3.9 EFFECTS OF IMPURITIES AND DOPING ELEMENTS ON PHASE STRUCTURE OF VANADIUM-BASE ALLOYS CONTAINING TITANIUM -- M. Satou (Tohoku University) and H.M. Chung (Argonne National Laboratory) 227

The thermal phase structure of vanadium-base alloys that contain Ti is strongly influenced by impurities. When the combined concentration of O, N, and C is >500 wt. ppm, Ti solutes form blocky Ti(O,N,C) precipitates during fabrication. When the O+N+C level is 400 wt. ppm. the Ti(O,N,C) phase is absent. With Si and Y in the alloy. Ti solutes form Ti_5Si_3 and $(Y,Si_{1-x})_2O_3$ precipitates. A low impurity concentration and Y doping promote preservation of Ti atoms in solution. Swelling of V-5Cr-5Ti specimens doped with Si, Y, and Al was low after irradiation at 406 and 600°C. The excellent resistance to swelling is attributed to dense distribution of ultrafine Ti_5Si_3 and Y_2O_3-like precipitates that are formed during irradiation and provide a large number of sinks for vacancies; and hence, they effectively suppress nucleation of voids during irradiation.

6.3.10 INFLUENCE OF BORON-GENERATED HELIUM ON THE SWELLING OF NEUTRON-IRRADIATED PURE VANADIUM AND VANADIUM-5% CHROMIUM -- N. Sekimura (University of Tokyo) and F.A. Garner (Pacific Northwest Laboratory) 235

In agreement with earlier reports. the addition of five weight percent chromium to pure vanadium leads to a significant increase in neutron-induced void swelling at 600°C. Although the swelling of V-5Cr increases strongly with irradiation temperature. the influence of chromium is reversed at lower temperatures, with pure vanadium swelling more than V-5Cr. The use of boron additions to generate large amounts of helium in V and V-5Cr leads to a very complex swelling response, depending on boron level, chromium level and irradiation temperature. The most pronounced response occurs in V-5Cr at 600°C, where boron levels of 100 appm or greater cause a significant reduction in swelling. The complexity of swelling response is thought to result from the competition between helium effects and the separate chemical effects of boron and lithium, each of which may exhibit its own dependence on irradiation temperature.

6.3.11 COMPATIBILITY OF VANADIUM ALLOYS WITH REACTOR-GRADE HELIUM FOR FUSION REACTOR APPLICATIONS -- G.E.C. Bell and P.S. Bishop (Oak Ridge National Laboratory) 238

Miniature tensile specimens of V-5Cr-5Ti, V-10Cr-5Ti, and V-12.5Cr-5 Ti were exposed in a once-through system to helium with 70 vppm-H_2 (measured oxygen partial pressures of 10^{-12} atm) and bottle helium (measured oxygen partial pressures of 10^{-4} atm) between 500 and 700°C for up to 1008 h. The weight changes in the specimens were recorded. The helium-exposed specimens were tensile tested, and the effects of exposure on mechanical properties were assessed. Exposure between 500 and 700°C for 1008 h in He+70 vppm-H_2 resulted in complete embrittlement of all the alloys in room temperature tensile tests. The fracture mode was primarily cleavage, probably caused by a hydrogen-induced shift in the ductile to brittle transition temperature (DBTT). Weight gains increased with temperature and were largest for the V-5Cr-5Ti alloy. Specimens exposed for 531 h between 500 and 700°C in bottle He exhibited two distinct fracture morphologies on the fracture surfaces. Brittle cleavage around the edges of the specimens gave way to ductile dimpling in the center of the specimens. The brittle region around the periphery of the specimen is most likely the higher vanadium oxide, V_2O_5.

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6.4.1 SWELLING OF COPPER ALLOYS IRRADIATED IN MOTA 2A -- F.A. Garner (Pacific Northwest Laboratory), D.J. Edwards (University of Missouri-Rolla), B.N. Singh (Riso National Laboratory) and H. Watanabe (Kyushu University) 253

Density measurements have been completed on copper alloys irradiated in MOTA 2A at (375°C, 12.7 dpa) and (423°C, 48.0 dpa). While most of the density changes observed are consistent with those of earlier studies, there were several surprises. The role of cold work on swelling of Cu-5Ni is relatively small and Cu-5Mn does not appear to swell at all.

6.4.2 COBRA-1A COPPER IRRADIATION EXPERIMENT IN EBR-II --F.A. Garner and M.L. Hamilton (Pacific Northwest Laboratory) 255

Specimen preparation for copper alloys to be irradiated in EBR-II Run 162 in the COBRA irradiation vehicle is complete. Specimens include TEM disks, miniature tensile and miniature fatigue specimens.

6.4.3 THE INFLUENCE OF TRANSMUTATION AND VOID SWELLING ON THE ELECTRICAL PROPERTIES OF COPPER AND SEVERAL COPPER ALLOYS -- D.J. Edwards (University of Missouri-Rolla) and F.A. Garner (Pacific Northwest Laboratory) 258

A comparison of the predicted and measured electrical conductivities of MARZ copper wand two copper alloys irradiated in FFTF shows that the calculated transmutation rates are ~15% higher than those required to produce the observed changes. It also appears that the contribution of transmutants and void swelling to conductivity changes are directly additive. Of the several models available, Euken's model has been found to best describe the contribution of void swelling.

6.4.4 STATUS OF LOW CYCLE FATIGUE STUDIES ON IRRADIATED COPPER -- F.A. Garner (Pacific Northwest Laboratory), B.N. Singh (Riso National Laboratory) and J.F. Stubbins (University of Illinois) ... 265

A joint irradiation program is being conducted by the Riso National Laboratory, Pacific Northwest Laboratory and the University of Illinois to study the influence of neutron irradiation on the low cycle fatigue behavior of copper alloys. This program is directed toward both NET and ITER goals. Radiation is proceeding on miniature specimens in the DR-3 reactor in Riso. and identical specimens have been prepared for the COBRA-1A experiment in EBR-II. A size effect study on unirradiated specimens is in progress.

6.5 ENVIRONMENTAL EFFECTS IN STRUCTURAL MATERIALS 267

6.5.1 DEVELOPMENT OF ELECTRICAL INSULATOR COATINGS FOR LIQUID-METAL BLANKET APPLICATIONS -- J.H. Park, M.R. Fox, and G. Dragel (Argonne National Laboratory) 269

Based on a preliminary survey of more than 15 oxides and nitrides, four ceramic materials (CaO, MgO, Y_2O_3, and BN) were identified as candidates for insulator coating development. These compounds were fabricated by various techniques and exposed to flowing Li at 400-410" to assess chemical compatibility. Yttrium oxide exhibited excellent corrosion resistance in flowing liquid Li at 400°C; its corrosion rate was calculated to be 0.042 µm/hr. Resistivity measurements by a standard four-probe method on Y_2O_3 in air at temperalures between –450 and 1000°C. before and after exposure to Li for 675 h at 410°C, indicated no deterioration in resistivity. The resistivity of in-situ-formed $(V,Ti)_xN$ reaction-product layers on V-20Ti and TiN on Ti was determined at room temperature and 80°C by a two-probe method. The resistivity of the film on the V-20Ti alloy was low (–20 Ωm) and the film on Ti exhibited metallic conduction. Adhesion bonding between Y_2O_3 and Y, V, Ti, Y, V-20Ti, V-3Ti-1Si, and Types 304 and 316 stainless steel was investigated in reducing and oxidizing gaseous environments at 927°C. Except for the V-20Ti alloy, the V-base alloys, Ti, and Type 304 stainless steel were well bonded to Y_2O_3 in the reducing atmosphere. In the oxidizing atmosphere, bond regions of Types 304 and 316 stainless steel were better than in the reducing atmosphere because of reaction between the oxide scale on the steels (Cr_2O_3) and Y_2O_3 to form $YCrO_3$. Neither V, Ti, nor the V-alloys bonded with Y_2O_3. These results suggest that a low-melting eutectic layer forms between Y_2O_3 and the oxides layers present on V, Ti, and V-alloys.

6.5.2 AQUEOUS STRESS CORROSION OF CANDIDATE AUSTENITIC STEELS FOR ITER STRUCTURAL APPLICATIONS -- D.M. French, W.K. Soppet, and T.F. Kassner (Argonne National Laboratory) 276

Susceptibility of Types 316NG and sensitized 304 stainless steels (SS) to SCC was investigated at temperatures of 60-289°C in slow-strain-rate-tensile (SSRT) tests in oxygenated water that simulates important parameters anticipated in first-wall/blanket systems. Several additional SSRT tests were performed on crevice specimens of Type 316NG SS in oxygenated water containing 100 ppb sulfate at steel exhibits good resistance to SCC under crevice and noncrevice conditions at temperatures <150°C in a nominal ITER coolant chemistry. In contrast, sensitized Type 304 SS exhibited intergranular stress corrosion cracking (IGSCC) at <100°C under crevice conditions. SSRT tests have been conducted on weldment specimens of Type 316L SS with matching filler metal under crevice conditions in oxygenated water containing 0.06-6.0 ppm chloride at 150-225°C. Most specimens fractured in the base metal, and several others fractured in the heat-affected zone (HAZ) of the weld, but none failed in the weld metal.

6.5.3 DEVELOPMENT OF IN-SITU-FORMED ELECTRICAL INSULATOR COATINGS ON HIGH-TEMPERATURE ALLOYS IN LITHIUM -- J.-H. Park and G. Dragel (Argonne National Laboratory) 285

Various intermetallic films were produced on vanadium, vanadium-base alloys, and Types 304 and 316 stainless steel (SS) by exposing the materials to liquid- and/or vapor-phase lithium containing dissolved elements (3-5 at. %) in sealed capsules at temperatures between 600 and 775°C. After each test, the capsules were opened and the samples were examined by optical and scanning electron microscopy; they were then analyzed by electron-energy-dispersive and X-ray diffraction techniques. The nature of the coatings. i.e., surface coverage, thickness, and composition, varied with exposure time and temperature, solute in lithium, and alloy composition. Solute elements that yielded adherent coatings on various substrates provide a means of developing in-situ electrical insulator coatings by oxidation of the reactive layers with dissolved oxygen andlor nitrogen in liquid lithium.

6.5.4 ELECTRICAL INSULATOR COATINGS FOR LIQUID-METAL BLANKET APPLICATIONS-YTTRIA COATING ON VANADIUM -- M.R. Fox and J.-H. Park (Argonne National Laboratory) 290

Research has been conducted to develop a diffusion coating of Y_2O_3 on the surface of V, which could help eliminate the MHD effect. The process involves yttriding, in which a diffusion coating of Y is formed on the surface of V by immersing the samples in a molten salt and applying a potential. The yttrium layer can then be oxidized to form the electrical insulator Y_2O_3. An yttrium coating up to 10 µm in thickness with a diffusion zone of –1 µm has been produced.

7.0 SOLID BREEDING MATERIALS AND BERYLLIUM 295

7.1 TRITIUM RELEASE FROM CERAMIC BREEDER MATERIALS -- J.P. Kopasz. C.A. Sells, and C.E. Johnson (Argonne National Laboratory) 297

Lithium aluminate is an attractive material (in terms of its chemical, mechanical. and irradiation properties) for breeding tritium in fusion reactors; however, its tritium release characteristics are not as good as those of other candidate materials. To investigate whether tritium release from lithium aluminate can be improved, we have studied tritium release from irradiated samples of lithium aluminate, lithium aluminate doped with magnesium, and lithium aluminate with a surface deposit of platinum. The release was studied using the Temperature Programmed Desorption (TPD) method. Both the platinum coating and magnesium doping were found to improve the tritium release characteristics as determined by TPD. Tritium release shifted to lower activation energies for the altered materials. In addition, information gained from the TPD experiments on the pure material were used to improve our tritium release model. The new model containing no adjustable parameters was used to successfully model in-pile tritium release from $LiAlO_2$.

7.2 TRITIUM MODELING/BEATRIX-II DATA ANALYSIS* -- M.C. Billone, H. Attaya, C.E. Johnson, and J.P. Kopasz (Argonne National Laboratory) 302

Models have been developed to describe the tritium transport in Li_2O. The mechanisms considered are bulk diffusion, surface desorption, surface adsorption, and solubility. These models have been incorporated into the TIARA steady-state inventory code and the DISPL2 steady-state and transient code. Preliminary validation efforts have focused on the inventory and tritium release rate data from in-reactor, purge-flow tests VOM-15H, EXOTIC-2, CRITIC-1, and MOZART. The models and validation effort are reported in detail in ANL/FPP/TM-260. Since the BEATRIX-II data were released officially in November 1991, validation efforts have been concentrated on the tritium release rate data from the "isothermal' thin-ring sample. In this report, results are presented for the comparison of predicted long-time inventory changes (in response to temperature and hydrogen purge pressure changes) to values determined from the tritium release data.

7.3 DESORPTION CHARACTERISTICS OF THE Li_2O SYSTEM' -- A.K. Fischer and C.E. Johnson (Argonne National Laboratory) 305

Preparations were completed for temperature programmed desorption (TPD) measurements of the kinetics of desorption from the D_2-H_2-HD-HDO-H_2O-Li_2O system. These preparations consisted of a series of blank and calibrating runs to determine the effects of the empty sample tube on the TPD spectra dn to calibrate the mass spectrometer for the gaseous species of interest. Data from the blank tube runs revealed the importance of isotope exchange reactions in interpreting desorption data. A preliminary examination was made of the raw spectra of desorption from Li_2O that had been treated with Ar-D_2 (921 vppm) at temperatures of 374, 673,873. and 1108 K (200,400,600, and 835°C). The TPD spectra appear to contain fewer peaks than were observed earlier for $LiAlO_2$.

7.4 TRITIUM TRANSPORT IN SINGLE CRYSTAL $LiAlO_2$ – J.P. Kopasz. C.A. Sells, and C.E. Johnson (Argonne National Laboratory) 308

Tritium transport in $LiAlO_2$ has been studied by performing isothermal anneals followed by sectioning of the sample to determine the tritium concentration profiles within the sample. The anneals were performed over the 528 to 783°C temperature range under a He + 0.1% H_2 purge gas flow. The results indicate that: (1) tritium diffusion in $LiAlO_2$ is fast, and is not sensitive to impurities, and (2) tritium release for these samples is in the mixed diffusion-desorption regime. For samples with a grain size of 100 µm or less, the tritium release will be desorption controlled.

7.5 NEUTRON IRRADIATION OF BERYLLIUM: RECENT RUSSIAN RESULTS -- D.S. Gelles (Pacific Northwest Laboratory) 312

Results on postirradiation tensile and compression testing, swelling and bubble growth during annealing for various grades of beryllium are presented. It is shown that swelling at temperatures above 550°C is sensitive to material condition and response is correlated with oxygen content. Swelling on the order of 15% can be expected at 700°C lor doses on the order of 10^{22} n/cm^2. Bubble growth response depends on irradiation fluence.

8.0 CERAMICS 319

8.1 MEASUREMENT OF ELECTRICAL AND OPTICAL PROPERTIES OF DIELECTRIC MATERIALS DURING NEUTRON IRRADIATION -- E.H. Farnum, F.W. Clinard, Jr.. J.C. Kennedy III, W.F. Sommer. and W.P. Unruh (Los Alamos National Laboratory) 321

An irradiation experiment was carried out during the summer of 1992 at the Los Alamos Spallation Radiation Effects Facility (LASREF). *In situ* measurements of electrical conductivity in alumina, sapphire and mineral-insulated electrical cables were made at 640°C, 590°C and 400°C. Both DC and AC (100 Hz Io 1 MHz) measurements were made Io a fluence of approximately 2 x 10^{23} n/m^2. Optical absorption from 200 nm Io 800 nm was measured in pure silica- and OH-doped silica-core optical fibers during the irradiation. A large number of passive samples were included in the irradiation, some at the furnace temperatures and some at ambient temperature. Data is being analyzed during the first quarter of FY93. All samples will be recovered for post-irradiation examination during the second quarter of FY93.

8 2 THE EFFECT OF VACANCIES ON THE THERMAL CONDUCTIVITY OF SINGLE CRYSTAL ALUMINA (SAPPHIRE) AT LOW TEMPERATURES -- D P White (Oau R.dge hationa Laboratory) **326**

The effect of radiation on Ine thermal conduct v ty 01 a umina is an important design considerat on n the development *of* microwave winoows lor ion cyclotron resonance heating (ICRH) systems for tne heating *of* plasmas n fus.on reactors Severa recent papers have aodresseo this quest on at nigner temperalures and tne present report extends the ca cu ation of tne effect of point defects to low temperatures Tnis extens on of the calcu at ons to ow temperatures is 01 interest oecause it nas oeen proposed Io cool tnese winoows lo quid n trogen temperatures n order to taue advantage *of* the much higher therma conductiv ty 01 alum na at tnese temperatures

8.3 FATIGUE CRACK GROWTH OF SiC/SiC AT 1100°C -- R.H. Jones and C.H. Henager, Jr. (Pacific Northwest Laboratory) 330

Fatigue crack growth tests have been conducted on a SiC/SiC composite at 1100°C and a stress intensity ratio of 0.1. Tests were conducted in pure Ar and Ar + 2000 ppm O_2 to determine the effects of an oxidizing environment. The crack growth rate-stress intensity relationship exhibits a K independent regime, stage II, which is not exhibited in monolithic ceramics. The crack velocity in this stage II regime ranged from a low 01 10^{-8} m/s to a high 01 10^{-7} *m/s.* Cyclic stresses were found to decrease the crack velocity relative to static loads while oxygen increased the crack velocity. Both effects are consistent with a model developed to describe the subcritical crack growth of these materials where the fibers bridging the crack wake produce crack closure forces which reduce the crack tip K value. The decrease in crack velocity with cyclic loading resulted primarily from the longer hold-times at a given K value without any apparent cyclic damage. Based on these tests and other published data, cyclic stresses may not pose a fatigue concern lor SiC/SiC if the stresses are below the proportional limit and the stress or stress intensity ratio is >0 and tension-tension. Further tests are in progress to evaluate the effect of hold-time on crack growth rates in SiC/SiC.

8.4 RADIATION ENHANCED CONDUCTIVITY IN SILICON CARBIDE MATERIALS -- L.L. Snead (Oak Ridge National Laboratory), Matthew Ohland (Rensselaer Polytechnic Institute) and Roger A. Vesey (Rensselaer Polytechnic Institute) **341**

The radiation enhanced conductivity (REC) in four types of silicon carbide based materials was measured. As expected, the material with the highest initial conductivity showed the lowest conductivity enhancement. Chemically vapor deposited material showed only a few percent change at ionizing fluxes of several Gy/s. Two materials with higher initial resistivities demonstrated significant REC, the highest resistivity of the two changing by more than a factor of thirty for a dose of 4.2 Gy/s.