STP-NU-044

NON DESTRUCTIVE EXAMINATION (NDE) AND IN-SERVICE INSPECTION (ISI) TECHNOLOGY FOR HIGH TEMPERATURE REACTORS

ASME STANDARDS TECHNOLOGY, LLC

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NON DESTRUCTIVE EXAMINATION (NDE) AND IN-SERVICE INSPECTION (ISI) TECHNOLOGY FOR HIGH TEMPERATURE REACTORS

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FOREWORD

This document is the result of work resulting from a Cooperative Agreement between the United States Nuclear Regulatory Commission (NRC) and ASME Standards Technology, LLC (ASME ST-LLC) for the Generation IV (Gen IV) Reactor Materials Project. The objective of the project is to provide technical information necessary to update and expand appropriate ASME materials, construction and design codes for application in future Gen IV nuclear reactor systems that operate at elevated temperatures. This report is the result of work performed under Task 12 titled "Non Destructive Examination (NDE) and In-service Inspection (ISI) Technology for High Temperature Reactors."

ASME ST-LLC has introduced the results of the project into the ASME volunteer standards committees developing new code rules for Generation IV nuclear reactors. The project deliverables are expected to become vital references for the committees and serve as important technical bases for new rules. These new rules will be developed under ASME's voluntary consensus process, which requires balance of interest, openness, consensus and due process. Through the course of the project, ASME ST-LLC has involved key stakeholders from industry and government to help ensure that the technical direction of the research supports the anticipated codes and standards needs. This directed approach and early stakeholder involvement is expected to result in consensus building that will ultimately expedite the standards development process as well as commercialization of the technology.

ASME has been involved in nuclear codes and standards since 1956. The Society created Section III of the Boiler and Pressure Vessel Code, which addresses nuclear reactor technology, in 1963 [4]. ASME Standards promote safety, reliability and component interchangeability in mechanical systems.

Established in 1880, the American Society of Mechanical Engineers (ASME) is a professional not-for-profit organization with more than 127,000 members promoting the art, science and practice of mechanical and multidisciplinary engineering and allied sciences. ASME develops codes and standards that enhance public safety, and provides lifelong learning and technical exchange opportunities benefiting the engineering and technology community. Visit www.asme.org for more information.

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EXECUTIVE SUMMARY AND CONCLUSIONS

The Gen IV / NGNP Materials Project Task 12 (Non Destructive Examination (NDE) and In-service Inspection (ISI) Technology for High Temperature Reactors) is sponsored through a Cooperative Agreement between the ASME Standards Technology, LLC (ASME ST-LLC) and the United States Nuclear Regulatory Commission (NRC). The results of the task are intended to complement the efforts of previous tasks sponsored by the U.S. Department of Energy (DOE) supporting the Generation IV / Next Generation Nuclear Plants (NGNP). The objective of Task 12 is to provide support to the NRC in developing a technical basis document to update and expand codes and standards for NDE and ISI methods and monitoring in next generation HTGRs that operate at elevated temperatures and to identify technology gaps where future research is needed (Appendix B). The findings of this study will assist codes and standards committees and jurisdictional authorities in adopting improved NDE methods into codes and standards. The approach recommended in this report reflects the Reliability and Integrity Management (RIM) strategy which forms the basis for the ASME Section XI Division 2 rewrite (ISI Code for HTGRs).

This report identifies several Non Destructive Examination (NDE) technologies applicable to components of High Temperature Gas-cooled Reactors (HTGRs) for in-service inspection. Several of the technologies identified may require additional technology development to support the transition from laboratory applications to field deployable systems. Other technologies may need additional development to harden the sensors for use in the harsh environments anticipated in an HTGR. Other technologies may only need additional code rules for the application of the technology for HTGR applications.

Part 1 of Task 12 provides an assessment of past HTGR reactor experience and identifies potential material degradation mechanisms and susceptibility criteria for the current design concepts. The assessment focuses on the PBMR design and service conditions but also encompasses ANTARES (AREVA) and GT-MHR (General Atomics) design and service conditions. All three concepts use currently available technology and fit within the current NGNP design envelope. Part 1 also provides an evaluation of appropriate NDE methods and ISI strategy. For the steel vessel HTGR concept, this paper proposes an approach which requires the owner to establish combinations of strategies for the reliability and integrity management (RIM) of passive components to achieve reliability goals. HTGRs are expected to be designed to accommodate both outage-based and on-line monitoring and examination. To emphasize this approach this report introduces the concept of Non Destructive Monitoring (NDM), analogous to Non Destructive Examination (NDE), where NDM is defined as the targeted on-line monitoring of active degradation mechanisms at potentially susceptible regions.

To provide a technical basis for the assessment of the applicability of existing and new technologies for in-service inspection and monitoring of HTGRs it was important to understand the potential degradation that HTGRs are subject to as a consequence of the design assumptions and service environment. Based on existing experience in Light Water Reactors (LWR) and current advancement of new material monitoring technologies, preferable technologies were selected for application in HTGRs. The needs for further developments were established to address the environmental specifics, such as elevated temperatures and a need for more extensive monitoring through prolonged operating cycles. Design and operating conditions characteristic of pressurized components in the steel vessel HTGR concepts have shown similar environmental conditions (inspected surface temperature) experienced in the existing LWRs during scheduled maintenance cycles. This has allowed utilizing the existing experiences from non destructive inspections (NDE) accumulated with LWR in-service inspection (ISI) programs. Specific environmental conditions and a need for on-line monitoring during the prolonged operating cycles expected in HTGRs have identified the recommendation of further developments. Areas of further NDE/NDM development include advancement in helium leak monitoring, non-contact UT (Laser UT and EMAT) and further extension of acoustic emission for crack detection, leak detection and loose part monitoring. The need for further improvement of remote robotic mechanisms to support elevated temperature environments was also identified. Recommendations were made to continue to follow advancements and new developments in the field of material characterization, with monitoring of acoustic and electromagnetic properties combined with advanced mechanical testing with micro sampling.

The original ASME work scope for Part 2 of Task 12 was to identify appropriate new construction and in-service NDE methods for examination of metallic materials (e.g., acoustic emission, ultrasonic). Studies would be based upon NGNP-relevant considerations, such as conclusions of the NERI group that developed Load and Resistance Factor Design (LRFD) based ASME Section III design equations.

However, the original scope was revised based on Westinghouse discussions with NRC via the ASME ST-LLC. The reference to the Nuclear Energy Research Initiative (NERI) should be a reference to the ASME Committee on Research Technology Development (CRTD) research activity that was documented in report CRTD-86 [2]. The agreed-to revised scope is to identify a methodology for inclusion of examination considerations in the LRFD approach and construct a road map that provides a path forward to develop the methodology.

Part 2 of Task 12 provides the proposed road map with six major activities for determining the advanced methods and their requirements for pre-service and in-service NDE of metallic components in the pressure boundary of advanced high-temperature gas-cooled reactors. The proposed road map (Figure 3) demonstrates how the inspection information from Part 1 of Task 12, along with the proposed nine step process for determining the NDE and NDM requirements based upon LRFD principles, can be used to develop the actual requirements for advanced inspection methods. The road map identifies both short-term and long-term NDE, NDM and LRFD research and development activities that can resolve technology gaps, support regulatory needs and provide a foundation for defining a future research agenda. This research plan also ties into completing the work identified in report CRTD-86 for Class 2/3 piping. Output from these activities is expected to be reported in a manner that would make implementation and adoption feasible and expedient into applicable codes and standards. However, no activities are included in the road map for approval by the codes and standards committees or regulators having jurisdiction.

Recommendations

- Existing and proven NDE and ISI techniques are recommended based on the structural similarity of components in the LWR and HTGR. Alternative methods are also listed to provide resources for augmenting existing practice by more accurate predictability of potential degradation mechanisms, for an efficient Reliability and Integrity Management (RIM) program with specific design and operation intervals. It is important to recognize that the existing practice in LWRs applies 10-year inspection intervals, and, based on accumulated experience, recent recommendations from the industry are suggesting further extending these intervals. Since the HTGR will be operating with maintenance intervals of 5 to 6 years the same ISI requirements could be directly applied. Alternative techniques are identified for possible application of the RIM methodology to be considered for improvement on productivity factors and to minimize unwanted repair shut-downs.

- Design and operating conditions characteristic of pressurized components in the steel vessel HTGR concepts have shown similar environmental conditions (inspected surface temperature) experienced in LWRs during scheduled maintenance cycles. This has allowed utilizing the existing experience from non destructive inspections (NDE) accumulated with LWR in-service inspection (ISI) programs.

- Based on existing empirical observations in operating light water nuclear power plants (LWRs), methods involving ultrasound and eddy current are recommended as priority for future developments.

- Specific environmental conditions and a need for on-line monitoring during the prolonged operating cycles expected in HTGRs have identified the recommendation of further developments. Areas of further NDE/NDM development include advancement in helium leak monitoring, non-contact UT (Laser UT and EMAT) and further extension of acoustic emission for crack detection, leak detection and loose part monitoring. The need for further improvement of remote robotic mechanisms to support elevated temperature environments was also identified. Recommendations were made to continue to follow advancements and new developments in the field of material characterization, with monitoring of acoustic and electromagnetic properties combined with advanced mechanical testing with micro sampling.
- Part 2 of Task 12 provides a proposed road map with six major activities for determining the advanced methods and their requirements for pre-service and in-service NDE of metallic components in the pressure boundary of advanced high-temperature gas-cooled reactors. The proposed road map demonstrates how the inspection information from Part 1 of Task 12, along with the proposed nine step process for determining the NDE and NDM requirements based upon LRFD principles, can be used to develop the actual requirements for advanced inspection methods.
- Current / Short / and Long Term NDE/NDM technique schedules are identified in Table 5 and Section 5.
- The need for new techniques and further development will be decided upon the finalization of specific designs, and with defined inspection criteria for specific components and environmental conditions dictated by the specific design and planned inspection outage durations.

1 INTRODUCTION

This section describes the Task 12 scope of work and the approaches used to address the scope of work.

1.1 Task 12 Scope of Work

The objective of Task 12 is to provide support to the NRC in developing a technical basis document to update and expand codes and standards for NDE and ISI methods and monitoring in next generation HTGRs that operate at elevated temperatures. The statement of work (Appendix B) is broken out into two parts:

Part 1:

Conduct a technology assessment of advanced monitoring, diagnostics and prognostics systems. The assessment is to include a review of technology and capabilities that can be leveraged from past experience that includes the current Light Water Reactor (LWR) industry. The technology assessment will identify technology that can support regulatory needs and identify technology gaps and provide a foundation for defining a future research agenda.

Part 2:

Identify appropriate new construction and in-service NDE methods for examination of metallic materials (e.g., acoustic emission, ultrasonic). Studies will be based upon NGNP-relevant considerations, such as conclusions of the Nuclear Energy Research Initiative (NERI) group that developed Load and Resistance Factor Design (LRFD) based ASME Section III design equations. Subtasks are as follows.

a) Define maximum acceptable flaw types and sizes based on the LRFD approach that is developed and the material properties of candidate materials that have been obtained.

b) Define non destructive examination methods needed to detect sub-critical flaws of the size and type defined in a) above, in pressure components during initial construction and for periodic examination during the life of the components. It is anticipated (per the statement of work) that new methods will be needed to reliably detect smaller discontinuities than those of concern for the current generation of pressure components. The methods will include the characterization of uncertainties in a manner that is suitable for reliability based LRFD development. Some methods to be considered include:

   i. Ultrasonic Time-of-Flight-Diffraction – provide detailed guidance for application.

   ii. Ultrasonic Phased Arrays – define requirements.

1.2 Assumptions

This report will identify and address issues based on the following assumptions.

- The operating conditions for next generation HTGRs are a Reactor Outlet Temperature (ROT) of up to 900ºC, a steel reactor pressure vessel operating temperature of 300-450ºC, at helium coolant pressures of 5–9MPa.
- Outage frequency may vary dependent on the design configuration and may be expected to range from 18 months to 5 years.
- The temperatures of the pressure boundary metallic surfaces, to be inspected during scheduled outages, are below 100ºC.
- The scopes of components are the vessels and piping that constitute the helium pressure boundary (see Figure 1) (more detailed breakdown provided in Table 1).

Note: The reactor designs that constitute Very High Temperature Reactors (VHTRs) are generally accepted to be able to achieve a Reactor Outlet Temperature (ROT) of up to 1000ºC. There is currently no design that fits this capability, and therefore, this study does not make any claims to be representative of VHTRs.

1.3 Task 12 Part 1 Approach

Part 1 of the Task 12 scope of work is addressed in Sections 2.0, 3.0 and 4.0. Section 4.0 includes an assessment of past HTGR operating experience and identifies potential material degradation mechanisms and susceptibility criteria. The assessment focuses on the PBMR design and service conditions but also encompasses ANTARES and GT-MHR design and service conditions. Section 3.0 provides an evaluation of appropriate NDE/NDM methods and ISI strategy including methods for advanced material characterization. Section 4.0 identifies technology developments needed to address damage mechanisms for which existing NDE/NDM methodologies are not optimal considering HTGR specific maintenance and operating environment as described in Section 1.2.

<u>Past Reactor Experience and Potential HTGR Material Degradation</u>

A review and assessment of past reactor experience and studies and their relevance to the Task 12 scope of work are provided in Section 2.1. An assessment of potential material degradation mechanisms to which HTGRs are subjected is provided in Section 2.2.

Potential degradation mechanisms include radiation embrittlement, mechanical fatigue, creep, creep-fatigue and others. For each potential material degradation mechanism, the conditions and attributes that create the degradation are defined and susceptibility criteria are developed. The susceptibility criteria define how likely the component /system is to be affected by the respective degradation mechanism and how the damage will be manifested, which may include altering of material properties, component geometry changes or cracking. Once the regions subject to potential degradation have been identified, along with the susceptibility criteria, one or more NDE methods are identified for selection. Information from Section 2.2 is used in Section 3.0 to identify ISI strategies and NDE methods to address the respective susceptibility criteria (Appendix A) for HTGRs.

<u>HTGR NDE Methods and ISI Strategy</u>

The operating and maintenance environments for HTGRs are not significantly different than the environment for LWRs. Due to the expected longer operating periods between maintenance outages, this report proposes in Section 3.0 an ISI methodology that applies combinations of strategies for the Reliability and Integrity Management (RIM) of passive components to achieve reliability goals. HTGRs should be designed to accommodate both outage-based and on-line monitoring and examination. The intent is to identify and detect in-service degradation for HTGRs using not only the traditional in-service inspection of ASME Section XI [1] but a combination of strategies including plant and component design elements, on-line in-service monitoring and non destructive examinations. The selection of specific strategies should be based on a degradation mechanism assessment and the level of reliability that is required. This approach is further described in Sections 2.0 and 3.0.

As part of this approach, the concept of Non Destructive Monitoring (NDM), analogous to NDE, is proposed. NDM is defined as the targeted on-line monitoring of active degradation mechanisms at potentially susceptible regions. The susceptibility criteria are contained in Appendix A of this report.

An evaluation of HTGR examination methods and ISI strategy is provided in Section 3.0. Section 3.1 includes Table 3 that provides a listing of available NDE/NDM techniques and their applicability to HTGRs. Table 3 summarizes NDE and NDM techniques recommended for additional development for HTGRs. These items for additional development are further discussed in Section 4.0 and are included in the integrated technology road map of Section 6.0.

A description of key environmental conditions and operating conditions specific to HTGRs is provided in Section 3.2 and a brief discussion of flaw acceptance resolution relative to acceptance criteria is included in Section 3.3. Section 3.4 contains a description of HTGR degradation mechanisms and NDE techniques for fast neutron radiation embrittlement, thermal transients and thermal stratification, flow induced vibrations, self welding and fretting fatigue, mechanical fatigue, stress corrosion cracking, creep and creep-fatigue. Finally, Section 3.5 provides a discussion of advanced material characterization including non destructive characterization, NDE techniques for fast neutron embrittlement of the reactor pressure vessel (RPV) steels and advanced mechanical property testing with micro samples.

HTGR NDE AND ISI Technology Assessment

A technology assessment is provided in Section 4.0 based on information provided in Sections 2.0 and 3.0. This section summarizes needed technology developments to address damage mechanisms for which existing NDE and NDM methodologies are not optimal, considering HTGR specific maintenance and operating environments. The assessment defines needed short term and long term technology developments and provides a technical foundation for defining a research agenda which is further discussed in Section 6.0.

1.4 Task 12 Part 2 Approach

The original ASME work scope for Part 2 of Task 12 is stated above in Section 1.1. However, the original scope was revised based on Westinghouse discussions with the NRC via the ASME ST-LLC. The reference to the NERI initiative should be a reference to the ASME Committee on Research Technology Development (CRTD) activity that was documented in report CRTD-86 [2]. The agreed-to revised scope is to identify a methodology for inclusion of examination considerations in the LRFD approach and to construct a road map that provides a path forward to develop the methodology. This scope is further described in Section 5.0 of this report.

Background information for the deterministic piping analysis methods in the current ASME Code and the reliability-based LRFD is provided in Sections 5.1 and 5.2. The proposed technical basis for determining the NDE/NDM requirements based upon LRFD principles is described in Section 5.3.

A proposed process on how the inspection information in Part 1 of Task 12 (Sections 2.0, 3.0 and 4.0 of this report) can be used with the proposed methods of Section 5.3 for LRFD development of the advanced inspection requirements is provided in Section 5.4.

Lastly, Section 6.0 provides an integrated road map that identifies NDE/NDM and LRFD research and development activities that can resolve technology gaps, support regulatory needs and provide a foundation for defining a future research agenda. Output from these activities is expected to be reported in a manner that would make implementation and adoption feasible and expedient into applicable codes and standards. However, no activities are included in the road map for approval by the codes and standards committees or regulators having jurisdiction.

2 PART 1- ASSESSMENT OF PAST HTGR REACTOR EXPERIENCE / STUDIES AND POTENTIAL HTGR MATERIAL DEGRADATION MECHANISMS

2.1 Assessment of Past HTGR Reactor Experience/Studies

This section provides an assessment of past HTGR experience and its relevance to this task. Much of the past HTGR experience is limited by designs that are not relevant to today's proposed configurations. For example, many of the past HTGR vessels were constructed as Pre-stressed Concrete Pressure Vessels (PCRV), which also enclosed the helium circulators and heat exchangers making access even for traditional inspection techniques difficult. The following paragraphs examine some of the past and present reactor configurations and assess them for relevance to this task. Documented experience is not easily obtainable because: (1) many of the reactors operated for time spans insufficient to build up a good body of operational experience and (2) much of the early German documentation has not been translated.

Dragon (U.K.) (1964–1977)

The Dragon reactor was built to fulfill a research and development role. The Dragon reactor was used to develop and qualify the BISO and TRISO fuels used in today's HTGRs. The Dragon reactor had a steel pressure vessel enclosed by a concrete confinement building. Periodic inspections of the Pressure Containment System were executed as part of an integrated inspection program and included pressure testing, remote visual inspections and helium leak monitoring on a continuous basis via the double containment and leak detection interspaces. A similar approach is now being proposed for next generation HTGRs.

Peach Bottom (U.S.) (1967–1974)

The authors of this report are not aware of relevant operational experience currently available that would be of use. Peach Bottom was considered a successful plant and many of the lessons learned were incorporated in the Fort Saint Vrain design.

Albeitsgemeinschaft Versuchsreaktor (AVR) (Federal Republic of Germany) (1967–1989)

The AVR was first and foremost a research reactor that was also successfully operated as a commercial power plant for 19 years. The AVR was the originator for the pebble bed fuel concept. It had a steel reactor pressure vessel. The authors of this report were unable to find specific operating experience documentation relating to diagnostic monitoring that would have relevance to this task.

Thorium Hochtemperatur Reaktor (THTR) (Federal Republic of Germany) (1985–1989)

The THTR was constructed with a PCRV vessel, the design of which is not relevant for today's advanced reactors. The THTR was an indirect cycle, consisting of a reactor vessel, six helical coil steam generators and helium circulators all enclosed by the PCRV. There is a large body of documents (in German) which includes information on operational experience, NDE and monitoring techniques. The following NDE techniques were used: visual inspection, leak testing, pressure test and weld inspection using X-ray or ultrasound for wall thickness measurements.

The THTR had videos of inspections carried out in the hot gas duct, steam generator structural support and the hot gas duct to core lower plenum interface. The THTR also conducted video inspection of some areas in the fuel handling system such as the core unloading device pebble collection box and associated piping.

The THTR continuously monitored the helium leakage via a leak detection system. THTR had double penetration closures and the interspace volumes were monitored for pressure build up over time. The system had a very low helium leakage/consumption in contrast to Fort Saint Vrain. Data on the exact helium quantities ordered for THTR and the amount of helium consumed due to charging and discharging of fuel pebbles and quantities vented for maintenance are available.

The THTR steam generator tubes were monitored continuously via the moisture monitoring and reheat steam activity. The THTR did not have any steam generator tube leaks during the three years of operation.

Fort Saint Vrain (FSV) (U.S.) (1974–1989)

There is a considerable body of documented experience relating to the operation and decommissioning of FSV [NUREG/CR-6839] [3]. FSV had two steam generator leaks in 13 years of operation (the first occurred one year after the plant began generating power). In the context of monitoring, diagnostics and prognostics, the following operational experience may be relevant to the monitoring of advanced reactors: (1) water incursion events or failures of moisture detection systems and (2) air or other unwanted gas incursion events and failures of gas detection systems. A similar approach is now being proposed for next generation HTGRs.

Other Gas-cooled Reactors

This report has no relevant information regarding the in-service inspection and monitoring of the Magnox, AGRs, HTTR and HTR-10 reactors. Information available in the public domain is largely related to reported operational experience and shows that different types of monitoring techniques were successfully applied. Since most of these plants had PCRVs, NDE was not an easy option as access was severely restricted. This is in contrast to LWRs where discrete examinations are mandated and monitoring techniques receive less emphasis. An increasing emphasis on the use of monitoring techniques, as a valid ISI technique, is anticipated for HTGRs, to demonstrate the ongoing safety of the plant, which is the ultimate objective of ISI. We found no detailed information regarding ISI programs or techniques used or planned for the HTTR or HTR-10.

There are also limited experimental facilities which may provide data relevant to Task 12.

Helium Test Facility (Republic of South Africa) (2006– present)

This is a new experimental facility, recently commissioned, intended to be used to test and qualify components in a high temperature helium environment. This facility may be used in the future for the testing of advanced NDE techniques, since it does contain a number of full-scale PBMR components.

German Test Facilities for HTGR Materials and Components

The majority of information available relates to materials testing and materials development for the Hot Gas Duct (HGD) design.

2.2 Potential HTGR Material Degradation Mechanisms

To provide a technical basis for the assessment of the applicability of existing and new NDE technologies for the in-service inspection and monitoring of HTGRs it is important to understand the potential degradation mechanisms that HTGRs will be subjected to as a consequence of the design assumptions and service environment. After identifying the potential degradation mechanisms, the conditions and attributes that create the potential for each degradation mechanism are defined. This information is used to screen for the potential presence of individual degradation mechanisms (Appendix A, Table IGA-2300-1 Degradation Mechanism Attributes and Attribute Criteria and Table 1: Summary of DMA Results for PBMR). Once the regions subject to potential degradation have been identified and the associated manifestation or imperfection recognized (Appendix A), one or more NDE methods may be selected as shown in Table 2. Section 3.0 discusses how the operating and maintenance environment together with the associated plant service conditions will be used to select and evaluate the most appropriate ISI strategy and technologies.

For this report the following three steel vessel modular HTGR concepts are considered: PBMR, ANTARES and GT-MHR. These three concepts are based on currently available steel pressure vessel technology and materials data. These concepts also meet the current NGNP design intent. The concepts differ, however, in their physical layout configuration and heat transport system (e.g., direct versus indirect cycle). The Helium Pressure Boundary (HPB) layout configuration for the ANTARES and GT-MHR are similar, both consisting of a Reactor Pressure Vessel (RPV), a cross vessel containing a hot duct and an Intermediate Heat Exchanger vessel (IHX) in the case of the ANTARES and a power conversion vessel in the case of the GT-MHR. The PBMR concept (Figure 1) is the most advanced in terms of design detail and consequently more design information is available regarding actual pressure boundary conditions during operation and shutdown. This information has been used to support the assumptions used to select the most appropriate ISI strategy and technologies. In the context of this study, which considers the vessels and piping that constitute the helium pressure boundary, the identified degradation mechanisms for PBMR will be generally applicable to the other configurations. One exception is the ANTARES "hot vessel option" (Mod 9 Cr-1 Mo, grade 91) for operation in the range 400^{o}C (752^{o}F) to 450^{o}C (842^{o}F). If the design does not operate in the negligible creep regime then creep and creep-fatigue are also possible degradation mechanisms.

PBMR is characterized as a high temperature 900°C (1652°F), helium-cooled, graphite-moderated, pebble-fueled, direct-power conversion cycle nuclear power plant (~165 MWe). The HPB layout configuration consists of an RPV, recuperator vessel, pre- and inter-cooler vessels, turbine casing, low pressure and high pressure compressor casings and gas cycle piping. The gas cycle piping conveying the high temperature helium contains an insulated gas duct to separate the hot gas from the HPB, the so-called double wall construction, thereby ensuring that the HPB temperature remains within ASME code limits ≤ 371ºC (700ºF).

For the indirect cycle HTGR configuration, the IHX is a critical component. ASME Task 7 will address in detail the design and inspection considerations for the different possible configurations. Consequently, this report will not focus on inspection strategies for the IHX.

Table 1 shows a summary of the Degradation Mechanism Assessment (DMA) results for the PBMR HPB. The data in Table **1** were created by systematically evaluating locations on the HPB having a potential for service degradation and screening against susceptibility criteria (Appendix A) for normal and upset conditions. Note that the potential for the mechanism is high relative to other areas that do not have the mechanism attributes; however, identification of a degradation mechanism does not necessarily mean that the mechanism will occur during the design life of the component. Note that Appendix A was compiled for PBMR and may not fully represent all the potential degradation mechanisms to which all HTGRs may be susceptible. Table IGA-2300-1 of Appendix A should be reviewed to make sure it is applicable to specific HTGRs by considering inputs from documents such as NUREG-CR 6944, Vol. 4. [4].

Table **1** was created as part of a pilot study (PBMR Passive Component Reliability Integrity Management (RIM) Pilot Study Executive Summary) [5], commissioned by PBMR, to validate use of the Reliability and Integrity Management (RIM) methodology as the technical basis for the rewrite of the ASME Boiler and Pressure Vessel Code, Section XI [1], Division 2 Rules for Inspection and Testing of Components of Gas-cooled Plants. Details of the RIM methodology were reported at the HTR-2006 conference: *RI-ISI Program For Modular HTGRs* (Paper HTGR2006-F00000123) [6] and *Risk-Informed In-Service Inspection for Modular High Temperature Gas-Cooled Reactors (MHRs), A White Paper Outlining the Technical Approach* [7]. The results of the pilot study were reported at the HTR-2008 conference: *ASME Evaluation of Design, Leak Monitoring and NDE Strategies to Assure PBMR Helium Pressure Boundary Reliability* (Paper HTGR2008-58037) [8] and *ASME Reliability and Integrity Management Program for PBMR Helium Pressure Boundary Components* (Paper HTGR2008-58036) [9] and in a PBMR report, *PBMR Passive Component Reliability Integrity Management (RIM) Pilot Study Executive Summary* [5]. The study provides the basis for a RIM program for the PBMR and provides guidance for ASME B&PV,

Section XI, Division 2, development. Table IGA-2300-1 (Appendix A) of the draft Division 2 rules contains the full descriptions of the degradation mechanisms, together with the attribute criteria, degradation features and susceptible regions.

For each degradation mechanism, the NDE method and technique capable of detecting the physical manifestation is shown in Table 1 and Table 2. To provide additional defense-in-depth for areas where no in-service degradation mechanism is identified, the RIM Program uses a sampling number of inspections, whose locations are identified as part of element selection.

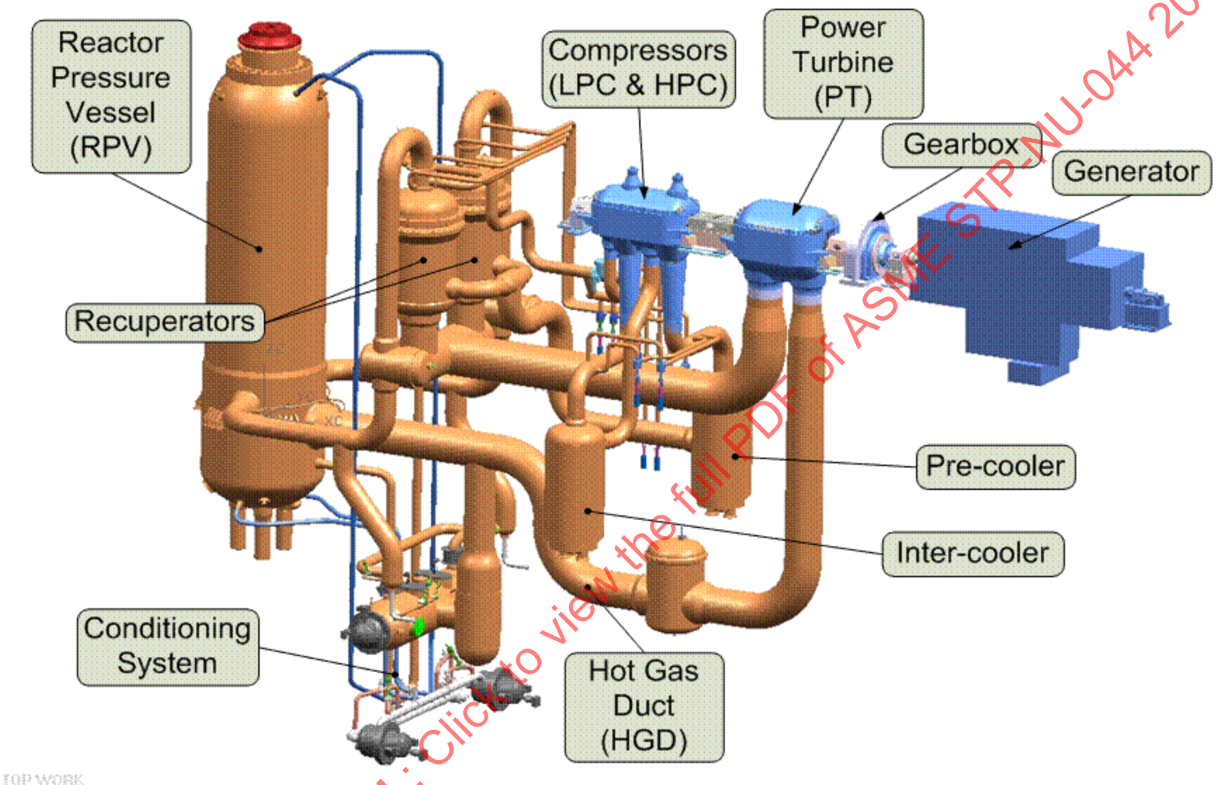

Figure 1 - Steel Vessel Modular HTGR Pressure Boundary (PBMR Brayton Cycle Concept)

Table 1 - Summary of DMA Results for PBMR

SYSTEM/COMPONENT		DEGRADATION MECHANISMS IDENTIFIED						
		RE	TT	TASCS	FIV	SF	MF	SCC
Reactor Pressure Vessel and Supports	Vessel Beltline	X						
	Support Attachment Welds						X	
	Support Interfaces					X		
Main Power System Brayton Cycle Piping	Core Outlet				X			
	Power Turbine Outlet		X		X			
	Core Inlet				X			
	Recuperator Low Pressure Outlet		X	X				
	Annular Cross Flow	No In-Service Degradation Mechanisms Identified						
	Pre-Cooler Outlet							
	Low-Pressure Compressor Outlet							
	Inter-Cooler Outlet							
	High-Pressure Compressor Outlet							
	Link Line			X				
Main Power System Heat Exchangers	Recuperator	No In-Service Degradation Mechanisms Identified						
	Pre-Cooler				X	X		X
	Inter-Cooler				X	X		X
Power Turbine and Compressors	High-Pressure Compressor Casing	No In-Service Degradation Mechanisms Identified						
	Low-Pressure Compressor Casing							
	Power Turbine Casing							
Gas Cycle Valves and Piping	Gas Bypass Valve		X					
	Diverse Gas Bypass Valve	No In-Service Degradation Mechanisms Identified						
	Low-Pressure Coolant Valve		X	X				
	Low-Pressure Compressor Bypass Valve	No In-Service Degradation Mechanisms Identified						
Vessel Over Protection System	Supply Line			X				

Table 2 - NDE Technique Applicability to HTGR Components for ISI / Monitoring

	Surface		Surface & Subsurface		Volumetric					Strains & Deformations			Material Property Condition Monitoring			Surface Temp. Monitoring
DM	VT	PT	MT	ET	RT	UTA	UTS	AE	UTT	VT	Laser Gap	ET Gap	UT Sound Velocity Change	UT Sound Attenuation Change	ET Electrical Conductivity & Magnetic Permeability Change	IR Cameras
RE	-	-	-	-	-	-	●	-	○	-	-	-	○	○	○	
TT	⊖	-	-	⊖	-	●	-	-	-	⊖	●	●	-	-	-	●
TASCS	⊖	-	-	⊖	-	●	-	-	-	⊖	●	●	-	-	-	●
FIV	●			●	●	●	●	-	●			-	-	-	-	-
SF	●	-	-	-	-	-	○	-	○	-	-	-	-	-	-	-
MF	●	●	●	●	●	●	●	○		-	-	-	○	○	○	-
SCC	-	●	●	●	●	●	○	○	-	-	-	-	○	○	○	-
CF	-	-	-	-	-	●		○	-	⊖	○	○	○	○	○	-

Acronyms and Definitions for Table 1 and Table 2

DM - Degradation Mechanism (*Physical Manifestation):*

RE - Radiation Embrittlement, Material *(reduced material elasticity and possible swelling)*

TT - Thermal Transients *(local shape deformation, buckling, surface cracking)*

TASCS - Thermal Stratification Cycling and Striping *(local distortions, surface cracking)*

FIV - Flow Induced Vibrations *(localized wear against support structures, distortions, surface fatigue cracking)*

SF - Self Welding and Fretting Fatigue *(localized fusion, increased surface roughness, metal transfer, deformations and fatigue cracking)*

MF - Mechanical Fatigue *(fatigue cracking, surface initiated micro-cracks, develops into deeper cycle progressive cracks)*

SCC - Stress Corrosion Cracking *(high stressed area exposed to corrosive environment, surface initiated cracking)*

CF - Creep and Creep Fatigue *(distortions, elongations, with plastic deformations, reduced elasticity, surface cracking progressing with loads and time)*

NDE Techniques:

VT - Visual Techniques

PT - Liquid Penetrant Techniques

MT - Magnetic Particle Technique

ET - Eddy Current Technique

RT - Radiographic Techniques

IR - Infrared Monitoring

UTA - Ultrasonic Angle Beam, Including TOFD and Phased Array

UTS - Ultrasonic Straight Beam

UTT - Ultrasonic Thickness Measurement

AE - Acoustic Emission

UT - Ultrasonic Technique

NDE Technique Applicability:

● - All or most standard techniques will detect this imperfection under all or most conditions.

⊖ - One or more standard technique(s) will detect this imperfection under certain conditions.

○ - Special technique, conditions and /or personnel qualification are required to detect this imperfection.

3 PART 1 – EVALUATION OF HTGR EXAMINATION METHODS AND ISI STRATEGY

Section XI of the ASME B&PVC provides rules for in-service inspection, examination and testing of the reactor coolant pressure boundary components [1]. These rules also address repair and replacement activities in nuclear power plants. The rules provide for a mandatory program of examination, testing and inspection to provide evidence of adequate safety and to manage deterioration and aging effects. Extensive experience has been accumulated over the past 40 plus years from numerous commercial LWRs operating around the world. This history of lessons learned has resulted in continuous improvement of plant operations and augmentation of in-service inspection, examination and testing requirements to address the current state of the art developments in non destructive examination as well as diagnostic and prognostic methodologies.

As touched upon at the end of Section 2.0, the operating and maintenance environment for HTGRs are not significantly different than the environment for LWRs. Due to the expected longer operating periods between maintenance outages, it is proposed to use the RIM methodology that applies combinations of strategies for the reliability and integrity management of passive components to achieve reliability goals. HTGRs should be designed to accommodate both outage based and on-line monitoring and examination. The intent is to identify and detect in-service degradation for HTGRs using not only the traditional in-service inspection of ASME Section XI but a combination of strategies including plant and component design elements, on-line in-service monitoring and non destructive examinations [6]. The selection of specific strategies should be based on a degradation mechanism assessment and the level of reliability that is required.

Strategies investigated in the RIM study (see reports referenced in Section 2.2) include design elements, on-line leak detection and leak testing approaches and destructive examinations. Specific combinations of strategies are determined to be necessary and sufficient to achieve target reliability goals for passive components. This study recommends a basis for the RIM program for HTGRs, such as PBMR, and provides guidance for ASME B&PV, Section XI, Division 2 (ISI Code for HTGRs).

Non Destructive Examination and testing (NDE) techniques have been the basis for in-service inspection programs. These techniques are used to interrogate the possible degradation mechanism effects on critical locations along the pressure boundary. These techniques have been proven to have no harmful effects on the components being inspected. Currently NDE is used primarily as a diagnostic tool to detect and size the geometry of degradation effects, e.g., wear scars, cracks, corrosions, deformations, etc.

In recent times, extensive empirical observations have triggered an interest in analyzing the complex results generated with these techniques to develop prognostic tools that could define other material properties (preconditions to physical degradation effects) conventionally obtained through destructive testing (residual stresses, susceptibility to stress corrosion cracking (SCC) and mechanical property changes). These methodologies exist in laboratory research programs and in some instances are finding practical application in the field. These are some of the areas that should be targeted for further development. In the listing of available NDE techniques (Table 3) these prognostic methods are identified as Material Property Condition Monitoring techniques (Table 2). Based on existing empirical observations in operating light water nuclear power plants (LWRs), methods involving ultrasound and eddy current are recommended as priority for future developments.

3.1 Available Non Destructive Examination Techniques

Existing examination and practice has developed an extensive list of available NDE techniques that are available from LWR ISI programs. Table 3 lists NDE/NDM techniques applicable for use on LWR components and some new techniques along with existing applicable code and standards for specific technique applications. Due to the similarity of pressure boundary components and inspection acceptance standards between LWR and the design of the HTGRs considered in this study, Table 3 will be used as a source for selection of NDE/NDM techniques that could be applied on HTGR pressure boundary components. Selection will be made based on the specific environmental conditions during operation and maintenance intervals, and predicted HTGR degradation mechanisms, as well as readiness in the NGNP time frame. Some of the listed techniques are directly applicable with existing governing codes and standards while others—ones that are being newly introduced—will need further development to establish proper guidelines and develop codes or standards and proper qualification of these techniques for application in HTGR ISI programs. The need for new techniques and further development will be decided upon the finalization of specific designs, and with defined inspection criteria for specific components and environmental conditions dictated by the specific design and planned inspection outage durations.

Table 3 - NDE/NDM Techniques Applicable to HTGR

Item	Type of Inspection	NDE / NDM Method	Existing Applicable Codes and Standards	Comments	Applicability to HTGR ISI Program
1.1	Volumetric	Radiography: • Film Recording • Digital Recording	ASME B&PVC: 1) Section V, Subsection A, Article 2 2) Section XI IWA-2231	Primarily a manufacturing inspection. Limited for ISI use due to access restrictions.	Primarily a manufacturing inspection. Current.
1.2	Volumetric	Ultrasonic	ASME B&PVC: 1) Section V, Subsection A, Article 4 and 5 2) Section XI IWA-2232	Most preferable technique for LWR. (temp < 50°C).	Improvements needed in sensors and robotics for high temperature application. Short term.
1.3	Volumetric	Ultrasonic TOFD (Time of Flight Diffraction)	ASME B&PVC: 1) Section V, Subsection A, Article 4 Appendix III	Wide applications in LWR for sizing. (temp < 50°C).	Improvements needed in sensors and robotics for high temperature application. Short term.
1.4	Volumetric	Ultrasonic Phased Array	ASME B&PVC: 1) Section V, Subsection A, Article 4 Appendix IV	Recently deployed in LWR. (temp < 50°C).	Improvements needed in sensors and robotics for high temperature application. Short term.
1.5	Volumetric	Ultrasonic Non-Contact Laser UT	No applicable standards	Limited experience in other industries.	Further development required. Long term.
1.6	Volumetric	Ultrasonic Non-Contact EMAT (Electro Magnetic Acoustic Transducers)	ASTM E-1774 Standard guide for EMAT	Limited experience in LWR.	Further development required. Long term.

Item	Type of Inspection	NDE / NDM Method	Existing Applicable Codes and Standards	Comments	Applicability to HTGR ISI Program
1.7	Volumetric	Eddy Current	ASME B&PVC: 1) Section V, Subsection A, Article 8 2) Section XI IWA-2233	Most preferable technique for thin wall tubular products (heat exchanger) in LWR. (temp < 50°C).	Improvements needed in sensors and robotics for high temperature application (50°C and above) Short term.
1.8	Volumetric	Remote Field Eddy Current	ASME B&PVC: 1) Section V, Subsection A, Article 17 2) Section XI IWA-2233	Limited use in LWR. (temp < 50°C). Thin wall tubular products. Thin wall plates. Ferromagnetic materials.	Improvements needed in sensors and robotics for high temperature application (50°C and above) Long term.
1.9	Volumetric	Magnetic Flux Leakage	ASME B&PVC: 1) Section V, Subsection A, Article 16	Limited use in LWR. (temp < 50°C). Limited to ferromagnetic materials.	Improvements needed in sensors and robotics for high temperature application (50°C and above) Long term.
2.1	Surface	Magnetic Particle	ASME B&PVC: 1) Section V, Subsection A, Article 7 2) Section XI IWA-2221	Manufacturing inspection. Limited for ISI use (loose particles). Class 2 & 3 components in LWR. (temp < 50°C). Limited to ferromagnetic materials.	Manufacturing inspection. Current.
2.2	Surface	Liquid Penetrant	ASME B&PVC: 1) Section V, Subsection A, Article 6 2) Section XI IWA-2222	Manufacturing inspection. Limited for ISI use (loose particles). (temp < 50°C).	Manufacturing inspection. Current.
2.3	Surface	Eddy current	ASME B&PVC: 1) Section V, Subsection A, Article 8 2) Section XI IWA-2223	Recently expanded use in LWR. Suitable for remote applications. (temp < 50°C).	Improvements needed in sensors and robotics for high temperature application (50°C and above) Short term.
2.4	Surface	Magnetic Flux Leakage	ASME B&PVC: 1) Section V, Subsection A, Article 16	Limited application in LWR. (temp < 50°C). Ferritic materials	Improvements needed in sensors and robotics for high temperature application (50°C and above) Long term.

Item	Type of Inspection	NDE / NDM Method	Existing Applicable Codes and Standards	Comments	Applicability to HTGR ISI Program
2.5	Surface	Giant Magneto Resistors	No applicable standards	No production experience with LWR	Further development required. Long term.
2.6	Surface	Laser UT Rayleigh waves	No applicable standards	No production experience with LWR.	Further development required. Long term.
2.7	Surface	EMAT Rayleigh waves	ASTM E-1774 Standard guide for EMAT.	No production experience with LWR.	Further development required. Long term.
3.1	Visual	Direct, Fiber Optics and Remote TV	ASME B&PVC: 1) Section V, Subsection A, Article 9 2) Section XI IWA-2210	Extensive experience with LWR.	Further development in high temperature ranges. Short term.
4.1	Visual Surface	Pattern Image Correlation Analysis	No applicable standards	Creep monitoring in high temperature components in fossil plants.	Further development required. Long term.
5.1	Visual Thermo Graphics	Infrared Monitoring	Further development required.	Limited experience with LWR.	Further development required. Long term.
6.1	Volumetric Monitoring	Acoustic Emission	ASME B&PVC: 1) Section V, Subsection A, Article 12 & 13 2) Section XI IWA-2234 The Section V Working Group Acoustic Emissions is currently working on revising standards for on-line flaw detection/monitoring.	Limited experience with LWR. Focused on the monitoring of known crack propagation.	Further development required. Short term.
7.1	Vibration and Loose Part Monitoring		No applicable standards	Extensive empirical experience at LWR and conventional power plants.	Further development in application of methods and identification of areas of use. Long term.
8.1	Leak Test	Helium Leak Test	ASME B&PVC: 1) Section V, Subsection A, Article 10.	Used in LWR as a confirmatory test.	Further development in application of methods and identification of areas of use. Long term.
8.2	Leak Monitoring	On-Line Helium Leak Detection Acoustic Emission	No applicable standards	No production experience with LWR.	Further development required. Short term.

Item	Type of Inspection	NDE / NDM Method	Existing Applicable Codes and Standards	Comments	Applicability to HTGR ISI Program
9.1	Material Characterization (NDC) used for Material Property Condition Monitoring	Detecting Electro Magnetic Micro Property Changes as result of microstructure states	No applicable standards	Some experimental experience in LWR and other industries.	Further development required. Long term.
9.2	Material Characterization (NDC) used for Material Property Condition Monitoring	Measuring Variation in Acoustic Velocity and Acoustic Attenuation	No applicable standards	Mechanical property (elasticity)	Further development required. Long term.
10.1	Displacement Measurement	Laser profiling. Eddy current gap measurement. Capacitive strain gauges.	No applicable standards	Creep or radiation induced strains (deformations).	Further development required. Long term.

3.2 Environmental Conditions

In this study, operating and environmental conditions characteristic of PBMR were used as guidelines for selection and application of specific NDE/NDM techniques. Since similar degradation mechanisms are identified for PBMR and other HTGR designs (see Section 2.2) this approach will produce a viable basis for selection of NDE/NDM techniques.

Environmental conditions specific to HTGRs are defined as those encountered during the operational phase and those expected during scheduled maintenance at shutdown intervals.

The PBMR HPB is designed to operate with a low temperature along the pressure boundary (≤150°C), with the exception of the RPV, where temperatures in the range of 280°C to 300°C may occur. During operation, the environment is also subjected to high radiation (neutron and gamma) from the reactor. These environmental conditions are similar to that encountered in LWR operation, apart from the fact that the neutron flux levels are about one order of magnitude lower in the case for PBMR**.**

During the PBMR scheduled maintenance shutdown intervals the temperatures for the RPV and adjacent cavity are expected to be in the range of 40°C to 70°C. The residual radiation fields are expected to be relatively high, similar to radiation conditions that are encountered in LWRs during scheduled maintenance intervals.

The presence of a relatively high radiation field will require remotely operated equipment to implement monitoring or inspection activities and avoid human exposure. This approach is implemented on LWRs, and extensive experience exists with special remotely operated manipulators and radiation hardened sensors used in ISI.

On-line monitoring techniques and deployment mechanisms for specific components in HTGR's requiring inspection and/or monitoring during operation and maintenance phases that could be exposed to higher surface temperatures will require further hardware improvements and temperature hardening of NDE/NDM components and robotic delivery systems (as noted in Table 3).

3.3 Flaw Acceptance Resolution

Experience with LWRs for applicable and approved volumetric and surface inspection methods has demonstrated the adequacy of existing techniques to comply with structurally defined acceptable flaw sizes (IWB-3000). Since a similar concept for defining these criteria will be implemented on pressure boundary components for the HTGR (IGA-2000), the existing experience from LWR inspection resolution criteria (detection of minimal size acceptable flaws) could be credited for NDE/NDM methods approved for use on the HTGR. If more stringent acceptance criteria will be implemented for HTGR components, further qualification will be required to demonstrate that applicable NDE/NDM methods will be in compliance.

3.4 Degradation Mechanisms and NDE/NDM Techniques

Potential degradation mechanisms and applicable NDE/NDM techniques for HTGR pressure boundary components have been previously presented in Table 1 and Table 2. Table 2 lists possible NDE/NDM techniques suitable for the detection of the degradation mechanisms identified in Table 1. The potential damage mechanisms are discussed further in this section.

3.4.1 High Energy Radiation Embrittlement (RE)

Present experience with monitoring this degradation in LWRs is accomplished with sacrificial test samples installed in the operating reactor vessel and exposed to the high energy radiation field. These samples are removed from the operating reactor at appropriate time intervals to undergo destructive testing and to provide information on material mechanical property changes. Similar concepts could also be used with the HTGR, provided that the RPV design allows for positioning of test samples inside it, adjacent to the beltline surface to simulate similar temperature and fast neutron flux exposure.

Material condition monitoring techniques could be an alternative way to monitor this degradation. Recent experimental applications in other fields (material manufacturing) have shown that non destructive monitoring using acoustic and electromagnetic techniques can be used to predict changes in material mechanical properties. Recent results from Idaho National Laboratory on characterization of material microstructure with laser based resonant ultrasound spectroscopy and from the Fraunhofer Institute for Non Destructive Testing with micromagnetic, multiple parameter, microstructure and stress analysis on neutron irradiated samples have produced encouraging results. These techniques are Long Term.

Electromagnetic property changes are limited to surface or relatively shallow subsurface zones, and require direct access to the altered material surface. An alternate approach by monitoring acoustic parameter changes (sound velocity, attenuation) could provide a method for extracting information on mechanical property characteristics for embrittled material. This Long Term concept will require proper investigation efforts that could be coordinated with the present practice of destructively examining test samples, and further basic non destructive material characterization research.

An alternative to this non destructive material condition monitoring approach is to follow existing practice used in LWRs with deploying volumetric inspection techniques that will interrogate possible degradations. Ultrasonic inspection from the outside surface provides the most practical approach for inspecting RPV zones exposed to this phenomenon. Current techniques that are regulated within the Section XI code (UTA, including TOFD, and Phased Array) provide adequate bases for inspection [6]. Further Short Term development will be needed on the Phased Array approach since this is a relatively new application and only initial technical regulations exist in the Section XI code.

3.4.2 Thermal Transients and Thermal Stratification Cycling and Striping (TT and TASCS)

The manifestations for this damage mechanism are defined as shape distortion and local cracking, buckling and distortion or movement at support structures and surface cracking. To monitor these effects, the following NDE methods are suggested: Visual and eddy current for surface cracking; Visual, laser gap and eddy current gap for local geometry change measurement; Infrared camera monitoring for unexpected temperature field distributions during plant operation.

For surface inspection, visual and eddy current techniques are recommended since these techniques could be deployed remotely with robotic tooling. Current regulations in the code provide an adequate basis to implement these techniques.

Some further Short Term development will be required to provide proper guidelines for implementation of deformation measurements with visual, laser gap, eddy current gap techniques and infrared monitoring.

3.4.3 Flow Induced Vibrations (FIV)

To monitor physical manifestation of this degradation mechanism (i.e., localized wear) visual, eddy current (from the affected surface side only) and volumetric inspection with ultrasonic techniques could be applied with remote robotic tooling. Radiography will have very restricted application due to limited access for the source and sensor (film or digital receptor).

For the detection of possible surface cracking, eddy current could be applied if the critical surface is accessible, otherwise volumetric inspection with ultrasonic angle beam (including TOFD and Phased Array) techniques should be used.

Current techniques that are regulated within the code (VT, ET, UTA, including TOFD, and Phased Array) provide adequate bases for implementing these inspections. Some further Long Term development should be needed on the Phased Array approach since this is a relatively new application and only initial technical regulation exists in the code.

3.4.4 Self Welding and Fretting Fatigue (SF)

The manifestations of these mechanisms are surface roughness and metal transfer and, in severe cases of adhesive wear, cracking can be initiated at the contact surfaces. For detection of self welding and fretting fatigue manifestation, visual and volumetric with straight beam UT methods should be applied. Current code requirements are sufficient for VT. Further Long Term guidelines for volumetric (UTS) could be required to properly characterize this phenomenon, since access to the interfaces is normally difficult and the damage at the interface is expected to be very irregular.

3.4.5 Mechanical Fatigue (MF)

For fatigue cracking detection the preferable surface inspections will be visual (VT) and eddy current (ET) since these two methods could be deployed with remotely operated robotic tooling. Magnetic particle (MT) and liquid penetrant (PT) could be used in isolated cases where human access is practical.

For detailed characterization of fatigue cracking, volumetric inspection will be required. Radiography will have very restricted application due to limited ability to allow proper access for source and sensor (film or digital receptor). Volumetric with ultrasound is a method of choice that allows deployment with remote robotic manipulators. Acoustic emission monitoring could be used to monitor crack progression. This will require on-line monitoring and existing transducers operating at temperatures up to 400°C as used in LWRs. Further sensor temperature hardening or alternative methods of inducing the ultrasound energy with laser or electromagnetic principles (Laser UT or EMAT) will be required (Short Term) for the higher operating temperature.

Current code regulations provide an adequate basis for implementation of all of these techniques. Some further Long Term development should be needed on UT Phased Array, Laser UT and EMAT approaches since this is a new application and only limited initial technical regulation exists in the code.

In addition to characterizing developed degradation (fatigue cracking), it could also be possible to implement early detection with material monitoring by interrogating local material fatigue induced hardening by monitoring sound velocity changes, sound energy attenuations and/or by monitoring local material micro structure electromagnetic property changes. These material condition monitoring techniques have shown some positive results in material manufacturing fields and a laboratory environment.

Further Long Term development will be needed to bring these material condition monitoring processes to practical applications. Concepts based on monitoring sound energy responses and electromagnetic changes will allow these processes to be remotely deployable by robotic manipulators for interrogations in high radiation areas.

3.4.6 Stress Corrosion Cracking (SCC)

Surfaces exposed to high levels of tensioning residual stresses combined with a chemically aggressive environment (exposure to water or humid environment combined with unwanted chemical contaminants) could lead to local surface sensitizations that will result with surface initiated cracking degradations.

If exposed surfaces are accessible for inspection, surface techniques like LP, MT and ET could be applied. The preferable surface inspection technique is ET since it could be deployed with remotely operated robotic tooling.

For inaccessible surface interrogations and for more detailed crack sizing, the volumetric methods are preferable. Volumetric with ultrasound is a method of choice that allows deployment with remote robotic manipulators. Acoustic emission monitoring could be used to monitor crack progression. This will require on-line monitoring and existing transducers operating at temperatures up to 400°C are used in LWRs. Further Short Term sensor temperature hardening or alternative methods of inducing the ultrasound energy with laser or electromagnetic principles (Laser UT or EMAT) will be required for higher operating temperature.

Current code regulations provide an adequate basis for implementation of all of these techniques. Some further Long Term development should be needed on UT Phased Array, Laser UT and the EMAT approach since this is a new application and only limited initial technical regulation exists in the code.

Material property condition monitoring techniques measuring electromagnetic property changes and acoustic characteristics have shown some initial positive results in LWRs (permeability changes due to increased residual stresses or deformed microstructure in austenitic steels and nickel based alloys). Further Long Term development will be required with these techniques to interrogate and quantify essential preconditions that lead to SCC degradations.

3.4.7 Creep and Creep Fatigue (CF)

To observe the manifestation of the creep fatigue damage mechanism, visual monitoring, combined with more accurate local deformation measurements (through the use of laser, eddy current gap measurements and/or capacitive strain-gauges), could be applied. Further investigation of changes in material properties that affect sound velocity and energy attenuation, combined with possible alterations in microstructure resulting with local changes of electromagnetic properties could also be used. Further temperature hardening could be required for ANTARES (hot vessel option) which will experience higher operating temperatures. These methods are Long Term.

3.5 Advanced Material Characterization

Present practices at operating LWRs utilize NDE as a testing technology to detect, characterize and size physical imperfections (material defects, geometrical deviation, etc.). Recent efforts have shown prospects for improved material characterization by using NDE sensing parameters to detect material lattice defects, and in-homogeneities of material microstructure that are precursors for material degradation (defects) that directly impede on originally designed structural integrity. These changes or alterations from normalized material affect material microstructure properties that could be detected and measured with non destructive testing techniques. Recent experiences with ultrasonic and electromagnetic techniques have shown the possibility of detecting early stages of material changes that lead to degradations influenced by thermal, mechanical or chemically induced microstructure alterations. Improperly conducted thermal treatments, inhomogeneous physical properties, creep and residual stresses have been detected by changes in the acoustic and electromagnetic property of the materials.

3.5.1 Non Destructive Characterization

Further Long Term evaluation and development of the following NDC (Non Destructive Characterization) techniques may advance early detection and allow for the proper mitigation actions to increase component reliability.

Magnetic Barkhausen Noise:

The magnetic Barkhausen effect is observed as transient pulses induced across a search coil placed near or around the ferromagnetic material undergoing a change in magnetization. These pulses can either be observed individually by counting and amplitude sorting or as an *RMS* signal as a function of the applied magnetic field. The B_E signal arises from irreversible magnetic domain wall movements as domain walls become successively pinned and jump over obstacles in the material. These obstacles are typically dislocation defects, second phases or grain boundaries and consequently the technique is particularly sensitive to the microstructure and mechanical properties of the component. The technique is also sensitive to the internal stress state because of the partial domain alignment along the maximum principal stress axis. Thus, tensile and compressive stresses usually increase and decrease the B_E signal respectively.

The application of this method does show promise for qualitative evaluation of irradiation damage, but it is questionable what its ability is with regards to determining the derivation of fracture toughness.

Micro-Magnetic Measurements:

The 3MA analyzer system (Micro-magnetic, Multi-parameter, Microstructure and Stress Analysis) has been developed by the Fraunhofer Institute for Non Destructive Testing in Germany. As its name implies, the instrument measures a combination of different magnetic parameters, enabling some degree of separation between variations in the stress and microstructure states. The 3MA analyzer employs the techniques of magnetic Barkhausen, conductivity (derived from Barkhausen profiles) and magnetic field frequency harmonics. The instrument is designed for use in a wide range of applications including detection of different heat treatments, residual stresses, hardness gradients and parameters loosely related to strength and toughness.

To achieve some quantitative measurement, the 3MA analyzer must be calibrated against samples containing the variations of interest. Indeed, a great deal of work has been done by the researchers in investigating a large range of materials and heat treatment conditions. Recently, new approaches have been developed which concentrate on using linear multiple regression or neural network algorithms to calibrate the system for limited, well-defined sets of specimen or component conditions. These calibrations rely on a detailed mathematical variation formalism that notably does not involve any empirical or fundamental understanding of the physical principles of the magnetic techniques.

This technique is not mature enough and would require a large database of test results to benchmark against to warrant its consideration for determining irradiation embrittlement.

Nonlinear Harmonic Analysis of Eddy Current Signals:

This technique utilizes the whole magnetic hysteresis loop and the way in which it is influenced by the micro-structural changes due to degradation. An oscillating sinusoidal magnetic field is applied to the material, and this is modified by the material that acts as a transfer function, so that a detector coil picks up a distorted signal, which is analyzed for amplitude and phase of different harmonics of the original signal frequency. To calibrate, the variation of these parameters is fitted using a "multidimensional regression analysis" to provide the best correlation with material property. Some degree of selectivity to the different mechanical properties is achieved.

This technique is not mature enough and the sensitivity to toughness variation is questionable.

Laser Ultrasonic:

Additional excitations of mechanical pulsing within the inspected material, not relying on the piezoelectric effect, are possible with laser induced ultrasound and electromagnetically induced ultrasound. This technique does not require direct coupling with the inspected surface with a media capable of transmitting mechanical pulses (liquid couplant is usually applied with piezoelectric transducers). Laser induced ultrasound relies on local thermal expansion of inspected material by laser energy. This effect generates ultrasonic waves within inspected material and reflections are observed. Laser ultrasonic uses two lasers, one with a short pulse for generation of ultrasound and another one, long pulse or continuous, coupled to an optical interferometer for detection. Laser ultrasonic allows for testing at long standoff distances and inspection of parts without any coupling liquid. The technique also features a large detection bandwidth, which is important for numerous applications, particularly those involving small crack detection, sizing and material characterization. The ability to perform testing with long standoff distances allows inspections on components with high surface temperatures (such as inspection in steel production mills). Several practical applications were investigated with positive results in the nuclear industry.

Further advancement of this technique should be observed since it could have possible application to material property characterization of operating components within a high temperature environment.

EMAT (Electro Magnetic Acoustic Transducers):

This approach of generating acoustic waves within the inspected materials relies on electromotive forces created by inducing electrical current within inspected material with an oscillating magnetic field (similar to eddy current technique), while simultaneously an outside static magnetic field is applied through the material’s interaction with the induced current which results in a Lorentz force that becomes a source of mechanical pulsing and creates ultrasonic vibration within the inspected materials. Reflected ultrasonic vibrations are sensed by proximity coils that monitor the inspected surface. No direct contact allows this concept to be applied on surfaces with elevated temperatures. Some practical applications inspecting high temperature components have been developed in the ship-building industry for monitoring integrity on high temperature components during the welding process.

Further advancement of this technique should be observed since it could have possible application to material property characterization of operating components within a high temperature environment.

3.5.2 NDE Techniques for Fast Neutron Embrittlement of RPV Steels

In recent times various non destructive testing methods have been developed to measure the degree of irradiation embrittlement, which manifests itself in an increase in yield and tensile strength, and a decrease in toughness (as measured through a shift in the Ductile-to-Brittle Transition Temperature

(DBTT)), through drop-weight and/or Charpy Impact testing. These techniques are in various stages of development and maturity. The most mature methods are briefly described below.

Automated Ball Indentation:

The Automated Ball Indentation (ABI) is a system developed and commercialized by U.S.-based Advanced Technology Corp. and it essentially converts instrumented hardness testing to tensile and fracture toughness data. The method is considered to be non destructive due to the shallow indentations. It is further claimed that the fracture toughness testing can produce results conforming to the Master Curve requirements in accordance with ASTM E1921-97 [10]. This technique has been fully qualified and is commercially available as laboratory equipment, and possibly in-field equipment.

The application of this method in the field and in an irradiation environment needs to be investigated.

Thermopower Measurements:

This system is based on the Seebeck effect, which leads to thermoelectric power in metals. Currently two devices have been developed, the first by Electricite de France (EdF) together with the Technical University INSA de Lyon, and the second by the Joint Research Council (JRC).

Laboratory measurements have established the variation of voltage generated when a temperature gradient is applied to a metal, which varies with hardness, toughness and with the Cu content of reactor pressure vessel steels. The generated voltage drop, DV, is measured to give the coefficient DV/DT = DTEP.

As an example, EdF has built a portable Thermo-Electric Power (TEP) system, which can be used on large components after some surface preparation. It has been demonstrated by the measurement of damage on a cast duplex steel elbow. The JRC device has shown its capability to detect material damage induced by irradiation.

This technique has reached a high level of maturity and developments regarding sensitivity and portability should be followed.

Magnetic Interrogation Method:

This method relies on the good correlation between the degrees of radiation-induced hardening and magnetic coercivity change in the steel of nuclear reactor pressure vessels. The part of the pressure vessel to be inspected is magnetized with a two-pole magnetic yoke and the magnetic field distributions on the surface are measured. Through magnetostatic field analysis, the coercivity distribution through the thickness of the RPV is determined, which could be correlated with the degree of irradiation embrittlement.

The level of maturity of this technique is not known and developments should be monitored.

3.5.3 Advanced Mechanical Testing with Micro Samples

In addition to new approaches with non destructive material condition monitoring, it is recommended to also consider newly developed mechanical testing with micro samples. Direct mechanical testing is recommended on sacrificial test coupons or surveillance samples and possible micro material samples from operating components.

Taking samples for further investigation directly from the point of interest in the component would be another approach for damage monitoring. Such samples would contain information just from the spot of interest. Such a method, however, can be successful only when the remaining damage from sample removal does not weaken or damage the structure. Until recently, it was necessary to use relatively large samples for testing, even when they were called miniaturized samples. This was the reason why, for component based monitoring, only local hardness tests and replica-techniques were used. With the advent of focused ion beam equipment and micro-machines for controlled deformation (Nano-indenter), a new era of mechanical testing started.

The most important methods for testing and analysis of sub-sized and micro/nano samples are given in Table 4. Items 1 through 5 refer to mechanical tests. Items 6 through 10 refer to relevant analytical methods and material modeling as necessary tools for understanding and quantitatively interpreting the experimental results.

Table 4 - Micro Sample Techniques

Item No.	Method	Comments
1	Miniature samples	Typically specimens for Charpy Impact, J_{IC}, stress-strain, creep testing - in dimensions of a few mm.
2	Ball/shear punch	Small discs, stress-strain behavior, finite element analysis required.
3	Thin strip	100-200 µm thin strips, irradiation creep, creep, stress-strain behavior.
4	Nano indenter	Instrumented hardness testing, hardness profiles, stress-strain behavior, finite element analysis required; cylindrical indenters for creep deformation.
5	Micro-samples	FIB machined micro/nano-pillars, bend-bars etc., stress-strain behavior and deformation in SEM or beamline possible.
6	Surface replica	Corrosion, surface microstructure.
7	Transmission Electron Microscope (TEM)	Heating and deformation stages, EELS and other analysis techniques, micro-and nanostructure, precipitates, irradiation defects.
8	Atom probe	Cluster formation.
9	Advanced neutron/X-ray techniques	Coordination chemistry, magnetic effects, micro- and nano-structure, complementary to TEM techniques.
10	Materials modeling	Relate the cast microstructure to stress-strain relationships, toughness and/or residual life.

It is proposed that these methods be considered as tools for residual life and damage assessments of advanced GEN IV plants. These methods can be used to get maximum possible information out of test coupons or surveillance samples. These methods, however, should be considered also for analysis of material coming directly from the components. The following steps of development are proposed.

For coupons/surveillance samples:

- Address components to be monitored;
- Define relevant damage mechanisms;
- Quantify expected damage in terms of changes of mechanical properties and microstructure.

For material taken from components directly:

- Define tools for sample extraction;
- Define and foresee locations for extraction of sample material from the component;
- Study safety aspects for component and sample removal;
- Develop a sound testing concept for an HTGR.

Finally, it is worth mentioning that there is considerable progress in the development of micro- and nano-sensors and micro-monitoring devices (smart materials, MEMS). These developments should be watched along with possible work on sensors which will be able to monitor on-line quantities like stress/strain or damage.

4 PART 1 - HTGR NDE AND ISI TECHNOLOGY ASSESSMENT ROAD MAP

This section identifies needed technology developments to address damage mechanisms for which existing NDE and NDM methodologies are not optimal considering HTGR specific maintenance and operating environments. Needed technology is identified as Short Term and Long Term and provides a technical foundation for defining a research agenda.

It should be noted that this technology assessment and research agenda cannot be fully completed at this time. This is because the required capabilities, such as detection level and sizing accuracy for the candidate NDE and NDM methods that are discussed in the following subsections, still need to be developed and quantified as described in Section 5.0 in general, and in Section 5.4 in particular. Figure 3 in Section 6.0 provides a proposed technology road map and a tentative schedule for the integration of the development of the requirements in Section 5.0 with the short and long term development of the examination and monitoring methods described in this section.

4.1 Technology Road Map – Short Term Needs

Design and operating conditions for pressurized components in HTGRs have shown similar environmental conditions (radiation fields, expected surface temperature) experienced in the existing LWRs. This finding has allowed utilization of existing experiences from non destructive inspections (NDE) accumulated with LWR ISI programs. Specific recommendations for further development are summarized below in Sections 4.1.1 thru 4.1.5.

4.1.1 Helium Leak Monitoring

Current practice defined in ASME B&PV Section V for helium leak monitoring can be directly applied [5]. Development of the techniques is not expected to be required but development of requirements for application as continuous monitoring is needed. IGA-5000 provides draft rules for on-line leakage monitoring as an element of the RIM Program. A more detailed evaluation of existing experience from experimental and similar helium reactors and development of proper design dependent strategies are required.

4.1.2 Development of Non-Contact UT with Laser UT and EMAT

Development of non-contact UT techniques with laser UT and EMAT technology will be required to support several examination requirements in high temperature environments for volumetric inspection and monitoring (acoustic emission, loose part and leak monitoring, volumetric inspections and surface inspection) based on ultrasound.

4.1.2.1 Acoustic Emission

For continuous monitoring during the operation phase further development and qualification will be required for deployment of AE. Current code addresses local monitoring of existing crack propagation. Further development will be needed to establish code qualified techniques that will address:

- detection of crack initiation;
- crack growth progression/growth – already addressed by the code;
- crack location via multiple sensors.

Present equipment with temperature hardened transducers and stand-off mounting concepts from the LWR could be directly applied to the steel vessel HTGR. For other higher temperature components that could be encountered, options of using non-contact UT transducers, such as laser UT or EMAT transducers, will need further investigation. The Center for Non Destructive Study Evaluation at the

Johns Hopkins University has successfully evaluated use of non-contact laser sensors for detection of acoustic emission on high strength steel components.

4.1.2.2 Loose Part Monitoring

Current experience in LWRs with AE for loose part monitoring and leak detection should be investigated and proper guidelines need to be developed for application in HTGRs.

Additional investigation for non-contact transducers with laser UT or an EMAT transducer will be required for application with high temperature surfaces.

4.1.2.3 Volumetric Inspections

Current techniques based on ultrasonic principles such as UTA, UTS, AE and TOFD, which are used in LWRs, are also available for use in HTGRs during scheduled maintenance outages. If such techniques will require deployment at elevated temperatures, further development will be required on ultrasonic sensors. This will require use of non-contact approaches with laser UT and/or EMAT transducers that have been used on high temperature components in other industries. Recent introduction of Phased Array UT in the LWR have shown advantages of this approach with more accurate sizing and improved understandings on degradation spatial characteristics. It is recommended to investigate detection and sizing limits with Phased Array combined with contact and non-contact transducers.

4.1.2.4 Surface Inspections

Environmental conditions involving higher temperature non-contact techniques using UT surface waves (Rayleigh waves) with laser UT and/or EMAT need to be further investigated and properly qualified for use as ISI techniques (Performance Demonstration Qualification per ASME B&PVC Sec. XI Appendix VIII) [1].

4.1.3 Infrared Monitoring

The same concept is used in current practice in other industries, and development of proper guidelines for application in HTGRs should focus on surface temperature monitoring with infrared thermo imaging systems for thermal transients and stratification. Experience from monitoring fossil boiler, gas and steam turbines and electric power components (transformers and generators) should provide adequate references for application developments to HTGRs.

4.1.4 Thin Wall Inspection Techniques

Eddy current and giant magneto resistors are techniques for thin walled tubing that would need further development and qualification for high temperature applications. Applicability would be for steam generator use for the HTGR producing process steam.

4.1.5 Remote Delivery Robotics

Current experience at LWRs uses robotic manipulators for inspection technique delivery along critical locations (welds) on inspected components. These manipulators in LWRs are commonly used at an ambient temperature of approximately but not exceeding 50°C. For application in HTGRs where higher temperatures could be encountered, further temperature hardening will be required for mechanical components to withstand these elevated temperatures.

4.2 Technology Road Map – Long Term Needs

Additional non destructive monitoring concepts selected through a reliability and integrity management (RIM) program require more complex non destructive monitoring (NDM) techniques to observe possible initiation and progression of damage mechanisms during the operating period between scheduled maintenance intervals. This concept was investigated with positive results shown in the pilot study for RIM strategy applied on pressure vessel components in PBMR.

To accomplish the expectation of this advanced degradation mechanisms monitoring and inspection program, further development of non destructive monitoring and material characterization will be required. Specific recommendations for further development are summarized below in Sections 4.2.1 and 4.2.2.

4.2.1 Creep Monitoring

Present experience with high temperature creep monitoring is associated with this type of damage mechanism in fossil power plants and the petro-chemical industries. Recent investigation with on-line monitoring for creep in high temperature piping with non-contact strain measurements and local optical surface pattern monitoring have shown positive results when detecting early stages of creep damage. The early detection approach allows proper preventive maintenance measures to avoid unwanted compromises of component integrity. These monitoring methods should be further investigated and guidelines need to be developed for proper implementation on HTGR components.

4.2.2 Continuous Material Monitoring

Further development will be required in the field of micro monitoring techniques that have shown potential in estimating material property changes by observing local electro-magnetic or acoustic characteristics. This research should be coordinated with proper material property verifications through mechanical testing on samples removed from operating components due to the demanded repairs and/or micro sampling processes and localized micro mechanical testing. The outcome of this development should establish qualified techniques for non destructive material characterization to potentially determine the following properties:

- Extent of neutron embrittlement – other than coupons (destructive techniques);
- Changes in fracture toughness – automated ball indentation (stress strain microprobe);
- Changes in tensile properties;
- Changes in electromagnetic properties as a result of changes in material structure induced by a specific damage mechanism;
- Changes in acoustic properties as a result of changes in material structure induced by a specific damage mechanism.

For HTGRs, this gives a real time view of the material condition as it is not possible to place representative material test coupons at a location that provides a lead factor for the RPV. Also, the amount of embrittlement is low and difficult to measure with coupons. Another advantage of this approach is the measurement of the actual material properties rather than deduced properties via coupon testing. The technique is generally applicable to any RPV where external wall surface is accessible.

5 PART 2 - METHODS AND REQUIREMENTS FOR EXAMINATION OF METALLIC MATERIALS

As indicated in Section 1.4 of this report, this Section on Part 2 of Task 12 provides a proposed road map for determining the advanced methods and their requirements for pre-service and in-service non destructive examination (NDE) of metallic components in the pressure boundary of advanced high-temperature gas-cooled reactors. The advanced methods could include, but are not limited to, advanced ultrasonic techniques, such as time-of-flight diffraction or phased arrays, or new acoustic emission techniques. Sections 5.1 and 5.2 provide background information for the deterministic piping analysis methods in the current ASME Code and the reliability-based load and resistance factor design (LRFD), respectively. Section 5.3 then describes the proposed technical basis for determining the NDE requirements based upon LRFD principles. Finally, Section 5.4 provides a multi-step process on how the inspection information in Part 1 of Task 12 (Sections 2.0, 3.0 and 4.0 of this report) can be used with the LRFD methods of Section 5.3 to develop the requirements for the advanced NDE and/or NDM.

5.1 Deterministic Piping Analysis Methods of Current ASME Code

For background information, the current ASME Code piping analysis methods can be summarized as follows.

1. The deterministic analysis approach of current Code design rules for Class 1 piping systems uses internal pressure, moment loading and thermal loading stress indices and flexibility factors for piping products and joints in straight pipe [NB-3680]. These factors assume no flaws exceeding those acceptable per the fabrication, examination and testing sections (NB-4000, 5000 and 6000) of Subsection NB to Section III, Division 1 [12].

2. The deterministic analysis approach of current Code design rules for Class 2 and 3 piping systems uses primary stress indices, flexibility factors and stress intensification factors for piping products and joints other than straight pipe (NC/ND-3673.2). These factors assume no flaws exceeding those acceptable per the fabrication, examination and testing sections (NC/ND-4000, 5000 and 6000) of Subsections NC/ND to Section III, Division 1 [12].

3. NC-3613.4 and ND-3614.5 impose quality factors for castings per Tables 1A, 1B and 3 of Section II, Part D, Subpart 1. The casting factors vary depending on examination methods. Subsection NB does not permit castings for Class 1 and does not have these factors.

   An example of technique reduction factors is Note G17 from Table 1A, Section II, Part D, where Class 3 cast products have a casting quality factor dependent on inspection method:

   - 0.80 for visual examination
   - 0.85 for magnetic particle and liquid penetrant examinations
   - 1.00 for RT and UT
   - 1.00 for magnetic particle or liquid penetrant plus UT or RT.

4. ND-3613.4 imposes weld joint efficiency factors for different types of longitudinal joints permitted in Class 3 piping. The factor for a single butt weld goes from 0.80 to 1.0 and for a double butt weld from 0.90 to 1.0 if 100% RT or UT is performed, respectively. NB and NC do not impose these factors. For Class 1, NB-3683.4(a) references NB-3683.2 that invokes an increase by a 1.1 or 1.3 multiplier on the "K" indices for flush welds and as-welded welds, respectively.

5. In addition to differences in design rules among Class 1, 2 and 3 piping, there are differences in requirements for materials, fabrication, examination, testing and overpressure protection. These

differences provide an implicit assumption of differences in reliability for different classes of Code rules— a greater level of reliability for Class 1 versus Class 2 versus Class 3. However, this difference has not been quantified.

5.2 Reliability-Based Load and Resistance Factor Design (LRFD) Methods

As additional background information, the research and development report CRTD-86 [2] provides the technical basis for reliability-based LRFD methods for Class 2/3 piping for primary loading that includes pressure, deadweight, seismic and accidental loading. Chapter 1 of CRTD-86 [2] provides background information including the history and benefits of LRFD design methods as well as a discussion on the challenges of developing LRFD for piping. The outcomes of the project include design models and equations, and partial safety factors that can be used to compose LRFD guidelines and criteria. It provides a proof of concept of the LRFD for the design of piping. Such design methods should lead to consistent reliability levels. The LRFD guidelines and criteria can initially be used in parallel with currently used procedures. The report provides results based on the following tasks: (1) a state-of-the-art assessment and selection of reliability theories, (2) review and evaluation of existing strength models for piping, (3) selection of strength models and equations deemed suitable for LRFD development, (4) preliminary analysis of basic random variables to characterize their uncertainties and (5) development of LRFD guidelines and criteria.

As described in Section 1.3 of CRTD-86[2], LRFD consists of the requirement that a factored (reduced) strength of a structural component is larger than a linear combination of factored (magnified) load effects as given by

$$\phi R \geq \sum_{i=1}^{n} \gamma_i L_i \qquad (1)$$

In this approach, load effects are increased, and strength is reduced, by multiplying the corresponding characteristic (nominal) values with factors, which are called strength (resistance) and load factors, respectively, or Partial Safety Factors (PSFs). The characteristic value of some quantity is the value that is used in current design practice, and it is usually equal to a certain percentile of the probability distribution of that quantity. The load and strength factors are different for each type of load and strength. Generally, the higher the uncertainty associated with a load, the higher the corresponding load factor; and the higher the uncertainty associated with strength, the lower the corresponding strength factor. These factors are determined probabilistically so that they correspond to a prescribed level of safety. It is also common to consider two classes of performance function that correspond to strength and serviceability requirements. The difference between the allowable stress design (ASD) and the LRFD format is that the latter uses different safety factors for each type of load and strength. This allows taking into consideration uncertainties in load and strength, and scaling their characteristic values accordingly in the design equation. ASD (also called working stress) formats cannot do that because they use only one safety factor. Piping designers can use the load and resistance factors in limit-state equations to account for uncertainties that might not be considered properly by deterministic methods without explicitly performing probabilistic analysis.

Section 2.4 of CRTD-86 [2] further describes performance functions in the following way. Reliability-based analysis and design procedures start with defining performance functions that correspond to limit states for significant failure modes. In general, the problem can be considered as one of supply and demand. Failure occurs when the supply (i.e., strength of the system) is less than the demand (i.e., loading on the system). A generalized form for the performance function for a structural system is given by

$$g_1 = R - L \qquad (2)$$

where g_1 = performance function, R = strength (resistance) and L = loading in the structure. The failure in this case is defined in the region where g_1 is less than zero, or R is less than L, that is

$$g_1 < 0.0 \text{ or } R < L \tag{3}$$

As an alternative approach to Eq. (2), the performance function can also be given as

$$g_2 = \frac{R}{L} \tag{4}$$

where, in this case, the failure is defined in the region where g_2 is less than one, or R is less than L, that is

$$g_2 < 1.0 \text{ or } R < L \tag{5}$$

If both the strength and load are treated as random variables, then the reliability-based design and analysis can be tackled using probabilistic methods. In order to perform a reliability analysis, a mathematical model that relates the strength and load needs to be derived. This relationship is expressed in the form of a limit state or performance function as given by Eq. (2) or Eq. (4). Furthermore, the probabilistic characteristics of the basic random variables that define the strength and loads must be quantified. Because the strength R and load L are random variables, there is always a probability of failure that can be defined as

$$P_f = \text{Prob}\,(g_1 < 0.0) = \text{Prob}\,(R < L) \tag{6}$$

or

$$P_f = \text{Prob}\,(g_2 < 1.0) = \text{Prob}\,(R < L) \tag{7}$$

The probability of failure given by Eqs. (6) and (7) correspond to the performance functions g_1 and g_2 of Eqs. (2) and (4), respectively. Figure 2, which is Figure 2-3 in CRTD-86 [2] schematically shows these two random variables.

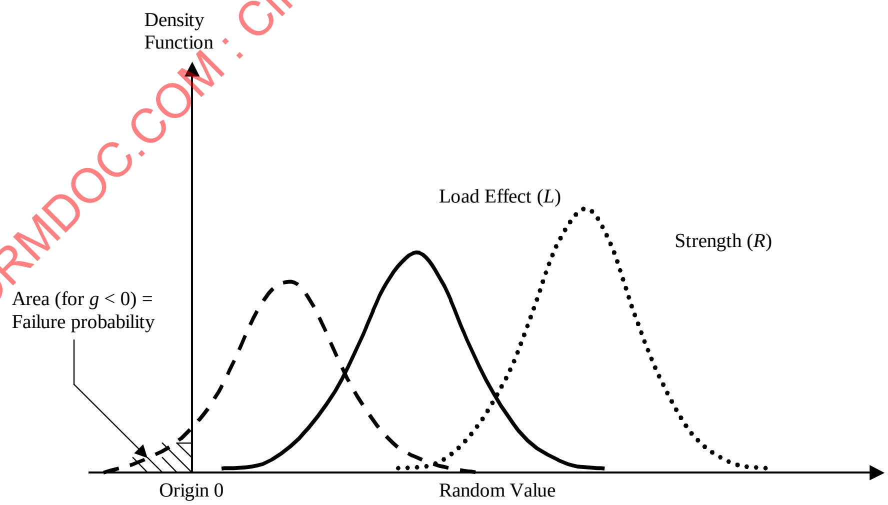

Figure 2 - Reliability Density Functions of Resistance R and Load L
(Figure 2-3, CRTD-86 [2])

5.3 Technical Basis for Advanced Inspection Requirements

The ASME Committee on Research Technology Development task force that developed the LRFD techniques for application to the ASME Section III design equations for piping was sponsored by the U.S. NRC and the International Institute of Universality, Tokyo, Japan [12]. The results of their work were published in Research and Development Report CRTD-86 [2] and summarized in Section 5.2. The following sample design equations for evaluating faulted loading conditions relative to Service Level D damage limits are taken from Table 6 in the conclusions of CRTD-86 [2], which is reproduced as Table 5 in this report. In these design equations for ASME Section III, the coefficients γ_1, γ_2 and γ_3 are partial safety factors on the loading and coefficients φ_1 and φ_2 are partial safety factors on the resistance, yield strength (S_y) and ultimate strength (S_u), respectively [12].

$$\gamma_2 \frac{PD_o}{2t} + \gamma_1 \frac{M_A}{Z_P} + \gamma_3 \frac{M_S}{Z_P} \le \min(\phi_1 S_y, \phi_2 S_u) \tag{8}$$

$$\gamma_1 \frac{M_A}{Z_P} + \gamma_2 \frac{M_S}{Z_P} \le \min(\phi_1 S_y, \phi_2 S_u) \tag{9}$$

The values of the partial safety factors are prescribed based upon the required level of reliability, which is quantified by the target reliability index β. The value of the index is a measure of the difference between the resisting strength and loading stress divided by the appropriate measure of the combined uncertainties on loading and resistance, which depends upon the types of statistical distributions involved, such as normal or log-normal.

For example, if the calculated rupture frequency for pressure boundary piping is required to be less than 10^{-6} per year and the faulted event of concern is the safe shutdown earthquake, which has a frequency of occurrence less than 10^{-3} per year, then the target reliability index β would be 3, for a rupture probability somewhat higher than 10^{-3}. From Table 6 of the CRTD report, for a target reliability index of 3, the values of φ_1 and φ_2 would be 0.92 for design equation (8) and 0.94 for the design equation (9). These partial safety factors on the resistance would be applicable to a piping structure component (e.g., a weld) that did not have any significant flaws or other aging degradation, such as irradiation or thermal aging induced embrittlement. The values of S_y and S_u can be thought of as critical stress values S_{C1} and S_{C2} for the unflawed and un-aged design conditions. With flaws and/or aging, the critical stress values would have to be appropriately reduced to maintain the same level of reliability. However, the partial safety factors on the loading, γ_1, γ_2 and γ_3, used in the LRFD techniques for the ASME Section III design equations, such as (8) and (9), should not be affected by potential flaws or other aging related degradation [12].

Consider the case of ductile rupture of flawed piping, which is used in the Westinghouse probabilistic methodology for piping risk informed in-service inspection [13]. Here the failure criteria for failure due to full rupture would be the primary stresses in the unflawed piping cross-section exceeding the material flow strength, which is often taken as the average of the yield strength S_y and ultimate strength S_u. If there was a fabrication flaw, which was missed during pre-service inspection, with a size of 5% of the weld cross-section that grew to 25% during plant operation due to fatigue and/or stress corrosion crack growth, then the critical stress after plant operation would only be 75% of the unflawed and un-aged values of S_{C1} and S_{C2}. Even without any aging effects, if the uncertainties in the initial flaw size and crack growth rate are also considered, then the values of the partial safety factors on the resistance, φ_1 and φ_2, would also have to be reduced to maintain the same level of reliability.

Finally, for embrittled and potentially flawed material, such as the reactor vessel belt-line (see Table 1), the critical stress values can be derived from the appropriate fracture toughness, such as the critical stress intensity factor for initiation of fast fracture, K_{IC}. However, the critical stress value would also be dependent upon the size of the flaws as the applied stress intensity factor, K_I, is a function of the component geometry, applied stress and the square root of the flaw size. Again, because the uncertainties in the initial flaw size and the change in fracture toughness with degree of embrittlement are quite large, the values of the partial safety factors on the resistance, φ_1 and φ_2, would also have to be reduced to maintain the same level of reliability.

Table 5 - Sample Target Reliability Levels and Partial Safety Factors for Demonstration Purposes

(Table 8-1, CRTD-86 [2])

Loading Condition	Design Equation	Target Reliability Index, β = 2				Target Reliability Index, β = 3			
		γ_1	γ_2	γ_3	ϕ_1 or ϕ_2	γ_1	γ_2	γ_3	ϕ_1 or ϕ_2
Design Condition (hoop stress)	$t_m = \frac{PD_o}{2(S+Py)} + A$ or $t_m = \frac{Pd+2SA+2yPA}{2(S+Py-P)}$	NA	NA	NA	NA	NA	NA	NA	NA
General Condition	$\gamma_1 \frac{M_A}{Z} \le \min(\phi_1 S_y, \phi_2 S_u)$	1.14	NA	NA	0.82	1.20	NA	NA	0.73
Operating Condition, Service Level A	$\gamma_2 \frac{PD_o}{2t} + \gamma_1 \frac{M_A}{Z} \le \min(\phi_1 S_y, \phi_2 S_u)$	1.05	1.22	NA	0.87	1.06	1.36	NA	0.81
Upset Loading Condition, Service Level B	$\gamma_2 \frac{PD_o}{2t} + \gamma_1 \frac{M_A}{Z} + \gamma_3 \frac{M_B}{Z} \le \min(\phi_1 S_y, \phi_2 S_u)$	1.01	1.04	2.23	0.94	1.01	1.03	3.55	0.92
Emergency Loading Condition, Service Level C	$\gamma_2 \frac{PD_o}{2t} + \gamma_1 \frac{M_A}{Z_P} + \gamma_3 \frac{M_B}{Z_P} \le \min(\phi_1 S_y, \phi_2 S_u)$	1.01	1.27	NA	0.94	1.01	1.38	NA	0.92
	$\gamma_1 \frac{M_A}{Z_P} + \gamma_2 \frac{M_B}{Z_P} \le \min(\phi_1 S_y, \phi_2 S_u)$	1.01	2.26	NA	0.95	1.01	3.59	NA	0.93
Faulted Loading Condition, Service Level D	$\gamma_2 \frac{PD_o}{2t} + \gamma_1 \frac{M_A}{Z_P} + \gamma_3 \frac{M_S}{Z_P} \le \min(\phi_1 S_y, \phi_2 S_u)$	1.18	1.18	2.21	0.94	1.20	1.20	3.53	0.92
	$\gamma_1 \frac{M_A}{Z_P} + \gamma_2 \frac{M_S}{Z_P} \le \min(\phi_1 S_y, \phi_2 S_u)$	1.01	2.26	NA	0.96	1.00	3.59	NA	0.90

5.4 LRFD Development of Advance Inspection Requirements

The combined integrated road-map for development of the technology for pre-service NDE and in-service NDE and NDM of metallic components in the pressure boundary of advanced high-temperature reactors is provided in Figure 3. The LRFD related tasks to develop and update the advanced inspection requirements include the following steps. Some of these steps may be performed in parallel and may be included in the Phase 1, Phase 2 or Phase 3 LRFD tasks. The LRFD task identification (ID) numbers in Figure 3 are indicated parenthetically after each step description.

1. Perform evaluations to establish linkage between the damage mechanisms and corresponding NDE and/or NDM, such as that shown in Table 2 in this report, with the application of LFRD methods. (ID #7, #26 and #35)

2. Estimate the uncertainties in the key damage mechanisms, similar to what was done in the structural reliability analyses [13] for piping risk informed in-service inspection per Method A in Supplement 1 of Non-mandatory Appendix R to Section XI of the ASME Code [1]. (ID #8)

3. Perform uncertainty analysis to determine the effectiveness of NDE and/or NDM methods to detect (as well as falsely detect) and accurately characterize flaws indicative of the damage mechanism being evaluated. (ID #9, #27 and #36)

4. Select the required reliability level, which is typically specified as a frequency (events per year) of different types of failure, which range from a small leak due to a through-wall flaw to a full pipe break due to ductile rupture or brittle fracture. For example, five plant level reliability goals for the PBMR were presented in Paper 58036 at the 2008 ASME Topical Meeting on High Temperature Reactor Technology [9]. (ID #10)

5. Select the key pressure boundary components that would challenge the plant level reliability requirements if potential fabrication flaws existed or flaws could be initiated by potential degradation mechanisms, such as fatigue, stress corrosion cracking or high temperature creep. Table 1 in this report provides an example degradation mechanism assessment for key PBMR plant components. (ID #11)

6. Establish an inspection philosophy. For example, the goal of the inspection could be that the detected flaw should be small enough that it would not grow to its critical size during the next inspection interval. An alternate inspection philosophy could include being prepared to repair any flaws that are detected during the inspection. Although this philosophy would be more expensive, it would allow for a larger detectable flaw size. (ID #12)

7. Evaluate and adjust the applicable LRFD partial safety factors to reflect the respective uncertainty levels in the NDE and damage mechanisms. As described in Section 5.3, the minimum difference between the loading (stress) and resistance (strength) gives an indication of the flaw tolerance. Depending upon the inspection philosophy selected in the third step, the allowable flaw size can be estimated taking into account the allowable flaw growth, if any, to the next inspection. The estimated uncertainties in initial flaw size detection and sizing and any crack growth until the next inspection, including the effects of temperature and residual stresses that may not be included in ASME Section III design analyses, should also be considered in the recalculation of the partial safety factors on the resistance, φ_1 and φ_2, as indicated in Section 5.3 [12]. (ID #13, #28 and #37)

8. Perform the ASME Section III design analyses on the selected key components using the appropriate reliability goals from Step 4, above, and limiting loading conditions with the LRFD methods (e.g.,Table 5) as described in CRTD-86 [2] and as modified in the previous step [12]. (ID #14, #29 and #38)

9. If the resulting initial flaw size is not feasible with existing methods, then the requirements for enhanced NDE and/or NDM methods (e.g., time-of-flight diffraction or phased arrays ultrasonic inspections, or new acoustic emission techniques) will be identified in Phase 1 and reevaluated and updated as needed in Phase 2. However, it may be more cost effective to modify the inspection philosophy to reduce the time between inspections, possibly to none as indicated in Step 6, above. If this is still not feasible, then redesign of the piping (layout and/or supports) may need to be considered to increase the margin between the loading (stress) and resistance (strength) and the associated flaw tolerance. These last two options would be considered only in the activities for Phases 2 and 3. (ID #15, #30 and #39)

Even if it is not possible to directly calculate the NDE/NDM requirements using LRFD methods, it is still possible to take advantage of the benefits of inspection and monitoring (for example, if in-service inspection (ISI) is performed at locations most susceptible to high temperature creep (highest temperature and stress location, including residual stress) and no flaw or other effects of aging are detected). This information increases the confidence that the reliability predicted using LRFD, which assumes no fabrication flaws or creep initiated flaws, would still be valid. The key consideration in this evaluation would be: “What is the chance of not detecting a flaw big enough to be of concern?” This detection capability also depends upon the NDE/NDM methods, including the advanced ones being developed in the road map of Figure 3, that are being used for inspection and/or monitoring and the associated uncertainty in their accuracy.

6 INTEGRATED TECHNOLOGY ROAD MAP

This section combines results of Sections 4.0 and 5.0 into an integrated technology road map for HTGRs. The road map identifies NDE, NDM and LRFD research and development activities that can resolve technology gaps, support regulatory needs and provide a foundation for defining a future research agenda. Output from these activities is expected to be reported in a manner that would make implementation and adoption feasible and expedient into applicable codes and standards. However, no activities are included in the road map for approval by the codes and standards committees or regulators having jurisdiction.

The integrated technology road map is shown in Figure 3 (HTGR NDE/NDM/ISI/LRFD Technology Road Map). The timeline used in the integrated technology road map assumes a January 2010 start date.

The road map consists of 6 major activities, each with a number of sub-activities. These are summarized in the following subsections.

6.1 Complete CRTD-86 LRFD Design Methodology

Research work reported in CRTD-86 [2] is not sufficiently complete to perform piping analysis. Only the first phase of the CRTD-86 research project is complete. As stated in Section 5.2 of this report, CRTD-86 provides the technical basis for reliability-based load and resistance factor design methods for Class 2/3 piping for primary loading that includes pressure, deadweight, seismic and accidental loading. In addition, members of the CRTD-86 research team extended the work beyond the first phase report by computing partial safety factors for primary loads, and developing preliminary design methods for fatigue with results expected to appear in journal publications. Additional research and development work is needed.

Table 6 provides a summary listing of the tasks needed to complete research activities to support the ASME LRFD code for Class 2/3 piping. These tasks are included in the Figure 3 integrated technology road map. These tasks do not have to be performed serially. With appropriate funding, some activities can run in parallel with one another thereby reducing the overall time needed to complete the development. The table describes the tasks that will be performed in order to produce new reliability-based design technologies.

Table 6 - Research Activities to Complete ASME LRFD Code for Class 2/2

TASK	DESCRIPTION	DURATION
1	**Code Committee Peer Review** Obtain committee review and feedback on basic random variables and update CRTD-86 and other published results as appropriate.	6 months
2	**Draft Alternative Piping Design Rules** Prepare alternate LRFD design rules in NC-3600 format using CRTD-86, referenced papers and results of Code Committee Peer Review.	4 months
3	**Code Calibration Benchmark Analysis** Provide example problem/analysis using Draft Alternative Piping Design Rules and benchmark against analysis using current Code deterministic design rules, per current NC-3600.	4 months
4	**Develop Draft Code Case** Prepare draft of code case and supporting technical basis document. Provide support, as needed, to Code committees.	4 months

6.2 Phase 1 LRFD Development Activities

These activities are described in Section 5.4. The durations are estimates based on experience with the work reported in CTRD-86.

6.3 Short Term NDE and NDM Development Activities

These activities are described in Section 4.1. Durations are estimated minimum times to develop a deployable system. It is expected that some qualification time period will be required after the system is deployed. Duration of the qualification period will be determined as part of the development activity.

6.4 Phase 2 LRFD Activities

These activities are described in Section 5.4. They are updates to Phase 1 LRFD activities to incorporate results of the Short Term NDE/NDM Development Activities. The durations are estimates based on experience with the work reported in CTRD-86.

6.5 Long Term NDE and NDM Development Activities

These activities are described in Section 4.2. Durations are estimated minimum times to develop a deployable system. It is expected that some qualification time period will be required after the system is deployed. Duration of the qualification period will be determined as part of the development activity.

6.6 Phase 3 LRFD Activities

These activities are described in Section 5.4. The activities are updates to Phase 1 and Phase 2 LRFD activities to incorporate results of the Long Term NDE/NDM Development Activities. The durations are estimates based on experience with the work reported in CTRD-86.

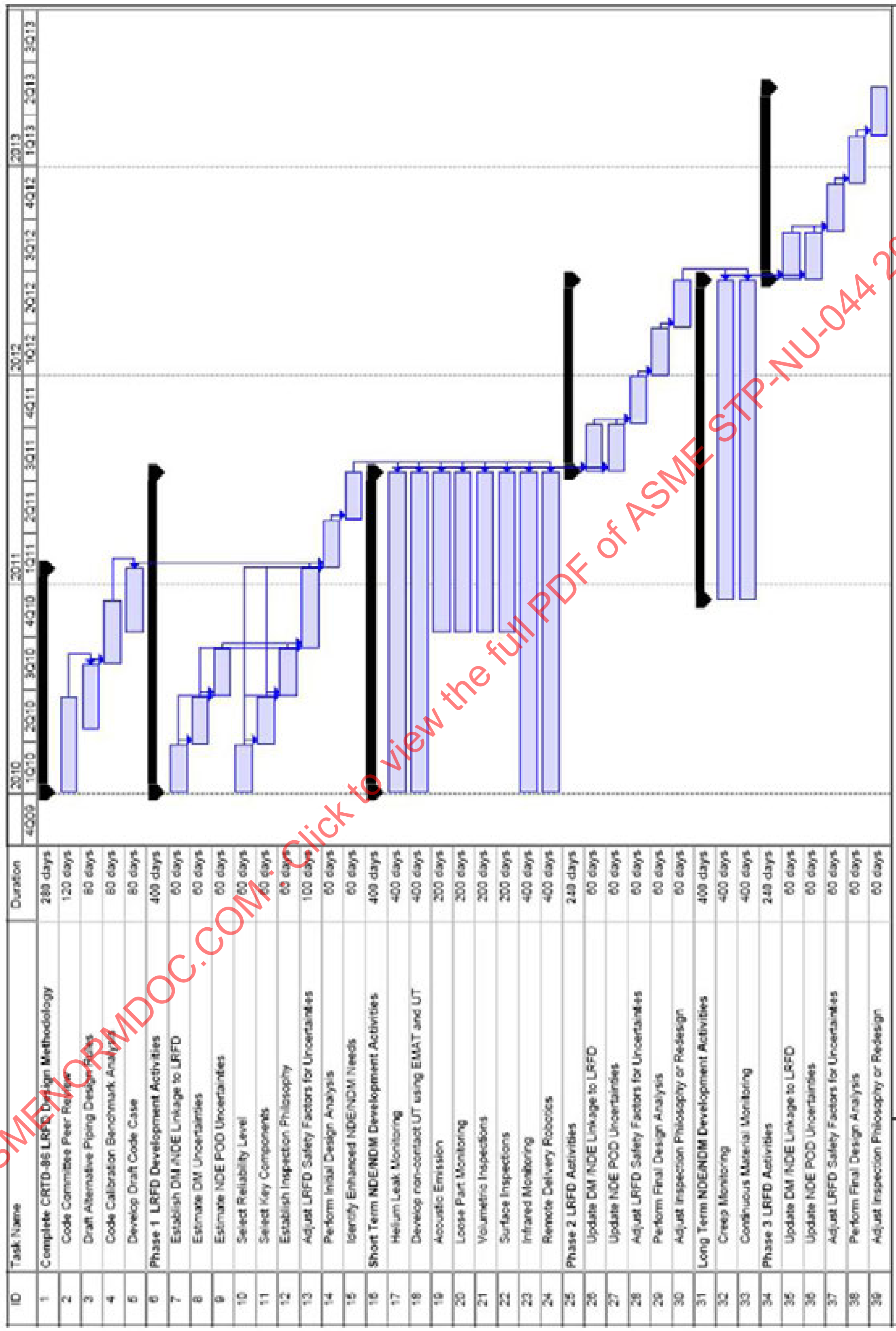

Figure 3 - HTGR NDE/NDM/ISI/LRFD Technology Road Map

APPENDIX A: TABLE IGA-2300-1 DEGRADATION MECHANISM ATTRIBUTES AND ATTRIBUTE CRITERIA

Degradation Mechanism		Attribute Criteria	Degradation Features & Susceptible Regions	Examination Method
TF	TASCS	- single pipe and operating temperature >104°C (220°F) and - piping > 25.4 mm (1 inch) NPS, and - pipe segment has a slope < 45° from horizontal (includes elbow or tee into a vertical pipe) and - potential exists for low flow in a pipe section connected to a component allowing mixing of hot and cold fluids or - potential exists for leakage flow past a valve (i.e., in-leakage, out-leakage, cross-leakage) allowing mixing of hot and cold fluids or - potential exists for convection heating in dead-ended pipe sections connected to a source of hot fluid or - potential exists for two phase (steam/water) flow or - potential exists for turbulent penetration in branch pipe connected to header piping containing hot fluid with high turbulent flow and - calculated or measured ΔT > 28°C (50°F) and - Richardson Number > 4.0 *OR* - helium counter flow in dual pipe and - relatively high velocity flow in the hotter pipe and relatively low velocity flow in the colder pipe and - the difference between the fluid temperature in the hotter and colder pipes >900°C (1620°F)	- cracks can initiate in welds, heat affected zones (HAZ) and base metal at the pipe inner surface - affected locations can include nozzles, branch pipe connections, safe ends and regions of stress concentration - TASCS can occur over extensive portions of the pipe inner surface - crack growth is relatively slow and through-wall cracking is not expected within an inspection period	Volumetric
	TT	- operating temperature > 132°C (270°F) for stainless steel or - operating temperature > 104°C (220°F) for carbon steel, *AND* - potential for relatively rapid temperature changes including: cold fluid injection into hot pipe segment, or hot fluid injection into cold pipe segment, *AND* - $\lvert \Delta T \rvert$ > 111°C (200°F) for stainless steel or - $\lvert \Delta T \rvert$ > 83°C (150°F) for carbon steel or - $\lvert \Delta T \rvert > \Delta T$ allowable or - allowable cycles < 10^6		

APPENDIX A: TABLE IGA-2300-1 DEGRADATION MECHANISM ATTRIBUTES AND ATTRIBUTE CRITERIA (continued)

Degradation Mechanism		Attribute Criteria	Degradation Features & Susceptible Regions	Examination Method
VF	FIV	- presence of attachments in a high velocity flow field, including: welded attachments or attachments with small radii at the attachment junction *OR* - high velocity cross flow over S/G or H/X tube bundles and - absence of vibration damping tube supports	- cracks can initiate in welds, HAZ and base metal at the component inner or outer surface - affected locations can include welded attachments and regions of stress concentration - crack growth can be relatively fast and through-wall cracks can occur within an inspection period	- volumetric for part-through-wall cracks at the inner surface - surface for part-through-wall cracks at the outer surface - leakage monitoring, leak testing or visual for through-wall cracks
	MF	- cyclic applied loads and - presence of partial penetration welds or - presence of small radii at the attachment junction *OR* - presence of attached vibration sources (e.g., pumps, compressors) and - no pre-operational vibration testing or monitoring or - no vibratory monitoring of vibration sources during operation		
	SF	- relative sliding motion between two contacting surfaces and - absence of a solid lubricating system at the contacting surfaces	- cracking, pitting, spalling wear or seizing can occur at the contact surfaces - cracking is expected to be localized and not grow through-wall	Volumetric or Visual

APPENDIX A: TABLE IGA-2300-1 DEGRADATION MECHANISM ATTRIBUTES AND ATTRIBUTE CRITERIA (continued)

Degradation Mechanism		Attribute Criteria	Degradation Features & Susceptible Regions	Examination Method
SCC	IGSCC	- BWR evaluated in accordance with existing plant IGSCC program per NRC Generic Letter 88-01 *OR* - material is austenitic stainless steel weld or HAZ and - operating temperature ≥ 93°C (200°F) and - susceptible material (carbon content ≥ 0.035%) and - oxygen or oxidizing species are present *OR* - material is Alloy 82 or 182 and - operating temperature ≥ 93°C (200°F) and - oxygen or oxidizing species are present *OR* - material is austenitic stainless steel weld or HAZ and - operating temperature < 93°C (200°F) and - susceptible material (carbon content ≥ 0.035%) and - oxygen or oxidizing species are present and - initiating contaminants (e.g., thiosulfate, fluoride, chloride) are present *OR* - material is in an aqueous environment and - oxygen or oxidizing species are present and - mechanically induced high residual stresses are present	- cracks can initiate in welds and HAZ at the pipe inner surface - affected locations can include pipe welds, branch pipe connections and safe end attachment welds, - crack growth is relatively slow and through-wall cracking is not expected within an inspection period	Volumetric
	TGSCC	- material is austenitic stainless steel and - operating temperature > 65°C (150°F) and - halides (e.g., fluoride, chloride) are present or - caustic (NaOH) is present and - oxygen or oxidizing species are present (only required to be present in conjunction w/halides, not required w/caustic)	- cracks can initiate in welds, HAZ and base metal at the pipe inner surface - crack growth is relatively slow and through-wall cracking is not expected within an inspection period	Volumetric

APPENDIX A: TABLE IGA-2300-1 DEGRADATION MECHANISM ATTRIBUTES AND ATTRIBUTE CRITERIA (continued)

Degradation Mechanism		Attribute Criteria	Degradation Features & Susceptible Regions	Examination Method
SCC	ECSCC	- material is austenitic stainless steel and - operating temperature > 20°C (68°F) and - an outside piping surface is within five diameters of a probable leak path (e.g., valve stems) and is covered with non-metallic insulation that is not in compliance with USNRC Reg. Guide 1.36 or - piping surface is exposed to wetting from chloride bearing environments (e.g., seawater, sea spray, brackish water, brine) during fabrication, storage or operation	- cracks can initiate in welds, HAZ and base metal at the pipe outer surface - ECSCC can occur over extensive portions of the pipe inner or outer surface when exposed to whetting from chloride bearing environments during fabrication, storage or operation - crack growth is relatively slow and through-wall cracking is not expected within an inspection period	Surface
	PWSCC	- piping material is nickel-based alloy (e.g. alloy 600) and - exposed to primary water at T > 298°C (570°F) and - the material is mill-annealed and cold worked or cold worked and welded without stress relief	- cracks can initiate in welds, HAZ and base metal at the pipe inner surface - affected locations can include welds and HAZ without stress relief, the inside surface of nozzles and areas of stress concentration - crack growth can be relatively fast and through-wall cracks can occur within an inspection period	- volumetric - leakage monitoring, leak testing or visual for through-wall cracks