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LWR PRESSURE VESSEL IRRADIATION SURVEILLANCE IMPROVEMENT PROGRAM

(Brief Consensus Description)

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LWR PRESSURE VESSEL IRRADIATION SURVEILLANCE IMPROVEMENT PROGRAM
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Aging light water reactor pressure vessels (LWR-PV) are accumulating significant neutron fluence exposures, with consequent changes in their steel embrittlement characteristics. Recognizing that accurate and validated measurement methods are needed to periodically evaluate the metallurgical condition of these reactor vessels, the U. S. Nuclear Regulatory Commission has established the LWR-PV Surveillance Dosimetry Improvement Program. The primary concern of this program will be to improve, standardize, and maintain neutron dosimetry and damage analysis procedures used for predicting integrated damage exposure of LWR pressure vessels. A vigorous research effort attacking the same measurement problems exists world-wide and cooperative links with the NRC supported activity have been established.

Immediate program objectives are (1) to prepare updated and improved dosimetry and the associated damage exposure correlation ASTM standards for metallurgical testing and LWR-PV Irradiation surveillance programs, and (2) to perform supporting validation and calibration experiments in benchmark fields, reactor test regions, and operating power reactor surveillance positions. The goal of this activity is to establish consistent and accurate dosimetry and damage analysis techniques as well as to guide required neutron field calculations that are used to correlate changes in material properties with the characteristics of the neutron radiation field. The accepted accuracy goal for neutron flux and fluence integral parameters has been set at ± (5-15)% (3σ), although a higher upper bound uncertainty could become acceptable.

The assessment of the radiation-induced degradation of material properties in a power reactor pressure vessel requires characterization of the neutron field from the edge of the reactor core to boundaries outside of the pressure vessel. Measurements of neutron fluence and spectrum for this characterization are associated with two distinct components of LWR-PV irradiation surveillance procedures: (1) proper calculational estimates of the neutron fluence delivered to the first 3/4-thickness of the vessel steel; and (2) understanding the relationship between material property changes within reactor pressure vessels and metallurgical test specimens irradiated in test reactors and at accelerated neutron flux positions near the pressure vessel in operating power reactors.

The first component requires validation and calibration in a variety of neutron irradiation test facilities, including LWR-PV mock-ups, power reactor surveillance positions, and related benchmark neutron fields--see Table I. The benchmarks also serve as a permanent measurement reference for neutron flux and fluence detection techniques, which are continually under development and widely applied by laboratories with different levels of capability. The second surveillance procedure component requires a serious extrapolation of neutron-induced mechanical property change data obtained from test reactors and power reactor surveillance positions to locations inside the body of the pressure vessel. The neutron flux at the vessel is up to one order of magnitude lower than at surveillance specimen positions and up to two orders of magnitude lower for test reactor positions. Furthermore, the neutron spectrum at and within the vessel is substantially altered.

In order to meet the LWR-PV radiation monitoring requirement, a variety of neutron flux and fluence detectors are employed, most of which are passive. Each detector must be validated for application to the higher flux and harder neutron spectrum of the test reactor test regions and to the lower flux and degraded neutron spectrum of the surveillance positions. Required detectors must respond to neutrons of various energies, so that multigroup spectra can be determined with accuracy sufficient for adequate damage response estimates. Proposed detectors for the program, many of which are common to both LWR-PV and fast reactor neutron dosimetry, are listed in Table II.

The necessity for a pressure vessel mockup facility for dosimetry investigations and for irradiation of metallurgical specimens was recognized early in the formation of the NRC program. High- and low-flux versions of a single pressure vessel mockup have been designed and construction has begun --see Figure 1. As a specialized benchmark, this facility will provide a well-characterized neutron environment where active and passive neutron dosimetry, various types of LWR-PV neutron field calculations, and temperature-controlled metal damage exposure are brought together for validation.

The results of the measurement and calculational strategies outlined here will be made available for use by the nuclear industry as ASTM Standards. Federal Regulation 10CFR50 already calls for adherence to several ASTM Standards which require incorporation of flux monitors and post-irradiation evaluation in LWR-PV irradiation surveillance. Revised and new standards in preparation will be carefully structured to be up-to-date, flexible, and, above all, consistent. The existing ASTM Standards are listed in Table III and those in preparation in Table IV. Highlights of the program components and organization are shown in Tables V and VI.

TABLE I VENDOR AND UTILITY CALCULATIONAL TOOLS VALIDATION/CALIBRATION

Neutron Fields*	Validation/Calibration Results
I. Standard, Reference and Controlled-Environment-Benchmarks	
• Fission Sources, Iron Shells, etc.	• Cross Section Libraries; Processing Codes; Group Structures; Diffusion, Transport, Monte Carlo Type Codes; etc.
• ORR-PCS and -PSF	• Geometrical Modesl, as well as above items; Extrapolation -- Core Region to Surveillance to and Within Pressure Vessel Wall Locations; etc.
II. Operating Power Reactor-Test Regions	
• Browns Ferry 3 (BWR)	• In- and Ex-Vessel "BWR" Test
• Garigliano (BWR)	• IN- and Ex-Vessel "BWR" Test
• McGuire I (PWR)	• In- and Ex-Vessel "PWR" Test
• Arkansas (PWR)	• In- and Ex-Vessel "PWR" Test

*Documented in Compendium and/or Technical Reports

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TABLE II SENSORS PROPOSED FOR LWR METALLURGICAL TESTING AND PRESSURE VESSEL SURVEILLANCE

DETECTION TYPE	GENERAL APPLICATION				SHORT EXPOSURE APPLICATION ONLY (benchmarks, test reactors)	
RADIOMETRIC	reaction	half life	reaction	half life	reaction	half-life
Threshold response	^{93}Nb(n,n')	~ 14 yr	^{23}Th(n,f)FP	*	^{103}Rh(n,n')	56m
	^{237}Np(n,f)FP	*	^{60}Ni(n,p)	5.3 yr	^{115}In(n,n')	4.5h
	^{238}U(n,f)FP	*	^{58}Ni(n,α)	2.7 yr	^{32}S(n,p)	14.7d
	^{54}Fe(n,p)	313d	^{63}Cu(n,α)	5.3 yr	^{56}Fe(n,p)	2.6h
	^{58}Ni(n,p)	71d	^{55}Mn(n,2n)	313d	^{27}Al(n,α)	15h
	^{46}Ti(n,p)	84d			^{47}Ti(n,p)	3.4d
					^{48}Ti(n,p)	44hr
Non-threshold response	^{235}U(n,f)FP	*	^{59}Co(n,γ)	5.3 yr	^{197}Au(n,γ)	2.7d
	^{239}Pu(n,f)FP	*	^{45}Sc(n,γ)	84d	^{23}Na(n,γ)	15h
	^{109}Ag(n,γ)	251d	^{58}Fe(n,γ)	45d	^{63}Cu(n,γ)	13h
	^{181}Ta(n,γ)	115d	^{54}Fe(n,γ)	2.7 yr		

ALL APPLICATIONS	
TRACK RECORDER	
Threshold	^{237}Np(n,f), ^{238}U(n,f), ^{238}Pu(n,f), ^{232}Th(n,f)
Non-threshold	^{235}U(n,f), ^{239}Pu(n,f), ^{233}U(n,f), others
HELIUM ACCUMULATION	^{10}B(n,α), ^{6}Li(n,α), S(n,α), N(n,α), Be(n,α), Fe(n,α), other elements
DAMAGE MONITORS	Quartz, Metallurgical Sensors
TEMPERATURE MONITORS	Melt Wires, Thermal Expansion Detectors

*Range of useful fission product half lives is ^{140}Ba(12.8d) to ^{137}Cs(30 yr).

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TABLE III EXISTING ASTM STANDARDS FOR METALLURGICAL TESTING PROGRAMS AND IRRADIATION SURVEILLANCE OF NUCLEAR REACTOR VESSELS

ASTM Standards referenced in E 185-73: Surveillance Tests for Nuclear Reactor Vessels (1973).(1)

• E 261	Measuring Neutron Flux by Radioactivation Techniques and Neutron Dosimetry for Reactor Pressure Vessel Surveillance.
• E 184	Recommended Practice for Effect of High-Energy Radiation on the Mechanical Properties of Metallic Materials.
• E 23	Notched Bar Impact Testing of Metallic Materials.
• E 21	Recommended Practice for Short-Time Elevated Temperature Tests of Materials.
• E 8	Tension Testing of Metallic Materials.

Relevant ASTM Standards Including Those Referenced in E 261-77: Determining Neutron Flux, Fluence and Spectra by Radioactivation Techniques.(1)

• E 262 and 481	Determining Neutron Flux, Fluence, and Spectra by Radioactivation Techniques.(1)
• E 263-526	Determining Fast-Neutron Flux by Radioactivation of Iron (263), Nickel (264), Sulfur (265), Aluminum (266), Uranium 238 (393), Copper (523), and Titanium (526).
• E 418	Fast Neutron Flux Measurement by Track Etch Technique.
• E 419	Guide for Selection of Neutron Activation Detector Materials.
• E 482	Practice for Neutron Dosimetry for Reactor Pressure Vessel Surveillance.
• E 560	Practice for Extrapolating Reactor Vessel Surveillance Dosimetry Results.

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(1) This recommended practice is under the jurisdiction of ASTM Committee E-10 on Nuclear Applications and Measurement of Radiation Effects.

TABLE IV NEW AND UPDATED ASTM STANDARDS FOR METALLURGICAL TESTING PROGRAMS AND REACTOR PRESSURE VESSEL IRRADIATION SURVEILLANCE

I. Recommended Practices for Surveillance & Correlation

- Extrapolation of Surveillance Dosimetry to Reactor Vessel
- DPA Exposure Unit
- Damage Correlation for Reactor Vessel Surveillance

II. Recommended Guides for Supporting Methodology

- Application of Spectrum Unfolding Codes
- ASTM ENDF/A Cross Section and Error File
- Sensor Set Design and Irradiation
- Benchmark Testing of Reactor Vessel Dosimetry
- Application of Neutron Transport Methods

III. Recommended Methods for Sensor Measurements (See Table II)

- Radiometric Monitors
- Solid State Track Recorder Monitors
- Helium Accumulation Fluence Monitors
- Damage Monitors
- Specimen Temperature Monitors

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TABLE V BENCHMARK NEUTRON FIELDS FOR LWR-PV IRRADIATION SURVEILLANCE IMPROVEMENT PROGRAM

I. Facilities in Use or Scheduled

- LWR Operating Reactor Test Regions(1)
  - BR3 (PWR) Belgium, Garigliano (BWR) Italy
  - McGuire (PWR), Browns Ferry (BWR)
  - BSR (ORNL), U. of Buffalo, U. of Va. (materials testing reactors)
  - Arkansas (PWR), (out-of-vessel)
- Controlled Environments(1)
  - LWR-PV Mockup: PCA and PSF at ORNL
- Standard and Reference Neutron Fields(1)
  - Fission Spectra (^{235}U and ^{252}Cf) at NBS and CEN/SCK
  - Intermediate-Energy Standard and Reference Neutron Fields (Near--1/E and Fast Reactor Related): ISNF, ISNF/CV at NBS, Sigma Sigma at CEN/SCK, CFRMF at EG&G
  - Fast-Neutron-Driven Iron Shells at CEN/SCK

II. Spectrum Determinations(2)

- Active Differential Spectrometry
  - LWR-PV Mockup (PCA), CFRMF, Iron Shells
  - Validate in Fission Spectra, ISNF, ISNF/CV, ΣΣ
- Integral Detector Spectrum Unfolding
  - All Controlled Environments and Test Regions
  - Validate in Standard and Reference Fields as appropriate

III. Validation/Calibration of Passive Dosimetry

- Multiple-Sensor Sets For Neutron Fluence Spectral Determination: Radiometric, Track Recorder and Helium Accumulation Fluence Monitors
  - Detection Efficiency Calibration
  - Spectrum Unfolding
  - Field Perturbations and Gamma Response
  - QA Procedures
- Damage Sensors: Quartz, Metallurgical

IV. Neutron Field Compendium

- Physical Description
- Evaluated Neutron Spectrum and Other Field Parameters Based on Computation and/or Measurement
- Detector Response Functions, Cross Sections, Spectral Indexes
- Selected Measurement Results

Footnotes

(1) Benchmark classifications: (1) Standard Field: permanent, stable and reproducible in well-specified physical surroundings and characterized to state-of-the-art accuracy in terms of neutron flux energy spectra, and spatial distribution; (2) Reference Field: permanent, reproducible in known physical surroundings, less well characterized than a standard field, and accepted as reference by a community of users; (3) Controlled Environment: known physical surroundings and some spectral characterization, employed for a restricted set of well-defined experiments; (4) Test Region: radiation field used to investigate neutron dosimetry measurement problems and related correlations of radiation damage in materials.

(2) Neutron spectrum determinations performed in controlled environments and test regions characterize these fields experimentally in order to test calculations. The standard and reference fields, generally with satisfactorily defined spectra, are employed to validate the spectrum characterization techniques.

TABLE VI DEVELOPMENT AND VALIDATION OF DAMAGE EXPOSURE AND CORRELATION PROCEDURES

I. Acquisition of Metallurgical-Mechanical Testing Data

- From Irradiations in ORR-PSF Pressure Vessel Mockup
- From Irradiations in LWR Test Reactor Regions (BSR, U of Va, etc.)
- From Tests on Surveillance Remnants From LWR Operating Reactors (Garigliano, BR3, Browns Ferry, McGuire)

II. Damage Correlation

- Damage Function Analysis of Metallurgical-Mechanical Testing Data Based on Damage Modeling
- Correlation with Standardized Dosimetry in LWR-PV Test Regions

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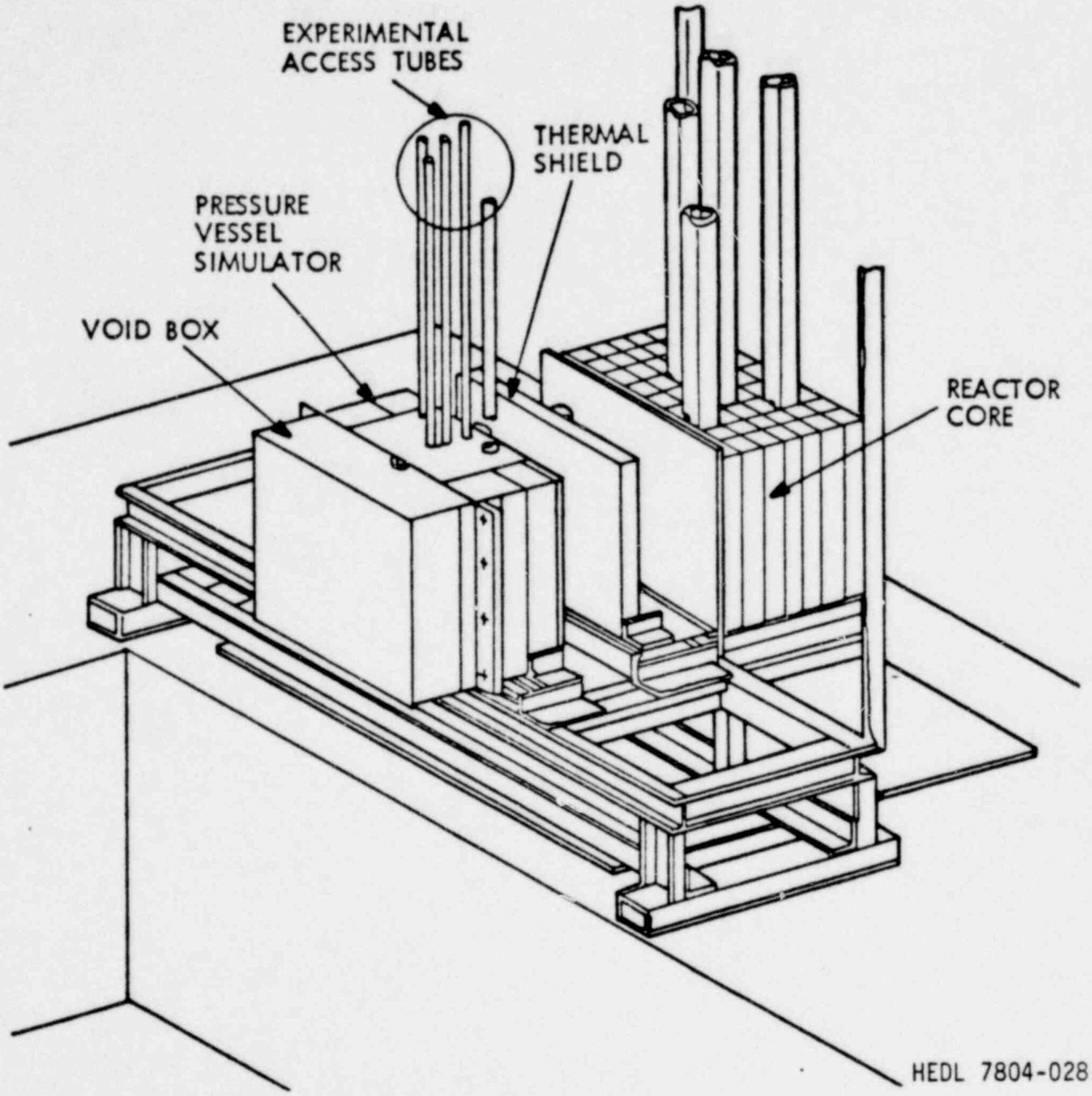

FIGURE 1. Pressure Vessel Wall Mockup Schematic of Two Equivalent Facilities Under Construction at ORNL. The high-flux version at ORR (PSF) will include damage exposure of metallurgical test specimens; the low-flux version near a low-power critical assembly (PCA) will focus on active and passive dosimetry measurements.

RECENT REFERENCE REPORTS

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