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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Prepared by:

Bruce Bishop, Ralph Hill, Zoran Kuljis, Edward L. Pleins and Sten Caspersson
Westinghouse Electric Company, LLC

Neil Broom, John Fletcher and Kobus Smit
PBMR

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TECHNOLOGY, LLC

Date of Issuance: December 15, 2011

This report was prepared as an account of work sponsored by the United States Nuclear Regulatory Commission (NRC) and the ASME Standards Technology, LLC (ASME ST-LLC).

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ASME Standards Technology, LLC
Three Park Avenue, New York, NY 10016-5990

ISBN No. 978-0-7918-3412-1

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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.

The ASME Standards Technology, LLC (ASME ST-LLC) is a not-for-profit Limited Liability Company, with ASME as the sole member, formed in 2004 to carry out work related to newly commercialized technology. The ASME ST-LLC mission includes meeting the needs of industry and government by providing new standards-related products and services, which advance the application of emerging and newly commercialized science and technology and providing the research and technology development needed to establish and maintain the technical relevance of codes and standards. Visit www.stllc.asme.org for more information.

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 to 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 component. 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).