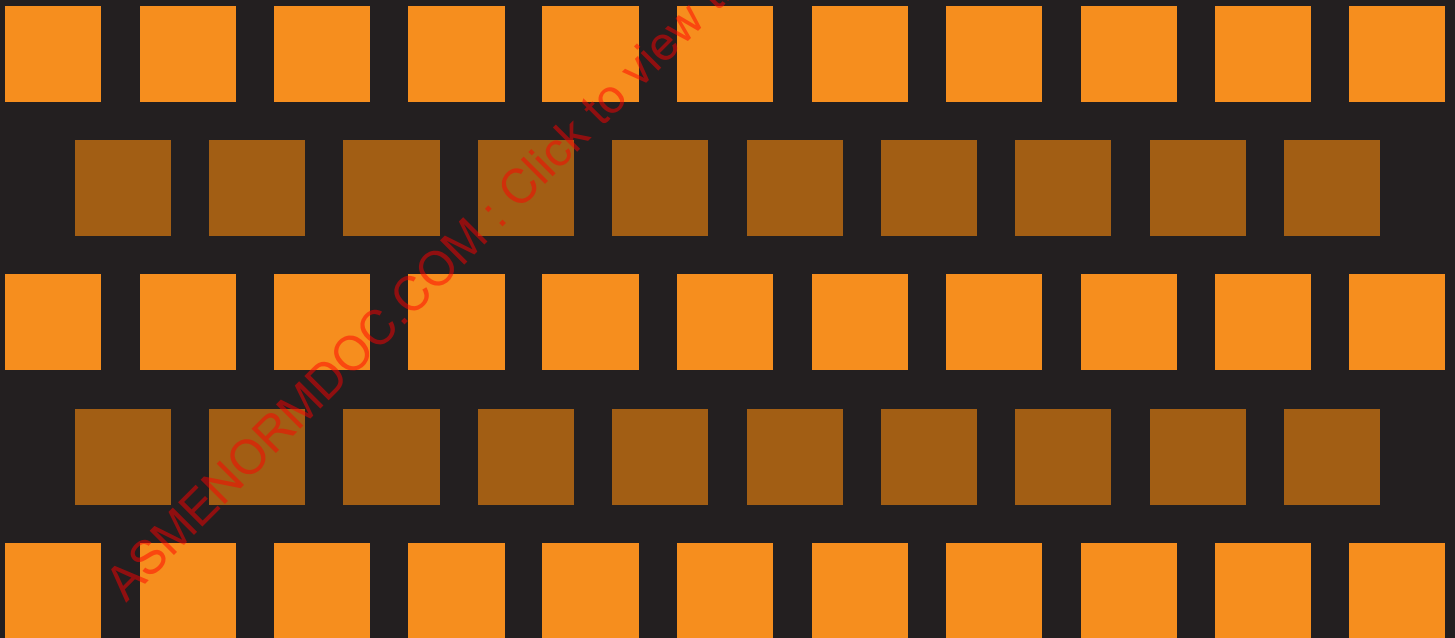


# ROADMAP TO DEVELOP ASME CODE RULES FOR THE CONSTRUCTION OF HIGH TEMPERATURE GAS COOLED REACTORS (HTGRS)



STP-NU-045-1

# ROADMAP TO DEVELOP ASME CODE RULES FOR THE CONSTRUCTION OF HIGH TEMPERATURE GAS- COOLED REACTORS (HTGRS)

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## FOREWORD

The Roadmap has been developed as a guide to the R&D and Code development tasks that could be considered in developing rules for High Temperature Gas-Cooled Reactors (HTGR). The primary focus of the Roadmap is on the development of a complete set of rules for the design and operating conditions that are being proposed for the Next Generation Nuclear Plant (NGNP). The near-term, Part I activities focus on development of ASME III, Division 5 Code rules based on the existing ASME II, Division 1, Subsection NH rules and existing Code Cases. The Phase I activities also include incorporation of the new graphite rules in Division 5. Intermediate term activities are also covered in the Roadmap in Phase II. The intermediate term activities focus on higher temperature service and advanced design methods applicable to future HTGR designs. Very long term activities, such as the development of risk-based or system-based code rules for the HTGR are not covered in this Roadmap.

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## 1 VISION STATEMENT

- 1.1 There is a need for a roadmap for the development of ASME Code rules for next generation High Temperature Gas-Cooled Reactors (HTGRs). The Roadmap will be required to set priorities and schedules for Code development work consistent with Stakeholder needs and schedules for publishing future ASME Code Editions.
- 1.2 Current ASME Code rules do not completely cover the design and construction of HTGRs. There is a near term, Phase I need to support the design of the Next Generation Nuclear Plant (NGNP) being funded by the U.S. Department of Energy and industry in an alliance. This need can be supported, for the most part, by using elevated temperature rules already incorporated in Section II and Section III, Subsection NH (BPV III- NH), several elevated temperature Code Cases and the new Graphite Rules. This material has recently been incorporated into a new Section III, Division 5, which completes Phase I. More work remains to be done in Phase II to complete the NGNP support effort, especially in the area of extending times and temperatures of stress allowables and in the area of simplified analysis methods.
- 1.3 It is envisioned that Division 5 will be revised on a continuing basis to support future reactor designs beyond current Stakeholders' needs. Research and development and Code revisions will be required over the next 5 to 10 years to make BPV III-5 into a document that is sufficient for the design and construction of advanced HTGR designs. Example areas that require attention for the Phase II effort include:
  - Extended times and temperatures for materials properties.
  - Standardized elastic-plastic design methods and material models.
  - Simplified rules for inelastic analyses for load and displacement controlled stresses.
  - Incorporation of Alloy 617 for high temperature service.
  - Development of design rules for compact heat exchangers.
- 1.4 It will be necessary to reach a broad consensus at each step of the Code rule development process and on each of the R&D projects. It is acknowledged that these consensus decisions could deviate from the recommendations in the roadmap in many cases. As this process evolves, provisions should be made for periodic updates to the roadmap to consider the effect of each decision on all aspects of the Code rule development activities.

## 2 BACKGROUND

- 2.1 The Roadmap has been developed as a guide to the R&D and Code development tasks that could be considered in developing rules for HTGRs. The primary focus of the Roadmap is on the development of a complete set of rules for the design and operating conditions that are being proposed for the NGNP. A Phase I effort has been recently completed that supported the creation of a new BPV III, Division 5 (III-5) for high temperature reactors that includes both HTGRs and Liquid Metal Reactors (LMRs). The Phase I effort included incorporation of Section III, Subsection NH rules in Division 5 (by reference) and by the direct incorporation of several Code Cases relevant to high temperature reactors, as well as the new graphite rules. The Phase I effort is included in the Roadmap for completeness. A Phase II effort has been initiated that covers intermediate term Code development, along with research and development work necessary for rule development. The Phase II work will support rules for future generations of HTGRs that are expected to operate at higher temperatures, and for other advanced reactors, such as LMR designs. Potential long term Code rule development for things like a risk-based or system-based Code rules are not included in this Roadmap.
- 2.1.1 As the ASME Code project teams, task groups, and committees deliberate, it is anticipated that some of these tasks will be revised or eliminated from consideration and others will be added. The tasks proposed here consist of a compilation of suggestions from individuals interviewed and from the author.
- 2.2 The Roadmap focuses primarily on those tasks that are needed to develop code rules. Tasks that may be needed to demonstrate performance or for specific designs are outside of the scope.
- 2.3 The Roadmap does not address resource issues. However, it is anticipated that projects developed by ASME Standards Technology LLC may be needed to sponsor individuals and groups to draft Code rules.
- 2.4 The Roadmap was developed using the assumption that the objective was to produce a complete set of Code rules for the HTGR that could be endorsed by regulators (e.g., the U.S. NRC) and referenced in regulatory guides and rules.

### 3 STAKEHOLDERS

The following stakeholders were considered in the development of this Roadmap. Although the interests of these stakeholders were considered by the author to the extent practicable, only a selected subset of these stakeholders was consulted during the course of preparation of the Roadmap:

- 3.1 Regulatory Community
  - 3.1.1 U.S. Nuclear Regulatory Commission (U.S. NRC)
  - 3.1.2 Other worldwide regulatory bodies
- 3.2 Standards Developing Organizations (SDOs)
- 3.3 Designers and Constructors of HTGR facilities. For example:
  - 3.3.1 Areva, Inc.
  - 3.3.2 General Atomics
  - 3.3.3 Pebble Bed Modular Reactor (Pty) Limited (PBMR)
  - 3.3.4 Westinghouse Electric Co., LLC.
- 3.4 DOE and DOE National Laboratories. For example:
  - 3.4.1 Argonne National Laboratory (ANL)
  - 3.4.2 Idaho National Laboratory (INL)
  - 3.4.3 Oak Ridge National Laboratory (ORNL)
- 3.5 Consultants
- 3.6 Materials suppliers
- 3.7 Equipment suppliers
- 3.8 Service providers. For example: NDE



## 4 INTRODUCTION AND ORGANIZATION

4.1 This document proposes processes and timelines for the development of ASME Code rules for the construction of components for HTGRs in three phases:

4.1.1 Phase I - Activities related to incorporating the existing elevated temperature rules and material data in Section II, Section III, Subsection NH (III-NH), the elevated temperature code cases (e.g., Code Cases N-499 and N-201) and the new graphite core support structure rules into a new III-5. These actions are complete.

4.1.2 Phase II - Intermediate term activities for developing rules to be incorporated into the new III-5 and Section XI, Division 2 (XI-2) to meet the needs identified by stakeholders worldwide for HTGR facilities that will be designed within the next decade. Work has already started in Phase II for extending the applicable temperature, time duration and environments for selected materials in III-5 to meet the needs of advanced NGNP designs.

4.1.3 Long Term - Activities related to developing rules to be incorporated into the new III-5 and XI-2 to meet the needs identified by stakeholders worldwide for facilities that will be designed more than a decade from now. It is expected that this will include the extension of operating temperatures to even higher levels which will require new materials, design and fabrication methods. Long term work may also include the development of a world class Code which includes risk-based and system-based elements. The Long Term phase of work is not included in the Roadmap.

4.2 The Roadmap is organized as follows:

4.2.1 Section 5 describes completed Phase I activities.

4.2.2 Section 6 describes the assumptions used in developing the Roadmap for Phase II.

4.2.3 Section 7 describes the reactor designs covered and the information about those designs that is needed to develop Phase II Code rules in a timely manner.

4.2.4 Section 8 describes recommended research and development (R&D) tasks to address issues that were identified during development of this Roadmap.

4.2.5 Section 9 describes “global” administrative and technical tasks that are recommended to establish the overall framework for the Code development activities and to provide direction to the cognizant Subcommittees, Subgroups, Working Groups, Project Teams and Task Groups.

4.2.6 Section 10 describes specific tasks recommended for completion of the Code rules. Section 10 also describes some recommended technical approaches to expedite the development of Code rules that utilize the best available technology.

4.2.7 Section 11 describes a recommended overall industry approach and organization to provide a framework for coordination with other SDOs.

4.2.8 Appendix 1 provides a list of acronyms used in the Roadmap.

4.3 The following abbreviations for Codes and Standards are used in this document.

4.3.1 BPV III-1 – ASME Boiler and Pressure Vessel Code, Section III, Division 1. Title: Rules for Construction of Nuclear Facility Components.

4.3.2 BPV XI – ASME Boiler and Pressure Vessel Code, Section XI. Title: Inservice Inspection of Nuclear Power Plant Components.

- 4.3.3 BPV III-5 - ASME Boiler and Pressure Vessel Code, Section III, Division 5. Title: Rules for the Construction of High Temperature Nuclear Reactors.
- 4.3.4 BPV XI-2 - ASME Boiler and Pressure Vessel Code, Section XI, Division 2 (in preparation). Tentative areas of coverage will include inspection, evaluation, and repair/replacement activities for HTGRs. The draft General Requirements (IGA) are based on risk-informed inservice inspection (RIM methodology based on Markov models).
- 4.3.5 BPV III-NH - ASME Boiler and Pressure Vessel Code, Section III, Subsection NH, Title: Class 1 Components in Elevated Temperature Service.
- 4.3.6 BPV VIII-2 - ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, Title: Rules for Construction of Pressure Vessels Division 2-Alternative Rules
- 4.3.7 BPV VIII-3 - ASME Boiler and Pressure Vessel Code, Section VIII, Division 3, Title: Rules for Construction of Pressure Vessels Division 3-Alternative Rules High Pressure Vessels.
- 4.3.8 QME - ASME Qualification of Active Mechanical Equipment used in Nuclear Power Plants.
- 4.3.9 OM – Committee on Operations and Maintenance of Nuclear Power Plants.
- 4.3.10 PRA – Probabilistic Risk Assessment.

## **5 PHASE I ACTIVITIES**

- 5.1 Incorporate III-NH (by reference), associated elevated temperature Code cases, and recently completed Graphite rules into a new Section III, Division 5 (BPV III-5) document. This is complete.

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## 6 ASSUMPTIONS USED IN DEVELOPING THE ROADMAP FOR PHASE II

- 6.1 Phase II Code activities will take place over the next three to five years and will provide input for revisions of BPV III - 5 rules for the 2013, through 2017 editions of the Code.
- 6.2 Currently available technology and materials data, or data that can be obtained with relatively short-term R&D programs (e.g., 2 years or less), will be used to develop the Phase II Code rules for elevated temperature metallic components. This is based on the assumption that materials of construction that are selected (see paragraph 7.1.2.3) are those with adequate available data. Short-term development work is needed in some areas. Assumptions about operating conditions used in developing this roadmap are:
- 6.2.1 The Phase II High Temperature Gas Cooled Reactors (HTGR), will have a normal operating reactor outlet temperature limited to 750°C - 850°C (1380°F - 1562°F). It is recognized that short-term temperature transients may be higher. The range of values to be considered should be confirmed with all stakeholders (see paragraph 7.1.2). A consensus should be reached with the stakeholders that these temperature and coincident pressure conditions will apply for developing the first set of Code rules that will cover reactors worldwide that are designed within the next decade.
- 6.2.2 Construction techniques that provide thermal barriers to avoid direct contact between hot process fluid and the primary pressure boundary will be used for the reactor pressure vessel and the hot gas piping to limit primary pressure boundary temperature to no higher than 370°C (700°F), with short-term excursions limited to 538°C (1000°F). These values should be confirmed with all stakeholders (see paragraph 7.1.2).
- 6.2.3 Metallic reactor core support structures will be exposed to temperatures of 500°C (930°F) to 520°C (970°F) in normal operation, with short-term excursions to 670°C (1240°F). These values should be confirmed with all stakeholders (see paragraph 7.1.2). Recent input from stakeholders indicates that Alloy 800H core support components may be exposed long-term to 800 to 850°C (1472 to 1562°F) for some types of reactor service.
- 6.2.4 Other components, such as compact heat exchangers, will see normal operating temperatures in local areas up to 850°C (1560°F), with short-term excursions to 900°C (1650°F). These values should be confirmed with all stakeholders (see paragraph 7.1.2).
- 6.2.5 It is anticipated that future Very High Temperature gas-cooled Reactors (VHTR) will have core outlet temperatures that are 100°C - 200°C (210°F - 390°F) higher than the NGNP (Phase II design basis). Code rules for these and for other reactor types (e.g. sodium cooled) will be developed in the Long Term Phase of effort. Long Term activities are not included in this Roadmap.
- 6.3 Rules for new construction of HTGRs will be contained in BPV III-5. BPV III-5 will reference existing material in other divisions and subsections as appropriate. However, BPV III-5 will be a self-contained Division, so it may be appropriate in some cases to incorporate material from other Divisions or Subsections rather than reference them. This is particularly true if changes are needed to the material that is incorporated to meet the needs of HTGRs. This is a case-by-case decision that should be made by the Committees that develop the rules.
- 6.4 Rules for inservice inspection and repair of HTGRs will be contained in BPV XI-2. BPV XI-2 references existing material in other Divisions and Subsections as appropriate. However, BPV

XI-2 is a self-contained Division, so it may be appropriate in some cases to incorporate material from other Divisions or Subsections rather than make a reference. This is particularly true if changes are needed to the material that is incorporated to meet the needs of HTGRs.

- 6.5 Rules and Guidelines for Operation and Maintenance of Nuclear Power Plants including preservice and inservice testing will be contained within the existing OM Code and OM-S/G.
- 6.6 Rules for Probabilistic Risk Assessment will be contained in the new Standard for Probabilistic Risk Assessment for Advanced Non-LWR Nuclear Power Plant Applications.
- 6.7 If rules are needed for the qualification of active mechanical equipment, they should be contained within the existing QME Code, Qualification of Active Mechanical Equipment used in Nuclear Power Plants.
- 6.8 This timeline was developed with the objective of producing Phase I, Part B Code rules for publication in July 2013 and July 2015. These dates should be confirmed by the stakeholders. However, preliminary assessments of the time required to develop methodology and materials data in some of the areas could push publication out to about the end of 2017 or later.
- 6.9 Close coordination will be needed among the committees developing BPV III-5, BPV XI-2, and the OM Code revisions to ensure that the new construction rules complement the inservice rules, particularly considering interaction among the new construction rules, inservice examination, and testing requirements. A Subgroup could be formed for this purpose. Examples of areas where coordination is needed are:
  - 6.9.1 Uncertainties in the design life that may result from a lack of detailed knowledge of long-term materials behavior at elevated temperatures in an HTGR environment can be addressed by imposing very conservative design margins based on available data and/or by imposing rigorous inservice NDE and/or surveillance coupon testing. The adequacy of this approach depends on ensuring that the NDE and/or surveillance coupon testing will be able to detect the expected degradation. Using this approach implies that damage may be detected prior to the desired 60-year design life that would require repair or replacement.
  - 6.9.2 Establishing requirements for inservice examination, monitoring and testing of graphite, ceramic and composite core support structures are important considerations. Some of these activities could be handled either in BPV XI-2 or in the OM Codes. This should be coordinated with BPV XI-2 developers. The Special Working Group for HTGRs has already drafted BPV XI-2 which is based on the Reliability and Integrity Management concept. It addresses only passive metallic systems, structures and components, and will have to be expanded to cover non-metallic core support structures.
  - 6.9.3 It is prudent to obtain “baseline” NDE results for primary pressure boundary structures and components during the construction phase. Therefore, the NDE methods used during new construction should be consistent with those used in service to allow comparison of data. This should be coordinated between BPV III-5 and BPV XI-2.

## 7 REACTOR DESIGNS AND INFORMATION REQUIRED

- 7.1 The Roadmap covers primarily the prismatic and pebble bed HTGR designs. One task that should be completed as soon as possible is to identify the design conditions (pressure - temperature histograms, operating environment, etc.) for these designs because the Code development process, particularly in the elevated temperature design and analysis area, depends on a detailed understanding of those conditions. This task is described below:

7.1.1 **Define types of components that will be needed.** For example:

- 7.1.1.1 Types of construction for elevated temperature heat exchangers.
- 7.1.1.2 Will elevated temperature bellows-type expansion joints be required?
- 7.1.1.3 Will a compact heat exchanger design be required?

7.1.2 **Define the temperature ranges of interest for the HTGR.** For each component or component part that will be operating in the “creep regime,” define the loads and operating temperatures, including those expected during transients, that will be used as a basis for developing Code rules for HTGRs. Consider the materials test data and conclusions in the ASME ST-LLC Tasks 1 - 14. If requirements are established that are outside of the limits of current databases or the limits of data that are readily obtainable in the short term, testing to determine required material properties may delay the development of Code rules significantly.

- 7.1.2.1 Time/Temperature/Load/Atmosphere envelope for each primary loop component including, but not limited to, the reactor pressure vessel, IHX, steam generator, reactor core support and internal structures.
  - 7.1.2.1.1 If equipment can be de-pressurized to reduce stress if metal temperatures exceed defined limits during upset events, this should be defined as a part of the envelope.
  - 7.1.2.1.2 The envelope should include all expected startup, shutdown and upset conditions.
  - 7.1.2.1.3 Local variations in temperature due to non-homogeneous distribution of coolant flow should be considered.
- 7.1.2.2 Fluid environment for each component, particularly potential contaminants.
- 7.1.2.3 Materials to be considered for each component (specification and grade).
- 7.1.2.4 Component design requirements should be determined considering the views and experience of all stakeholders, including the elevated temperature experts who will be primarily responsible for developing the Code rules.

## 8 RESEARCH AND DEVELOPMENT TASKS

- 8.1 The term R&D as used in the Roadmap is intended to include the following categories of tasks:
- 8.1.1 Tests to develop material properties and information about the long-term performance of materials.
  - 8.1.2 Development and validation of new design and analysis methods.
  - 8.1.3 Development of new methods for fabrication and examination.
  - 8.1.4 Development of drafts of Code rules based on existing methods and data, and the validation of those rules, are not considered to be R&D. It may be necessary to initiate R&D projects to obtain more data or to develop modified or alternative methods.
- 8.2 **Phase I R&D tasks.** No R&D tasks are included.
- 8.3 **Phase II R&D tasks.** In order to provide comprehensive rules for the “Phase II” HTGRs, it is anticipated that some R&D will be needed. A cost-benefit analysis should be performed to evaluate each R&D program prior to authorizing funding. Existing documentation of HTGR research needs (such as the NRC NGNP Materials PIRT (Vol. 4 of NUREG/CR-6944, March 2008) and revisited by Bill Corwin in 2010) should be reviewed. Examples of currently recommended R&D tasks are described below.
- 8.3.1 **Identify causes and potential actions to address anomalous creep rupture data for Type 304 and 316 stainless steel.** This is currently being performed as part of ASME ST-LLC Task 14.
  - 8.3.2 **Extend allowable stresses for Alloy 800H to cover 850°C and 500,000 hours.** This is currently being performed as part of ASME ST-LLC Task 13.
  - 8.3.3 **Develop Standard Material Models and Analysis Methods for Inelastic Analyses.** BPV III-5 currently provides no standardized methodology for performing inelastic analyses for components that do not satisfy restrictions on the application of simplified inelastic analysis methods and/or do not meet the conservative design limits of the simplified methods. Material models for all Division 5 materials are also needed. The R&D for this task has already been initiated in a Subgroup ETD Taskforce.
  - 8.3.4 **Develop Improved Creep-Fatigue Rules for Mod 9Cr.** The cyclic strain softening behavior of this material makes the current III-5 rules for creep-fatigue very conservative, and a revision to the rules may be required. Some research into the creep-fatigue behavior of Mod 9Cr has already been performed in ASME ST-LLC Tasks 3, 5 and 10. R&D is required to build on this work to develop specific creep-fatigue rules for the alloy.
  - 8.3.5 **Develop Improved “Negligible Creep” Rules.** The current negligible creep criteria cannot be applied to Mod 9Cr alloy because of its strain softening cyclic behavior. In addition, ETD experts have shown that pressure vessel low alloy steels such as SA-508 or 533 exhibit non-negligible creep at temperatures below the III-5 cut-off of 700°F. R&D should be performed to establish realistic negligible creep rules for these ferritic alloys that will ensure significant creep-fatigue interactions will not occur in-service. In particular, the R&D should show whether the 700°F cut-off for III-5 rules should be lowered for the low alloy steels.
  - 8.3.6 **Develop Simplified Methodology for Exemption from a Formal Creep-Fatigue Damage Evaluation.** The III-5 rules for determining whether a component is exempt



from a formal creep-fatigue evaluation are difficult to apply and time consuming. Simplified, but still conservative rules based on novel analytic methods are required.

**8.3.7 Establish an “NDE Database”** by means of an ongoing Joint Industry Project (JIP) to:

8.3.7.1 Document current capabilities as demonstrated by equipment manufacturers, NDE service firms, users and research facilities. Capabilities would be subject to peer review.

8.3.7.2 Document current R&D activities and identify gaps that could be closed by additional research projects.

8.3.7.3 The database should include NDE for metallic and non-metallic materials.

**8.3.8 Investigate Structural Brazes and other High Temperature Bonding Methods.** Structural joining using brazing, diffusion bonding or other joining methods is needed for components such as intermediate heat exchangers. A program to document potential degradation mechanisms affecting long-term performance of these joints at the temperatures identified in Section of this Roadmap 7 is needed.

8.3.8.1 Long-term testing is needed to define the behavior of structural components joined by brazing or other high temperature bonding methods under load and thermal exposure. This testing is expected to take many years and should be done in parallel with the construction and commissioning of operating reactors. The tests should be based on accelerating the damage by using more severe levels of load and temperature so that the results can be used to provide an early warning of potential problems in operating units. Methods should also be developed to establish the uncertainties and limits for extrapolating from test conditions to actual service. Alternatively, the tests can be started well in advance of commissioning.

**8.3.9 Develop/Continue Programs to Support the Carbon, Graphite, Ceramic and Composite Rules** (e.g. for core support structures). See ASME ST-LLC STP-NU-009 *Graphite for High Temperature Gas-Cooled Nuclear Reactors* and NUREG/CR-6944, Volume 5; ORNL/TM-2007/147, Volume 5 *Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTS), Volume 5: Graphite PIRT*s.

**8.4 Long Term R&D Tasks.** A number of long term R&D tasks should be initiated during the Phase II time period to support long term Code development. A cost-benefit analysis should be performed to evaluate each R&D program prior to authorizing funding. Existing documentation of HTGR research needs (such as Vol. 4 of NUREG/CR-6944, March 2008), and revisited by Bill Corwin in 2010) should be reviewed. While Long Term Phase Code development is not covered in this Roadmap, some R&D programs have been proposed and are recommended for initiation in Phase II, as follows:

**8.4.1 Generalize the “New Simplified” Analysis Methods.** Develop a method to expand the applicability of the simplified analysis methods in 8.3.6 to load and displacement controlled stresses (“primary” and “secondary” stresses in III-NB) over temperatures ranging from ambient to the upper end of the creep regime. The method would obviate the need for stress classification. This would be a key technology for the Long Term goal of developing Division 5 into an all temperature, all loading design based Code. While the success of this effort is unlikely, the benefits of success are very high. This work should be performed in parallel with R&D that simply refines current analytic methods, like those described in 8.4.3 and 8.4.4 below.



- 8.4.2 **Develop Initial Loading and Cyclic Stress-Strain Curves** for all materials to be used for BPV III-5 construction for the complete temperature range of interest if these data are needed for the analysis methods selected. For elevated temperatures, include creep relaxation curves and perform tests at a range of strain rates.
- 8.4.3 **Develop Improved Design Methodology for Creep-Fatigue Evaluation by Analysis.** This approach should take full advantage of modern analysis tools, such as elastic-plastic finite element analysis with creep strain capability. Note that R&D is recommended to develop the necessary material models (see paragraph 8.4.3.5) as well as cyclic stress-strain and creep relaxation curves (see paragraph 8.4.2). Also see reports on ASME ST-LLC *Task 9: Update and Improve Subsection NH - Simplified Elastic and Inelastic Design Analysis Methods*. In addition, see report on ASME ST-LLC *Task 10: Update and Improve Subsection NH - Alternative Simplified Creep-Fatigue Design Methods*. Elastic follow-up should be addressed as a part of the analysis procedure. The following approaches are among those that should be considered:
- 8.4.3.1 API 579-1/ASME FFS-1 Standard for fitness-for-service
  - 8.4.3.2 R5 methods for high temperature analysis and flaw evaluation
  - 8.4.3.3 RCC-MR Code for fast reactors
  - 8.4.3.4 BPV III-NH Appendix T
  - 8.4.3.5 **Develop the Necessary Materials Models for Creep-Fatigue Evaluation by Elastic-Plastic Creep Analysis** considering the interaction of time-dependent creep strain and time-independent plastic strain on the material. This could be a very long-term effort. Therefore, consideration should be given to using the existing work in this area to develop very conservative (bounding) models. This project should also use statistical analysis to address the issue of whether to use minimum or average properties in the analysis (also see paragraph 8.3.3).
  - 8.4.3.6 **Validation Testing of Design Methodology for Creep-Fatigue Evaluation by Analysis.** Proposed rules should be validated by round robin analyses and extensive peer review.
- 8.4.4 **Develop Improved Methodology for Strain Limits and Ratcheting** based on the results of elastic or simplified inelastic analysis and taking full advantage of modern analysis tools. Current methods have geometry and loading restraints that limit their applicability and can result in either unnecessary redesign or application of significantly more complex evaluation methods based on the results of inelastic (elastic-plastic creep) analysis. See ASME ST-LLC *Task 9: Update and Improve Subsection NH - Simplified Elastic and Inelastic Design Analysis Methods*.
- 8.4.5 **Investigate Remote UT Methods** for detecting cracks in components without physical contact (e.g., laser methods). Consider additional **R&D** recommendations in this area, if any, based on the ASME ST-LLC Task 12 report. See paragraph 8.3.7.
- 8.4.6 **Review Technology for Continuous AE Monitoring** of critical components during operation. ASME ST-LLC *Task 12: NDE and ISI Technology for HTGRs* should provide some guidance in this area. The R&D should be developed and guided by a Task Group with members from ASME BPV Sections III, V and XI. Problems of signal to noise ratio and the threshold for damage detection (e.g. void/cavity formation or finite crack) should be addressed, as well as accept/reject criteria. See 8.3.7.

## 9 RECOMMENDED “GLOBAL” ADMINISTRATIVE AND TECHNICAL TASKS FOR PHASES I AND II

- 9.1 This section of the document describes tasks that should be completed as soon as possible to be able to provide appropriate direction to the project teams that will draft the individual parts of the Code rules. It is important that a broad consensus be reached on the recommendations that result from each of these “global” tasks (e.g. at the BPV III Standards Committee level and, in some cases, at the BNCS level) prior to expending a lot of effort on detailed development of Code rules.
- 9.2 The following “global” or general tasks are recommended to establish the basis and framework for the HTGR code rules. A recommended organizational structure and process to accomplish required tasks are provided in paragraph 11. In some cases, ASME Code rules will not be developed to address an issue, but that other SDOs or regulatory bodies will provide rules or guidance.
- 9.2.1 **Establish an Administrative Structure to Oversee the Phase I and II Tasks.** An oversight group should be appointed to monitor the progress of the Phase I, Part A activities. This has been assigned to the Working Group for High-Temperature Gas Reactors.
- 9.2.2 **Establish Physical Boundaries of Scope** (Phases I and II). The physical boundaries of the scope of coverage of BPV III-5 and BPV XI-2 should be established considering the thermodynamic cycles currently proposed (e.g., direct Brayton cycle or secondary steam Carnot cycle). It is recommended that the scope be limited to components that are in or directly support the operation of the primary coolant loop or systems directly related to reactivity control or core cooling.
- 9.2.3 **Define Code needs for Confinement Building** (Phases I and II) Determine whether the confinement building will be built to BPV Section III, Division 2, a new ASME Code, or a general purpose building code such as ACI-349 (see paragraph 11.1.1.3.1). This decision should be made in close collaboration with the regulator.
- 9.2.4 **Scope of BPV III-5, BPV XI-2, OM Modifications and QME** (Phases I and II). Define the scope of coverage of these documents and get BPV III, BPV XI, OM Committee, QME and BNCS endorsement. Also define the role of the PRA standard that has been developed. The basic assumption should be that the scope of coverage will be the same as for the existing BPV III, BPV XI, OM codes and QME, with the potential additions and deletions listed below. In particular, provide clear scope statements for BPV XI-2, the OM modifications and QME to avoid overlap, duplication and gaps.
- 9.2.4.1 Define the boundary between “new construction” (BPV III-5) and “post construction” or “inservice” (BPV XI-2) rules. One possibility is to define the transition as the moment that the ASME Code Certification Mark is applied to the vessel.
- 9.2.5 **Obtain Consensus for a Component Classification System** (Phases I and II). Develop an appropriate system for classification of components and supports. If the decision is to retain a classification system, consideration should be given to placing pressure boundary components into one of two or three categories based on the results

of a PRA. This task should be accomplished as described in paragraph 11.1.1.2<sup>1</sup> (also see footnote<sup>2</sup>).

- 9.2.6 **BNCS, BPV III and BPV XI Direction.** In order to avoid misunderstandings and possible rework, the following decisions should be made by BNCS in consultation with BPV III, BPV XI, the OM Committee and the Regulators. Specific proposals for presentation to BNCS and the Standards Committees should be developed by the Project Team on Overall Guidance and Coordination. All decisions should be documented:

- 9.2.6.1 Reach a consensus among BPV III, BPV XI and BNCS the extent to which the new BPV III-5 and BPV XI-2 will directly incorporate or reference other Code Sections, Subsections and Divisions, including non-nuclear Sections such as Section VIII. Also decide whether to incorporate the necessary HTGR O&M requirements in the existing OM Code under the O&M Committee on Operation and Maintenance of Nuclear Power Plants or in a new OM Code section. Similarly, the roles of the following Committees should be defined with regard to the HTGR:

- 9.2.6.1.1 Standards Committee on Nuclear Risk Management (CNRM)
- 9.2.6.1.2 Standards Committee on Nuclear Quality Assurance (NQA)
- 9.2.6.1.3 Standards Committee on Qualification of Mechanical Equipment Used in Nuclear Facilities (QME).
- 9.2.6.1.4 Standards Committee on Nuclear Air and Gas Treatment Equipment

- 9.2.6.2 Provide direction to all of the groups that are drafting parts of ASME Codes and Standards to ensure that new construction rules consider the post-construction activities that are needed in order to provide:

- 9.2.6.2.1 Access for inspection/examination.
- 9.2.6.2.2 Baseline NDE data on new components taken with the same methods and at the same locations as will be used in post-construction to the applicable extent.
- 9.2.6.2.3 Appropriate surveillance coupons, test frequency, their location and test methods.

- 9.2.6.3 Phase II - Obtain BPV III and BNCS concurrence with individual decisions made during code development in consultation with the Regulators. Examples include:

- 9.2.6.3.1 Component classification system.

<sup>1</sup> The design rules could be the same for all component classes, but fabrication and examination requirements could be more stringent for some classes. This is similar to the approach in Section I and VIII-1 (e.g., for “lethal service”).

<sup>2</sup> ANS 53.1, *Nuclear Safety Criteria and Safety Design Process for Modular Helium-Cooled Reactor Plants*, is in the final review and approval stage. This document classifies systems, structures and components (SSC) into the following categories: Safety-related; Non-safety related; Non-safety related with special treatment. The first and last of these correspond to Class A and B, respectively, as specified in BPV III-5.

- 9.2.6.3.2 Overall philosophy of elevated temperature design rules. For example, determine whether elevated temperature rules should be based on a 60-year life, with periodic surveillance coupon testing to confirm design life. Number of cycles should also be considered and the testing interval should be defined.
- 9.2.6.4 Determine whether the existing BPV Section III, Division 1, Subsection NF on supports should be modified for the HTGR. It may be better to review and update this subsection rather than writing a new book or incorporating the requirements into BPV III-5.
- 9.2.7 **Develop Common Terminology and Units of Measure.** A common set of terminology, acronyms, abbreviations and units of measure should be developed for use in all HTGR Code rules. It is suggested that the SI system be the primary units, but provisions for the use of alternative units should be made.

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## 10 RECOMMENDED SPECIFIC CODE RULE TASKS FOR PHASE II

### 10.1 Code Rule Development

10.1.1 The following tasks should be completed to support Code rules development over the Phase II period.

10.1.1.1 **Expand the General Requirements Portion of III-5.** Based on Section III, Subsection NCA and needs identified by stakeholders, consider whether the Design Specification provided by the Owner should identify items such as anticipated degradation mechanisms and online monitoring or other NDE techniques to detect each type of degradation mechanism in a timely manner for significance assessment and disposition. Examples of degradation mechanisms to be considered include:

10.1.1.1.1 Time/Temperature/Load envelope for each primary loop component including the IHX and reactor pressure vessel internals.

10.1.1.1.1.1 State whether equipment can be de-pressured when metal temperatures exceed defined limits to reduce stress at high temperatures.

10.1.1.1.2 Corrosion/erosion allowances.

10.1.1.1.2.1 Consider requiring that the Owner document the basis for the corrosion/erosion allowance. Consider the need for Code rules with requirements for the testing.

10.1.1.1.3 Change in material properties due to carburization/decarburization.

10.1.1.1.4 Allowance for metal loss due to wear at heat exchanger tube supports and core supports where sliding can occur.

10.1.1.1.4.1 Consider requiring the Owner to document the basis for the allowance for metal loss. The need for Code rules with requirements for the testing should also be considered.

10.1.1.1.5 End-of-life strength and toughness properties for metallic and non-metallic materials that are expected to degrade due to thermal aging, radiation, and interaction with the environment. Such properties may be in a range rather than a single set of values because of the operation of several types of degradation mechanisms.

10.1.1.1.5.1 Consider requiring the Owner to document the basis for the end-of-life properties. The need for Code rules with requirements for the testing should also be considered.

10.1.1.1.6 Beginning-of-life and end-of-life emissivity for components.

10.1.1.1.6.1 Consider requiring the Owner to document the basis for the end-of-life emissivity. The need for

Code rules with requirements for the testing should also be considered.

**10.1.1.2 Correct and Extend Allowable Stresses Values.**

10.1.1.2.1 Correct errors in the Type 304 and Type 316 allowable stress values identified in ASME ST-LLC Task 6.

10.1.1.2.2 Identify and mitigate low creep rupture strength of several Type 304 and 316 heats identified in ASME ST-LLC Task 14.

10.1.1.2.3 Extend allowable stress values in Division 5 to 500,000 hours (currently 300,000 hours), as has been initiated in ASME ST-LLC Tasks 13 and 14a.

**10.1.1.3 Define Procedures and Material Models for Inelastic Analysis.** Designs that do not meet restrictions imposed by Division 5 for simplified inelastic analysis methods and/or do not meet the applicable conservative design limits require a full inelastic analysis. Standardized methods and materials models are required in Division 5 to accomplish this. This is currently a Subgroup ETD Task Force work topic.

**10.1.1.4 Address Negligible Creep and Creep-Fatigue Rules for Mod 9Cr and the Low Alloy Steels A508 and A533.** The strain softening behavior of Mod 9Cr makes the negligible creep rules in Division 5 impossible to implement and the creep-fatigue rules overly conservative. There is some evidence that creep effects can be observed in low alloy steels below the 700°F BPV III-NH cut-off. Rules that address these issues are required.

**10.1.1.5 Develop Reference Stress or Other Methods for Load-Controlled Stress Analysis.** Simplified methods that do not require stress classification are required for efficient component sizing in preliminary designs.

**10.1.1.6 Incorporate Alloy 617 into Division 5.**

10.1.1.6.1 While Alloy 800H can be successfully used in high temperature reactor service as a pressure boundary material, an alloy with higher creep resistance is required for thin sections exposed to reactor outlet temperatures, such as in the compact heat exchanger. There exists a large body of creep test data for nickel base Alloy 617, which facilitates its incorporation into BPV III-5.

10.1.1.6.2 Rules for welding/joining Alloy 617 in thin sheets are required for ASME Code Section IX.

10.1.1.6.3 Review ASME material specifications for Alloy 617 plate and sheet, tube, bar stock and forgings for adequate quality for BPV III-5, Class A service.

**10.1.1.7 Develop Rules for Compact Heat Exchangers.**

10.1.1.7.1 Rules for the design or testing qualification of the compact heat exchanger are required in Division 5.

10.1.1.7.2 Since there is little experience with compact heat exchanger design, rules may have to be developed over the years. In the

meantime, requirements should be incorporated into BPV III-5 for the qualification of the design by testing.

- 10.1.1.8 **Develop Safety Class B Rules.** Class B rules currently in Division 5 are taken directly from Code Case N-253. These rules have not been reviewed in years and may contain errors or inconsistencies. They may require a complete review and possible revision to be applicable to the HTGR.
- 10.1.1.9 **Develop Exemption Rules for Creep-Fatigue.** Current rules in Division 5 for determining when creep-fatigue interactions need not be considered are complex and time consuming to apply. Revised rules are required to streamline the design process for components with relatively low stress levels.
- 10.1.1.10 **Coordinate Division 5 with Section XI, Division 2.**
  - 10.1.1.10.1 Perform a review of the inservice inspection and testing requirements of the new Section XI, Division 2 to ensure Division 5 design and fabrication rules are consistent with Section XI. This may result in restrictions on weld placement for accessibility and restrictions on the surface geometry of welds for inservice inspections.
  - 10.1.1.10.2 Incorporate creep-fatigue crack growth methods developed in ASME ST-LLC Task 8 into Section XI.
- 10.1.1.11 **Update Rules for Welding and Post-Weld Heat Treatment (PWHT).** For materials to be used at temperatures above the “negligible creep” threshold (see paragraphs 10.1.1.4 and 7.1.2.3), consider the need for restrictions on welding and PWHT in addition to those in current ASME Codes (e.g. see API RP 934-A). Some examples of areas where modified rules may be needed:
  - 10.1.1.11.1 Evaluate the need to further restrict the range of temperatures permitted during PWHT.
  - 10.1.1.11.2 Evaluate whether metal temperatures should be measured and recorded during PWHT to ensure that the limits are not exceeded.
  - 10.1.1.11.3 Evaluate the need for rules for field fabrication and testing.
- 10.1.1.12 **Develop/Update Rules for Structural Brazing, Diffusion Bonding or Other High-Temperature Joining Techniques.** If structural brazing, diffusion bonding or other high temperature joining techniques are identified as necessary for the IHX or other components, the rules in Section IX should be reviewed and updated as necessary.
- 10.1.1.13 **Develop Rules for NDE for New and Post-Construction.** NDE rules should be developed for new and post construction in parallel. The rules should be similar to those in the current Section III and Section XI (Appendix VIII) Codes, except that the following potential requirements should be considered:
  - 10.1.1.13.1 For new construction, consider 100% wet fluorescent magnetic particle (WFMT) for pressure boundary welds in carbon and low alloy steel materials and 100% PT for welds in austenitic



materials. It may be necessary to grind and prepare the welds to be able to detect small flaws.

10.1.1.13.2 For new construction consider requiring UT as the primary volumetric examination technique, with performance demonstration requirements to ensure that small flaws can be detected and categorized.

10.1.1.13.2.1 Adopt the same UT methodology and performance demonstration requirements for post construction.

10.1.1.13.3 If there are areas where UT cannot be demonstrated to find small flaws, consider RT. However, consider how this method can be used for post construction applications. If that is impractical, consider requiring a re-design of the component.

10.1.1.14 **Consider the Need for New Construction Rules for Performance Testing of Valves and Systems.** It is anticipated that several important valves will operate in a very high temperature (e.g. greater than 650°C, 1200°F) environment. If the ability of a specific valve to block flow is important to the integrity of the plant, it may be desirable to demonstrate the performance of valves in that service by testing prior to installation. If so, this should be covered in the new construction rules. New construction qualification requirements should be covered in the QME rules. In-service testing should be covered in the OM Code rules.

10.1.1.15 **Consider the Need for New Construction Rules for Rotating Machinery.** It is anticipated that several important items of rotating machinery, such as helium blowers, circulators and compressors, and turbines will operate in a very high temperature environment. If the proper functioning of a particular machine is important to the integrity of the plant, it may be desirable to demonstrate the performance of a prototype machine in that service prior to installation. If so, new construction qualification requirements should be covered in the QME rules. In-service testing should be covered in the OM rules (see paragraph 10.1.1.17.3). Consider modifying OM 14 to address components in helium service.

10.1.1.16 **Develop Rules for Pressure/Temperature Limits and In-Service Testing.** The following tasks should be assigned.

10.1.1.16.1 Preheat prior to pressurization for pressure boundary components that can be subject to embrittlement due to thermal aging (e.g. temper embrittlement and/or radiation embrittlement).

10.1.1.16.2 Testing of valves. The requirements will probably differ from the requirements in the OM Code for LWRs because of the higher operating temperatures.

10.1.1.16.3 In-service testing of circulators (compressors). Existing vibration analysis methods for pumps should be modified. Experience in the petrochemical industry with machinery monitoring should be considered.



- 10.1.1.17 **Verify Applicability of Nuclear QA Requirements.** The current QA requirements are probably applicable in most cases, but a paragraph by paragraph review should be conducted to verify this, and to determine which requirements to bring into the new III-5 and XI-2. Recommend assigning this task to the Project Team on Nuclear QA.
- 10.1.1.18 **If the BNCS Decides to Develop ASME Code Rules for Confinement Buildings** (see paragraph 9.3.3), develop rules including:
- 10.1.1.18.1 Design rules for internal pressure loadings from helium releases (if any).
  - 10.1.1.18.2 Design rules for withstanding projectiles from failed components (if any).
  - 10.1.1.18.3 Design rules for filters.
  - 10.1.1.18.4 Design rules for aircraft impact.
- 10.1.1.19 **Determine Whether Additional Rules are Needed for Qualification of Active Mechanical Equipment for New Construction** and, if so, develop those rules. Recommend assigning this task to the QME Task Group on Equipment for HTGRs.
- 10.1.1.20 **Update Rules for Controlled Chemistry and Processing.** For materials to be used at temperatures above the “threshold of concern” (see paragraph 10.1.1.4), develop restrictions on chemistry and processing requirements, such as normalizing and tempering in addition to those in the materials specifications and current code rules (e.g. see API RP 934-A and Subsection NH, Section NH-4000).

## 10.2 Stakeholder Activities

- 10.2.1 Potential stakeholders in the HTGR program will be required to provide input to the ASME technical working groups regarding design, operation and inspection needs relevant to ASME Code Rules. Some inputs already identified are shown below.
- 10.2.1.1 **The Standard for Probabilistic Risk Assessment for Advanced Non-LWR Nuclear Power Plant Operations** should be used to develop preliminary PRAs on all candidate systems to identify areas for Code rule development. This should be done by each of the Owner organizations. The results should be fed back to the CNRM for distribution to the appropriate committees and subgroups. **Perform Preliminary PRAs** on all candidate systems to identify critical areas for code rule development. This should be done by each of the Owner organizations. The results should be fed back to the CNRM for distribution to the appropriate committees and subgroups (see paragraph 9.3.10.2). This information may also be useful in deciding whether a component classification system is needed.
- 10.2.1.2 **Owner Organizations Should Recommend System Boundaries for Component Safety Classification (Class A, Class B and Non-Safety Class).** This will help provide input to the ASME regarding the expected quality level for design, fabrication and inspection in the Class A and B designations.
- 10.2.1.3 Define fluid **environment** including contaminants. Nominally expected compositions as well as “worst case” conditions should be provided.