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Oak Ridge National Laboratory ATF Neutron Irradiation Program Technical Plan

J.W. Geringer
Y. Katoh

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Materials Science and Technology Division

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OVERVIEW

The Japan Atomic Energy Agency (JAEA) under the Civil Nuclear Energy Working Group (CNWG) is engaged in a cooperative research effort with the U.S. Department of Energy (DOE) to explore issues related to nuclear energy, including research on accident-tolerant fuels and materials for use in light water reactors.

This work develops a draft technical plan for a neutron irradiation program on the candidate accident-tolerant fuel cladding materials and elements using the High Flux Isotope Reactor (HFIR).

The research program requires the design of a detailed experiment, development of test vehicles, irradiation of test specimens, possible post irradiation examination and characterization of irradiated materials and the shipment of irradiated materials to JAEA in Japan.

This report discusses the technical plan of the experimental study.

CONTENTS

ACRONYMS

Acronym	Definition
ASME	American Society of Mechanical Engineers
ASTM	ASTM International
ATF	Accident Tolerant Fuel
CNWG	Civil Nuclear Energy Working Group
dpa	displacements per atom
DOE	Department of Energy
FT	Fracture toughness
HFIR	High Flux Isotope Reactor
HHF	High heat flux
ID	Identification / Identifier
IMET	Irradiated Materials Examination and Testing
ISO	International Organizations for Standardization
JAEA	Japan Atomic Energy Agency
LAMDA	Low Activation Materials Development and Analysis
NQA	Nuclear Quality Assurance
ORNL	Oak Ridge National Laboratory
QMS	Quality Management System
R&D	Research and Development
SSTT	Small Specimen Test Technology
US	United States

1. INTRODUCTION

As part of the Accident Tolerant Fuel (ATF) Development for Light Water Reactors program the Civil Nuclear Energy Working Group (CNWG) of Japan seeks to investigate the behaviors of candidate cladding materials in neutron irradiation environments. The current focus is on advanced steels and ceramic cladding materials which include FeCrAl alloys and SiC composites.

This plan proposes an irradiation campaign using the High Flux Isotope Reactor (HFIR), to enable post-irradiation investigation on mechanical properties and residual stresses.

2. PROPOSED PROGRAM LAYOUT

The suggested irradiation campaign consists of 3 milestones that need to be accomplished in order to be successful.

Milestone 1: <u>Agreed Technical Plan</u>

The Proposed Technical Plan is laid out in this document. The Agreed Technical Plan will incorporate input from the customer on the proposed test matrix as well as on pre- and post-irradiation activities.

Milestone 2: <u>Supplied Specimens</u>

The Agreed Technical Plan will specify the proposed specimens to be irradiated. This milestone comprises the preparation of these specimens. It includes the supply of machined specimens, with individual engraving or marking, inspection inspected as per specification (that will be supplied) and where required, undergone pre-irradiation examination.

Milestone 3: <u>Developed and Constructed Test Vehicles</u>

For this task ORNL will create the detail engineering designs specific to the program. Multi-dimensional thermal modeling and analyses will be performed to ensure that the variation in sample temperatures in test vehicles and the variation in temperatures in individual samples are maintained within acceptable ranges. Safety analyses will be performed to ensure that all safety requirements for experiments, which will operate in HFIR, are satisfied. The test specimens will be cleaned and measured for HFIR acceptance. Finally, the specimens will be carefully assembled inside the holders and the test vehicles will be individually constructed.

Milestone 4: <u>Irradiated Test Vehicle</u>

The test vehicles will be inserted in the HFIR flux trap for a predetermined number of cycles and at the best possible positions until the required displacements per atom (dpa) has been reached.

Milestone 5: <u>Test Vehicle Disassembly, Post-Irradiation Examination and/or Specimen Shipment</u>

ORNL will clean or disassemble the test vehicles that have been irradiated at the Irradiated Materials Examination and Testing, IMET, 3025E hot cell facilities. The test vehicles containing specimens can be shipped to Japan in unopened or disassembled condition. ORNL can also perform specimen examination at the IMET facility or at the Low Activation Materials Development Analysis (LAMDA) laboratory. To open the capsules will require the use of manipulators inside a hot cell. The specimens will be removed from the capsules, packaged and prepared for shipment. Technical details of the shipment and/or examination will be defined through discussion with JAEA-CNWG.

3. SUGGESTED TEST MATRIX AND IRRADIATION CONDITIONS

The test matrix is compiled with the purpose to examine the properties of alternative cladding materials under typical light water reactor operating temperature at 300°C and at a heat flux of 0.6 MW/m^2 (as specified). As mentioned the materials for evaluation are FeCrAl alloys and SiC composites. The campaign is designed to irradiate 5 rabbit capsules containing tensile, fracture toughness, flexure bars and cladding tube specimens. The fast fluence target is set to achieve ~8 dpa for both the SiC composite and the FeCrAl alloy. The fast fluence is based on the flux position and the number of HFIR cycles. The SiC clad tube rabbits are designed for high heat flux and will therefore be positioned in peak flux locations. This will reduce the number of cycles. A lower flux position may increase the irradiation time but will reduce the sensitivity to temperature deviations which may be more appropriate for the FeCrAl alloy.

Table 1: Suggested Test Matrix and Irradiation Conditions

Material type	FeCrAl		SiC	
Test capsule design type	Tensile	Fracture Toughness	Tube	Flexure
Irradiation conditions				
Temperature target (°C)	300	300	300	300
DPA target	8	8	8	8
Fast fluences (1E+25 n/m2, E > 0.1MeV)	± 8	± 8	± 8	± 8
HFIR cycles	5 -6	5 -6	4	4
Number of capsules	1	1	2	1
Number of specimens	36	4	6	12
Properties that can be determined				
Tensile properties	x			
Fracture toughness		x		(x)
Hardness	x	x		(x)
Density and Swelling			x	x
Dynamic Young's modulus			(x)	x
Coefficient of Thermal Expansion (CTE)				x
Thermal diffusivity			x	(x)
Residual stress			x	
TEM	(x)	(x)	(x)	(x)
Thermometry	x	x	x	x

Type, Dimensions and Number of Samples	Geometry	Dimensions [mm]	Total Qty Non-irradiated	Total Qty Irradiated	Total Qty Machined
FeCrAl alloy					
Tensile	SSJ2	16 x 4 x 0.5	36	36	72
Fracture toughness (4 notch bar)	M4-PCCVN	45 x 3.3 x 1.65	4	4	8
SiC composite					
Flexural miniature bar	Bar	25 x 2.8 x 1	30	20	50
Cladding tube specimen	Tube	16 x 8.5 (OD)	4	6	10
TOTAL			**34**	**26**	**60**

The specimens have tight tolerances and in some cases fragile which can result in breakage during assembly. It is therefore requested that additional samples will be provided to ensure on time construction. The extra specimens can be used for control or reference testing in the case examination is to be performed at ORNL or returned to Japan upon request.

For SiC composite a total of 50 flexure bar specimens and 10 clad tube specimens will be required. For the FeCrAl alloy a total of 72 tensile specimens and 8 fracture toughness bars will be required.
Table 1 lists potential properties that can be determined by ORNL. This list doesn't provide the extensive materials analysis and capabilities that is possible at ORNL.

4. IRRADIATION VEHICLES

The irradiation vehicles that are used for these irradiation campaigns are small capsules that have typical outer dimensions of 65mm in length and 10mm in diameter as shown in Figure 1. A capsule consists of an outer housing, an inner holder, end caps and springs to position the inner holder. The material used depends on the specific design but aluminum alloy is a popular choice for the temperature region suggested for this campaign. A capsule of these dimensions are generally referred to as a "rabbit" capsule. These rabbit capsules are specifically designed for the HFIR's flux trap. More detail is discussed in the irradiation design report [2].

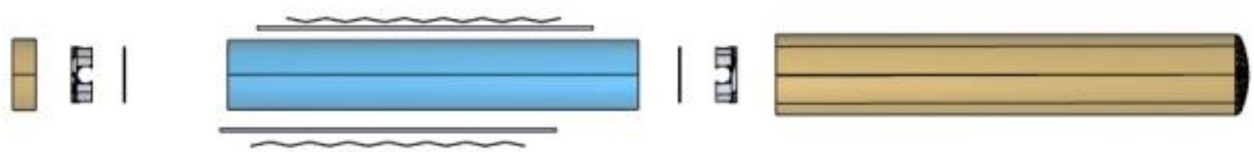

Figure 1: Expanded side view of a generic small "rabbit" capsule used for irradiation

5. SPECIMENS

Specimens included in the test vehicles are based on Small Specimen Test Technology (SSTT). The SSTT have been used for many years by both US and US-Japanese collaborations. The specimen geometries and test procedures are in according to ASTM, but not necessarily adopted by ASME. The testing procedures and methods and the properties to be evaluated is discussed in detail in the post-irradiation activities report [2]. The following figures are to provide typical specimens detail suggested in the Test Matrix, Table 1. The suggested capsule designs are based on the characteristic specimen type and configuration provided below.

5.1 SPECIMEN TYPES

5.1.1 Tensile specimens

Type SS-J2 miniature tensile specimens are proposed for the FeCrAl alloy. Typical dimensions are shown in Figure 2.

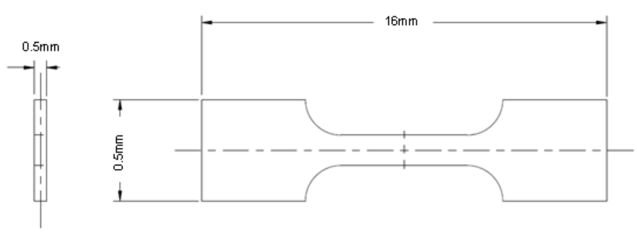

Figure 2: SS-J2 type specimen

5.1.2 Fracture toughness specimens

For FeCrAl fracture toughness (FT) type 4M-PCCVN miniature bending bar specimens with 4 notches are proposed. The specimens will be pre-cracked prior to irradiation in according with ASTM E1920 and E1820. Typical dimensions are shown in Figure 3.

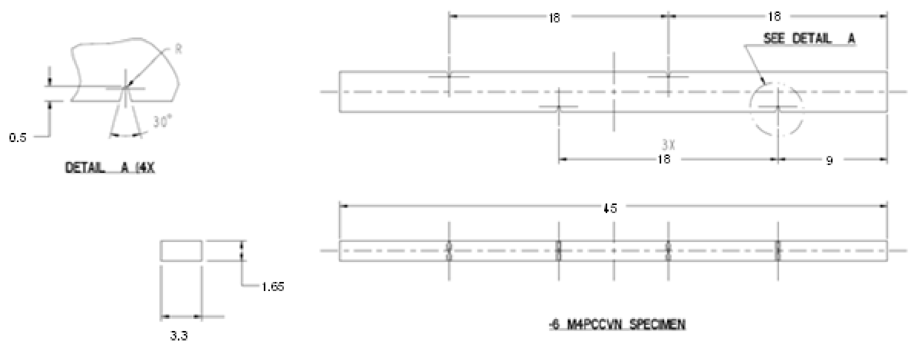

Figure 3: M4-PCCVN type specimen

5.1.3 Flexural Beam

For the SiC/SiC composite, miniature flexural beam specimens are proposed for flexural tests as shown in Figure 4.

Figure 4: Flexure bar type specimen

5.1.4 Cladding Tube Specimen

The SiC/SiC composite clad tube specimen are proposed for HHF testing and the configuration are shown in Figure 5.

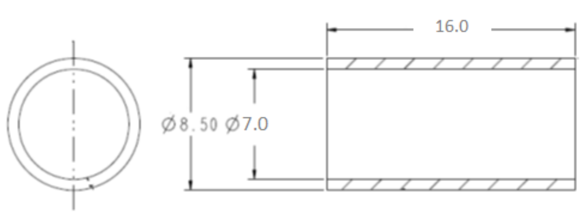

Figure 5: Clad tube specimen type

5.2 SPECIMEN MARKINGS

All specimens shall be laser engraved according to a predetermined ID code. In most cases not more than 4 characters can be used on small specimens.

With agreement to the proposal a final loading matrix will be generated that will detail the specimen IDs. ORNL has a wealth of experience from hot cell disassembly to post irradiation examinations to apply best practice with regards to specifying characters to use, size, specimen location, material type and associated engraving specification. Details regarding markings will be discussed during specimen ID designation process.

5.3 ADDITIONAL SPECIMEN REQUIREMENTS

Lubrication should be avoided when preparing ceramic specimens to prevent contamination of the material.
Factory dimensional inspection of specimen prior to assembly reduces the risk of specimens not fitting due to tight tolerances. Pre-irradiation inspection is required for all ceramic specimens.
Specimens are cleaned before assembly. Cleaning products include Ethanol, Acetone and distilled water.
All capsule components including specimens must be supported showing the elemental composition for each material type.

6. PROPOSED SCHEDULE

There are slight timeline differences between the two candidate materials schedules as shown in Table 1. Both cases assume that the specimens are prepared and delivered on time. SiC composite capsules may require more analysis and design, while it can be anticipated that the FeCrAl alloy will require longer irradiation period. Post-irradiation activities will be largely affected by the shipping arrangement variability and time delays that include customs control of radioactive materials.

Table 2: Proposed schedule

Task		Month																									
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
FeCrAl	Technical Plan Agreed	■																									
	Supplying specimens		■	■	■																						
	Test vehicle development			■	■	■	■	■	■	■																	
	Irradiation									■	■	■	■	■	■	■	■	■	■	■	■						
	Post Irradiation Activities																			■	■	■	■	■	■	■	■
SiC	Technical Plan Agreed	■																									
	Supplying specimens		■	■	■																						
	Test vehicle development			■	■	■	■	■	■	■	■																
	Irradiation										■	■	■	■	■	■	■	■									
	Post Irradiation Activities																	■	■	■	■	■	■	■	■		

7. QUALITY ASSURANCE

ORNL has an established Quality Management System (QMS) that supports excellence in our science and technology missions through development of a quality culture. This QMS culture contributes to scientific and operational excellence, research integrity, and continual improvement based on the needs of each client. ORNL implements and is registered to the international quality standard, ISO 9001:2008, as the baseline for its QMS. In addition to the ISO standard, ORNL further enhances the conduct of its nuclear R&D activities implementing a targeted quality assurance program based on and compliant with the ASME NQA-1-2008 quality assurance standard, *Quality Assurance Requirements for Nuclear Facility Applications*.

8. REFERENCES

[1] Geringer J.W, Katoh y., “JAEA-CNWG Irradiation Vehicle Design Concept” (ORNL/TM-2016/123)
[2] Geringer J.W, Katoh y., “JAEA-CNWG Post Irradiation Plan” (ORNL/TM-2016/124)
[3] ASTM E1920 “Standard Test Method for Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range”
[4] ASTM E1820 “Standard Test Method for Measurement of Fracture Toughness”.