



Alloy Development for Irradiation Performance

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U.S. Department of Energy
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CONTENTS

FOREWORD. iii

1. ANALYSIS AND EVALUATION STUDIES. 1

1.1 Ferritic Stainless Steels for Fusion Applications
(General Atomic Company). 2

The *magnetics aspects* of utilizing ferromagnetic *martensitic* stainless steels as structural materials for *tokamak* reactors were studied by analytical means. For purposes of solving the associated non-linear *3-dimensional magnetostatic* field problems a computer program based on an integral equation method was implemented. The program was primarily geared for geometries that are envisioned in connection with the future design of *martensitic* steel blankets of *tokamak* fusion reactors. The field perturbations and magnetic loads due to both toroidal and poloidal currents were computed and discussed.

Essentially the solutions are obtained by discretizing only the *magnetized* body and solving the associated linearized equations iteratively by matrix inversion for each improved value of the magnetizing vectors and susceptibilities.

The results show that the field perturbations caused by the magnetization of the blanket are in general small within the plasma region. This is due to the high degree of saturation which makes the effective permeability to approach that of vacuum. A further small decrease in permeability is caused by the poloidal field *excited* by field control and plasma *currents*. The largest perturbations which appear in the region of blanket *penetrations*, that is port holes for fueling, diagnostics, etc., are still small, particularly when the penetrations are midway between the toroidal coils. The *cylindrical* structures analyzed tend to be self-supporting and the forces create pressures of the order of a few atmospheres. All the results indicate that the use of magnetic materials in fusion reactors should not present any feasibility *questions*. The effects introduced by the magnetic blanket structure can be countered by proper engineering design and selection of control parameters.

2. TEST MATRICES AND TEST METHODS DEVELOPMENT. 15

2.1 Application of the Electropotential Technique to *J-Integral*
Measurements (Hanford Engineering Development Laboratory) 16

The *electropotential* technique has been applied to develop single specimen *J-integral* measurement *capability*. Calibration curves for voltage change versus crack extension have been obtained at room temperature. Using these calibration curves, *J* versus Δa curves were generated at

room temperature from single *specimens* of A286 and HT9. These curves compare *favorably* with multiple specimen results on the same materials. Based on these encouraging results, irradiation test matrices *can be* formulated to provide *approximately* five times as many fracture toughness measurements for a *given* test volume than with the multiple *specimen* technique.

- 2.2 Development of the Miniature Fatigue Crack Growth Machine (Hanford Engineering Development Laboratory). 29

A baseline study of Path A, Path E, and Path D alloys has been initiated. Results of ambient temperature fatigue crack *growth* testing on 20% CW 316 SS, alloys E1, B2, B3, B4, B6 and HT-9 are presented. The miniature fatigue machine designed as a prototype for high volume low cost, *in-cell* operation was used for testing these *alloys*. Elevated temperature tests performed on Path A 316 SS at 260°C and 595°C are compared with results of other *investigators*.

- 2.3 Elevated Temperature Fatigue Crack Propagation Testing of 2.54 mm Thick CT Specimens (Naval Research Laboratory) . . . 43

Elevated temperature fatigue crack propagation tests were conducted to determine the nature of specimen thickness effects in preparation for *postirradiation* testing. The results show that the crack propagation rate in 2.54 mm (0.10 *in.*) thick Type 316 stainless steel was in agreement with results produced by conventional crack propagation specimens at 593°C.

- 2.4 Design and Construction of Irradiation Experiments in the ORR Using Spectral Tailoring and Reencapsulation (Oak Ridge National Laboratory). 47

The design for ORR-MFE-4 is now complete, and parts are being machined. Fine tuning calculations are being made to determine the optimum time for removing the first core piece. *Neutronics* calculations will continue as dosimetry data become available during the irradiation of ORR-MFE-4. Specimen fabrication is also under way.

- 2.5 Results of Prototypic Testing for the MFE-5 In-Reactor Fatigue Crack Propagation Experiment (Hanford Engineering Development Laboratory). 50

Prototypic testing of key components of the in-reactor fatigue crack propagation *experiment* has been completed. A prototypic pressurization system, designed to actuate a specimen chain by cycling the pressure inside of a bellows, has been demonstrated. Chains of miniature center-cracked-tension specimens were tested on a conventional MTS machine to investigate the viability of chain testing. The results of each chain test adequately define one crack growth curve. *When* only the initial and final crack length values are known, the same crack growth curve can be constructed through statistical analysis.

- 2.6 Miniature Tensile Testing (Hanford Engineering Development Laboratory). 66

The apparatus and *techniques* required to carry out postirradiation tensile tests on *miniaturized* wire specimens have been *developed* and tested. Results of tests on nine AISI 316 stainless steel wire *specimens* demonstrate that the test *machine* operates in a reproducible manner and that the specimen geometry yields results comparable to conventional specimens.

This report will briefly describe the *apparatus*, specimen geometry and preliminary test results.

3. PATH A ALLOY DEVELOPMENT - AUSTENITIC STAINLESS STEELS. 79

- 3.1 Fatigue Behavior of 20%-Cold-Worked Type 316 Stainless Steel After Irradiation in the HFIR (Oak Ridge National Laboratory). 80

Work is now in progress to *extend* our previously reported fatigue data to the high-cycle regime. We have tested control specimens before testing irradiated specimens. Data from the high-cycle tests correlate well with low-cycle strain controlled data for control *specimens*.

- 3.2 Fabrication of Homogeneous Path A Prime Candidate Alloy (Oak Ridge National Laboratory). 83

Previous work identified inhomogeneity in the as-received Path A Prime Candidate Alloy (PCA) plate stocks (and probably other finished forms as *well*). Fabrication experiments indicated that hot working had produced titanium-rich MC precipitation and that although initially fine and *uniform*, *this* phase could coarsen during further hot working. Solution treating to dissolve titanium-rich MC precipitate particles requires temperatures above 1150°C. The *Ti(C,N)S* and titanium-rich MN particles dissolve only at temperatures near melting, if at all. *Homogenization* before fabrication is essential. Our investigations addressed and *solved* all the problems encountered when producing final form material for specimens [*0.25-mm-thick transmission* electron microscope (*TEM*) discs punched from *sheet*]. Sheet 0.5 mm thick was also fabricated for thermal aging *response* studies of the Path A PCA.

- 3.3 Time-Temperature-Precipitation Curve Determination of the Path A Prime Candidate Alloy for Microstructural Design (Oak Ridge National Laboratory). 103

Thermal aging of the Prime Candidate Alloy (PCA) with no cold working and with 10 and 25% cold working for time-temperature-precipitation (TTP) curve determination shows that MC precipitate particle distribution, either at the •grain boundary or in the *matrix*, is considerably more sensitive to initial dislocation density than to either time

or temperature. Fine spacial and size distributions of *matrix* MC precipitate particles can be achieved in 25%-cold-worked PCA after as little as 5 min at 750°C. The formation of MC precipitate particles helps control phase instability by retarding *intragranular* precipitation of $M_{23}C_6$, eta, and Laves phases in the PCA as in titanium-modified type 316 stainless steel. The increases in nickel and decrease in chromium of the PCA relative to titanium-modified type 316 also appear to retard *intergranular* $M_{23}C_6$ and/or eta phase formation, thus allowing titanium-rich MC to replace them as the grain boundary phase in the PCA. Occasional Laves phase particles precipitate at the grain boundaries of the PCA, as they also do in titanium-modified type 316. These differences in response of the PCA relative to titanium-modified type 316 forced us to *reevaluate* the conceptual *preirradiation* microstructural design. However, the ease of MC precipitation and the variety of particle distributions available, together with better resistance to formation of undesirable phases, make the PCA superior to types 316 or titanium-modified 316 stainless steel. *Thermal-mechanical* treatments have been developed to yield the designed *preirradiation* microstructures.

- 3.4 The Influence of Irradiation on the Properties of Path A Alloy Weldments (Oak Ridge National Laboratory). 128

Weldment samples have been irradiated in the HFIR in the temperature range 55 to 620°C to fluences producing 4.5 to 12 dpa and 100 to 410 at. ppm He in the weld metal zone. Tensile tests at temperatures near the irradiation temperatures showed appreciable strengthening up to 375°C. At 475 to 620°C the strength values were close to those of the control material. Tensile elongation showed a broad minimum in the range 300 to 400°C, with the lowest recorded total elongation of 3.5%.

4. PATH B ALLOY DEVELOPMENT - HIGHER STRENGTH Fe-Ni-Cr ALLOYS 135
5. PATH C ALLOY DEVELOPMENT - REACTIVE AND REFRACTORY ALLOYS 137
- 5.1 Preparation of Vanadium and Niobium Path C Scoping Alloys (Westinghouse Electric Corporation). 139

Three vanadium alloy and two niobium alloy compositions are being prepared for *consumable* arc melting and processing to plate, sheet, and rod for the Fusion Materials Stockpile. These are the Path C (V, Nb) Scoping Alloys selected for initial evaluations as candidate fusion reactor structural materials. All rod materials have been previously shipped to ORNL. During this reporting period, the plate and sheet materials of the niobium alloys have been prepared and are currently being readied for *shipment*. Final secondary processing to flat product finish *sizes* (2.5 mm plate and 1.5 mm and 0.76 mm sheet) is underway for

the vanadium alloys. All *materials associated* with this *contract will* be shipped to ORNL by mid-October. An informal final report which *provides* detailed documentation of processing histories and final product chemical analyses will be prepared and forwarded to ORNL within thirty days of contract completion.

- 5.2 Mechanical Property Testing of Unirradiated Path C Alloys (Oak Ridge National Laboratory). 141

The multipurpose system designed for testing Path C scoping alloys in high vacuum has been completed and is in operation. A series of strain-controlled fatigue tests of Nb-1% Zr has been initiated. Results of two room temperature tests in high vacuum showed that Nb-1% Zr is significantly more fatigue resistant than 20%-cold-worked type 316 stainless steel when tested in the same condition at a cyclic strain range of 0.5%.

6. PATH D ALLOY DEVELOPMENT - INNOVATIVE MATERIAL CONCEPTS 145

7. STATUS OF IRRADIATION EXPERIMENTS AND MATERIALS INVENTORY 147

- 7.1 Irradiation Experiment Status and Schedule. 148

The schedule for irradiation experiments being conducted by the Alloy Development Program is presented.

- 7.2 ETM Research Materials Inventory (Oak Ridge National Laboratory). 155

Procurement status and inventory of Path A, B, and C Alloys are reported.

8. CORROSION TESTING AND HYDROGEN PERMEATION STUDIES. 161

- 8.1 The Compatibility of Type 316 Stainless Steel with Nitrogen-Contaminated Static Lithium (Oak Ridge National Laboratory). 162

Data on the weight loss and grain boundary penetration of type 316 stainless steel exposed to lithium with varying concentrations of nitrogen are presented. We observed no penetration at 600 and 700°C for nitrogen concentrations below 3000 ppm.

- 8.2 Thermal-Convection Loop Tests of Fe-Ni-Cr Alloys (Oak Ridge National Laboratory). 170

The status of the various lithium thermal-convection loops (TCLs) is reviewed. The effect of prior loop operation on the corrosion of new type 316 stainless steel specimens was slight: the corrosion rate of this steel in flowing lithium was not greatly enhanced when α -ferrite was also present in the system. Additionally, the reaction of aluminum in lithium with type 316 stainless steel at 500 to 600°C was very rapid and resulted in thin surface films. This process is consistent with the observed kinetics of the growth of aluminum-steel reaction layers.

- 8.3 Corrosion Rate of Type 316 Stainless Steel in Flowing
KNO₃-NaNO₂-NaNO₃ (Oak Ridge National Laboratory). 175

The status of the molten-salt thermal-convection loops (LiF-BeF₂, KNO₃-NaNO₂-NaNO₃, and LiF-LiBr-LiCl) is reviewed. The corrosion rates of type 316 stainless steel in KNO₃-NaNO₂-NaNO₃ and the composition of the salt are reported as a function of time and temperature. Corrosion rates varied from about 5 mg/m²h (4 μm/year) at 430°C to 66 mg/m²h (59 μm/year) at 550°C.