ASME

SETTING THE STANDARD

1880 — 2005

High Temperature Materials and Design Issues for Gen IV Reactors

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Structural Mechanics in Reactor Technology

Jim Ramirez (ASME)
Tim McGreevy (Consultant –formerly ORNL)

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Outline

- DOE-ASME Standards Technology, LLC (ASME ST-LLC) Cooperative Agreement for Gen IV
- Initial Tasks (Tasks 1-5)
- Key Remaining Tasks

Acknowledgment of Technical Advisors & Task Investigators

Task	Technical Advisors	Task Investigators
1	**Chris Hoffmann** Westinghouse Electric Co.	**University of Dayton Research Institute** Lead Investigator – Michael Swindeman Assisting: Bob Swindeman, Doug Marriott, Brian Thurgood, and Blaine Roberts
2	**Bryan Erler** Erler Engineering **Amy Hull** – NRC Office of regulatory Research (RES)	**O'Donnell Engineering Consulting** Lead Investigator – Bill O'Donnell, Ph.D. Assisting: Donald S. Griffin
3	**Wolfgang Hoffelner**, Ph.D. RWH Consult GmbH	**Areva NP, Inc** Lead Investigator – Bernard Riou Assisting: Claude Escaravage
4	**Robert Jetter** Consultant	**Westinghouse Electric Company** Lead Investigator – John Kielb (WEC) Assisting: Kobus Smit (PBMR), John Mullooly, Mit Basol
5	**Bernard Riou** Areva NP, Inc.	**Japan Atomic Energy Agency** Lead Investigator – Tai Asayama Yukio Tachibana

U.S. DOE & ASME CRADA – 5 of 12 Key Materials Tasks Make Significant Progress

1. Verification of Allowable Stresses
2. Regulator Safety Issues in ASME Sec III Subsection NH
3. Improvement of ASME Sec III NH rules for negligible creep & C-F of Gr91
4. Updating of ASME Nuclear Code Case N-201
5. Creep-fatigue procedures for Gr91 steel & Hastelloy XR

Additional Materials Tasks To Be Addressed in Future (US. DOE & ASME CRADA)

6. Graphite & ceramic ASME Code development.
7. Evaluation of ASME-NH and simplified methods.
8. Identification of testing needs to validate elevated temperature design procedures
9. Environmental & neutron fluence effects
10. ASME Code rules for intermediate heat exchanger (IHX)
11. Flaw assessment & Leak Before Break
12. Improved NDE methods for metals

TASK 1: Verification of Allowable Stresses in ASME Section III, Subsection NH With Emphasis on Alloy 800H and Grade 91 Steel

- **Goals**
  - Correct discrepancies in current allowable stress values
  - Extend time duration to be compatible with GEN IV/VHTR
  - Extend temperature range for Alloy 800H

- **Status**
  - Alloy 880H
    - Base metal database assembled, assessed and most analyses complete
    - Filler metal database assembled; assessment ongoing
  - Grade 91 (aka 9Cr-1Mo-V)
    - Base metal and weldment data mostly assembled

TASK 1 (Cont.):

- **Current Results**
  - Draft report issued, "…. Yield and Ultimate Strengths for Alloy 800H", March, '07
    - Tentative minimum yield and ultimate strength values to 900C recommended
    - Supplemental tensile testing needed above 760C to support:
      - Hot tensile curves for isochronous stress-strain curves
      - Threshold for significant strain rate effects
  - Draft report issued, "Creep Rupture Data…. And Strength Estimates for Alloy 800H at 750C and Above…", March, '07
    - Database adequate to meet needs for time dependent properties to 900C for 600,000hr
    - Minimum stress-to-rupture versus time provided
- 800H database is large, contains good quality data with multiple samples at temps from 750C to 1000C; sufficient data for use in VHTR and Gen IV; reports lack (future) specific test recommendations.
- ASME Subgroup ETD Task Force created to review, discuss, develop proposal(s) for revision of Code.

TASK 1: Verification of Allowable Stresses in ASME Section III, Subsection NH With Emphasis on Alloy 800H and Grade 91 Steel

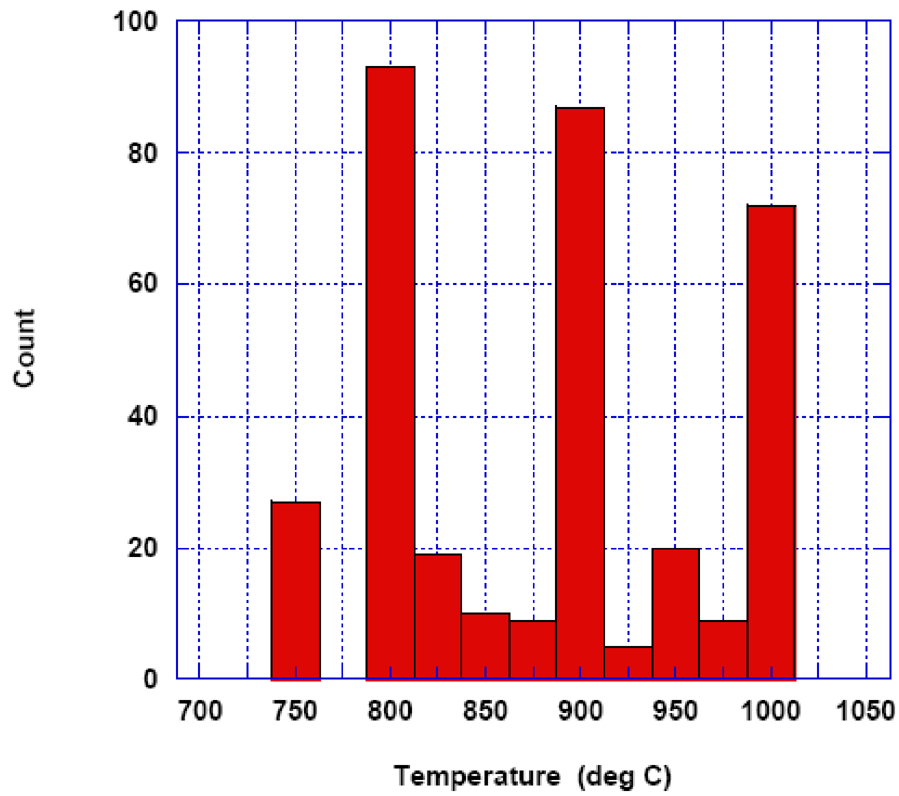

Figure 4. Distribution of testing temperatures for 37 lots of alloy 800H

TASK 2: Regulatory Safety Issues in Structural Design Criteria of ASME Section III Subsection NH and for Very High Temperatures for VHTR & GEN IV

- **Goals**
  - Identify ETD safety issues to be resolved for licensing
    - Prior to cancellation, CRBR required defined research program to address ACRS/NRC concerns
  - Describe how Subsection NH addresses these issues and further needs to cover unresolved safety concerns

- **Status**
  - Prior regulatory reviews of elevated temperature reactors acquired and reviewed
    - CRBR (‘83) & PRISM (’94)
      - Creep crack growth in weldments and notches, inelastic analysis, and environmental effects are primarily the issues brought up
    - REG Guides, NRC presentations, INEEL reports (’02 – ’06) related to advanced reactors and HTGR – Report issued and available summarizing the R&D issues and were more development work is needed.
  - True collaboration with the NRC – Amy Hull, Joe Mascara, Stew Rubin

TASK 2 (Cont.):

- **Current Results**
  - Draft final report for peer review, Nov. '06
    - "Regulatory Issues for … VHTR & GEN IV"
    - In addition to extension of ETD to 950C and 60 years the following issues were identified
      - Materials behavior characterization for cyclic loads at very high temperatures
      - Adequacy of structural analysis methods for cyclic loads at very high temperatures.
      - Fatigue, creep, and creep-fatigue interaction
      - Coolant impurities and crevice concentration impacts
      - Metal carburization, decarburization, and oxidation
        - Sensitization of austenitic steels
      - Alloy aging behavior at elevated temperatures
  - Comments received and revision in work
    - Evaluate how current version of NH addresses, or doesn't, identified issues and indicate path forward for issues relevant to the VHTR
  - NRC review of same for NGNP (PBMR / AREVA), as well as PRISM and CRBR in process; ongoing interaction ASME & DOE continues.
  - Issues will be discussed in ASME Subgroup ETD and consideration given towards existing and future action items.

<u>TASK 3</u>: Improvement of ASME Subsection NH Rules for Grade 91 Steel (negligible creep and creep-fatigue)

- **Goals**
  - Negligible creep
    - Examine current approaches and check their applicability
    - Identify the tests required to support the definition of negligible creep
  - Creep fatigue
    - Compare Subsection NH and RCC-MR creep-fatigue procedures
    - Evaluate validity of current material data
    - Recommend improvements to existing procedures
    - Define a test program to validate the improved procedures
- **Status**
  - Negligible creep
    - Data collection & evaluation, criteria evaluation, proposed approach and test program completed (revised creep law and criteria)
    - **Task Force created in Subgroup ETD to discuss, review, propose future direction for analysis, testing, and/or revisions to Code.**
  - Creep-fatigue
    - Data collection & evaluation, criteria evaluation, proposed improvements completed (cyclic stress-strain curve, relaxation methods)
    - Test program definition in work
    - **Task Force created in Subgroup ETD to discuss, review, propose future direction for analysis, testing, and/or revisions to Code.**

TASK 4: Updating of ASME Nuclear Code Case N-201 to accommodate the needs of High Temperature Gas Cooled Reactors currently in development

- **Goals**
  - Recommend the expansion of the Code Case to include additional materials and materials with higher allowable temperatures,
  - Extend the temperature limits of current materials
  - Confirm that the design methodology is acceptable core support structures operating in elevated temperature service
- **Status**
  - HTGR questionnaire on metallic core support structure design parameters developed
    - Response from PBMR, AREVA, JAEA, General Atomics
  - Detailed review of current CC N-201 completed
    - Numerous errors and discrepancies found (revision in NH not captured in CC-201 historically)

Task 4 – Updating ASME Code Case N-201

HTGR Questionnaire Response Highlights

	PBMR	Areva	JAEA	General Atomics
Materials	316H 2.25Cr-1Mo	800H Grade 91 IN 718 (bolting)	316 2.25Cr-1Mo	800H
Normal Operating Metal Temperature and Duration	440°C (824°F) 280,000 hrs (32 EFPY)	400°C (752°F) 470,000 hrs (53.6 EFPY)	500°C (932°F) 100,000 hrs (11.4 EFPY)	760°C (1,400°F) Duration NA
Transient Maximum Metal Temperature and Duration	640°C (1,184°F) 60 hours	670°C (1,238°F) 100 hours	500°C (932°F) 1,000 hours	NA

Task 4: (Cont.)

- **Current Results**
  - Report “Applicability of … Code Case N-201to Accommodate Needs of … High Temperature Gas Cooled Reactors …” Dec. ’06
    - Normal operating conditions (except for GT-MHR) do not exceed 900C
      - Creep and environmental effects negligible or insignificant
      - Current design methods adequate
    - Off-normal conditions on fringe where creep may need to be considered
    - Current Code Case requires updating and corrections
      - Proposed changes presented in Appendix
    - Additional material needs include:
      - Type 321 & 347 SS
      - Grade 91 and Inconel 718 (already in NH)
      - Need to address life extension to 60 years
  - Comments received and responses issued, Feb. ’07
  - Draft Update to CC N-201 incorporating comments in work
  - **Task has been extended until Sept. 07, end result likely to be CC N-201-6**

Task 4: (Cont.)

Next Steps – Long Term

- Consider rewrite of Code Case N-201 to directly reference the rules in ASME Subsection NH; This will allow Code Case N-201 to automatically keep up with changes made to Subsection NH
- Consistency with Subsection NH
- Addition of 9Cr-1Mo-V data from Subsection NH
- Metrication
- Removal of data now available in Section II, Part D (E, α)
- Includes current updates to NH (K′ = 0.9 for Elastic analysis and 0.67 for Inelastic Analysis)
- Consider additional materials for inclusion into Subsection NH and Code Case N-201

Task 5: Collect available creep-fatigue data and study existing creep-fatigue evaluation procedures for Grade 91 steel and Hastelloy XR

Objectives:

Collect data on Gr 91 & Hastelloy XR

- Evaluate C-F criteria:
  - ASME NH, RCC-MR, Japanese FBR Code procedures
  - Assessment of method of strain range, initial stress, relaxation behavior, and formulation of creep damage
  - Investigate damage envelope in conjunction with modeling of cyclic softening behavior (Gr91)
  - Applicability of the criteria (conclusions obtained in the task) to Haynes 230 and Inconel 617 will be discussed qualitatively.

- Provide suggestions on how to improve creep-fatigue rules in ASME NH
- Provide recommended test program (Gr91 & Alloy617/230)

Task 5: (Cont.):

Results & Status

- **Gr91:**
  - Use cyclic stress-strain curve, not monotonic
  - Creep relaxation equation
  - Use interaction of (0.3,0.3), not (0.1, 0.01)
- **XR:**
  - Use elastic+creep constitutive law (no plasticity)
  - Failure modes (in NH) cover failure modes in XR (617/230).
  - Strain rate and hold time effects in XR are adequately compensated for inherently in safety factors in procedure; likely apply to 617/230.

Task Force in Subgroup ETD created (same TF as in Task 3) to address issues, discuss, propose recommendations, including additional testing, analysis, or proposal of modification / revision of Code.

Task 7: Evaluation of NH and Simplified Methods (ORNL led effort, no CRADA effort to date)

Issues:

- ASME draft code case for Alloy 617 does not permit use of simplified for temperatures in excess of 649°C.
- The NRC has raised concerns regarding uncertainty in analytical tools.
- The NRC has not yet endorsed ASME Sec III Subsection NH.

Objectives:

- Review international code advances, e.g. RCC-MR, BC5500, Monju Code, and R5:
  - Elastic analysis, limit load analysis, inelastic shakedown & ratcheting, and full inelastic analysis.
- Investigate or develop methods that eliminate stress classification or provide consistent and acceptable methodology to classify stresses.
- Obtain a more fundamental understanding of the creep-fatigue damage process and incorporate understanding in life prediction methodology and testing programs.

Task 7: (Cont.)

Results:

- **Simplified Methods for Primary Load Criteria:**
  - Reference stress approaches proposed for simplifying and/or eliminating categorizing stresses (primary vs. secondary).
- **Simplified methods for Cyclic Load Criteria:**

Ratcheting:

  - Investigations support use of simplified methods (App. T of NH) in excess of 649ºC for Alloy 617; similar guidance on other alloys at very high temperature; attention/guidance on cyclic softening.
  - The 'Elastic Core' analytical design approach for simple pressure vessel shown to be conservative for complex load histories.
  - New simplified methods were developed by integrating fundamental basis of code with modern analysis tools to provide an equivalent 'Elastic Core' approach for complex structures and loading; verified for numerous cases.
  - Task Force created to review further, and develop proposals on modification/revision of App. T.

Creep-Fatigue:

  - Extension of new simplified methods planned to C-F analysis.
  - No effort on fundamental C-F interaction mechanisms initiated.

Task 8: Identify Testing Needs to Validate ETD Procedures for VHTR

Issues:

- Coupon and component testing is utilized by ASME Sec III Subsection NH to validate elevated temperature design procedures.
- The very high temperatures (850ºC and higher), very long service lives (plant life of 60 years), and a desire to approve use of nickel based super alloys (617 or 230) warrants verification of procedures.

Objectives:

- Review VHTR design features from viewpoint of elevated temperature design and summarize necessary design procedures that require validation.
- Review international accomplishments in validation of design procedures related to VHTR needs.
- Identify existing validation test data and recommend future testing for verification of failure modes addressed by ASME Sec III Subsection NH, including additional anticipated failure modes relevant to VHTR (if any).

Status: not initiated.

Task critical in process of verification of ETD procedures and obtaining regulatory approval and acceptance of such procedures.

Task 10: ASME Code Rules of IHX

Issues:

- The NGNP will require an indirect cycle for energy transfer through an intermediate heat exchanger (IHX) to produce hydrogen.

Objectives:

- Determine how and where within the ASME codes and standards the IHX, safety valves, and similar components should be addressed.
- Consider all aspects of IHX design:
  - Materials, design, fabrication, examination, testing, in-service inspection, working fluid, temperature, time, pressure, load cycles.
- Identify alternative concepts, if available.
- Emphasis on design criteria & cyclic life, construction codes of record and designated pressure boundaries, qualification of materials and fabrication, environmental effects.

Task 10: (Cont.)

Issues:

- Industrial system reactor design and component suppliers not identified.

Objectives:

- Once reactor design and suppliers are determined:
  - Re-evaluate IHX design approaches (results of previous slide)
  - Conduct scoping analysis to identify critical design configurations and loading conditions.
  - Evaluate all safety and operational aspects of a gas-gas IHX in light of practice and experience.
  - Recommend changes and additions to current construction codes and/or identify features of new construction code; current codes to consider include ASME Sec III Subsection NB, NC, ND, and NH and relevant code cases, and Sec VIII Div 1 & Div 2.

Task 10: (Cont.)

Status: not initiated.

- The IHX is a key critical component for the success of NGNP via secondary cooling system to produce hydrogen and/or process heat.

- Key issues include:
  - Product size (sheet vs. plate/tube)
  - Joining processes
  - Inspection; safety classificaiton
  - Creep-fatigue; active creep mechanisms (diffusion vs. power law)
  - Environmental effects

- DOE's request and support for development of conceptual designs for the NGNP, followed by design selections should open door for true & focused efforts and developments in this arena, including ASME, industry, national laboratories, and regulatory bodies.

Significant Progress in Materials and Design R&D

- Significant technical progress has been achieved in short time frame.

- Successful relationship building and enhancement between DOE, National Labs, ASME, NRC, and international organizations such as GIF (Generation Four International Forum).

- Significant & continued efforts for Codification are required in the areas of materials, design procedures, verification, and revision/new Code to support NGNP.

- DOE & ASME CRADA is effective and will expedite revision process within ASME Codes & Standards.

Acknowledgements

- U.S. DOE
- ASME
- Numerous technical experts within and outside of ASME Subgroup ETD
- INL & ORNL

Contact Information

Jim Ramirez, ramirezj@asme.org, 212-591-8033

Three Park Avenue
New York, NY 10016-5990

More information visit: www.stllc.asme.org

TASK 3 (Cont.):

Part I – Negligible Creep Regime

- Collect of data for Grade 91 Steel from CEA, ORNL, NIMS and JNC (~450°C and 500°C) *(Completed)*
- Reevaluation of creep properties *(Completed)*
  - Creep stress to rupture
  - Creep strain law
  - Proposed creep strain law compared to ORNL (Brinkman et al, ORNL-TM- 10504 – November 1987) and Japanese laws
- Evaluation of negligible creep criteria *(Completed)*
- Proposed Approach *(Completed)*
  - Based on RCC-MR approach
  - Based on ASME approach
- Test program *(Underway)*

TASK 3 (Cont.):

- **Current Results**
  - Negligible Creep
    - Report "Improvement of ASME NH for Grade 91 (negligible creep)", Jan. '07
      - Criterion based on austenitic stainless steel inappropriate for Grade 91 due to cyclic softening
      - Proposed alternate criterion for NH gives limit of 450C for 420,000hr
      - Available creep correlations not reliable in low temperature regime
      - Comments address need for physical rationale for alternate criterion
    - Report "Proposed Test Program to Assess Negligible Creep…", March, '07
      - Improve evaluation of criterion
      - Evaluate margin between negligible creep and significant reduction in fatigue life
  - Creep-fatigue
    - "Proposal of Improvement of NH", Oct. '06
      - Changes k' factor in elastic creep-fatigue rules in NH from 0.67 to 0.9 (less conservative)
      - Letter ballot on BC06-1573 approved by SC-III

Task 4 – Updating ASME Code Case N-201

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