ORNL/TM-2021/2186

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Post-irradiation Examination Plan for the ORNL and University of California Santa Barbara Assessment of the UCSB ATR-2 Irradiation Experiment and a Reference Document for the Irradiated Archival RPV Materials Stored in the NSUF Nuclear Fuels and Materials Library.

August 2021

Prepared by

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UT-BATTELLE

ORNL-27 (4-00)

ORNL/TM-2021/2186

Light Water Reactor Sustainability Program

Post-irradiation Examination Plan for the ORNL and University of California Santa Barbara Assessment of the UCSB ATR-2 Irradiation Experiment and a Reference Document for the Irradiated Archival RPV Materials Stored in the NSUF Nuclear Fuels and Materials Library

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Date Published: August 2021

Prepared under the direction of the
U.S. Department of Energy
Office of Nuclear Energy
Light Water Reactor Sustainability
Materials Research Pathway

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283 managed
by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ACKNOWLEDGMENTS

This research was sponsored by the U.S. Department of Energy, Office of Nuclear Energy, for the Light Water Reactor Sustainability (LWRS) Program research and development effort as well as the ATR National Scientific Users Facility (NSUF) that supported the irradiation experiment. The authors specifically extend their appreciation to Drs. Jeremy Busby and Keith Leonard for LWRS Materials Research Pathway programmatic support and to Jordan Reed who prepared the 1,000-line spread sheet with the ATR-2 specimen and irradiation details. We also specifically acknowledge the major NSUF contributions of Jim Cole, Brandon Miller, Collin Knight, Paul Murray, Joe Nielsen, Mitch Meyer, Mike Sprenger, Tom Maddock and other ATR National Scientific User Facility staff for conducting the UCSB ATR-2 irradiation. Finally, we thank Drs. Maxim Gussev and Lizhen Tan for their review of this report.

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ABSTRACT

This report, which was originally submitted relative to the Level 3 Milestone M3LW-14OR0402012 – "Complete report on post-irradiation examination plan for ORNL and University of California Santa Barbara assessment of ATR-2 capsules," has been expanded and made public to provide a detailed reference to access and / or perform characterization of irradiated archival RPV materials that were transferred to the Nuclear Science User Facility (NSUF), Nuclear Fuels and Materials Library (NFML). Specifically, this report will be used in conjunction with the ~ 1,000-line Excel spreadsheet that will provide critical information concerning the specimen material code, material description, sample type, dimensions, irradiation conditions including capsule, temperature, and composition, and ORNL storage location.

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1. INTRODUCTION

The reactor pressure vessel (RPV) in a light-water reactor (LWR) represents the first line of defense against a release of radiation in case of an accident. Thus, regulations that govern the operation of commercial nuclear power plants require conservative margins of fracture toughness, both during normal operation and under accident scenarios. In the unirradiated condition, the RPV has sufficient fracture toughness such that failure is implausible under any postulated condition, including pressurized thermal shock (PTS) in pressurized water reactors (PWR). In the irradiated condition, however, the fracture toughness of the RPV may be severely degraded, with the degree of toughness loss dependent on the radiation sensitivity of the materials. As stated in previous progress reports, the available embrittlement predictive models, e.g. [1], and our present understanding of radiation damage are not fully quantitative, and do not treat all potentially significant variables and issues, particularly considering extension of operation to 80y.

The major issues regarding irradiation effects are discussed in [2, 3] and have also been discussed in previous progress and milestone reports. As noted previously, of the many significant issues discussed, the issue considered to have the most impact on the current regulatory process is that associated with effects of neutron irradiation on RPV steels at high fluence, for long irradiation times, and as affected by neutron flux. It is clear that embrittlement of RPV steels is a critical issue that may limit LWR plant life extension. The primary objective of the LWRSP RPV task is to develop robust predictions of transition temperature shifts (TTS) at high fluence (φt) to at least 10^{20} n/cm^2 (>1 MeV) pertinent to plant operation of some pressurized water reactors (PWR) for 80 full power years. Correlations between the high flux test reactor results and low flux surveillance specimens must be established for proper RPV embrittlement predictions of the current nuclear power fleet. Additionally, a complete understanding of defect evolution for high nickel RPV steels is needed to characterize the embrittlement potential of Mn-Ni-enriched precipitates (MNPs), particularly for the high fluence regime. While understanding of copper-enriched precipitates (CRPs) have been fully developed, the discovery and experimental verification [4] of 'late blooming' MNPs with little to no copper for nucleation has stimulated research efforts to understand the evolution of these phases. New and existing databases will be combined to support development of physically based models of TTS for high fluence-low flux ($\varphi < 10^{11}$n/cm^2-s) conditions, beyond the existing surveillance database, to neutron fluences of at least 1×10^{20} n/cm^2 (>1 MeV). All references to neutron flux and fluence in this report are for fast neutrons (>1 MeV).

The RPV task of the LWRS Program works with various organizations to obtain archival surveillance materials from commercial nuclear power plants to allow for comparisons of the irradiation-induced microstructural features from reactor surveillance materials with those from similar materials irradiated under high flux conditions in test reactors, such as the UCSB ATR-2 experiment. This report, which originally submitted relative to the Level 3 Milestone M3LW-14OR0402012 – "Complete report on post-irradiation examination plan for ORNL and University of California Santa Barbara assessment of ATR-2 capsules," has been expanded to provide a detailed reference to access and / or perform characterization of irradiated archival RPV materials that were transferred to the Nuclear Science User Facility (NSUF), Nuclear Fuels and Materials Library (NFML). Specifically, this report will be used in conjunction with the ~ 1,000-line Excel spreadsheet that will provide critical information concerning the specimen material code, material description, sample type, dimensions, irradiation conditions including capsule, temperature, and composition, and ORNL storage location.

2. BACKGROUND AND REVIEW OF ATR-2 EXPERIMENT

To obtain high fluence data in a reasonable time (e.g., ~ one or two years), test reactor experiments must be performed in such a way to enable development of a mechanistic understanding of the effects of flux [2, 3]. As described previously, such an irradiation experiment is currently underway as part of the Idaho National Laboratory (INL) Advanced Test Reactor (ATR) National Scientific User Facility (NSUF). The experiment was awarded to University of California, Santa Barbara (UCSB) and its collaborator, ORNL, several years ago with full funding for the facility provided by DOE through the NSUF. A description of the UCSB ATR-2 experiment and materials will be summarized briefly here.

In collaboration with UCSB the INL staff carried out conceptual design of the sophisticated instrumented irradiation test assembly (capsule). The INL staff carried out the engineering design, construction and insertion of the test assembly, and is currently responsible for operation of the UCSB ATR-2 irradiation experiment. The scientific experiment itself was designed by UCSB in collaboration with ORNL. The total of 87 alloys included in the experiment were acquired by UCSB and ORNL. Additionally, surveillance materials from various operating nuclear reactors that were provided by Westinghouse and the Electric Power Research Institute (EPRI) are included to enable a direct comparison of results from a test reactor at high flux and a power reactor at low flux. The specific surveillance materials are summarized in Section 3 of this report. Fabrication of the specimens was carried out by UCSB with the assistance of ORNL. The specimens were loaded into thin-walled cups at UCSB and the cups were loaded into the test assembly at INL.

The irradiations were carried out in the so-called "Small I" position in ATR just inside the pressure vessel and reflector. The test assembly has a 20 mm inside diameter and is ≈ 1.2 m long. The UCSB ATR-2 experiment includes 959 small specimens in three basic geometries. These include (1) tensile specimens, for a large matrix of alloys; (2) so-called multipurpose disc coupons that will support microhardness, shear punch and a wide variety of microstructural characterization studies (e.g., small-angle neutron scattering, atom probe, etc.) for all the alloys; (3) 20-mm diameter disc compact tension (DCT) fracture specimens for three alloys - the Palisades B weld and two UCSB forgings (C17 and LP). The DCT specimens were irradiated at a nominal temperature of 290°C. The test assembly includes a gadolinium thermal neutron shield and active temperature control with three major regions at nominal temperatures of 270, 290 and 310 °C, and one small region at 250°C. The specimens were irradiated at a peak flux of about 3.3×10^{12} n/cm^2-s (>1 MeV) to a target fluence of 1×10^{20} n/cm^2. The objective is to obtain a high f1uence, intermediate flux database to couple to a large body of existing data for a large set of common alloys (≥ 100) irradiated over a wide range of flux and fluence. Figure 2.1 shows the flux/fluence range for the ATR-2 experiment (red line). The results from the experiment will allow for direct comparisons with two existing test reactor databases (IVAR and REVE, shown in filled triangles and circles, respectively).

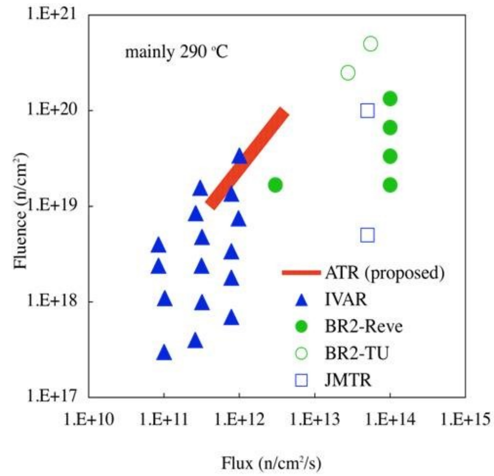

Figure 2.1. Schematic depiction of the flux/fluence range for the ATR-2 experiment, showing overlap of existing data from the IVAR and REVE databases.

Table 2.1 provides the identification, general specimen types, target irradiation temperature, and nominal target fluence (φt) for each of the 13 sub-capsules included in the ATR-2 capsule, while Figure 2.2 shows the capsule layout relative to the specimen temperature and to the flux/fluence level normalized to the peak value of 1 on the abscissa. Relative to the peak flux/fluence of 1 at the center position of the capsule (zero on the ordinate), the sub-capsules near the ends of the capsule (i.e., at about + 550 and -550 mm) will achieve a flux/fluence from about 35 to 45% of the peak value. Thus, a variety of relatively small specimens of many different RPV steels have been incorporated, including many materials that have been irradiated and tested in previous test reactor programs at different flux levels. The materials irradiated in the ATR-2 capsule are described in greater detail in Section 3.

Table 2.1. Subcapsules in the ATR2 Capsule.

Capsule ID	Materials	Target Temp.	Nominal Target ft ($x10^{19}n/cm^2$)
UCSB-1	coupon/tensile	290 ºC	low 4.2
UCSB-2	coupon/tensile	290 ºC	low 6.2
UCSB-3	coupon/tensile	290 ºC	med 8.8
UCSB-4	coupon/tensile	270 ºC	med 10.3
UCSB-5	coupon/tensile	250 ºC	med/hi 10.9
UCSB-6	DCT	290 ºC	hi 11.7
UCSB-7	coupon/tensile	290 ºC	hi 12.2
UCSB-8	coupon/tensile	290 ºC	hi 12.3
UCSB-9	DCT	290 ºC	hi 11.7
UCSB-10	coupon/tensile	310 ºC	med/hi 11.0
UCSB-11	coupon/tensile	290 ºC	med 9.8
UCSB-12	DCT	290 ºC	low 7.6
UCSB-13	coupon/tensile	290 ºC	low 5.5

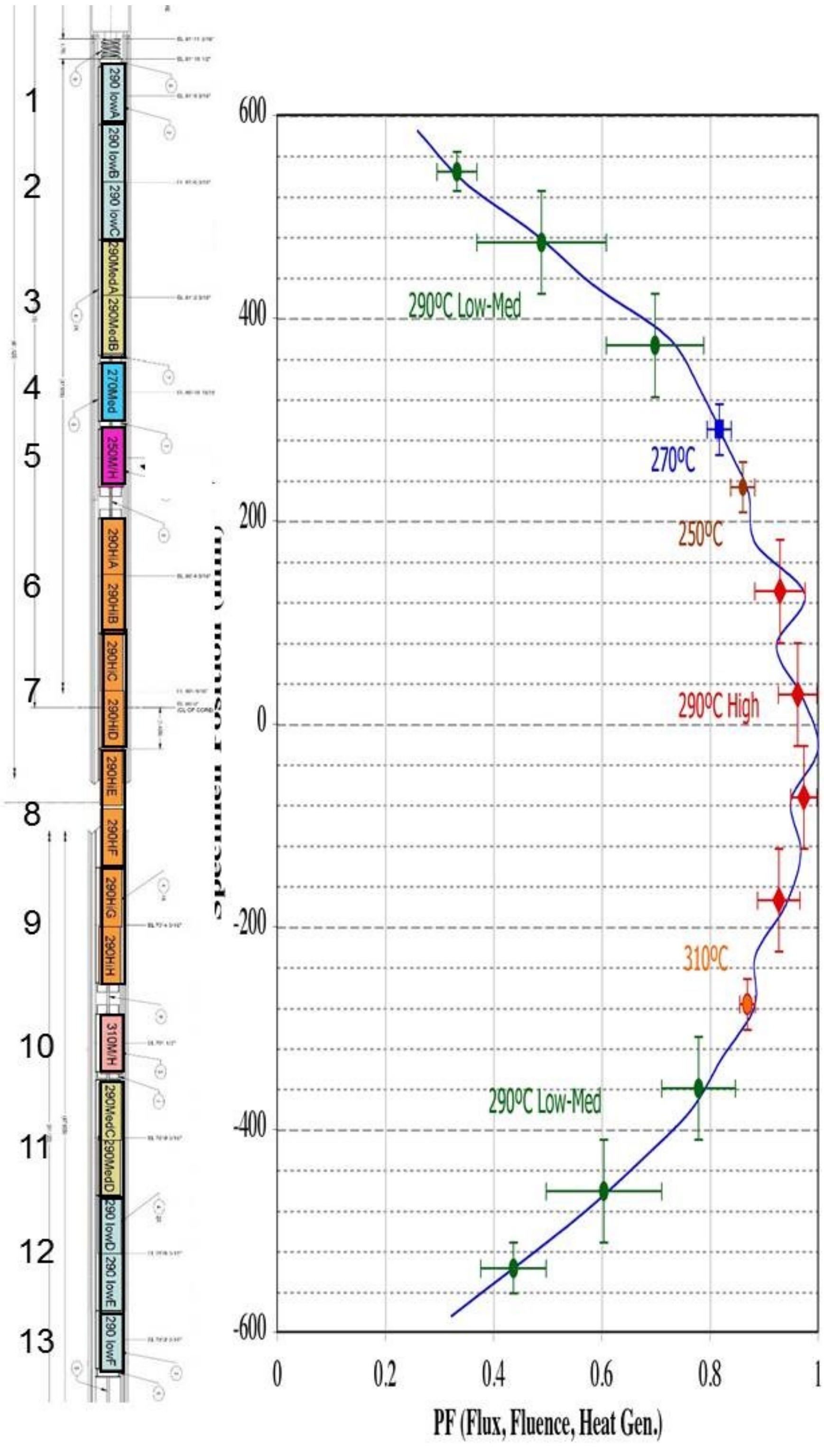

Figure 2.2 Capsule layout relative to the specimen temperature and to the flux/fluence level. The numbers on the left, 1-13, refer to the sub-capsules described in Table 2.1.

3. DESCRIPTION OF MATERIALS AND SPECIMENS

A summary of the materials, specimen types and numbers is provided in Table 3.1. As mentioned earlier, 87 alloys with 959 specimens are included in the capsule. The DCT matrix includes three alloys, the Palisades B weld and two UCSB forgings (C17 and LP), while the UCSB commercial alloys include HSST Plate 02, HSSI Weld 73W, Midland Beltline Weld (WF-70), and other alloys from the UCSB IVAR project in cooperation with ORNL and funded by the US NRC. Additionally, surveillance materials from various operating nuclear reactors, designated ORNL alloys in Table 3.1, are included to enable a direct comparison of results from a test reactor at high flux and power reactors at low fluxes. A variety of surveillance materials were identified as those that would provide results of particular interest to the ATR-2 experimental objectives. These materials were identified based not only on their chemical composition but also on their inclusion in capsules intended for relatively high fluence to allow for comparisons of results from surveillance conditions and the test reactor conditions in the ATR-2 and subsequent experiments. From the group of materials identified as potential candidates, and with the major assistance of ATI-Consulting, we were able to procure nine specific RPV surveillance materials for inclusion in the ATR-2 capsule and they are shown in Table 3.2 below.

Table 3. 1 Specimen Matrices Summary

	Lg Disc		Sm Disc		Tens		DCT		Any Type	
Total # alloy/irrad cond	Alloy	Spc.	Alloy	Spc.	Alloy	Spc.	Alloy	Spc.	Alloy	Spc.
Total # spc	82	647	16	79	47	319	3	45	87	1090
DCT matrix	3	14			3	54	3	45	3	113
CM alloys	21	231			13	92			21	323
Laval alloys	10	72			8	48			10	120
UCSB Commercial alloys	13	107	1	4	9	53			13	164
EPRI alloys	20	141			6	21			20	162
ORNL alloys	5	64	5	41	8	51			9	156
OV model alloys	9	15	10	34					10	49
Diffusion Multiples	1	3							1	3

More detailed lists of alloys and specimens are shown in Appendix A and Appendix B, with Appendix B indicating the irradiation temperatures for the various alloys and specimens. Additionally, Appendix C contains individual tables for the various groups of materials for easier reference by material group. In summary, a variety of relatively small specimens of many different RPV steels have been irradiated in UCSB ATR-2, including many materials that have been irradiated and tested in previous test reactor and surveillance programs at different flux levels.

Table 3.2. List of archival surveillance materials supplied by Westinghouse

Material	Heat Number	Specimen Provided
SMAW	BOLA	One (1) 1/2T-CT **"CW25"**
SA533B-1	C7466-1	Two (2) 1/2T-CT **"CT29"** and **"CL28"**(a)
Linde 124 Weld	4P4784	One (1) 1/2T-CT **"CW26"**
Linde 1092 Weld	1P3571	0.5" x 3" x 1.5" slice of weldment (weld marked)
Linde 1092 Weld	1P3571	Two (2) untested tensile "**4KL"** and **"3J2"** Two (2) broken Charpy halves from specimen **"372"**
Weld	33A277	
Plate	B9004-1	Block 5×2.25×2.375 in.
Forging, SA 508-2	B6307-1	Block 3.19×0.875×0.55 in.
Linde 80 Weld, SA1094	Weld wire heat #71249 and Linde 80 flux lot 8457.	Block 3.375x4.25x8.625 in. (Block returned following machining of specimens)

Notes: (a) "CT" refers to transverse orientation and "CL" refers to longitudinal orientation.

Regarding test specimens, Figure 3.1 shows the multi-purpose coupon (MPC), also referred to as multi-purpose disc specimen, that will be used to perform microhardness testing and shear punch testing, and will also provide material for subsequent fabrication of specimens for microstructural examination by various techniques such as atom probe tomography (APT), small-angle neutron scattering (SANS), transmission electron microscopy (TEM), etc. Figure 3.2 shows the loading concept for the multi-purpose disc, the square coupons, and dosimetry canisters into the sub-capsule holders. Figure 3.3 shows the tensile specimen and the sub-capsule loading concept. Tensile specimens will be tested in accordance with ASTM Standard Test Procedure E8 to obtain yield and ultimate strengths for comparison with those of the unirradiated condition and with the microhardness and shear punch results. Those results will be correlated to ascertain the effects of irradiation on hardening. In that regard, Figure 3.4 shows the excellent correlation between tensile specimen yield strength and shear punch strength measurements. The linear fit to those data is $\sigma_y = 1.77\tau_y \pm 16$ MPa, with the value of 1.77 very close to the von Mises value of 1.73 [5]. Figure 3.5 shows the DCT specimen design and sub-capsule loading concept. The DCT specimens will be tested in accordance with ASTM Standard Test Method E-1921 to obtain the reference temperature, T_0, for comparison with that of the unirradiated condition.

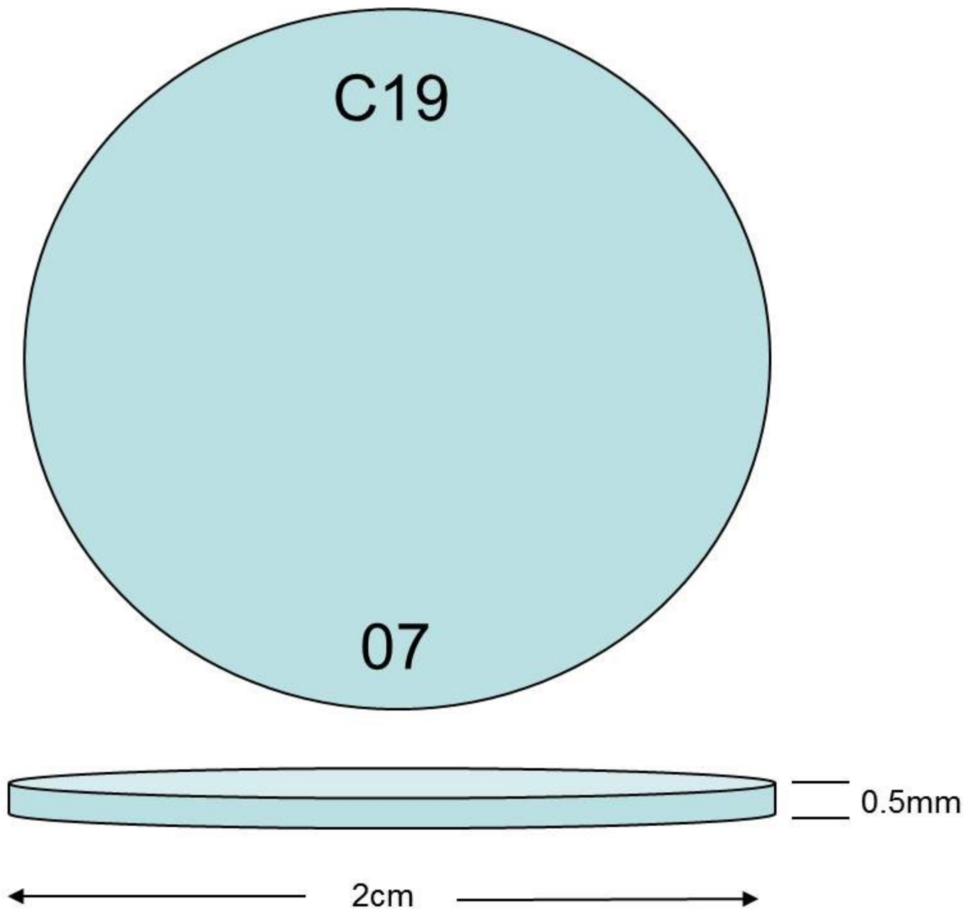

Figure 3.1. Schematic diagram of multi-purpose disc specimen with diameter and thickness indicated.

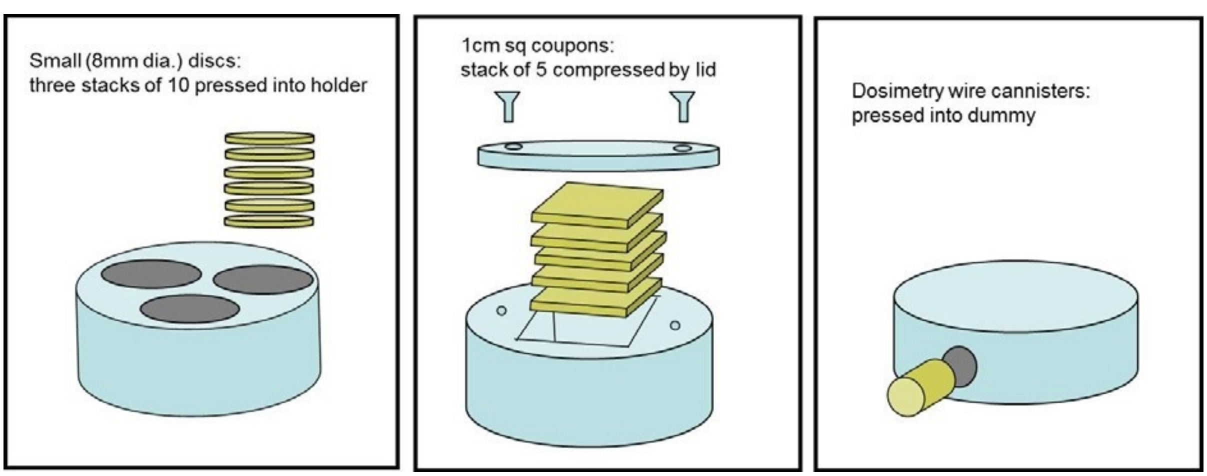

Figure 3.2. Schematic diagram showing concept for loading of multi-purpose disc specimens, square coupons, and dosimetry wire canisters into the sub-capsule holders.

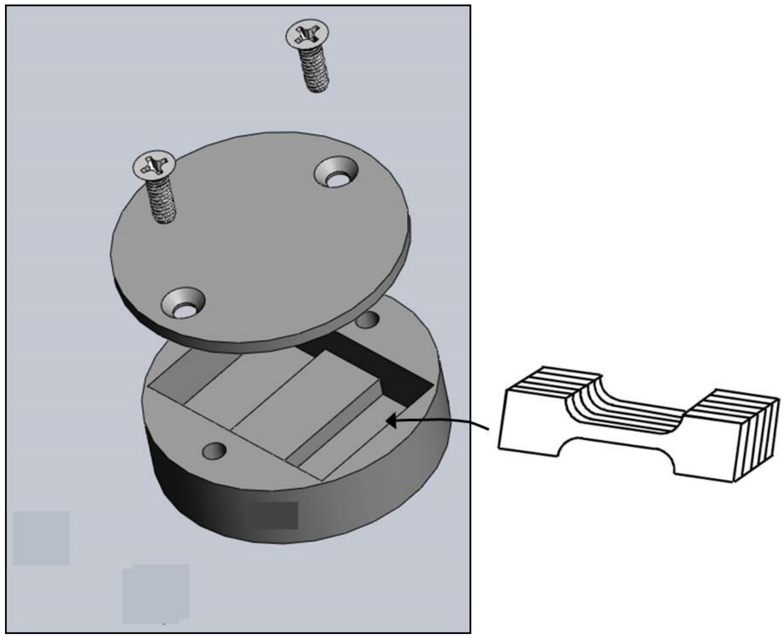

Figure 3.3, Schematic diagram showing concept for loading of tensile specimen into sub-capsule holders.

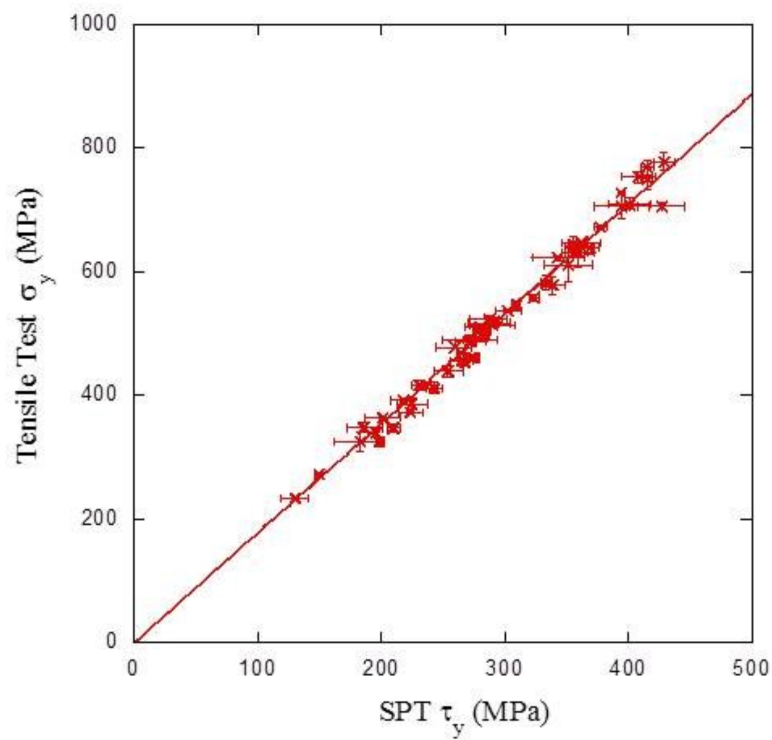

Figure 3.4. Yield strength from tensile specimens vs shear punch tests indicating an excellent correlation.

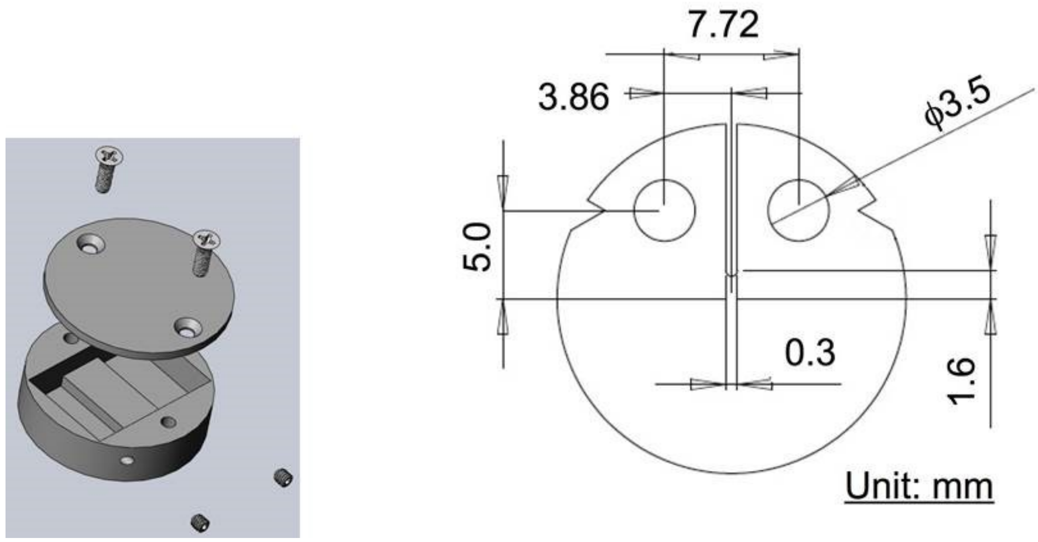

Figure 3.5. Schematic diagram showing disc compact specimen design and holder for loading specimens into sub-capsules.

Figure 3.6 shows a schematic diagram of the device designed by UCSB to perform shear punch testing of the multi-purpose disc specimens.

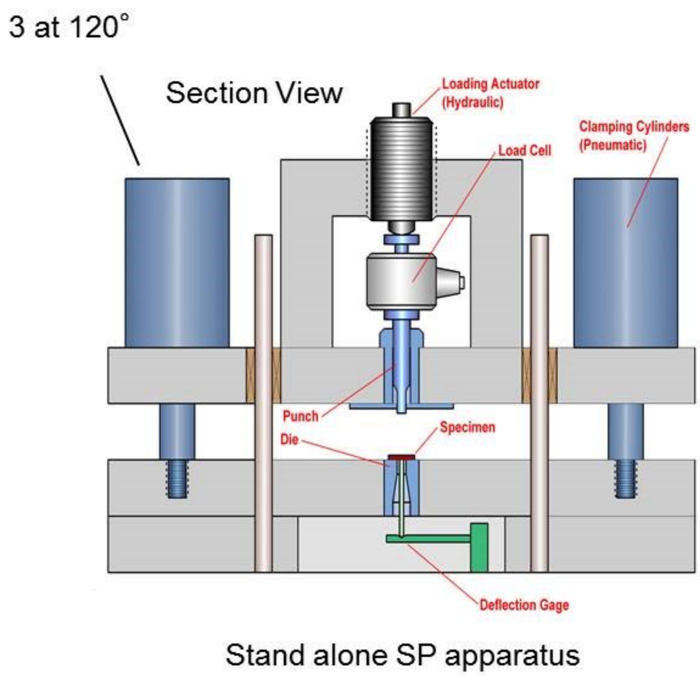

Figure 3.6. Stand-alone conceptual apparatus designed by UCSB for shear punch testing of the multipurpose disc specimens.

A diffusion-multiple specimen was also designed and prepared by UCSB and is included in the capsule. A schematic drawing of the specimen is shown in Figure 3.7 and consists of two pure elements, copper and nickel, compressed into an opening in a larger disc. Three of these specimens are included in the capsule at positions of 290°C (two flux levels) and 310°C to allow for evaluations of Cu-Ni diffusion variables and phase boundaries. The larger disc is a UCSB Alloy designated OV1, a Fe/1.6Mn material.

4. THE ATR-2 EXPERIMENT

Fabrication and assembly of the UCSB ATR-2 irradiation test assembly was completed in late spring of 2011 and was successfully installed in the ATR on May 26, 2011. The irradiation began on June 7, 2011 and was anticipated to achieve its target fluence of 1×10^{20} n/cm^2 (E>1 MeV) in the autumn of 2012. Thermocouple monitors during the course of the irradiation campaign have shown that the specimens are generally being irradiated at or close to their target temperatures, but the final determination of irradiation temperatures and dosimetric information (i.e., neutron flux and fluence) will be performed following removal of the capsule from the reactor.

A number of delays in operation of the ATR pushed the completion of the ATR-2 irradiation campaign into March of 2014. Chief among these was the Powered Axial Locator Mechanism (PALM) cycle, which was occasionally performed by the ATR for complex transient testing and which can simulate multiple start-up and shutdown cycles of tests for fuels and materials [6]. The PALM tests normally last from a few hours to a couple of days, but some experiments must be removed from the reactor when a PALM test is performed. This is the case for the ATR-2 capsule that was removed for the PALM cycle experiment, which occurred in the Spring of 2013.

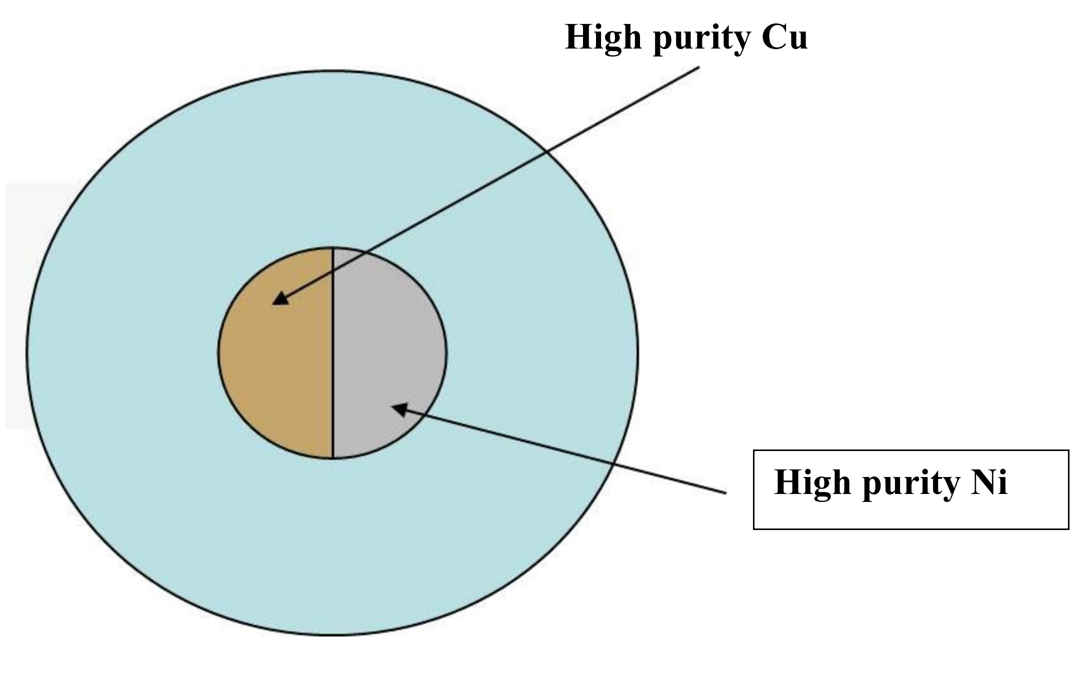

Figure 3.7. Schematic drawing of diffusion-multiple specimen, with high purity Cu and Ni embedded in a larger disc (UCSB Alloy OV1, an Fe/1.6Mn alloy).

At the time of the ATR shutdown, the average neutron fluence (>1 MeV) for the ATR-2 capsule was 6.34×10^{19} n/cm^2, with a peak fluence of 8.76×10^{19} n/cm^2. Thus, a decision was made to have the capsule reinserted following the PALM cycle. This decision compelled design of a mock-up experiment to load and remove the capsule. The ATR experiment team designed such an experiment and the necessary tool, and performed a mock-up experiment. A mockup of the ATR-2 test train was placed in the ATR tank and was successfully transferred through the drop chute into the canal. A new tool was designed to grip the bottom of the experiment without damaging the thin-walled tubing. The mockup test demonstrated that the new tool could maintain the correct orientation of the experiment needed to complete the transfer. Subsequently, the real test train was successfully transferred to the canal using the same process that was practiced with the mockup. The experiment remained in the canal through the PALM cycle, then was transferred back into the ATR for additional cycles. The ATR-2 Experiment Manager reported that the team performing this work did an excellent job in transferring the capsule.

Based on the projected cycle times, the average and peak fluences would be 8.71 and 12.0×10^{19} n/cm^2 after two additional cycles (cycles 154A and 154B), while they would be 1.01 and 1.40×10^{19} n/cm^2 after three additional cycles, respectively. Because of additional delays in reactor operation, a decision was made to withdraw the ATR-2 capsule at the end of cycle 154B, for the end of March 2014.

Following completion of the irradiation campaign, the ATR-2 capsule resided in the ATR canal until shipped to ORNL for disassembly and the post-irradiation testing and characterization activities. The current plan for conduct of the post-irradiation examination (PIE) activities is described in Section 5.

5. POST-IRRADIATION EXAMINATION PLAN

The PIE plan for examination of the ATR-2 experiment was flexible to accommodate changing emphasis on results in order to meet project objectives. Specific test sequences were determined by priority guidelines as well as on the final determination of irradiation temperatures and dosimetric data for the wide range of specimens and materials. The PIE activities were substantial due to the very large number of materials and specimens and involved multiple collaborations with many organizations. Moreover, the availability of facilities and test equipment required changes to the initial schedule in order to maximize productivity. Cost estimates for the PIE were highly dependent on the number of tests that were needed to be performed in remote hot cells as opposed to the ORNL Low Activated Materials Development and Analysis (LAMDA) laboratory. The general steps for the PIE evaluation are as follows:

1. The ATR-2 capsules were shipped from INL to ORNL for receipt at the hot cells of Building 3525, the Irradiated Fuels Examination Laboratory (IFEL).
2. The capsules were opened in the IFEL to retrieve and identify the sub-capsules.
3. Sub-capsules were shipped to the hot cells of Building 3025E, the Irradiated Materials Examination and Testing (IMET) facility.
4. Sub-capsules were opened to retrieve and identify individual specimens, with further packaging of like specimens by material/specimen type/irradiation temperature/fluence.
5. Dosimeter packets were retrieved for individual dosimeter identification and shipment to IFEL for counting and analysis of the fluence for each dosimeter.
6. Activity measurements of individual specimen packets were performed in preparation for shipment to other locations for testing, such as the LAMDA laboratory in Building 4508. It is

notable that the ATR-2 experiment was specifically designed with a gadolinium shield to significantly reduce the thermal neutron flux with the intended consequence of reduced activation of the specimens. This minimized the need for mechanical testing in remote hot cells, with concomitant reductions in cost and increases in productivity.

7. Small specimens were punched from selected mutli-purpose discs and shipped to UCSB. Microhardness measurements were used to complement mechanical testing at ORNL and to conduct mechanism experiments, including post-irradiation annealing studies based on microhardness testing. The annealing studies, if funded will also provide a basis to develop remediation annealing and reirradiation models. The small specimens were also used for extensive characterization studies, including APT, TEM, SANS, and other microstructural / microanalytical evaluations.
8. However, the majority of mechanical property tests were performed at ORNL. The plan included performing shear punch tests on a majority of the alloy/irradiation conditions at UCSB using the automated shear punch instrument developed by UCSB in collaboration with ORNL.
9. The plan is also included performing redundant room temperature tests on the tensile specimens for all corresponding alloy/irradiation conditions.
10. The compact tension specimens were tested to establish transition temperature shifts and provide additional insight on fracture toughness Master Curve methodology.
11. Testing of the specimens were performed in accordance with the standard practices where applicable.

The nominal order of priority regarding testing of the various materials is as follows:

1. In the case of the MPC and tensile specimen testing, a initial priority sequence of testing was on the high fluence (290°C) irradiation condition as follows:
    a. ORNL surveillance materials,
    b. UCSB alloys that were irradiated over a wide range of flux in IVAR and other experiments,
    c. Selected EPRI alloys that specifically complement the matrix of tests cited in a through c above,
    d. Additional tests on other alloys.
2. For MPC and tensile testing, a selected subset of key alloys were characterized at the lower fluences and at the lower and higher irradiation temperatures in order to establish the hardening dependencies on these variables. The matrix included the down-selected alloys from items 1a through 1c. Establishing these dependencies will have an equal priority with the compositional-based assessments in item 1 above.
3. The compact tension specimens for each material were tested in accordance with ASTM E1921 at a minimum of three temperatures to provide ΔT_0 shifts and information on possible changes in Master Curve shape for highly embrittled materials.
4. Additional mechanical property tests were conducted on a subset of alloys to complement the mechanistically oriented annealing experiments at UCSB and provide a basis for developing remediation annealing models.
5. Extensive microstructural/microanalytical characterization studies using a variety of complementary techniques were conducted based on mechanistic insight that identified gaps and as guided by the mechanical property test results.

The following is an example of the sequence of measurements that were made on a specific high priority alloy for various irradiation conditions. This specific example was developed for the Palisades RPV weld:

1. Shear punch, tensile and microhardness measurements to establish the changes in yield strength and post-yield constitutive properties for the matrix of irradiation fluences and temperature conditions.
2. Fracture toughness tests to provide ΔT_0 shifts and information on possible changes in Master Curve shape for highly embrittled materials and to relate the ΔT_0 shifts to changes in yield strength. The fracture analysis on this alloy included fractography and micromechanical evaluations to inform fracture modeling of Master Curve issues.
3. The as-irradiated conditions have been characterized by APT, TEM, SANS and PAS.
4. Each material was subject to a series of post-irradiation annealing treatments followed by microhardness tests, shear punch tests and microstructural/microanalytical characterizations.

6. SUMMARY

The primary objective of the LWRSP RPV task is to develop robust predictions of transition temperature shifts (TTS) at high fluence (φt) to at least 10^{20} n/cm^2 (>1 MeV) pertinent to plant operation of some pressurized water reactors (PWR) for 80 full power years. The RPV task of the LWRS Program worked with various organizations to obtain archival surveillance materials from commercial nuclear power plants to allow for comparisons of the irradiation-induced microstructural features from reactor surveillance materials with those from similar materials irradiated under high flux conditions in test reactors. Additionally, the task collaborated and cooperated with the University of California Santa Barbara regarding post-irradiation examination of the materials and specimens in the ATR-2 experiment. The ATR-2 capsule irradiation campaign was completed at the end of March 2014 with average and peak neutron fluences of about 0.87 and 1.20×10^{20} n/cm^2 (>1 MeV), respectively. This report has summarized the experiment, a detailed description of the materials and test specimens, and the planed testing and examination of the irradiated specimens.

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APPENDIX A
UCSB ATR-2 Material Key Summary

	Type			Lg Disc	Sm Disc	Tens	DCT	Total	
		Total # alloy/irradiation conditions		594	161	110	3		
		Total # spc		647	79	319	45	1090	
		Total # unique alloy conditions		82	16	47	3	173	
	DCT	Pal. B weld	PBW	3		19	14	36	
		UCSB forging (C17 as tempered)	XY	4		18	14	36	
		UCSB forging (LP as tempered)	LP	7		17	17	41	
	CM	UCSB forging slo stress rel	C3	16		6		22	
		UCSB forging slo stress rel	C4	12				12	
		UCSB forging slo stress rel	C5	12		6		18	
		UCSB forging slo stress rel	C6	25		20		45	
		UCSB forging slo stress rel	C7	12		6		18	
		UCSB forging slo stress rel	C8	6				6	
		UCSB forging slo stress rel	C9	13		6		19	
		UCSB forging slo stress rel	C10	12		6		18	
		UCSB forging slo stress rel	C11	14		6		20	
		UCSB forging slo stress rel	C12	3				3	
		UCSB forging slo stress rel	C13	12				12	

	Type			Lg Disc	Sm Disc	Tensile	DCT	Total	
		UCSB forging slo stress rel	C14	4				4	
		UCSB forging slo stress rel	C15	5				5	
		UCSB forging slo stress rel	C16	12		6		18	
		UCSB forging slo stress rel	C17	12		6		18	
		UCSB forging slo stress rel	C18	4				4	
		UCSB forging slo stress rel	C19	14		6		20	
		UCSB forging slo stress rel	C20	15		6		21	
		UCSB forging slo stress rel	C21	4				4	
		UCSB forging slo stress rel	C22	12		6		18	
		UCSB forging slo stress rel	C31	12		6		18	
	LV	UCSB forging	LA	3				3	
		UCSB forging	LB	6		6		12	
		UCSB forging	LC	10		7		17	
		UCSB forging	LD	10		7		17	
		UCSB forging	LG	9		7		16	
		UCSB forging	LH	10		6		16	
		UCSB forging	LI	9		6		15	
		UCSB forging	LJ	7		6		13	
		UCSB forging	LK	4		3		7	
		UCSB forging	LO	4				4	

	Comm	**BW A weld**	**WA**	**8**		**6**		**14**	
		BW B weld	**WB**	**7**		**6**		**13**	
		BW C weld	**WC**	**7**		**6**		**13**	
		BW 62 weld	**W62**	**9**		**6**		**15**	
		BW 63 weld	**W63**	**9**		**6**		**15**	
		BW 65 weld	**W65**	**6**	**4**	**5**		**15**	
		BW 67 weld	**W67**	**9**		**6**		**15**	
		ORNL 73 weld	**W73**	**11**		**6**		**17**	
		Midland weld	**MW**	**10**				**10**	
		ORNL HSST02 plate	**02**	**7**				**7**	
		BW A302B plate	**O32**	**6**				**6**	
		BW A508 plate	**58**	**8**				**8**	
		JRQ comm plate	**Q**	**10**		**6**		**16**	
	EPRI	**A 320B plate**	**EA**	**10**				**10**	
		Linde 0080 wld	**EC**	**8**		**6**		**14**	
		Linde 0090 wld	**ED**	**5**				**5**	
		A533 B plate 1bG	**E1**	**8**				**8**	
		A533 B plate 1bJ	**E2**	**8**				**8**	
		A533 B plate 1bN	**E3**	**8**				**8**	
		A533 B weld 1mT	**E5**	**8**				**8**	

		A533 B weld 1mU	E6	8				8	
		A533 B weld 1sX	E7	8				8	
		A508-2 plate 2bA	E8	8				8	
		A508-1 plate 5bA	E9	6				6	
		EPRI / Westinghouse	QC1	10		3		13	
		EPRI / Westinghouse	QC2	5		3		8	
		EPRI / Westinghouse	D3	9		3		12	
		EPRI / Westinghouse	HB	8		3		11	
		EPRI / Westinghouse	MP	7		3		10	
		EPRI / Westinghouse	TW	7				7	
		FRG 8460	FD	3				3	
		FRG 8240	FE	4				4	
		FRG 8310	FM	3				3	
	ORNL	EPRI / Westinghouse	F1W	11		6		17	
		EPRI / Westinghouse	F2B		8	6		14	
		EPRI / Westinghouse	KP	15		7		22	
		EPRI / Westinghouse	MY		10			10	
		EPRI / Westinghouse	BV	14		6		20	
		EPRI / Westinghouse	KW	16		8		24	
		EPRI / Westinghouse	F2W		10	6		16	

		EPRI / Westinghouse	**VCW**		**10**	**6**		**16**	
		EPRI / Westinghouse	**TP**	**8**	**3**	**6**		**17**	

	OV	**UCSB model**	**OV1**	**1**	**2**			**3**	
		UCSB model	**OV2**	**3**	**2**			**5**	
		UCSB model	**OV3**	**2**	**7**			**9**	
		UCSB model	**OV4**	**2**	**3**			**5**	
		UCSB model	**OV5**	**2**	**5**			**7**	
		UCSB model	**OV6**	**2**	**3**			**5**	
		UCSB model	**OV7**		**6**			**6**	
		UCSB model	**OV17**	**1**	**2**			**3**	
		UCSB model	**OV18**	**1**	**2**			**3**	
		UCSB model	**OV20**	**1**	**2**			**3**	
	DM	**Diff Multiple**	**DM**	**3**				**3**	

APPENDIX B
UCSB ATR-2 Material Key Details

Description			290 hi				290 med			290 lo				250		270		310
	I.D.	Lg Disc	Sm Disc	Ten	DC	Lg Disc	Sm Disc	Ten	Lg Disc	Sm Disc	Ten	DCT	Lg Disc	Sm Disc	Lg Disc	Sm Disc	Lg Disc	Sm Disc
D.C.T. matrix																		
Pal. B weld	PBW	3		19	14													
UCSB forging (C17 as tempered)	XY	4		18	14													
UCSB forging (LP as tempered)	LP	1				2			4		17	17						
CM alloys																		
UCSB forging slo stress rel	C3	3		3		3		3	5				1		2		2	
UCSB forging slo stress rel	C4	3				3			2						2		2	
UCSB forging slo stress rel	C5	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C6	8		9		6		11	6				1		2		2	
UCSB forging slo stress rel	C7	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C8	1				1			3								1	
UCSB forging slo stress rel	C9	3		3		3		3	3						2		2	

Description			290 hi				290 med			290 lo				250		270		310
	I.D.	Lg Disc	Sm Disc	Ten	DC	Lg Disc	Sm Disc	Ten	Lg Disc	Sm Disc	Ten	DCT	Lg Disc	Sm Disc	Lg Disc	Sm Disc	Lg Disc	Sm Disc
UCSB forging slo stress rel	C10	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C11	3		3		3		3	3				1		2		2	
UCSB forging slo stress rel	C12	1				1			1									
UCSB forging slo stress rel	C13	3				3			2						2		2	
UCSB forging slo stress rel	C14	1				1			1								1	
UCSB forging slo stress rel	C15	1				1			1								2	
UCSB forging slo stress rel	C16	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C17	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C18	1				1			2									
UCSB forging slo stress rel	C19	3		3		3		3	4						2		2	
UCSB forging slo stress rel	C20	4		3		3		3	4						2		2	
UCSB forging slo stress rel	C21	1				1			1								1	
UCSB forging slo stress rel	C22	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C31	3		3		3		3	2						2		2	

Description			290 hi				290 med			290 lo				250		270		310
	I.D.	Lg Disc	Sm Disc	Ten	DC	Lg Disc	Sm Disc	Ten	Lg Disc	Sm Disc	Ten	DCT	Lg Disc	Sm Disc	Lg Disc	Sm Disc	Lg Disc	Sm Disc
Laval alloys																		
UCSB forging	LA	1				1			1									
UCSB forging	LB	1		3		1		3	1				1		1		1	
UCSB forging	LC	3		4		2		3	2				1		1		1	
UCSB forging	LD	3		4		2		3	2				1		1		1	
UCSB forging	LG	3		4		2		3	2						1		1	
UCSB forging	LH	3		3		2		3	2				1		1		1	
UCSB forging	LI	3		3		2		3	2						1		1	
UCSB forging	LJ	2		3		2		3	2								1	
UCSB forging	LK	1				2		3	1									
UCSB forging	LO	1				2			1									
Comm. IVAR alloys																		
BW A weld	WA	2		3		2		3	2						1		1	
BW B weld	WB	2		3		2		3	1						1		1	
BW C weld	WC	2		3		2		3	1						1		1	
BW 62 weld	W62	3		3		2		3	2						1		1	
BW 63 weld	W63	3		3		2		3	2						1		1	
BW 65 weld	W65	3		3		2		2		1				1	1	1		1

BW 67 weld	W67	3		3		2		3	2						1		1	
ORNL 73 weld	W73	4		3		2		3	2						1		2	

Description			290 hi				290 med			290 lo				250		270		310
	I.D.	Lg Disc	Sm Disc	Ten	DC	Lg Disc	Sm Disc	Ten	Lg Disc	Sm Disc	Ten	DCT	Lg Disc	Sm Disc	Lg Disc	Sm Disc	Lg Disc	Sm Disc
Midland weld	MW	3				3			2						1		1	
ORNL HSST02 plate	02	2				1			2						1		1	
BW A302B plate	O32	2				2			2									
BW A508 plate	58	3				3			2									
JRQ comm plate	Q	3		3		3		3	2						1		1	
EPRI alloys																		
A 320B plate	EA	4				3			1						1		1	
Linde 0080 wld	EC	4		3		3		3	1									
Linde 0090 wld	ED	2				2			1									
A533 B plate 1bG	E1	2				3			3									
A533 B plate 1bJ	E2	2				3			3									
A533 B plate 1bN	E3	2				3			3									
A533 B weld 1mT	E5	2				3			3									
A533 B weld 1mU	E6	2				3			3									
A533 B weld 1sX	E7	2				3			3									

A508-2 plate 2bA	E8	2				3			3									
A508-1 plate 5bA	E9	1				3			2									
Description			290 hi				290 med			290 lo				250		270		310
	I.D.	Lg Disc	Sm Disc	Ten	DC	Lg Disc	Sm Disc	Ten	Lg Disc	Sm Disc	Ten	DCT	Lg Disc	Sm Disc	Lg Disc	Sm Disc	Lg Disc	Sm Disc
EPRI / Westinghouse weld	QC1	3		3		2			3						1		1	
EPRI / Westinghouse weld	QC2	2		3		1									1		1	
EPRI / Westinghouse	D3	3		3		2			2						1		1	
EPRI / Westinghouse	HB	2		3		2			2						1		1	
EPRI / Westinghouse	MP	2		3		2			1						1		1	
EPRI / Westinghouse	TW	2				2			2						1			
FRG 8460	FD								1						1		1	
FRG 8240	FE	1							1						1		1	
FRG 8310	FM								1						1		1	
ORNL surv. alloys																		
EPRI / Westinghouse	F1W	4		3		2		3	3						1		1	
EPRI / Westinghouse	F2B		2	3			2	3		1				1		1		1
EPRI / Westinghouse	KP	4		3		3		4	4				1		2		1	
EPRI / Westinghouse	MY		3				3			1				1		1		1
EPRI / Westinghouse	BV	4		3		3		3	4				1		1		1	
EPRI / Westinghouse	KW	4		3		3		3	5		2		1		2		1	

EPRI / Westinghouse	**F2W**		**3**	**3**			**3**	**3**		**1**				**1**		**1**		**1**
EPRI / Westinghouse	**VCW**		**3**	**3**			**3**	**3**		**1**				**1**		**1**		**1**
EPRI / Westinghouse	**TP**	**3**		**3**			**3**	**3**	**3**						**1**		**1**	

OV model alloys																		
Description			**290 hi**				**290 med**			**290 lo**				**250**		**270**		**310**
	I.D.	**Lg Disc**	**Sm Disc**	**Ten**	**DC**	**Lg Disc**	**Sm Disc**	**Ten**	**Lg Disc**	**Sm Disc**	**Ten**	**DCT**	**Lg Disc**	**Sm Disc**	**Lg Disc**	**Sm Disc**	**Lg Disc**	**Sm Disc**
UCSB model	**OV1**	**1**	**2**															
UCSB model	**OV2**	**1**	**2**						**2**									
UCSB model	**OV3**	**1**	**3**						**1**	**1**				**1**		**1**		**1**
UCSB model	**OV4**	**1**	**2**						**1**					**1**				
UCSB model	**OV5**	**1**	**2**						**1**					**1**		**1**		**1**
UCSB model	**OV6**	**1**	**2**						**1**	**1**								
UCSB model	**OV7**		**2**							**1**				**1**		**1**		**1**
UCSB model	**OV17**	**1**	**2**															
UCSB model	**OV18**	**1**	**2**															
UCSB model	**OV20**	**1**	**2**															
Description			**290 hi**				**290 med**			**290 lo**				**250**		**270**		**310**
	I.D.	**Lg Disc**	**Sm Disc**	**Ten**	**DC**	**Lg Disc**	**Sm Disc**	**Ten**	**Lg Disc**	**Sm Disc**	**Ten**	**DCT**	**Lg Disc**	**Sm Disc**	**Lg Disc**	**Sm Disc**	**Lg Disc**	**Sm Disc**

APPENDIX C. Separate tables for alloys.

Table C.1 Disc Compact Tension (DCT) Specimen Matrix

description		290 hi				290 med			290 lo				250		270		310	
	I.D.	Lg Disc	Sm Disc	Tens	DCT	Lg Disc	Sm Disc	tens	Lg Disc	Sm Disc	Tens	DCT	Lg Disc	Sm Disc	Lg Disc	Sm Disc	Lg Disc	Sm Disc
D.C.T. matrix																		
Pal. B weld	PBW	3		19	14													
UCSB forging (C17 as tempered)	XY	4		18	14													
UCSB forging (LP as tempered)	LP	1				2			4		17	17						

Table C.2 UCSB CM Alloys

CM alloys																		
UCSB forging slo stress rel	C3	3		3		3		3	5				1		2		2	
UCSB forging slo stress rel	C4	3				3			2						2		2	
UCSB forging slo stress rel	C5	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C6	8		9		6		11	6				1		2		2	
UCSB forging slo stress rel	C7	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C8	1				1			3								1	
UCSB forging slo stress rel	C9	3		3		3		3	3						2		2	
UCSB forging slo stress rel	C10	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C11	3		3		3		3	3				1		2		2	
UCSB forging slo stress rel	C12	1				1			1									
UCSB forging slo stress rel	C13	3				3			2						2		2	
UCSB forging slo stress rel	C14	1				1			1								1	
UCSB forging slo stress rel	C15	1				1			1								2	
UCSB forging slo stress rel	C16	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C17	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C18	1				1			2									
UCSB forging slo stress rel	C19	3		3		3		3	4						2		2	
UCSB forging slo stress rel	C20	4		3		3		3	4						2		2	
UCSB forging slo stress rel	C21	1				1			1								1	
UCSB forging slo stress rel	C22	3		3		3		3	2						2		2	
UCSB forging slo stress rel	C31	3		3		3		3	2						2		2	

Table C.3 Laval and IVAR Commercial Alloys

Laval alloys																		
UCSB forging	LA	1				1			1									
UCSB forging	LB	1		3		1		3	1				1		1		1	
UCSB forging	LC	3		4		2		3	2				1		1		1	
UCSB forging	LD	3		4		2		3	2				1		1		1	
UCSB forging	LG	3		4		2		3	2						1		1	
UCSB forging	LH	3		3		2		3	2				1		1		1	
UCSB forging	LI	3		3		2		3	2						1		1	
UCSB forging	LJ	2		3		2		3	2								1	
UCSB forging	LK	1				2		3	1									
UCSB forging	LO	1				2			1									
Comm. IVAR alloys																		
BW A weld	WA	2		3		2		3	2						1		1	
BW B weld	WB	2		3		2		3	1						1		1	
BW C weld	WC	2		3		2		3	1						1		1	
BW 62 weld	W62	3		3		2		3	2						1		1	
BW 63 weld	W63	3		3		2		3	2						1		1	
BW 65 weld	W65	3		3		2		2		1				1	1	1		1
BW 67 weld	W67	3		3		2		3	2						1		1	
ORNL 73 weld	W73	4		3		2		3	2						1		2	
Midland weld	MW	3				3			2						1		1	
ORNL HSST02 plate	02	2				1			2						1		1	
BW A302B plate	O32	2				2			2									
BW A508 plate	58	3				3			2									
JRQ comm plate	Q	3		3		3		3	2						1		1	

Table C.4 EPRI Alloys

EPRI alloys																		
A 320B plate	EA	4				3			1						1		1	
Linde 0080 wld	EC	4		3		3		3	1									
Linde 0090 wld	ED	2				2			1									
A533 B plate 1bG	E1	2				3			3									
A533 B plate 1bJ	E2	2				3			3									
A533 B plate 1bN	E3	2				3			3									
A533 B weld 1mT	E5	2				3			3									
A533 B weld 1mU	E6	2				3			3									
A533 B weld 1sX	E7	2				3			3									
A508-2 plate 2bA	E8	2				3			3									
A508-1 plate 5bA	E9	1				3			2									
weld	QC1	3		3		2			3						1		1	
weld	QC2	2		3		1									1		1	
weld	D3	3		3		2			2						1		1	
weld	HB	2		3		2			2						1		1	
weld	MP	2		3		2			1						1		1	
weld	TW	2				2			2						1			
FRG 8460	FD								1						1		1	
FRG 8240	FE	1							1						1		1	
FRG 8310	FM								1						1		1	

Table C.5 Model Alloys and Diffusion Multiples

OV model alloys																		
UCSB model	OV1	1	2															
UCSB model	OV2	1	2						2									
UCSB model	OV3	1	3						1	1				1		1		1
UCSB model	OV4	1	2						1					1				
UCSB model	OV5	1	2						1					1		1		1
UCSB model	OV6	1	2						1	1								
UCSB model	OV7		2							1				1		1		1
UCSB model	OV17	1	2															
UCSB model	OV18	1	2															
UCSB model	OV20	1	2															
Diff Multiple	DM	1							1								1	

APPENDIX D. Preliminary Schedule for post-irradiation examination of ATR-2 experiment.

POST-IRRADIATION EVALUATION-UCSB ATR-2 IRRADIATION EXPERIMENT

Task	Subtask	Task Title	FY14-Qtr1	FY14-Qtr2	FY14-Qtr3	FY14-Qtr4	FY15-Qtr1	FY15-Qtr2	FY15-Qtr3	FY15-Qtr4	FY16-Qtr1	FY16-Qtr2	FY16-Qtr3	FY16-Qtr4	FY17-Qtr1	FY17-Qtr2	FY17-Qtr3	FY17-Qtr4
1		**PIE Plan development**																
	1.1	Preliminary palnning																
	1.2	Discussions with UCSB																
	1.3	Discussions with INL																
	1.4	Discussions with ORNL hot cells																
2		**Shipment of Capsule**																
	2.1	Ship cask to INL																
	2.2	Ship cask to ORNL																
	2.3	Receipt of cask at ORNL-IFEL																
3		**Dissassemly of capsule in IFEL**																
	3.1	Development of dissassembly plan																
	3.2	Dissassemly of capsule, identification of subcapsules																
	3.3	Shipment of subcpsules to IMET																
4		**Disassembly of subcapsules in IMET**																
	4.1	Receipt of subcapsule cask at ORNL-IMET																
	4.2	Development of subcapsule dissassembly plan																
	4.3	Dissassembly of subcapsules, identification and packaging of specimens																
	4.4	Shipment of specimens to LAMDA																
	4.4	Shipment of dosimeters to IFEL																
	4.6	Shipment of specimens to other organizations																

POST-IRRADIATION EVALUATION-UCSB ATR-2 IRRADIATION EXPERIMENT

Task	Subtask	Task Title	FY14-Qtr1	FY14-Qtr2	FY14-Qtr3	FY14-Qtr4	FY15-Qtr1	FY15-Qtr2	FY15-Qtr3	FY15-Qtr4	FY16-Qtr1	FY16-Qtr2	FY16-Qtr3	FY16-Qtr4	FY17-Qtr1	FY17-Qtr2	FY17-Qtr3	FY17-Qtr4
5		**Activities in LAMDA/Hot Cells**																
	5.1	Tensile tests (367)																
	5.2	Microhardness tests (TBD)																
	5.3	Shear punch tests (500)																
	5.4	Fracture toughness tests (45)																
	5.5	FIB and prepare atom probe samples (TBD)																
	5.6	Prepare SANS, SAXS samples (TBD)																
	5.7	Prepare TEM samples(TBD)																
6		**Microstructural examinations and annealing studies**																
	6.1	Atom probe tomography (TBD)																
	6.2	Small angle neutron scattering (TBD)																
	6.3	Transmission electron microscopy (TBD)																
	6.4	Annealing studies																
7		**Dosimetric assessments**																
	7.1	Dosimeter counting																
	7.2	Dosimetric analysis																
8		**Data Analysis and reporting**																
	8.1	Data Analysis																
	8.2	Progress reports																