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Roadmap for Nondestructive Evaluation of Reactor Pressure Vessel Research and Development by the Light Water Reactor Sustainability Program

September 2012

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Computer Science and Engineering Division

ROADMAP FOR NONDESTRUCTIVE EVALUATION OF REACTOR PRESSURE VESSEL RESEARCH AND DEVELOPMENT BY THE LIGHT WATER REACTOR SUSTAINABILITY PROGRAM

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EXECUTIVE SUMMARY

The Department of Energy's (DOE's) Light Water Reactor Sustainability (LWRS) Program is a five year effort that works to develop the fundamental scientific basis to understand, predict, and measure changes in materials and systems, structure, and components as they age in environments associated with continued long-term operation of existing commercial nuclear power reactors. This year, the Materials Aging and Degradation (MAaD) Pathway of this program has placed emphasis on emerging nondestructive evaluation (NDE) methods that support these objectives. DOE-funded research and development (R&D) on emerging NDE techniques to support commercial nuclear reactor sustainability is expected to begin next year. This summer, the MAaD Pathway invited subject matter experts to participate in a series of workshops that developed the basis for the research plan of these DOE R&D NDE activities. This document presents the results of one of these workshops, the DOE LWRS NDE R&D Roadmap for Reactor Pressure Vessels (RPVs). These workshops made a substantial effort to coordinate the DOE NDE R&D with that already underway or planned by the Electric Power Research Institute (EPRI) and the Nuclear Regulatory Commission (NRC) through their representation at these workshops.

This series of workshops was held in the Oak Ridge, Tennessee, area during the week of July 30 through August 2, 2012. The workshops addressed four areas of NDE interest: (1) Cable Flaw Detection (Monday, July 30); (2) Concrete Aging Monitoring (Tuesday, July 31); (3) Reactor Pressure Vessel Monitoring (Wednesday, August 1); and (4) Fatigue Piping Assessment (Thursday, August 2). The Cable Flaw Detection workshop was held at the Analysis and Measurement Services (AMS) Corporation's AMS Technology Center at 9119 Cross Park Drive in Knoxville, Tennessee. The other three workshops were held at the Oak Ridge National Laboratory (ORNL) Conference Center at 1 Bethel Valley Road, Oak Ridge, Tennessee.

The purpose of the August 1 workshop was to develop content for this *Roadmap for Nondestructive Evaluation of Reactor Pressure Vessel Research and Development by the Light Water Reactor Sustainability Program*. The focus was on technical gaps in NDE techniques for detecting embrittlement and weld cracking in reactor pressure vessels. The workshop was attended by 25 people: two representatives from the Nuclear Regulatory Commission (NRC); one representative from the Electric Power Research Institute (EPRI); four representatives from universities (Georgia Tech, Northwestern, and Iowa State); three representatives from industry (Southwest Research Institute, Zetec, and WesDyne); and 15 representatives from national laboratories [ORNL, Pacific Northwest National Laboratory (PNNL), Argonne National Laboratory (ANL), and Idaho National Laboratory (INL)].

The development of a DOE vision for RPV NDE R&D is important because experimental evidence from the LWRS MAaD Pathway indicates that the currently utilized models for RPV lifetime may not be conservative at high fluence. Development of one or more NDE techniques that can assist in the determination of current RPV fracture toughness as well as in prediction of fracture toughness with further aging of the vessel (particularly in the presence of microcracks or other stress concentrators) is essential. The NDE measurements and the corresponding models that can verify their applicability to the problem, sensitivity to embrittlement and microcracking, and accuracy in characterizing physical properties of RPV steel to establish correlations with RPV fracture toughness will provide important information to the LWRS program.

The major emphasis of this workshop discussed the feasibility of using NDE techniques to determine embrittlement of commercial nuclear RPVs. Minor emphasis was placed on emerging NDE techniques that provide better insight into cracking and especially incipient cracking of RPVs.

Three important NDE research areas relative to RPVs were identified during the workshop:

1. NDE measurements towards RPVs embrittlement determination must measure steel properties that can be correlated with the steel's crack propagation during reactor accident conditions.
2. A comprehensive and well-characterized set of irradiated RPV steel samples needs to be assembled to support NDE technique research.
3. NDE techniques utilized towards RPV embrittlement determination must provide information on embrittlement throughout the thickness of the RPV.

Attempts to use NDE techniques to detect RPV embrittlement have been ongoing since the 1960s without significant success. The traditional approach to determining NDE applicability to detection of embrittlement in steels has been mainly experimental, with measurements on samples with varying degrees of embrittlement to see if there is any correlation to the fracture toughness of the steel. In many cases, these measurements have been made on surrogate specimens (i.e., specimens with varying hardness levels but not necessarily the same sort of microstructure that is indicative of irradiation embrittlement). While this type of research is essential (and still necessary), the DOE vision for NDE research on RPVs needs to expand upon this experimental work to include modeling efforts that assist in first principle understanding of NDE measurements versus changes in steel physical properties, as well as approaches to determine the correlation of that measurement with any crack propagation during accident conditions.

The fracture toughness of steel depends upon several factors, especially lattice defects such as vacancies, dissolved atoms, dislocation loops, solute clusters, precipitates, dislocation, and grain and phase boundaries. Major obstacles to the use of NDE for embrittlement quantification have been (1) the length scales of the features of interest (several nm) relative to the gauge length of typical NDE methods (100s of um and up), and (2) the sensitivity of NDE techniques to multiple factors. The result is the inability (with high confidence), with a single measurement, to distinguish between multiple factors and correlate the measurement to the fracture toughness.

The vision for DOE work in this area centers around efforts to understand how embrittlement (or the presence of microcracking, especially in the vicinity of fabrication flaws in welds) impacts the physical properties of the steel that NDE techniques are capable of measuring, the sensitivity of these NDE techniques, and how those measurements can then be related to the fracture toughness of the steel (or to other related properties). Research into NDE for RPV steels under the LWRS program needs to focus on addressing these gaps.

A consistent theme from all the LWRS NDE workshops and especially from the RPV workshop was that a comprehensive and fully characterized common set of samples for NDE experimentation needs to be assembled. The required RPV sample set is somewhat unique in that it needs to (1) be irradiated over a range of fluence using the appropriate flux and temperature conditions, (2) represent a number of base material and impurity compositions, and (3) be able to allow verification of NDE techniques from ½-Charpy-sized samples to those representative of full RPV thicknesses. To achieve the DOE vision for NDE research on RPVs, this sample set must be assembled. Statistical design of experimental methods may be applied to reduce the number of specimens that may be necessary for comprehensive evaluation of NDE methods.

The workshop concluded that some emerging NDE techniques appear to show promise for detecting and characterizing microstructural changes in RPV steels. These techniques include nonlinear ultrasonic, micromagnetic measurements and Seebeck-effect-based techniques. These techniques may offer a method for nondestructive characterization of RPV steel which can then possibly be correlated to its fracture toughness.

1. INTRODUCTION

The Department of Energy's (DOE's) Light Water Reactor Sustainability (LWRS) Program is developing the fundamental scientific basis to understand, predict, and measure changes in materials and systems, structure, and components as they age in environments associated with continued long-term operation (LTO) of existing commercial nuclear power reactors. Research under the LWRS Program is being conducted within five pathways:

- Materials Aging and Degradation
- Instrumentation, Information, and Control
- Risk
- Fuels
- Economics

A key element of LTO of LWRs is expected to be the management of aging and degradation in materials that make up the passive safety system components. Understanding the likely degradation mechanisms in these materials under LTO is essential. At the same time, approaches to assess the condition of these materials in a nondestructive fashion will also be necessary to assure adequate safety margins and ensure that an effective aging management program can be set up for LTO. The objective of the Materials Aging and Degradation R&D pathway is to create a greater level of safety through application of increased knowledge and an enhanced economic understanding of plant operational risk beyond the first license extension period. R&D is being conducted to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in NPPs. Data and methods to assess the performance of SSCs essential to safe and sustained NPP operations are being developed. These R&D products will be used to define operational limits and aging mitigation approaches for materials in NPP SSCs that are subject to long-term operating conditions.

License extensions for extended LTO (i.e., 60–80 years) will require a shift to a more proactive approach to aging management in addition to updated approaches to periodic in-service inspection (ISI). Three overarching elements of research are necessary to develop a proactive aging management philosophy:

- Integration of materials science understanding of degradation accumulation, with nondestructive measurement science for early detection of materials degradation
- Development of robust sensors and instrumentation, as well as deployment tools, to enable extensive condition assessment of passive NPP components
- Analysis systems for condition assessment and remaining life estimation from measurement data

It is likely that tackling these research elements in parallel will be necessary to address anticipated near-term deadlines for life extension decision-making (the first of the second-round license extension packets may be received by the NRC in 2014/15, with decision needed by 2019 or 2020).

To address the research needs, the Materials Aging and Degradation (MAAD) Pathway of the LWRS program supported a series of workshops in the summer of 2012, with the objective of identifying technical gaps and prioritizing research in nondestructive evaluation (NDE) methods. This document summarizes the findings of the workshop addressing NDE R&D for reactor pressure vessels (RPVs).

1.1 BACKGROUND

The US fleet of commercial nuclear power reactors has an average age of more than 30 years [1], and most of the fleet has either applied for or received an extension of the operating license from 40 years to 60 years (NRC 2011). Attention is now turning to the potential for a second round of license extensions [2–5]. A challenge to safe long-term operations is the life-limiting nature of materials aging and degradation, as such aging and associated degradation in the structural response of the material can limit safety margins [1]. Replacement of a subset of components (such as the steam generator) may be possible, though the costs associated with the replacement (including the time offline) may be challenging. Moreover, it is economically prohibitive to replace several of the larger components, including the RPV and primary piping. Thus, management and mitigation of aging-related degradation in these critical components becomes important to maintaining safety margins.

One component of concern is the RPV. In the context of long-term operations, the increased exposure to time-at-temperature, along with the effects of extended irradiation, is expected to reduce the fracture toughness of the pressure vessel. As a result of this, and the operational stresses experienced, issues of concern (in RPV and other Class 1 components) with respect to long-term operation include [6].

- stress corrosion cracking,
- helium-induced degradation and cracking in weld repairs,
- phase transformations due to irradiation,
- crack initiation, especially in nickel-based alloys, and
- embrittlement and hardening of RPV steels.

Each of these degradation types, as well as other degradation mechanisms that occur in these components, likely have different underlying mechanisms (many of which are poorly understood) that drive the accumulation of damage and initiation of cracking. Apart from the potential for coolant leaks from cracking, especially in welds in RPV penetrations, embrittlement (especially when combined with stress concentrators that promote crack growth) can, under the right conditions, increase the potential for failure of the RPV.

From a regulatory perspective, commercial nuclear power plants (NPPs) are required to demonstrate adequate safety margins through multiple, independent, and redundant layers of protection[7]. Regulatory guidance towards the management and mitigation of the effects of passive SSC aging in this regard is contained in the Generic Aging Lessons Learned (GALL) reports [8–11]. These reports provide the technical basis for determining whether plant aging management programs (AMPs) at operating reactors are adequate or need modification as plants enter extended operation. The AMP applies to all SSCs that are safety-related or whose failure could affect safety-related functions, as well as those SSCs relied on for compliance with fire protection, environmental qualification, pressurized thermal shock, anticipated transients without scram, or station blackout regulations. Specific programs that need modification are also identified, and the information in these reports is also included in the NRC's Standard Review Plan for Review of License Renewal Applications [12].

One component of the AMP is the scheduled in-service inspection (ISI) of passive components, codified in 10 CRF 50.55a[13], which specifies the requirements for nondestructive inspection (such as inspection periodicity, inspection techniques, and qualification procedures). These elements are contained in the American Society for Mechanical Engineers (ASME) Boiler & Pressure Vessel (BPV) Code, which the *Code of Federal Regulations* incorporates by reference. The ASME Code specifies the minimum requirements for NDE. Specifically, Section XI of the Code defines the acceptable volumetric and surface examination techniques, the minimum requirements for acceptable procedures, and the acceptance criteria for flaws that are detected. In addition, requirements for qualification of the procedures, equipment, and personnel are specified to ensure reliable inspections. Currently, degradation in the RPV and Class 1 components is managed through periodic ISI as mandated by the ASME BPV Code, with risk-based principles used to determine ISI intervals and the components for inspection in any given interval.

In the United States, for certain inspection techniques and components, the nuclear industry has developed additional examination guidelines, such as those developed under the Boiling Water Reactor

Owners Group's Vessel and Internals Project (BWRVIP) program, and the Materials Reliability Program (MRP)(for instance, [14, 15]). A number of studies have also examined the reliability of NDE techniques [16–25] and determined that several sources of variability were present that impacted the reliability of NDE. These results were codified in Section IX, Appendix VIII of the ASME BPV Code and are the basis for performance demonstration procedures for NDE techniques [26].

While the ISI program for metallic components (particularly Class 1 components) has been in existence for a number of years, there are still gaps associated with the reliable measurement of embrittlement, and the reliable detection of fabrication flaws and microcracking (which can be initiator sites for brittle failure under the right conditions). This report is the outcome of a workshop on RPV aging that examined the measurement and inspection needs and the current state of the art with respect to NDE for embrittlement detection (and to a lesser extent, detection of stress corrosion cracking), with the objective to identify technical challenges in the application of NDE methods for RPV aging detection and characterization, and to define a research roadmap to address these challenges. The objective of the proposed research is the development of the scientific basis for reliably detecting and characterizing RPV aging and degradation, to serve as input to licensing decisions for long-term operations.

1.2 REPORT ORGANIZATION

The document is organized as follows. Section 2 discusses the measurement needs from a materials science perspective. Specifically, the impact of degradation mechanisms of concern on materials microstructure, and the key measurements that are needed for assessment of impact on structural integrity are summarized. Section 3 summarizes the state of the art in nondestructive measurements that may be applicable to the problem at hand. Section 4 discusses the gaps (as identified at the workshop) in NDE measurements for LTO, and a research roadmap to address high priority gaps. Finally, Section 5 concludes the report and identifies a timeline for follow-on R&D. In addition, a series of Appendices are included that provide details of the workshop process, outcomes of the workshop, and list the attendees.

2. PROBLEM STATEMENT

2.1 INTRODUCTION TO REACTOR PRESSURE VESSEL EMBRITTLEMENT

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. The available embrittlement predictive models (e.g., [27]) 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 80 years.

The major issues regarding irradiation effects are discussed in [28, 29] and, 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 shift (TTS) at high fluence (ϕt) to at least 10^{20} n/cm^2 (>1 MeV) pertinent to plant operation of some PWRs for 80 full-power years. New and existing databases will be combined to support developing physically based models of TTS for high fluence–low flux ($\phi < 10^{11}$n/cm^2-s) conditions, beyond the existing surveillance database, to neutron fluences of at least 1×10^{20} n/cm^2 (>1 MeV). This document provides a brief overview of RPV materials, irradiation-induced embrittlement, and the underlying radiation damage mechanisms.

2.2 REACTOR PRESSURE VESSELS, MATERIALS, AND OPERATING CONDITIONS

The RPVs for LWRs are fabricated of cylindrical and hemispherical sections of quenched and temperature low-alloy (Mn-Mo-Ni) plates or forgings, welded together (usually by submerged-arc process), clad on the inside with stainless steel weld metal, and given a final postweld heat treatment. Such vessels may weigh up to 800 tons with wall thicknesses to ~330 mm (~13 in.). The RPV is a unique structural component in that a continuous nuclear fission reactor is realized in the nuclear core inside the RPV; a large boiling water reactor (BWR), for example, contains ~75,000 fuel rods with about 140 tons of uranium. The RPV must ensure long-term and safe operation under conditions of high pressure [~18 MPa (2500 psi) for a PWR], high temperature [~288°C (550°F)], and radiation. The chemical composition specifications for LWR RPV materials have evolved somewhat over the past five decades, primarily with control of elements discovered to cause loss of fracture toughness from exposure to irradiation or high temperatures. The most notable element in this regard is copper, which was discovered in the late 1960s to cause extreme radiation sensitivity of these RPV materials. Although some plates and forgings contain a relatively high concentration of copper, the most significant cases are welds that were fabricated with copper-coated weld wire.

2.3 MECHANICAL PROPERTIES OF RPV MATERIALS

Various specified tests are required to document the mechanical properties of RPV materials, primarily tensile strength and toughness. The tests normally performed include tensile tests (for strength and ductility), Charpy V-notch (CVN) impact tests (for toughness), and drop-weight tests (DWT) (to determine the nil-ductility transition temperature). Such tests are performed according to consensus specifications published by ASTM International and the American Society for Mechanical Engineers (ASME) Boiler and Pressure Code. The CVN and DWT tests are performed to establish a reference temperature (RT_{NDT}) that is used to index each material to a common fracture toughness curve. The CVN test is used to characterize the ductile-to-brittle transition behavior of the material, and to allow for determination of the temperature at which the material achieves 41 J (30 ft-lb), loosely correlated with the DWT NDTT. This temperature is designated the 41-J transition temperature, T_{41J}, and is also used as the index for determining the irradiation-induced embrittlement. Figure 1 shows a schematic plot of CVN energy vs. temperature data and a curve fit to the data that allows for determination of T_{41J} and the so-called upper-shelf energy (USE) denoted Fully Ductile in Fig. 1.

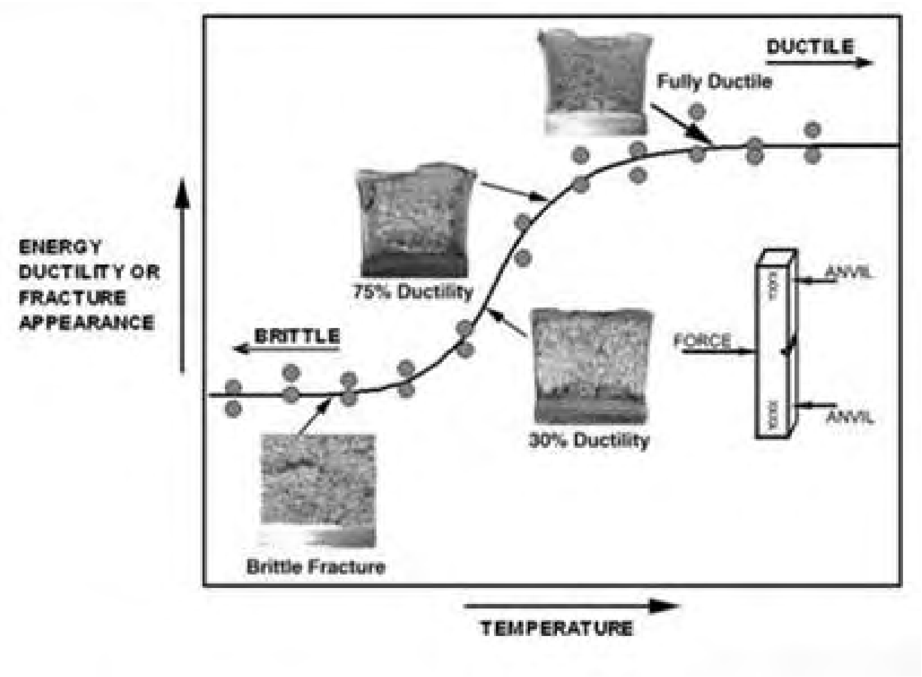

Fig. 1. Pressure vessel steels exhibit a rapid transition from brittle to ductile behavior by measuring the energy to break a Charpy V-notch specimen under impact loading.

Charpy impact energy is a qualitative measure of toughness that cannot be used directly to evaluate structural integrity. The fracture-mechanics-based fracture toughness, however, is a quantitative measure that can be directly related to the applied stress on a flaw of given size, either known or assumed. Figure 2 shows the linear elastic fracture toughness, K_{Ic}, data and bounding curve in the ASME Code that is normalized to the RT_{NDT}. Note that the fracture toughness and CVN toughness are similar in that they are both temperature dependent. The evolution of elastic-plastic fracture mechanics now allows for fracture toughness measurements with relatively small specimens and construction of a mean curve that also allows for probabilistic evaluations of structural integrity, including those associated with PTS.

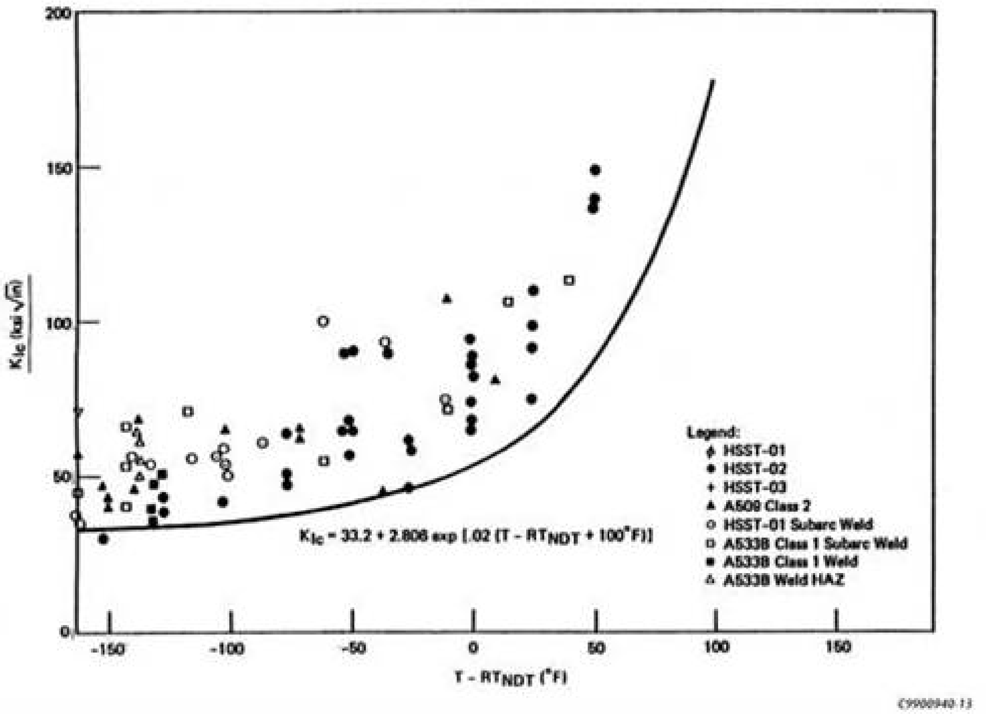

Fig. 2. Large compact specimens of 11 different heats of steel that were tested and the results used to construct a lower bound curve of K_{Ic} vs temperature normalized to the RT_{NDT}.

2.4 EFFECTS OF NEUTRON IRRADIATION OF RPV MATERIALS

Reactor vessel integrity assessments must account for the potential degrading effects of neutron irradiation. Depending on the sensitivity of the particular material, neutron irradiation causes an upward shift in the ductile-brittle TTS and a decrease in the upper-shelf energy. The schematic diagram in Fig. 3 (left) depicts how the irradiation-induced strength increase results in an upward shift in the toughness transition temperature, while Fig. 3 (right) shows that irradiation affects the Charpy impact toughness by shifting the ductile-brittle transition to higher temperatures and reducing the upper-shelf energy. The significant role of copper content is shown in the figure for two welds, very similar except for copper content, that exhibit significantly different radiation sensitivity because of the presence of copper. The TTS increases with operating time in a way that depends in a complicated way on the exposure rate (flux, ϕ), irradiation temperature (T_i), and the alloy type and composition (e.g., content of copper, nickel, manganese, phosphorus, silicon, and so on).

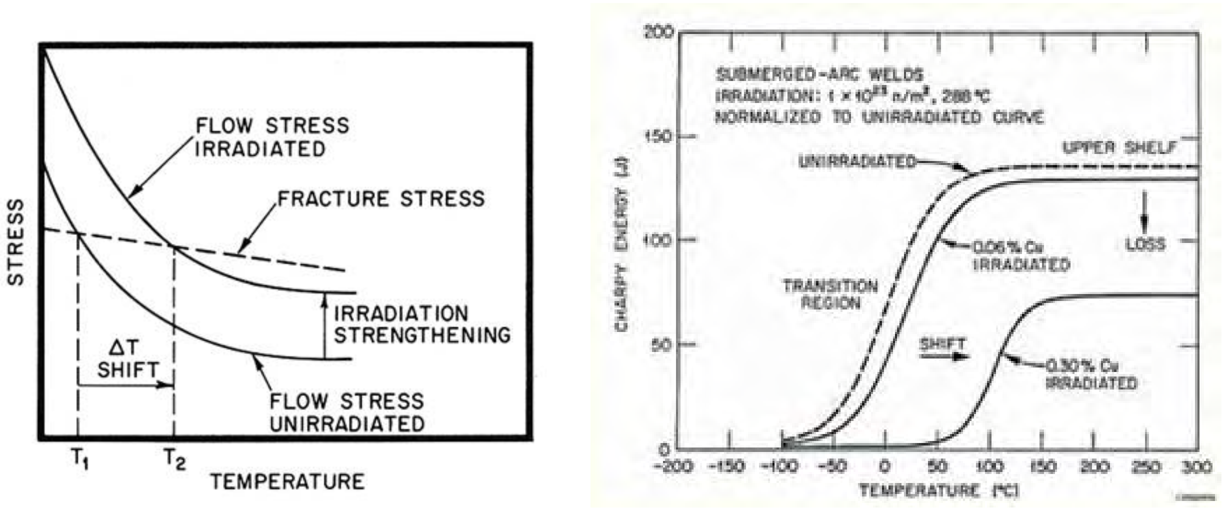

Fig. 3. Schematic diagrams depicting *(left)* how the irradiation-induced strength increase results in an upward shift in the Charpy impact toughness transition temperature, and *(right)* the significant role of copper content towards increasing radiation sensitivity.

Unfortunately, different vessels and even the same vessel contain different steels and experience different irradiation conditions. To monitor the irradiation embrittlement, reactors are required to include tensile and CVN specimens in surveillance capsules that are inside the RPV. The surveillance capsules are irradiated at somewhat higher flux than the RPV and are withdrawn periodically to test the specimens and determine the TTS vs neutron fluence. The results are compared with the predictive model in US Nuclear Regulatory Commission (NRC) Regulatory Guide 1.99, Revision 2 [30] and with 10 CFR 50 [31]. Currently, the irradiation-induced shift of the fracture toughness is assumed to be the same as the CVN-based TTS.

2.5 Radiation Damage Mechanisms

This brief overview of radiation damage mechanisms is taken from [6], which is a brief summary of a detailed discussion of Chapter 2 in [27]. High-energy neutrons generate primary recoil atoms with energies up to several tens of keV. The primary recoil atoms slow down in a branching series of collisions with atoms that are ejected from their lattice sites in what is known as a displacement cascade. This produces a large concentration of vacancies and self-interstitial atoms in the cascade region. Many self-interstitial atoms quickly recombine with vacancies, thus minimizing damage, or they aggregate in clusters of like defects, typically in the form of complexes with various solute atoms. At RPV operating temperatures ~520–570°F (~270–300°C), the residual vacancies and interstitials subsequently diffuse long distances to various sinks.

The two-feature model presented below includes separate terms for two important types of radiation damage, “matrix features” (MF) and “copper-rich precipitates” (CRP). The matrix features mainly form in the cascades, producing hardening in both low-Cu and high-Cu steels. MF are believed to be vacancy-solute cluster complexes or their solute (Ni, Mn, P, and Si) remnants. MF may be partially stabilized and may grow by long-range diffusion of vacancies and solutes. The hardening embrittlement caused by MF increases with decreasing irradiation temperature and roughly with the square root of fluence. The corresponding temperature dependence can be rationalized as being a consequence of the MF thermal stability; that is, more MF survive at lower temperatures. The square root fluence dependence is consistent with linear scaling with fluence of the number of MF that act as dispersed barriers to dislocation glide.

Embrittlement also arises due to hardening caused by precipitation, accelerated by the excess concentration of vacancies under irradiation. Well-formed CRP composed of Cu, Ni, Mn, and Si form above a threshold level of about 0.07 wt % Cu. If there are high enough concentrations of these alloying elements in the steel, the Mn, Ni, and Si content in the precipitates can exceed the corresponding Cu content [27, 32–35]. However, for simplicity and clarity, we will refer to all precipitate features with at least 0.07 wt % Cu as CRP throughout this report.

The CRP are distinguished from Ni-Mn-Si precipitates that contain only small amounts of Cu, which can form in steels with <0.07 wt % Cu [36]. These features, which probably develop from matrix feature precursors, are referred to as late blooming phases (LBP) because they generally evolve at high fluence. Late blooming phases are *not* specifically accounted for in the current model. However, the potential for embrittlement due to LBP and other hardening features that may evolve late in life must be carefully considered when establishing the fluence limit for use of the TTS model reported here.

Evolution of CRP is the dominant mechanism of embrittlement in the most irradiation-sensitive western RPV steels [27, 32–35]. Radiation-enhanced diffusion of solute atoms (e.g., Cu, Ni, Mn, and Si) occurs because of the much higher concentration of vacancies in the steel under irradiation. Coherent CRP quickly nucleate and continue to grow by radiation-enhanced diffusion until the Cu is nearly depleted from the matrix. The chemical potentials (effective free energies) of Ni, Mn, and Si atoms are higher in the matrix, so these elements (and Cu) flow into the precipitates where the chemical potentials are lower. The rate of CRP nucleation depends on the alloy Cu content (as well as other elements) and temperature, but it is generally very rapid due to the large supersaturation in higher Cu steels. The resulting high number of precipitates ($>10^{23}/m^3$) efficiently pins dislocations, producing significant hardening in RPV steels with Cu contents above about 0.07 wt %, and the hardening leads to the TTS. The sigmoidal shape of the TTS versus fluence curve is the direct consequence of CRP nucleation, growth, and saturation (or slow coarsening). However, Ni, Mn, and Si can continue to accumulate in CRP after Cu is depleted; thus, these solutes, especially Ni, also affect the fluence dependence of hardening and embrittlement. For a given fluence, the total amount of solute diffusion decreases with increasing neutron flux, thus delaying CRP and MF hardening and TTS. Flux effects are discussed further in the section below comparing the TTS model derived in this work with the IVAR database. As discussed in Chapter 6 of [27] and associated references, P is also enriched in the CRP, but in small absolute amounts that have little effect on hardening. However, P may also form phosphide precipitates with alloying elements (such as Mn) that lead to hardening, and this may rationalize the Mn-P interaction term found in fitting the MF parameters described below.

In very high-Cu steels, the amount of Cu remaining in solid solution that is available for radiation-enhanced precipitation is typically less than the measured bulk content, due to pre-precipitation during heat treatments performed during the fabrication of an RPV. The maximum amount of copper that remains in solution following typical heat treatments is about 0.25 to 0.3 wt % [27, 32–38] regardless of bulk Cu content. This is the mechanism responsible for the maximum effective copper limit (Max Cu_e) in the model presented below.

As noted above, the chemical potentials of Ni, Mn, and Si are lower in CRP because of stronger atomic bonding between these elements (see Chapter 2 of [27] and associated references). The effects of Si are mixed and may be confounded by correlations with product form in the surveillance data. Also, as discussed below and in Chapters 2 and 6 of [27], an unambiguous and systematic effect of Mn on both hardening and microstructure is shown in the IVAR database. However, the effect of Mn in the surveillance database is almost completely confounded by its association with product form. Variations in Ni in the surveillance data are larger and more ubiquitous than the variations in Si and Mn, so there is a clear effect of Ni enhancing the effects of Cu on TTS, as reflected in all the predictive embrittlement formulas based on the US LWR surveillance database [27, 39–43], the Japanese LWR surveillance database [44, 45], and data on other commercial reactor vessel steels [46, 47]. One of many examples of atom probe tomography studies in [48] shows enrichment of CRP with Ni, Mn, P, and Si, consistent with other characterization studies such as small angle neutron scattering, TEM, and resistivity-Seebeck coefficient characterization studies [27, 32–35, 49, 50]. These studies have shown the strong synergistic interaction between Ni and Mn. A report on an International Atomic Energy Agency (IAEA) Cooperative Research Project notes that "for a given high level of nickel in the material and all other factors being equal, high manganese content leads to much greater radiation-induced embrittlement than low manganese content for both VVER-1000 and PWR materials" [51]. These interactions were predicted long ago based on theoretical models [34, 52–54] that were subsequently verified by careful single-variable experiments and detailed nano-analytical characterization studies [27, 33–36, 55].

2.5 ISSUES FOR DETERMINATION OF RPV FRACTURE TOUGHNESS WITH NDE

The objective is to have a technique(s) that can, with acceptable uncertainties, determine the fracture toughness of the materials in an irradiated RPV. As discussed above, the embrittling parts of the irradiated microstructure are extremely fine scale features (e.g., ≤3 nm). These features include solute clusters and precipitates/clusters, dislocation loops, point defect/solute atom complexes, and grain boundary segregation (e.g., phosphorus). The following questions are posed for consideration:

- Can the technique(s) resolve differences in the features, for example, CuNiMn precipitates vs NiMnSi precipitates? If we can resolve precipitates vs matrix features, can we relate their contribution to embrittlement?
- Can we relate the resolution of features to fracture toughness, or can we relate it to the change in fracture toughness as a consequence of irradiation? Note that, in many cases, archive materials are not available.
- The RPV is from ~203 to 305 mm (8 to 12 in.) thick. Can we probe the RPV within the thickness, (e.g., at the ¼ t location)?
- Can the technology replace the current procedures, that is, Charpy/fracture toughness surveillance testing in regulatory space?

Figure 4 is a schematic diagram of fracture toughness vs temperature for radiation-sensitive steel at different levels of neutron fluence that result in different curves as the irradiation-induced shift increases. Assuming the NDE measurements are performed at one temperature, the diagram indicates that the fracture toughness of the material changes. The lowest point shows that the fracture toughness is the same for the two highest curves at the measurement temperature but that the two curves have different fracture toughness at higher temperatures.

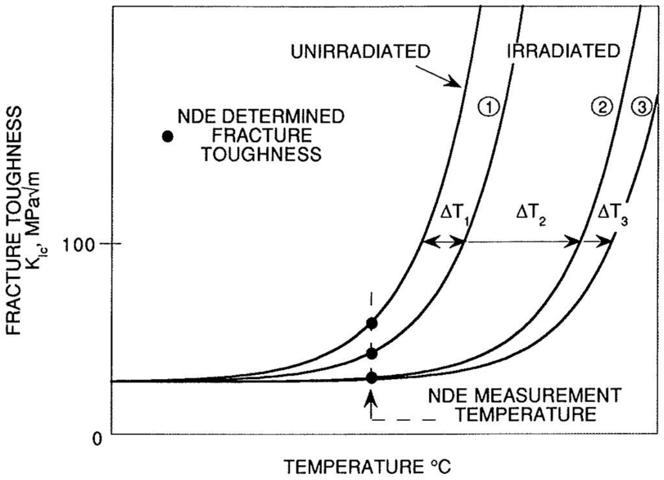

Fig. 4. Schematic diagram showing potential drawback of performing NDE measurements at a fixed temperature. The curves with the two highest shifts have the same fracture toughness in the lower portions of the curves but different fracture toughness with increasing temperature.

3. NDE FOR REACTOR PRESSURE VESSELS: CURRENT STATE OF THE ART

3.1 NDE TECHNIQUE FEASIBILITY OVERVIEW

Attempts to use nondestructive evaluation (NDE) techniques to detect RPV embrittlement have been ongoing since the 1960s without significant success. To date, no NDE technique has been applied to an in-service RPV with the intent of characterizing its embrittlement. All studies and research have been conducted on representative samples. The traditional approach to determining NDE applicability to detection of embrittlement in steels has been mainly experimental, with measurements on samples with varying degrees of embrittlement to see if there is any correlation to the fracture toughness of the steel. In many cases, these measurements have been made on surrogate specimens. These surrogate specimens have varying hardness levels but not necessarily the same sort of microstructure that is indicative of irradiation embrittlement. In addition to some surrogate samples not having the same sort of microstructure that is indicative of irradiation embrittlement, the microstructure changes with level of irradiation fluence. Even if irradiated samples are available, often the neutron fluence range in their level of irradiation is limited. Additionally, most samples utilized for NDE technique evaluations have been ½-Charpy-sized samples (10 × 10 × 27 mm). There is significant concern for extrapolation of results obtained from evaluations on this size sample versus the 250- to 310-mm-thick steel sections of in-service RPVs. Further complicating the utilization of test samples for NDE feasibility evaluations is the variety of base metal and weld compositions and base metal and weld impurities used for RPV fabrication. Both the composition and impurity factors influence the resultant microstructure of the irradiated RPV steel. To date, a comprehensive, well-characterized set of samples for NDE technique evaluation of RPV embrittlement has not been assembled.

However, as recently as the late 1990s through the mid 2000s, several organizations have sponsored research or reviewed the NDE applications into this area. Of particular note are four studies by four different organizations: (1) Westinghouse in the mid-1990s [56], (2) the Korean Atomic Energy Research Institute in the late 1990s [57], (3) the National Institute of Standards and Technology in 1998 [58], and (4) the European Commission’s Project GRETE in the early 2000s [59]. These organizations reviewed the applicability of a wide variety of NDE techniques to the RPV embrittlement problem.

The Westinghouse feasibility study evaluated (1) electrical resistivity, (2) magnetic hysteresis, (3) magnetic Barkhausen effect, (4) magnetic acoustic emission, (5) eddy current, (6) ultrasonic velocity and attenuation, and (7) microhardness. For their study, Westinghouse utilized steel samples of nuclear RPVs from two nuclear reactor surveillance programs. Since these samples were irradiated during operation of commercial nuclear reactors, they were representative of the radiation embrittlement that actually occurred over time during reactor operation, but they were ½-Charpy-sized samples and represented only a limited range of neutron fluence. The Westinghouse study concluded that there were substantial difficulties with electrical resistivity and eddy current techniques. Additional research was needed for magnetic techniques, but ultrasonic NDE techniques, especially nonlinear ultrasonic techniques, hold the most promise for sensing the microstructure of RPV steel. Microhardness techniques are not traditional NDE and offer some promise, but how to apply them throughout the thickness of typical RPVs is yet to be determined. The specific comments on each technique from the Westinghouse evaluation are contained in Table 1.

Table 1. Westinghouse feasibility comments on various NDE techniques

Electrical Resistivity	“Although the microstructure of the material may be monitored by resistivity measurements, these values were not shown to correlate with the mechanical properties of the material such as the yield strength, Charpy transition temperature, or the upper shelf energy.”
Magnetic Techniques	“Studies have shown that changes in magnetic parameters occur in irradiated and annealed samples. The difficulty in using this technique to detect embrittlement arises from both the complex changes in the microstructure of pressure vessel steels and the inadequate modeling of the hysteresis loop. In turn, this inadequate modeling poses challenges for separating the specific contributions, such as material chemistry, heat treatment, and residual stresses, to the changes in the parameters. It also presents a challenge for interpreting results in terms of fundamental changes in the sample properties.”
Eddy Current	“It is not surprising that opposing trends have been observed in these studies given the number of factors that can influence the results of the measurement. Detailed examination of the frequency dependence of the results could be used to separate the effects of the resistivity and permeability, and to give a better understanding of what the eddy current values represent. It is not clear how the results will be related to the mechanical properties of the steel.”
Ultrasonic Techniques	“The ultrasonic techniques appear to be closely related to the mechanical properties of interest in the embrittlement of pressure vessel steels and seem to be most promising for monitoring embrittlement. Further studies are warranted for the development of a nonintrusive ultrasonic measurement technique.”
Microhardness	“Because microhardness measurements are not traditionally viewed as being nondestructive in nature, their use as a nonintrusive tool has been overlooked. The microhardness technique should be pursued as a viable NDE technique in monitoring the level of embrittlement in pressure vessel steels.”

The Korean Atomic Energy Research Institute (KAERI) evaluated the NDE feasibility of (1) magnetic hysteresis, (2) magnetic Barkhausen effect, and (3) ultrasonic velocity and attenuation. Like Westinghouse, the Koreans also used samples for their evaluation. Their samples were of SA508 Cl.3 forgings and weld surveillance specimens of ½ Charpy size exposed with a fluence of 2.2×10^{19} n/cm^2 by neutrons of energy >1.0MeV. The KAERI evaluation study concludes that both magnetic and ultrasonic techniques are promising and indicates that they are sensitive to the microstructure changes that occur during embrittlement, but that more work is needed to relate the microstructural changes that can be detected by them to the embrittlement of the steel. The specific comments on each technique from the KAERI evaluation are contained in Table 2.

Table 2. KAERI feasibility comments on various NDE techniques

Magnetic Techniques	“The magnetic hysteresis parameters showed changes with fluence, and the magnetic Barkhausen effect/magnetic acoustic emission (MBE/MAE) results were sensitive to the size of the precipitates and to the dislocation density. However, more work is needed to determine how each microstuctual change affects each parameter and to separate the contribution of each microstructural effect. Finally, the results must be shown to correlate with the mechanical changes in the material.”
Ultrasonic Techniques	“A parametric analysis by ultrasonic techniques may be useful for identifying the material state related to neutron irradiation embrittlement and can be considered useful for supplementing the current technology for the evaluation and prediction of reactor vessel integrity if further research to identify an inconsistent phenomenon can be performed” and “the magnetic and ultrasonic techniques appear to be closely related to the mechanical properties of interest in the radiation embrittlement of pressure vessel steel and seem to be promising for monitoring embrittlement. Further study has to be

	continued in order to achieve more accurate and reliable results for the assessment of radiation embrittlement.”

The National Institute of Standards and Technology (NIST) evaluated the NDE feasibility of (1) elastic properties, (2) X-ray diffraction, (3) nonlinear ultrasonic, (4) magnetic properties, (5) micromagnetic techniques, (6) dislocation mobility under static stress, and (7) measurements under cladding. The NIST evaluation also utilized samples that were predominantly surrogate steel samples hardened to simulate the hardness of embrittled RPV steels. Some evaluations did utilize irradiated RPV steel, but in limited quantities. The samples were ½ Charpy sized. Several of the NDE techniques evaluated were not implemented in a form that would ever be applicable to field measurements. The most applicable NDE techniques evaluated by NIST were the nonlinear ultrasonic techniques, and they concluded that “the nonlinear ultrasonic parameter β, the maximum transverse incremental permeability μ_t, and the high field average magnetostriction $\lambda\infty$ appear capable of predicting the ultimate tensile strength, the hardness, and the ductile to brittle transition temperature (DBTT) of a steel in which the embrittlement mechanism is similar to that responsible for embrittlement of RPVs. All three properties can be deduced from ultrasonic measurements that can be performed nondestructively.”

Project GRETE, conducted by the European Commission in 2000 and 2001, studied NDE technique feasibility for both neutron irradiation damage and fatigue damage. Fifteen European organizations within the European Commission participated in Project GRETE. Eight of the partners participated in evaluating NDE techniques for neutron irradiation damage. The Project GRETE feasibility study evaluated (1) ThermoPower (Seebeck and Thomson coefficients), (2) micromagnetic measurements, (3) magnetic Barkhausen noise, (4) non-linear harmonic analysis of eddy current signals, and (5) automated ball indenter (microhardness). Project GRETE used samples from five partners, which were irradiated at up to five different fluence levels in both commercial and test nuclear reactors. The fluence range of the samples ranged from 0.7×10^{19} to 10.2×10^{19} n/cm^2 (E > 1 MeV) as well as unirradiated. Project GRETE concluded that the micromagnetic and magnetic Barkhausen noise techniques show the most promise for indicating the microstructure of RPV steels. Since 2001, the Fraunhofer Institute for Non-Destructive Testing (IZEP), who performed the magnetic Barkhausen noise study under Project GRETE, has continued with the investigation into using Barkhausen noise to characterize steel microstructure with some success. The specific comments on each technique from the Project GRETE evaluation are contained in Table 3.

Table 3. Project GRETE feasibility comments on various NDE techniques

ThermoPower	“The techniques based on the measurement of the ThermoElectric Power (Seebeck and Thomson coefficient) have shown good linear correlation between the measured signal and the accumulated fluence or the transition temperatures shift. The determination quantitative information by the non-destructive methods may only be done on individual set of specimens because of the influence of other parameters such as chemical composition, segregation, and hear treatment.” “The measurement of TEP and STEAM (ThermoElectric Power measurements), based on the same physical principle has shown the ability of these techniques to follow qualitatively the embrittlement of RPV steel. Some developments are needed in order to achieve quantitative data….”
Micromagnetic Measurements & Magnetic Barkhausen Noise	“The Micromagnetic techniques … were in general sensitive to the irradiation damage…. There is a strong interaction between the precipitates and the magnetic Bloch walls of the domain…. The effect of the embrittlement of the irradiated specimens on the measured values is probably small compared to the effect of the residual stresses in the specimens … the strong plastic deformation (of the ½ Charpy specimens on the front versus back) has also reduced the number of possible local measurement positions on the specimens and has therefore also influenced the statistics.”

Microhardness	"The Automated Ball Indenter (ABIT) method based on ball indentation has promising capabilities to follow the hardening of the specimen by the determination of the tensile strength."

3.2 PROMISING NDE TECHNOLOGIES FOR DETECTION OF EMBRITTLEMENT IN RPVS

When metallurgists are characterizing the microstructure of RPV steels, they employ multiple techniques such as transmission electron microscopy, atom probe tomography, small angle neutron scattering, and positron annihilation. To estimate the remaining useful lifetime of RPVs, they typically use microstructure characterization from some or all of these techniques along with Charpy V-notch test results and DBTT changes. It is probably unreasonable to expect that a single NDE technique will be able to provide a comprehensive characterization of the microstructure of RPV steels, much less an estimate of the remaining useful life of a RPV. Therefore, it is prudent to investigate using multiple NDE methods to obtain a reasonable, if not completely comprehensive, characterization of the RPV steel microstructure in hopes of being able to then correlate this microstructure with remaining useful life. In this section, some NDE techniques are described that have been shown in laboratory studies to be responsive to steel microstructure changes and are therefore candidates for future R&D work to indicate RPV embrittlement.

3.2.1 Nonlinear Ultrasonic

Nonlinear ultrasonic techniques are a promising candidate for NDE of irradiation damage in RPV components. Nonlinear ultrasound (NLU) measures higher order harmonics that are generated in the material as the wave propagates, and this effect is quantified with a measurable nonlinear ultrasonic parameter. This parameter is sensitive to microstructural changes in the material such as dislocation formation and interactions, precipitates, and grain boundary effects. Standard *linear* ultrasonic techniques can monitor damage in material, but these methods are limited by the wavelength of the signal. *Nonlinear* ultrasonic techniques, on the other hand, are not wavelength-limited, and microstructural features that are orders of magnitude smaller than the wavelength of the propagating wave can be detected. Another attractive feature of NLU is that the necessary sensors and instrumentation are the same as those used in typical linear ultrasonic ISI measurements. It is crucial that material modeling efforts for irradiation effects be integrated with these nonlinear ultrasonic techniques to extract relevant parameters for RPV NDE.

Nonlinear ultrasound (NLU) to monitor damage has received a lot of attention throughout the literature. NLU has been used to monitor embrittlement in surrogate steel samples. In this work, NLU measurements were made on thermally aged ASTM A710 steel samples, showing that the NLU parameter was related to plastic strain and hardness, and the effects of copper-rich precipitates on NLU were investigated [60]. Other work has shown NLU has the ability to monitor fatigue damage in a variety of metallic materials [61]. This is because NLU is sensitive to dislocations, dislocation pinning by precipitates, and dislocation dipoles [62], which are all microstructural features that evolve throughout fatigue. Nonlinear ultrasound was briefly used to investigate neutron irradiation in copper crystals, and results showed that irradiation caused dislocations to be pinned [63]. It has also been shown that nonlinear ultrasound is related to tensile properties of cold worked stainless steel [64], and also creep damage in titanium alloys [65].

As a tone burst ultrasonic wave propagates through a nonlinear material, higher order harmonics are generated. The received signal consists of a summation of ultrasonic waves at the input frequency plus a second harmonic wave, which can be directly related to a material property called the material nonlinearity. This is a direct result of considering the nonlinear stress-strain relationship of a material instead of the linear approximation. The material nonlinearity of, for example, steel results from the inherent anharmonicity of the lattice structure and will increase with increasing microstructural evolution. Microstructural features such as the lattice anharmonicity, dislocations, and precipitates produce local atomic strain fields since they cause a geometric incompatibility with the crystalline structure. This strain field is highly nonlinear, and so when an ultrasonic wave perturbs these features, they act as a nonlinear body force to the ultrasonic wave and cause higher order harmonics to be generated. As the microstructure evolves from some sort of damage mechanism (e.g., neutron irradiation), the ultrasonic wave interacts with the increasing amount of dislocations, precipitates, and other matrix defects, which cause an increase in nonlinearity and thus an increase of the amplitude of the second harmonic wave. This phenomenon can be directly measured with slightly modified typical ultrasonic testing equipment.

A typical laboratory measurement of the nonlinearity of a material using longitudinal (bulk) waves is as follows. Two commercial piezoelectric transducers are mounted in a pitch-catch fashion on a material sample with light-grade oil for acoustic couplant. A high-power gated amplifier is used to generate a tone burst signal in one transducer, while the other transducer receives the signal that is then transferred to an oscilloscope and ultimately a computer for post-processing. A fast Fourier transform is then performed on the received signal to obtain the frequency response, and the amplitudes of the first and second harmonic frequency components are analyzed to obtain the nonlinearity parameter of the material. An example schematic of this measurement setup for Charpy impact samples is depicted in Fig. 5. Note that while this measurement setup uses longitudinal waves in a pitch-catch manner, the NLU phenomenon can be measured using other ultrasonic waves including Rayleigh surface waves, Lamb waves, and potentially longitudinal waves in a pulse-receive or double-echo type setup to eliminate the need for a mounted transducer on two opposing faces of the material.

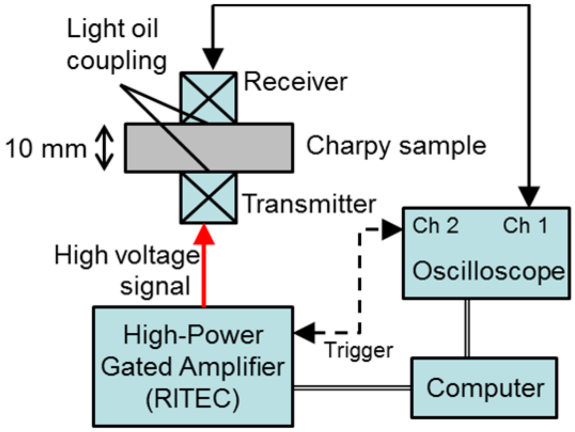

Fig. 5. Experimental schematic for typical laboratory NLU measurement on Charpy-type samples.

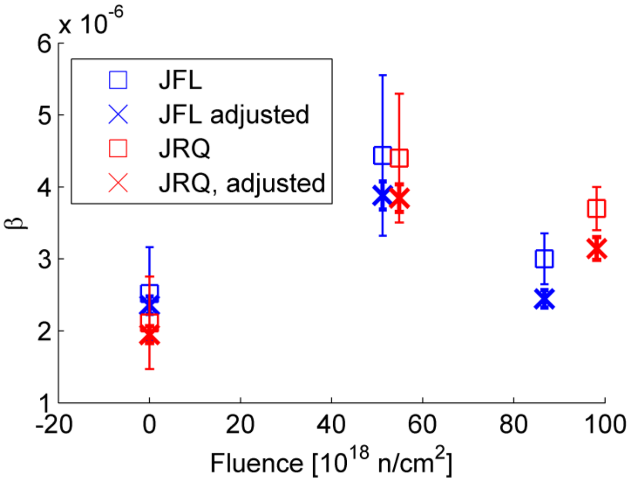

Fig. 6. Measurements of the nonlinear ultrasonic parameter on RPV steel over neutron fluence. Raw results and adjusted results (for experimental effects) are shown.

Previous work has shown that nonlinear ultrasonic NDE methods are sensitive to radiation damage in RPV steel [66]. The nonlinear ultrasonic parameter was measured on Charpy impact samples of a reference RPV steel material, ASTM A533B Cl.1, at increasing levels of neutron fluence up to 10^{20} n/cm^2 (E > 1 MeV). Results showed that the nonlinear ultrasonic parameter increased up to a “medium” fluence of roughly 5×10^{19} n/cm^2 and then decreased or leveled off to the maximum fluence of the sample set (Fig. 6). The increase of the NLU parameter from unirradiated to the medium fluence samples was attributed to an increase in dislocation density that occurs throughout radiation damage, and the decrease or leveling off from medium to high fluence was attributed to increased formation of precipitates, which can act to immobilize dislocation motion and thus decrease their contribution to the NLU parameter. To further investigate the applicability of NLU methods to irradiation damage, a sufficient sample set must first be obtained to monitor sufficient fluence levels, fluxes, and composition effects. Then, the nonlinear ultrasonic parameter must be monitored across these parameters, and these results must be integrated with material models to relate to radiation embrittlement.

3.2.2 Magnetic Barkhausen Effect

A number of magnetic measurements have been investigated for correlations with irradiation embrittlement and cracking in ferromagnetic steels. Fundamentally, all of these measurements rely on changes in the magnetic properties in materials as a result of microstructural changes due to external stressors (irradiation, mechanical and thermal stress, chemical attack, etc.). Broadly, these measurements are all dependent on the fact that magnetic domain wall motion in ferromagnetic materials is impacted by the presence of lattice defects. The interaction of magnetic domain walls with these defects results in changes in the shape of magnetic hysteresis loops, with corresponding changes in a number of magnetic parameters such as the coercivity, remanance, and other major and minor loop parameters [67, 68]. Irradiation (and other stressors) changes the amount of Cu and Ni precipitates in legacy RPV steels. The presence of Cu- and Ni-rich precipitates, or the presence of other lattice defects (such as slip-bands, or solute vacancy clusters) results in the formation of magnetic domain wall pinning sites that inhibit the movement of domain walls in response to an externally applied magnetic field. As a result, changes occur in magnetic coercivity and remanance (due to a change in the shape of the hysteresis curve).

A related effect is the Barkhausen effect [69, 70]. The magnetic flux density in ferromagnetic materials placed in an external applied magnetic field is a function of the applied magnetic field, with larger numbers of magnetic domains within the material aligning with the applied field direction with increasing applied field strength. This realignment is, however, not a continuous process, because the presence of dislocations or other damage precursors results in domain wall pinning. Increasing the applied field strength results in abrupt realignment of some domains, and is accompanied by a release of energy that may be detected using a sensing coil (Fig. 7) (called the magnetic Barkhausen effect), or by an acoustic sensor (the acoustic Barkhausen effect). Studies indicate that the magnetic Barkhausen effect in many materials is primarily due to the motion of 180° domains, and its interactions with dislocation tangles [71, 72], whereas the acoustic Barkhausen effect is due to magnetostrictive strain from the motion of non-180^{o} domain walls [73].

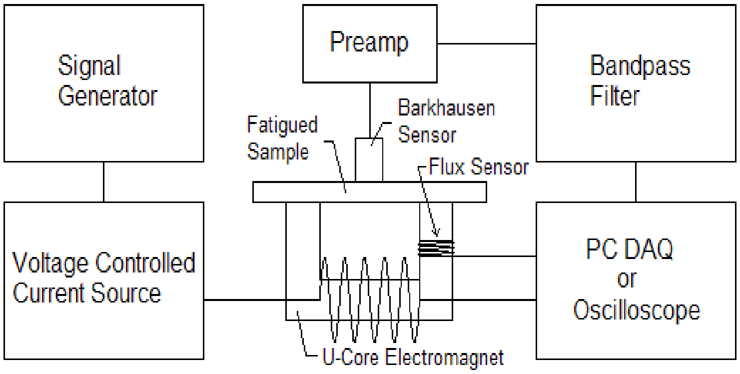

Fig. 7. Schematic of MBN measurement system.

The number of Barkhausen counts depends on the permeability and conductivity of the sample, the density of domain walls at the applied field, the average critical velocity of a domain wall when it is released from pinning sites, and the average change in the local magnetic induction due to unit displacement per unit area of domain walls [73]. Two Barkhausen bursts are present—one for the positive magnetization and the other for negative magnetization.

The Barkhausen noise measurement method has been applied to determine residual stresses in ferritic steels and to determine the amount of hardening or cold work. Studies have also shown that this technique is sensitive to damage precursors in ferromagnetic materials, and quantities such as the energy and peak value in the Barkhausen signal have been shown to correlate well with level of damage in materials [74–78]. Application of these methods to identify irradiation embrittlement has also been demonstrated to a limited extent in laboratory-scale studies [79–81], though the correlations identified are not always linear. This is generally due to the effect of multiple factors on the response. A number of factors (in addition to precipitate volume fraction) affect the Barkhausen response, including initial microstructure (prior to embrittlement), grain size, grain-boundary segregation, precipitate size, and stress relaxation, and numerous models have been developed to predict Barkhausen response to these factors [82–84]. Additional uncertainty is introduced by the fact that damage accumulation and crack initiation is a stochastic process [85]. Thus, the location selected for the measurement will likely introduce some uncertainty. Further, the measurement process (i.e., manual or automated probe placement, probe coupling pressure, etc.) also adds some error. These sources of error apply to other measurement methods as well. In addition, the measurement is subject to uncertainty due to:

- orientation of strain direction, relative to the applied external field direction and the magnetic easy axis [86];
- specimen fabrication variability as well as residual stress in the specimen [86, 87]; and
- number, location, and orientation of magnetic domains. In particular, in two-phase steels, the volume fraction and distribution of the ferromagnetic phase will have a significant impact on the recorded measurement [88].

Like all electromagnetic methods, the magnetic Barkhausen method (and other magnetic measurement methods) is predominantly a near-surface measurement, with the standard depth of penetration (the distance into the material at which the induced current density decreases to 37% of its value at the surface) decreasing with increasing frequency [89], defined as

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \tag{1}$$

where f is the excitation frequency, μ is the magnetic permeability of the material, and σ is the electrical conductivity. For non-ferritic steel (such as 304 or 316L), the skin depth at 1 kHz is about 13.1 mm.

3.2.3 Thermoelectric Power

Thermoelectric power measurements are one of the approaches that have been proposed for irradiation embrittlement detection. This approach utilizes the Seebeck effect, wherein a temperature differential across a junction of dissimilar metals produces an electromotive force. This effect is due to electron diffusion and phonon drag, which results in coupled electric and heat transfer across the junction [90]. This effect may be used for the nondestructive characterization of metals, by measuring the potential difference generated as a result of a temperature difference between two junctions, where the "hot" junction is formed by a reference electrode (that is maintained at some temperature) in contact with the material under test, and the "cold" junction is formed by the measurement electrode in contact with the material under test. In general, the measurement is a function of many variables, including chemical composition, heat treatment, thermal aging, hardening, grain structure, etc. As a result, the approach has been applied to the characterization of a number of aging and degradation processes in metals. One potential application is the characterization of irradiation embrittlement [91–95], where numerous studies have described the potential for correlating embrittlement and DBTT shifts due to irradiation.

While the approach has shown potential, TEP is sensitive to a number of other operational variables, including the interface imperfections [90], the thermoelectric coefficient of the material under test relative to that of the electrode materials, and the anisotropy and material property gradients in the material under test [96]. As a result, additional studies are needed to further evaluate this promising method.

3.2.4 Other Electromagnetic NDE Methods

Other electromagnetic nondestructive examination methods have been proposed for the characterization of irradiation embrittlement and cracking in metals. Many of these methods have been applied for crack detection and characterization, including eddy current testing, remote field testing, potential drop methods, and magnetic flux leakage and the related magnetic particle method [89]. All of these approaches measure the response of the material (with degradation or cracking) to applied electromagnetic energy. In the case of magnetic methods, the applied energy is a DC or low frequency magnetic field. Eddy currents and remote field methods use an induced current in the material under test, where a coil carrying AC is used to induce the current in the material. Potential drop methods, on the other hand, inject current (AC or DC) into the material and measure the resulting potential drop. While these approaches have been demonstrated for crack detection (and ECT and magnetic particle inspection are included in the ASME Code as acceptable NDE methods for crack detection in NPP), the applicability of these approaches to embrittlement characterization and early-stage crack detection is still in the early stages of assessment.

3.3 PROMISING NDE TECHNOLOGIES FOR DETECTION OF DEFECTS IN RPVS

The goal is to detect small defects caused by radiation damage using sensors that can be used on the RPV. The defect range is in the range of a few microns to approximately 300 μm. The primary area of concern is the 1/4T to 3/4T of the RPV wall. For pressurized water reactor (PWR) vessels, conventional tripod deployment technology, or robotic deployment technology, or flat scanner units will be required to convey sensor(s) to the surface of the RPV. For boiling water reactors (BWRs), flat scanner units, magnetic crawlers, or units attached to the RPV using tracks will be used to convey the sensors to the outside surface of the vessel.

The sensor technology that seems to have the most potential is the nonlinear harmonic ultrasonic technique. This technique usually works in the 5–10 MHz range. The basic concept is that acoustic (sound) vibrations in material generate increasing amounts of higher order harmonics (nonlinear effect) when increased material damage is present. Work has been done using bulk waves as well as surface waves [97]. This technology appears to have great potential for detecting dislocation, persistent slip bands, and microcracking. However, good calibration samples are required and due to the large thicknesses of the RPV materials and the high frequencies used, attenuation of the generated waves may make it difficult to observe.

Phased array technology using time-of-flight diffraction (TOFD) for defect detection and sizing and operating in the frequency range 5–10 MHz has shown good capability for detecting small defects in thick wall material. The Plate Inspection Steeing Committee II (PISC II) was the first public trial for TOFD, and the results were encouraging [98]. Overall sizing accuracy for the United Kingdom Atomic Energy Authority (UKAEA) Risley team was a few millimeters on plate hundreds of mm thick (i.e., ~1%). Data was obtained by use of Olympus NDT equipment [99]. Data quoted from Kopp [100] for shell plate showed defect detection and sizing for defects in the range of 1 mm and greater (Fig. 8).

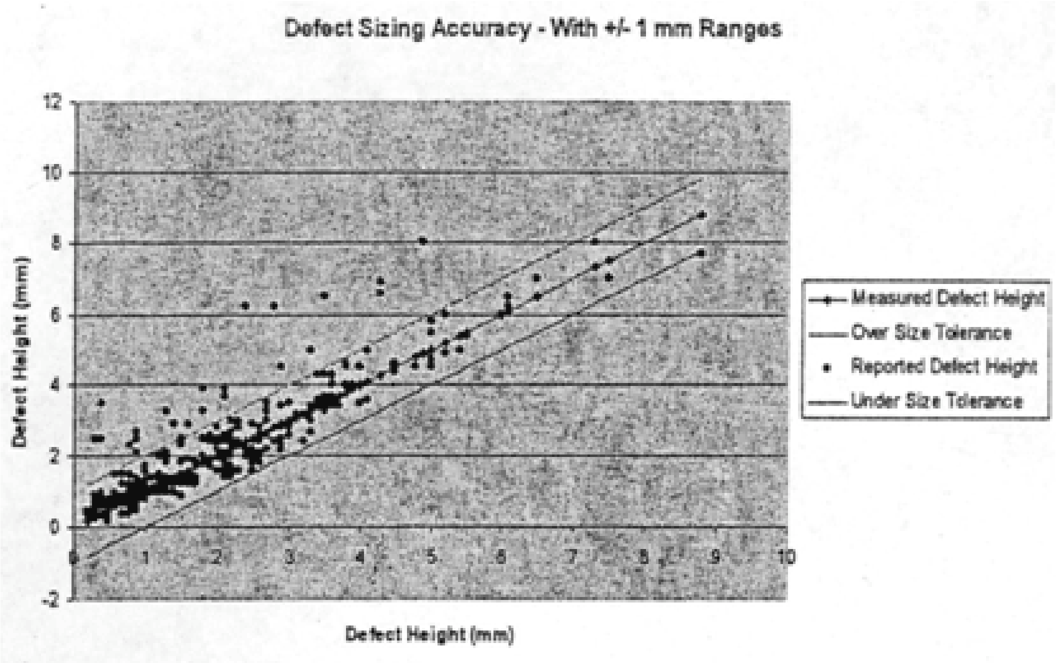

Fig. 8. Sizing data from Kopp et al. [100].

If the primary question to be answered is the radiation damage and if the damage condition of the first 10% of the wall can be useful to estimating the level of damage throughout the vessel wall, perhaps high frequency surface waves or eddy current techniques could also be used with the scanner units to detect cluster, vacancy scattering, and conductivity changes that might be caused by radiation damage, respectively. If this is the case, then perhaps a very sensitive near-surface approach such as eddy current could be useful in characterizing the damage that exists in the material.

The phased array and eddy current techniques require scanning. However, the fixed angle ultrasonic approach could be used in a monitoring mode where the sensor is permanently attached to the RPV and periodic data is collected. In the monitoring mode, often the defect detection sensitivity can be increased by a factor of 2–5. It would be interesting to conduct experiments using this approach on well-characterized test samples to determine if conventional ultrasonic bulk waves can be used to adequately detect and characterize radiation-type damage.

Zone-focused transducers can be used to form highly focused inspection beams at various depth in the pressure vessel wall. This approach has been proven effective in the detection of titanium alpha regions in large billets of titanium. However, if zone focus is used, many more transducers are required and the inspection scan speed is reduced by perhaps a factor 10. Some attempts have been made to use phased array transducers to generate focused beams that have focuses varying as a function of time at high speeds; however, phased arrays usually cannot achieve the high degree of focus that single, large diameter transducer elements can achieve. Work needs to be done to evaluate this concept for detecting defects on the order of 300 μm or less.

4. NDE RESEARCH ROADMAP

The purpose of the LWRS NDE RPV workshop was to develop content for this report. The focus was on technical gaps in NDE techniques for detecting embrittlement and weld cracking in RPVs. It was felt that it was important to develop a comprehensive vision for what DOE should attempt to accomplish with its research funding in regard to NDE techniques applied to RPVs. The resulting Roadmap would then be a detailed plan for implementing this vision; specific and concrete early in the plan's execution, but less detailed and more directional later in the plan to allow for incorporation of research accomplishments and integration with EPRI and NRC efforts. The vision is extremely important because it must mesh with the goals and accomplishments of the EPRI and NRC efforts and enumerate and guide long-term goals and commitments on DOE's part.

The development of a DOE vision for RPV NDE R&D is important because experimental evidence from the LWRS MAaD Pathway indicates that the currently utilized models for RPV lifetime may not be conservative at high fluence. Accelerated test reactor irradiations suggest that current models underpredict the DBTT at 30 year life, which means that the predicted RPV lifetime may be less than actual. However, this may be due to the accelerated testing at higher flux rates and may not actually occur in an operating RPV. Conversely, new phenomena may emerge at high exposures over long times, like late blooming phases which is rapid embrittlement of steels due to increased manganese-nickel-rich precipitates forming at high fluence levels.

Development of one or more NDE techniques that can assist in the determination of current RPV fracture toughness as well as in prediction of fracture toughness with further aging of the vessel (particularly in the presence of microcracks or other stress concentrators) is essential. The NDE measurements and the corresponding models that can verify their applicability to the problem, sensitivity to embrittlement and microcracking, and accuracy in characterizing physical properties of RPV steel to establish correlations with RPV fracture toughness will provide important information to the LWRS program. This incorporation of an NDE modeling effort into the DOE vision is important. Modeling efforts that correlate theoretical calculations with experimental results are extremely important to the current RPV lifetime predictions, which are model based, and there is no reason to expect contributions from NDE technologies to be any different.

The major emphasis of this workshop discussed the feasibility of using NDE techniques to determine embrittlement of commercial nuclear RPVs. Minor emphasis was placed on emerging NDE techniques that provide better insight into cracking and especially incipient cracking of RPVs.

Three important NDE research areas relative to RPVs were identified during the workshop:

1. NDE measurements towards RPV embrittlement determination must measure steel properties that can be correlated with the steel's crack propagation during reactor accident conditions.
2. A comprehensive and well-characterized set of irradiated RPV steel samples needs to be assembled to support NDE technique research.
3. NDE techniques utilized towards RPV embrittlement determination must provide information on embrittlement throughout the thickness of the RPV.

Attempts to use NDE techniques to detect RPV embrittlement have been ongoing since the 1960s without significant success. The traditional approach to determining NDE applicability to detection of embrittlement in steels has been mainly experimental, with measurements on samples with varying degrees of embrittlement to see if there is any correlation to the fracture toughness of the steel. In many cases, these measurements have been made on surrogate specimens (i.e., specimens with varying hardness levels but not necessarily the same sort of microstructure that is indicative of irradiation embrittlement).

While this type of research is essential (and still necessary), the DOE vision for NDE research on RPVs needs to expand upon this experimental work to include modeling efforts that assist in first principle understanding of NDE measurements versus changes in steel physical properties, as well as approaches to determine the correlation of that measurement with any crack propagation during accident conditions.

In the past, metallurgists have based their models for RPV lifetime predictions on irradiation temperature, phosphorous and manganese content in the RPV steel, effective fast fluence, neutron flux rate, effective copper content, standard reference materials, threshold for copper effects, and copper saturation effects. These models are supported by Charpy V-notch testing and the resulting DBTT. Metallurgists are just now beginning to build models that are hoped to be able to predict RPV lifetime based on destructive microstructure characterizations. As these models continue to be developed and refined, there will be a growing need to establish nondestructive microstructure characterization capabilities. The development of NDE techniques that can establish the necessary microstructure characterization throughout the thickness of an RPV for incorporation into RPV lifetime prediction models based upon microstructure characterization is the vision for DOE NDE RPV R&D research.

The fracture toughness of steel depends upon several microstructure factors, especially lattice defects such as vacancies, dissolved atoms, dislocation loops, solute clusters, precipitates, dislocation, and grain and phase boundaries. Major obstacles to the use of NDE for embrittlement quantification have been (1) the length scales of the features of interest (several nm) relative to the gauge length of typical NDE methods (100s of um and up), and (2) the sensitivity of NDE techniques to multiple factors. The result is the inability (with high confidence), with a single measurement, to distinguish between multiple factors and correlate the measurement to the fracture toughness.

As stated previously, when metallurgists are characterizing the microstructure of RPV steels, they employ multiple techniques such as transmission electron microscopy, atom probe tomography, small angle neutron scattering, and positron annihilation. Therefore, it is probably unreasonable to expect that a single NDE technique will be able to provide a comprehensive characterization of the microstructure of RPV steels, much less an estimate of the remaining useful life of a RPV. Therefore, it is prudent to investigate using multiple NDE methods to obtain a reasonable, if not completely comprehensive, characterization of the RPV steel microstructure in hopes of being able to then correlate this microstructure with remaining useful life. This multi-method characterization is supported by current research by the Fraunhofer Institute for Non-Destructive Testing (IZFP) in Saarbruken, Germany [101]. There, a method called the Micromagnetic 3MA-method (micromagnetic, multi-parameter microstructure, and stress analysis) is used to provide an NDE-based microstructure characterization. The 3MA-method combines the NDE methods of Barkhausen noise, incremental permeability, time-dependent magnetic field strength, and multifrequency eddy current in an attempt to characterize steel microstructure. This roadmap must include evaluation of multi-method NDE characterization research.

The vision for DOE work in the RPV area centers around efforts to understand how embrittlement (or the presence of microcracking, especially in the vicinity of fabrication flaws in welds) impacts the physical properties of the steel that NDE techniques are capable of measuring, the sensitivity of these NDE techniques, and how those measurements can then be related to the fracture toughness of the steel (or to other related properties). The DOE research into NDE for RPV steels under the LWRS program needs to focus on addressing these gaps. The correlation of the measurement output from NDE technologies to the performance of the RPV under accident conditions is difficult and must encompass several related, but different relationships: (1) correlate the NDE measurement with the steel microstructure, (2) correlate the steel's microstructure with the fracture toughness, and (3) correlate the fracture toughness with performance under accident conditions. All of these correlations and relationships must be considered in this roadmap.

A consistent theme from all the LWRS NDE workshops and especially from the RPV workshop was that a comprehensive and fully characterized common set of samples for NDE experimentation needs to be assembled. The required RPV sample set is somewhat unique in that it needs to (1) be irradiated over a range of fluence using the appropriate flux and temperature conditions, (2) represent a number of base material and impurity compositions, and (3) be able to allow verification of NDE techniques from ½-Charpy-sized samples to those that representative of full RPV thicknesses. A study needs to be included in the roadmap to determine the required (1) fluence levels, (2) irradiation flux, (3) irradiation temperature, (4) necessity of using irradiated samples, (5) base material(s), (6) material impurities, (7) material impurity concentration, (8) sizes, and (9) number of samples. Statistical design of experimental methods may be applied to reduce the number of specimens necessary for comprehensive evaluation of NDE methods. To achieve the DOE vision for NDE research on RPVs, this sample set must be assembled under the implementation of the roadmap.

The workshop concluded that some emerging NDE techniques appear to show promise for detecting and characterizing microstructural changes in RPV steels. These techniques include nonlinear ultrasonic, micromagnetic measurements and Seebeck-effect-based techniques. These techniques may offer a method of nondestructive characterization of RPV steel which can then possibly be correlated to its fracture toughness and finally to predict the RPV lifetime and performance under accident conditions. The roadmap must include some evaluation, research, and development of a limited number of NDE techniques that show promise. However, the roadmap's vision should allow for advancements in other techniques and allow their inclusion should they prove to be viable.

4.1 SHORT-TERM IMPLEMENTATION STRATEGY

4.1.1 Assemble Comprehensive, Well-Characterized Sample Set for NDE Research – Priority 1

All four workshops identified this as a critical need for DOE NDE R&D. A study to determine all required and necessary aspects of the sample set should be undertaken. The available and existing samples should be determined, and the needed samples should be procured through the appropriate steps.

4.1.2 Evaluate, Research, and Develop Candidate NDE Techniques for RPV Microstructure Characterization – Priority 1

Multiple NDE techniques are probably required for RPV material characterization. The RPV workshop identified three NDE candidate technologies: (1) nonlinear ultrasonic, (2) Barkhausen noise, and (3) Seebeck coefficient. These candidate NDE technologies should be further evaluated and, if deemed appropriate for the task, researched to determine their capabilities and limitations using the portion of the sample set that is currently available.

There is also some basic research to be performed under this task, such as identifying the degradation modes in RPV materials and determining the material parameters measurable by these NDE techniques that correlate with the identified degradation. Once this is accomplished, the appropriate NDE sensing modes that capture the degradation signature can be determined, and the sensors necessary to make these measurements with adequate sensitivity can be developed. With adequate sensors, the number of sensors necessary to provide coverage for critical areas throughout the depth of RPV sections can be determined, and NDE signatures to identify degradation mechanisms of interest can be developed.

4.1.3 Establishment of NDE Modeling Efforts – Priority 2

A modeling effort needs to be undertaken to establish modeling of the NDE measurements and development of models to verify the applicability of their measurement to embrittlement and microcracking. Additionally, modeling of NDE techniques must be begun to determine their accuracy in characterizing physical properties of RPV steels and to establish model correlation with RPV fracture toughness and prediction of RPV remaining useful life.

4.1.4 Integration of MAaD Pathway RPV Lifetime Modeling with NDE Modeling Effort – Priority 2

An effort must be initiated to coordinate the MAaD Pathway modeling efforts based upon destructive microstructure characterization with the NDE modeling efforts based upon nondestructive microstructure characterization.

4.1.5 Short-Term Implementation Notional Milestones and Budget

Task	Milestone	Budget
Assemble Comprehensive, Well-Characterized Sample Set for NDE Research	**9/13**	**$400K**
Determine necessary aspects (fluence levels, material makeup, impurity composition, size, etc.) of the sample set		
Use statistical design of experimental methods to reduce the number of samples required		
Determine how much of the needed sample set is already available		
Determine how to obtain needed samples that are not already available		
Obtain needed samples that are not already available	**9/15**	**$1M**
Evaluate, Research, and Develop Candidate NDE Techniques for RPV Microstructure Characterization	**9/17**	**$4.2M**
Identify degradation modes in materials of interest		
Determine measurable material parameters that correlate with degradation		
Identify a small number of appropriate NDE sensing technologies to capture the degradation signature		
Develop the sensors and processing necessary to make these measurements with adequate sensitivity		
Determine the effective field of view for these sensors to determine optimal inspection locations		
Determine the numbers of sensors needed to provide coverage for critical areas using risk-based methods		
Analyze NDE measurements to identify signatures corresponding to degradation mechanisms of interest		
Establishment of NDE Modeling Efforts	**9/20**	**$12M**
Develop physical models to identify the measurable parameters		
Develop physical models to identify the NDE sensing modes		

Model NDE measurements		
Develop models that verify the applicability of measurements to embrittlement and microcracking		
Model the accuracy of NDE techniques in characterizing physical properties		
Establish model correlation with RPV fracture toughness		
Establish model of prediction of RPV remaining useful life		
Integration of MAaD Pathway RPV Lifetime Modeling with NDE Modeling Effort	**9/20**	**$7M**
Coordinate destructive materials microstructure characterization models with nondestructive characterization models		
Introduce nondestructive microstructure characterization into developing materials microstructure characterization models to predict RPV remaining useful life		

4.2 LONG-TERM IMPLEMENTATION STRATEGY

DOE NDE R&D efforts in the long term should continue, refine, and expand all of the short-term aspects. Additionally, as appropriate, the R&D efforts should be expanded to include evaluation and R&D of microstructure characterization throughout the RPV thickness. The long-term R&D efforts should furthermore include the development of NDE characterization multi-methods as well as the correlation of NDE measurements to microstructure phenomenon, the correlation of microstructure phenomenon with fracture toughness, the correlation of fracture toughness with predicted RPV useful lifetime, and the correlation of fracture toughness with RPV performance under accident conditions. The long-term R&D strategy should also allow the incorporation of new or improved NDE technologies not included in the short-term NDE technology evaluation and R&D.

4.2.1 Long-Term Implementation Notional Milestones and Budget

Task	Milestone	Budget
Evaluate, research, and develop microstructure characterization throughout the RPV thickness	9/18	$1M
Develop NDE characterization multi-methods	9/16	$1M
Correlate NDE measurements to microstructure phenomenon	9/17	$2M
Correlate microstructure phenomenon with fracture toughness	9/18	$4M
Correlate fracture toughness with predicted RPV useful lifetime	9/20	$4M
Correlate fracture toughness with RPV performance under accident conditions	9/22	$4M
Incorporate new or improved NDE technologies	9/19	$3M

5. CONCLUSIONS

Application of NDE techniques to determine embrittlement of in-service RPVs is a very difficult problem. Work has been ongoing in this area since the 1960s with little success. However, recent research in this area has been encouraging. Several NDE techniques, including nonlinear ultrasonic, magnetic Barkhausen noise, and Seebeck coefficients, have shown promise in laboratory tests for characterizing important microstructure aspects of steel related to embrittlement. Additionally, metallurgists are beginning to develop models that relate steel microstructure characteristics obtained from destructive testing to its embrittlement. As these modeling efforts develop and are refined, there will be a need to provide nondestructive methods for microstructure characterization that can be applied to RPVs in-situ to assist in confirming their remaining useful lifetime.

This report has identified several important R&D tasks for NDE research related to RPVs:

- Evaluate, research, and develop candidate NDE techniques for RPV microstructure characterization
    - Identify degradation modes in materials of interest
    - Determine measurable material parameters that correlate with degradation
    - Identify a small number of appropriate NDE sensing technologies to capture the degradation signature
    - Develop the sensors and processing necessary to make these measurements with adequate sensitivity
    - Determine the effective field of view for these sensors to determine optimal inspection locations
    - Determine the numbers of sensors needed to provide coverage for critical areas using risk-based methods
    - Analyze NDE measurements to identify signatures corresponding to degradation mechanisms of interest

- Assemble a comprehensive, well-characterized sample set for NDE research
    - Determine necessary aspects (fluence levels, material makeup, impurity composition, size, etc.) of the sample set
    - Use statistical design of experimental methods to reduce the number of samples required
    - Determine how much of the needed sample set is already available
    - Determine how to obtain needed samples that are not already available

- Establish NDE modeling efforts
    - Develop physical models to identify the measurable parameters
    - Develop physical models to identify the NDE sensing modes
    - Model NDE measurements
    - Develop models that verify the applicability of measurements to embrittlement and microcracking
    - Model the accuracy of NDE techniques in characterizing physical properties
    - Establish model correlation with RPV fracture toughness
    - Establish model of prediction of RPV remaining useful life

- Integrate MAaD Pathway RPV lifetime modeling with the NDE modeling effort
    - Coordinate destructive materials microstructure characterization models with nondestructive characterization models

    - Introduce nondestructive microstructure characterization into developing materials microstructure characterization models to predict RPV remaining useful life
- Evaluate, research, and develop microstructure characterization throughout the RPV thickness
- Develop NDE characterization multi-methods
- Correlate NDE measurements to microstructure phenomenon
- Correlate microstructure phenomenon with fracture toughness
- Correlate fracture toughness with predicted RPV useful lifetime
- Correlate fracture toughness with RPV performance under accident conditions
- Incorporate new or improved NDE technologies

Note that coordinating activities with the LWRS Risk pathway (to integrate prognostics results into dynamic PRA models) and the LWRS I&C pathway [to integrate results into plant Instrumentation and Controls (I&C) systems and Operations and Maintenance (O&M) practices] will be necessary to ensure that the results of these activities are appropriately included in the license extension decision-making process and plant O&M activities.

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APPENDIX A: LIST OF ATTENDEES FOR LWRS NDE RPV R&D ROADMAP WORKSHOP

Light Water Reactor Sustainability Nondestructive Evaluation Workshops
Reactor Pressure Vessel Workshop Attendee List
August 1, 2012

Name	Affiliation
Sasan Bakhtiari	Argonne National Laboratory
Leonard Bond	Iowa State University
Cy Smith	Oak Ridge National Laboratory
Dwight Clayton	Oak Ridge National Laboratory
Kevin Simmons	Pacific Northwest National Laboratory
Pradeep Ramuhalli	Pacific Northwest National Laboratory
David Brenchley	Pacific Northwest National Laboratory
Wes Hines	University of Tennessee, Knoxville
John Lareau	WesDyne
James Wall	Electric Power Research Institute
John Burke	Nuclear Regulatory Commission
Carol Nove	Nuclear Regulatory Commission
Venu Varma	Oak Ridge National Laboratory
Thomas Rosseel	Oak Ridge National Laboratory
Jamie Coble	Pacific Northwest National Laboratory
Mike Anderson	Pacific Northwest National Laboratory
Kevin Newell	Zetec
Glenn Light	Southwest Research Institute
Larry Jacobs	Georgia Tech
Katie Matlack	Georgia Tech
Bradley A. Regez	Northwestern University
Randy Nanstad	Oak Ridge National Laboratory
Blake Van Hoy	Oak Ridge National Laboratory
Roberto Lenarduzzi	Oak Ridge National Laboratory
Mike Hileman	Oak Ridge National Laboratory

APPENDIX B: LWRS NDE RPV R&D WORKSHOP AGENDA

LWRS RPV NDE Workshop Agenda

August 1

The purpose of this workshop is to develop content for the LWRS NDE R&D Roadmap. The focus will be on NDE techniques for detecting embrittlement and weld cracking in reactor pressure vessels.

7:30 am Registration	
8:00 am Welcome & Workshop Overview	Cy Smith (ORNL)
8:10 am Introductions	David Brenchley (PNNL)
8:30 am Definition of the Problem	
Randy Nanstad – ORNL	Reactor Pressure Vessel Steel Embrittlement
9:00 am Promising NDE Technologies & Methodologies	
Cyrus Smith – ORNL	Survey of NDE Technologies - RPV Embrittlement
Pradeep Ramuhalli – PNNL	Electromagnetic Methods
Katie Matlack – GA Tech	Ultrasonic NDE Methods for RPV Components
Glenn Light – SWRI	NDE System Deployment Methods
10:30 am Break	
10: 45 am Brainstorming Session	Brenchley
11:15 am Define R&D Actions to Address Gaps	Brenchley
Working LUNCH	
1:30 pm Group Reports & Discussion	Brenchley
2:30 pm Prioritize R&D Actions	Brenchley
3:30 pm Break	
4:00 pm What Next and Assignments	Smith
4:30 pm Check-out	Brenchley
5:00 pm Thank You & Adjourn	Smith

APPENDIX C: SUMMARY OF DOE LWRS NDE WORKSHOP AT ORNL ON NON-DESTRUCTIVE EVALUATION METHODS FOR NUCLEAR REACTOR PRESSURE VESSELS

C.1. INTRODUCTION

This workshop was held at the Conference Center of the Oak Ridge National Laboratory (ORNL) on Wednesday, August 1, 2012. David Brenchley presided over the management of the workshop working together with Cyrus Smith. The workshop began with a “check-in” session whereby each attendee was asked to submit a short list of the topics of their main interest. The overwhelming majority of the responses asked for “correlation between NDE measurements and fracture toughness and a comprehensive.”

Next, presentations were made by Randy Nanstad of ORNL on Reactor Pressure Vessel Steel Embrittlement, Cyrus Smith of ORNL presented an overview of NDE Technologies which has been applied to RPV Embrittlement in the past, Pradeep Ramualli of PNNL discussed Electromagnetic NDE Methods, Katie Matlack of Georgia Tech University gave an overview of Ultrasonic NDE Methods of RPV Components and Glenn Light of Southwest Research Institute discussed NDE System Deployment Methods. Following a brainstorming and discussion session, the participants, which added up to be about 25 people, were divided into three groups to assemble in different breakout rooms. Each group was given the assignment to arrive at a proposal for R&D to address the NDE related gaps in detecting RPV steel embrittlement or RPV cracking. Table C.1 shows the three groups and their respective members:

Table C.1 Work Group Members

Group 1	Group 2	Group 3
– **Pradeep Ramuhalli (Lead)** PNNL	– **Cyrus Smith (Lead)** ORNL	– **Dwight Clayton (Lead)** ORNL
– **Sasan Bakhtiara** ANL	– **Blake Van Hoy** ORNL	– **Joe Wall** EPRI
– **Roberto Lenarduzzi** ORNL	– **Leonard Bond** Iowa State University	– **Thomas Rosseel** ORNL
– **Randy Nanstad** ORNL	– **John LaReau** WesDyne Corporation	– **Venu Varma** ORNL
– **Jamie Cobble** PNNL	– **Larry Jacobs** Georgia Tech University	– **Glenn Light** SWRI
– **Katie Matlack** Georgia Tech University	– **Saurin Majumdar** ANL	– **John Burke** NRC
– **Kevin Newell** Zetec Corporation	– **Mike Anderson** PNNL	– **Mike Hileman** ORNL
– **Carol Nowe** NRC	– **Richard Wright** INL	– **Bradley Regez** Northwestern University
	– **Mikhail Sokolov** ORNL	

C.2. CONCLUSION OF BREAKOUT SESSIONS

The breakout sessions had about two hours to arrive at their proposals. Following are the main conclusions of work from each group.

C.2.1 GROUP 1 (Head of the Group: Pradeep Ramuhalli)

This group introduced four areas of important gaps and R&D needs to fill these gaps. These areas are identified in the following tables.

Topic 1. Develop & Evaluate Methods to Improve Coupling of Probes and Influence of Environmental Factors on Sensors	
Measurements wanted:	Embrittlement, Dynamic Binary Translation (DBT), Flaw Detection and Sizing
Current NDE Capability:	Coupling changes measurement
The GAP:	Better coupling mechanisms and coupling materials for probes • Stationary probes may alleviate issue • Thermoelectric Power (TEP) – Sensor need contact but perhaps coupling (force) not an issue
Research Objective:	Develop and evaluate methods to improve coupling of probes (any kind) and the influence of environmental factors (heat, radiation, corrosive environment, etc.) on the sensors.
Scope of Work:	• Samples (Surface characterization needed as well) • Identify measurement methods and probes • Evaluate effect of coupling variability (and surface condition) • Evaluate flexible membranes (for Ultrasonic Testing (UT) or conformable probes) • Other environmental parameters
Expected Outcomes:	• Define minimum probe liftoff requirements • New probes robust to surface condition and environmental factors
Schedule:	Not Provided
Budget:	Not Provided
Ranking:	Medium (Will wait for technique demonstration)

Topic 2. Measurements to Resolve/Identify Radiation Induced Features and Understand Volume Effect of Measurement Versus Localized Measurement	
Measurements wanted:	Fracture Toughness, Yield Strength, Ductility to Brittleness Transition Temperature (DBTT)
Current NDE Capability:	Not Provided
The GAP:	Correlate NDE to embrittlement state
Research Objective:	• Measurements to resolve/identify radiation induced features – Type and volume fraction of precipitate • Understand volume effect of measurement versus localized measurements

Scope of Work:	• Literature review • Compare a variety of measurement techniques (nonlinear ultrasonic, electromagnetic, Seebeck, resistivity, etc) on standard set of samples representing – Various aging Levels – Compositions – Through Thickness Fluence Variations (look at effect of inside versus outside) as well as distance away from beltline – Welds versus Base Material • Elevated Temperature Examinations
Expected Outcomes:	Data to correlate NDE with fracture toughness
Schedule:	1 to 2 Year evaluation, down-select, intensive evaluation
Budget:	Not Provided
Ranking:	High

Topic 3. Evaluate Fracture Toughness Models for Linkage Between Microstructure and Fracture Toughness	
Measurements wanted:	Evaluate Fracture Toughness Models for Linkage Between Microstructure and Fracture Toughness
Current NDE Capability:	Current NDE capability is limited to flaw detection and sizing (sizing capability limited for small flaws)
The GAP:	Correlation between NDE and Fracture Toughness
Research Objective:	Develop correlation between NDE and Fracture Toughness
Scope of Work:	• Analysis methodology • Compare RPV calculations to integrity measurements
Expected Outcomes:	Correlation Models
Schedule:	Wait on Previous Research Topic
Budget:	Not Provided
Ranking:	High

Topic 4. Understand Flaws and Their Impact on Microstructure	
Measurements wanted:	Not Provided
Current NDE Capability:	Not Provided
The GAP:	• Not Provided
Research Objective:	Understand flaws and their impact on microstructure (flaw initiation, correlation for closer exam, micro-macro interaction)
Scope of Work:	Compare a variety of measurement techniques (nonlinear ultrasonic, electromagnetic techniques, Seebeck/Resistivity, etc.) on standard set of samples flaws as well as microstructure differences
Expected Outcomes:	Not Provided
Schedule:	Not Provided
Budget:	Not Provided
Ranking:	Medium-High

C.2.2 GROUP 2 (Head of the Group: Cyrus Smith)

This group introduced five areas of important gaps and R&D needs to fill these gaps. These areas are identified in the tables that follow.

Topic 1. Adequacy of Current Models to Address Up to 80 Years RPV Life Predictions	
Measurements wanted:	Are the current material models adequate for up to 80 year life span predictions? The existing models may not be conservative at the higher fluence values as related to the toughness predictions.
Current NDE Capability:	ASME Section XI Requirements, Inspections every 10 years originally, now some are every 20 years
The GAP:	Is ASME Section XI sufficient for 80 year operation? ASME Section XI was written before the Pressurized Thermal Shock (PTS) problem.
Research Objective:	• Test fracture toughness at 80 years radiation levels to statistical levels • Develop an NDE techniques to characterize micro-structural changes with correlation to the fracture toughness
Scope of Work:	Irradiate samples to required levels or utilize existing samples Determine the appropriate NDE technologies and down select
Expected Outcomes:	Model validation and the tools required to perform that task
Schedule:	3 to 4 years
Budget:	• Hot cell work • Irradiated samples and measurements • 3 FTE/year
Ranking:	High for weld material

Topic 2. Micro-Crack Detection in Welds	
Measurements wanted:	Micro-crack (micron sized originating from slag) detection in welds
Current NDE Capability:	No in-situ capability; lab based material property capability exists
The GAP:	Develop is-situ capability to detect down to the micron size crack
Research Objective:	Develop NDE tools for micro crack detection in first 10% of the RPV thickness
Scope of Work:	• Calibrated micro-crack samples with known geometries • Develop NDE techniques (non-linear acoustics) • Signal processing and algorithms
Expected Outcomes:	New inspection methodology (feasibility evaluation).
Schedule:	2 years
Budget:	2 FTE
Ranking:	Medium

Topic 3. Crack Detection Under Pressure Vessel Cladding to Address Pressurized Thermal Shock (PTS)	
Measurements wanted:	Detection of cracks under pressure vessel cladding to address PTS issue
Current NDE Capability:	Electromagnetic capability, ultrasonic high angle longitudinal capability
The GAP:	Expand diagnostic techniques to eliminate false positives and develop possible electromagnetic techniques
Research Objective:	Combine detection and sizing with hybrid technologies (electromagnetic/acoustic) to image with adequate resolution to detect and size flaws under cladding
Scope of Work:	• Utilize and gain access to existing samples • Qualify combined techniques utilizing commercial instruments with multiple frequency capabilities • Data fusion to resolve combined outputs

Expected Outcomes:	An improved method for detection, sizing and discrimination (from false positives) of under cladding flaws
Schedule:	1 year
Budget:	4 FTE (1 UT, 1 EM, 1 Simulation, 1 Lead)
Ranking:	High

Topic 4. NDE Techniques to Qualify RPV Toughness Throughout the Weld Thickness	
Measurements wanted:	Quantify toughness throughout the weld thickness
Current NDE Capability:	No NDE techniques can measure fracture toughness directly
The GAP:	Develop NDE technique comparable to mechanical V-Notch Charpy test
Research Objective:	Provide remote evaluation that discriminates between jacket and other cable elements. Provide a tool that can quantify degree of degradation.
Scope of Work:	Provide an NDE technique can be correlated to fracture toughness
Expected Outcomes:	Correlation of one or more NDE techniques that can measure a physical property that can be input into fracture toughness evaluation or models
Schedule:	3 to 5 years for proof of concept
Budget:	4 FTE/year + equipment and samples
Ranking:	This is the Crusade. Without this data, the models will not be valid to predict the material degradation effects in the 60 – 80 year life range

Topic 5. Comprehensive and Well Characterized Material Sample Set for RPV NDE Studies	
Measurements wanted:	Samples • For cracking that reflect real work conditions (i.e. cladding processes for the base metal and the weld area are at different times and methods) • For irradiation studies • Use existing samples for micro-cracking studies
Current NDE Capability:	• Crack: Existing samples use fatigue cracking as training samples • Embrittlement: Limited sample set in terms of fluence, material, and size
The GAP:	Acquire existing or construct new samples for cracking, embrittlement, and under cladding cracking (508 Class II forging material)
Research Objective:	Assemble a comprehensive and well characterized material sample set for RPV NDE studies
Scope of Work:	• Crack: Samples need defects such that they can be isolated, separated, and grouped for discrimination • Embrittlement: Samples need various fluence levels, material composition, and physical size • Need a study to determine a sufficient sample set
Expected Outcomes:	Comprehensive and well characterized RPV material sample set
Schedule:	1 year
Budget:	Under Cladding Crack: 1 foot X 3 foot X 3 inch thick sample - $250K Micro-crack: Machined part
Ranking:	Necessary - High

C.2.3 GROUP 3 (Head of the Group: Dwight Clayton)

This group also introduced five areas of important gaps and R&D needs to fill these gaps. These areas are summarized in the following tables.

Topic 1. Detection of Microstructure Defects as a Function of Depth	
Measurements wanted:	Detection of microstructure defects (vacancies, clusters, & dislocations) as a function of depth
Current NDE Capability:	Ultrasonic, small angle neutron scattering
The GAP:	Develop field deployable system for characterizing thick sections
Research Objective:	Develop a field deployable system to characterize microstructure defects (vacancies, clusters, dislocations) as a function of depth
Scope of Work:	• Identify/use well characterized test samples • Identify technologies • Laboratory demonstration of suite of sensors
Expected Outcomes:	Demonstration of a field deployable system
Schedule:	4 years
Budget:	Year 1: 5 FTE/yr + $300K/year equipment Year 2–4: 3 FTE + $150K year equipment
Ranking:	High

Topic 2. Mechanical Properties at ¼ to ¾ Thickness	
Measurements wanted:	Mechanical properties at ¼ to ¾ thickness
Current NDE Capability:	Limited mechanical properties can be obtained by Eddy Current and high frequency ultrasonic
The GAP:	Develop method for unambiguous measurements of mechanical properties
Research Objective:	Develop a field deployable system to measure mechanical properties
Scope of Work:	• Identify/use well characterized test samples • Identify technologies • Laboratory demonstration of suite of sensors
Expected Outcomes:	Demonstration of a field deployable system
Schedule:	4 Years
Budget:	3 FTE + $150K/year equipment
Ranking:	High

Topic 3. Correlate the Models for Microstructure Conditions as a Function of Measurement Techniques	
Measurements wanted:	Correlation between models and measurements
Current NDE Capability:	Insufficient
The GAP:	Validation of thick sample models
Research Objective:	Correlate the model for microstructure conditions as a function of measurement techniques at different wavelengths
Scope of Work:	Determine relationship between microstructure and inspection field (wavelength) and appropriate signal processing methods
Expected Outcomes:	A correlated model that can be used to predict safety critical microstructure damage
Schedule:	2 Years
Budget:	2.5 FTE/year +$100K/year equipment
Ranking:	Medium

Topic 4. Develop Well Characterized Samples with Different Levels of Radiation Damage	
Measurements wanted:	Develop well characterized samples with different levels of radiation damage
Current NDE Capability:	Insufficient samples exist for NDE development
The GAP:	Need well characterized samples
Research Objective:	Fabricate well characterized test for various RPV steels up to 10^19 to 10^20 n/cm^2 fluence
Scope of Work:	Identify several materials and sample geometry
Expected Outcomes:	Well characterized samples
Schedule:	2 Years
Budget:	1.5 FTE/year + $150K/year materials
Ranking:	Very High

Topic 5. Develop Platform for Testing Various NDE Sensors	
Measurements wanted:	A system for testing various sensors on a deployment platform.
Current NDE Capability:	Current deployment is for ultrasonic
The GAP:	This effort has to be coupled with sensor
Research Objective:	Validate the sensors being developed can be deployed on an RPV (BWR & PWR)
Scope of Work:	Mechanical resolution and accuracy, coupling, attachment requirements
Expected Outcomes:	• A platform for demonstrating/mapping (microstructure and physical properties) • A system to provide a full field image of the RPV
Schedule:	2 Years, but delayed by 2 Years
Budget:	3 FTE/Year + $500K/year materials
Ranking:	High (delayed)

C.3. SPECIFIC RPV RESEARCH-RELATED QUESTIONS

In addition to the proposals submitted by each group, Cyrus Smith assigned a specific RPV related question to each group. These questions and the groups' responses are summarized in Table C.2.

Table C.2. Specific RPV questions for each group

Item	**Group 1: What Would an Ideal Sample Set Be for NDE Research on RPV Steels**
1.	Some databases available, but may need additional characterization • ORNL 1990's specimens (un-irradiated & single fluence level, weld, and base metal) • Bob Odette? • ATR Library? • Others?
2.	Parameters – Composition • High Cu weld metal • Low Cu • Various Ni, Mn, P, Si
3.	Specimen Size
4.	Fluence – Different Levels
5.	Flux – Rate Effects – Different Levels?
6.	Irradiation Temperature, Test Temperature (!room temp to 100C), Time at Temperature
7.	Weld Metal versus Base Metal
8.	Clad
9.	Statistical Design of Experiments to Minimize Number of Samples
Item	**Group 2: Is The NDE Problem with Respect to RPV a Sensor, Measurement, or Correlation problem**
1.	Sensor Standpoint – Indications are that the electromagnetic physics may work – Barkhausen Noise
2.	Non-Linear ultrasonic show promise
3.	The physics are there; No new sensors need to be developed, but optimization will be required
4.	Measurement results require signal processing, and they must be more robust for field work
5.	Improvements in accuracy, repeatability, sensitivity are required especially for infant technologies
6.	Root cause effects for each measurement result in variations for each techniques which needs to be understood
7.	It is necessary to decouple sensitivity variable to achieve correlation to final data desired
8.	Allows a multi-variant / multi-physics approach to the problem
9.	Assuming changes in microstructure after irradiation are related to changes in the physical property of fracture toughness. Might be other players.
Item	**Group 3: What are the Two or Three Most Promising NDE Techniques to Detect Embrittlement and RVP Cracking**
1.	Nonlinear Ultrasonic • Why? o Demonstrated in lab that it is effective • What are benefits/drawback? o Benefits: ▪ Is sensitive to radiation damage in RPV materials o Drawbacks: ▪ May be difficult to deploy ▪ Repeatability ▪ Understanding total volumetric effects

2.	Eddy Current for detecting near surface embrittlement • Why? o Radiation damage mechanism is propagated from the inside • What are benefits/drawbacks? o Benefits: ▪ Established technology; ease of use o Drawbacks: ▪ Uncertain understanding of effects of cladding to vessel interface

C.4. CONCLUSION

Following the breakout sessions, which lasted about two hours (including working lunch time); the groups reconvened and discussed the work that was done by each group. As part of these discussions, votes were held on the various proposals submitted by each group to help prioritize where efforts would best be focused. Table C.3 provides a summary of the voting results. Of the proposals presented, there was significant overlap in the scope of work for several of the projects. In discussions with Cyrus Smith, four primary topics came to the forefront based on the topics and voting results and are listed in order of priority below. While there are several nuances associated with each, it is expected that these topics would cover the majority of concerns expressed by the meeting participants.

NDE measurements must measure RPV steel properties which can be correlated to fracture toughness. (30 votes)

A comprehensive and well characterized irradiated RPV steel sample set for NDE research needs to be assembled. (23 votes)

NDE Techniques utilized for RPV embrittlement determination must provide information on embrittlement throughout the depth of the RPV. (38 votes)

NDE techniques utilized for RPV embrittlement determination may need to be made at temperatures other than room temperature. (18 votes)

Table C.3. Voting results of topics proposed during workshop

ITEM	PROPOSAL DESCRIPTION	RESULTS OF VOTE
	GROUP 1	
1.	Detection of Microstructure Defects as a Function of Depth	**12**
2.	Measurements to Resolve/Identify Radiation Induced Features and Understand Volume Effect of Measurement Versus Localized Measurement	**18**
3.	Evaluate Fracture Toughness Models for Linkage Between Microstructure and Fracture Toughness	**5**
4.	Understand Flaws and Their Impact on Microstructure	**0**
	GROUP 2	
1.	Adequacy of Current Models to Address Up to 80 Years RPV Life Predictions	**13**
2.	Micro-Crack Detection in Welds	**9**
3.	Crack Detection Under Pressure Vessel Cladding to Address Pressurized Thermal Shock (PTS)	**7**
4.	NDE Techniques to Qualify RPV Toughness Through the Weld Thickness	**7**
5.	Comprehensive and Well Characterized Material Sample Set for RPV NDE Studies	**2**
	GROUP 3	
1.	Detection of Microstructure Defects as a Function of Depth	**13**
2.	Mechanical Properties at ¼ to ¾ Thickness	**6**
3.	Correlate the Models for Microstructure Conditions as a Function of Measurement Techniques	**12**
4.	Develop Well Characterized Samples with Different Levels of Radiation Damage	**21**
5.	Develop Platform for Testing Various NDE Sensors	**10**