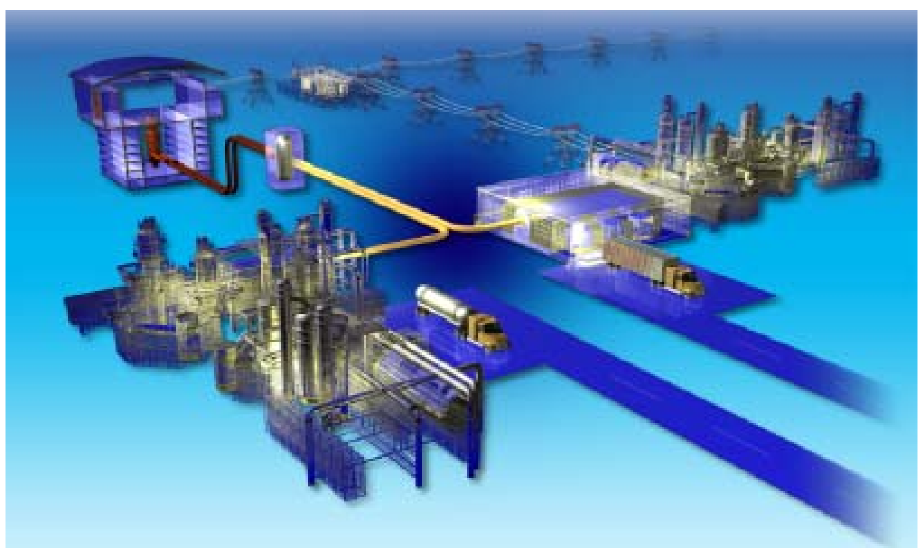
INL/EXT-08-14108
Rev. 1

Next Generation Nuclear Plant Reactor Pressure Vessel Materials Research and Development Plan

July 2010



The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

Idaho National Laboratory

INL/EXT-08-14108
PLN-2803
Rev. 1

Next Generation Nuclear Plant Reactor Pressure Vessel Materials Research and Development Plan

July 2010

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Prepared by:

Jill Wright 7/14/10

Jill Wright
Staff Scientist

Date

Reviewed by:

07/14/2010

Richard N. Wright
NGNP Materials Principle Investigator

Date

Approved by:

David Petti 7/14/10

David A. Petti
VHTR TDO Director

Date

REVISION LOG

Rev.	Date	Affected Pages	Revision Description
0	04/30/08	All	New document
1	07/14/10	All	Updates throughout document

SUMMARY

The U.S. Department of Energy (DOE) has selected the High-Temperature Gas-cooled Reactor (HTGR) design for the Next Generation Nuclear Plant (NGNP) Project. The NGNP will demonstrate the use of nuclear power for electricity and hydrogen production, with an outlet gas temperature in the range of 750°C, and a design service life of 60 years. The reactor design will be a graphite-moderated, helium-cooled, prismatic, or pebble bed reactor and use low-enriched uranium, Tri-Isotopic (TRISO)-coated fuel. The plant size, reactor thermal power, and core configuration will ensure passive decay heat removal without fuel damage or radioactive material releases during accidents.

Selection of the technology and design configuration for the NGNP must consider both the cost and risk profiles to ensure that the demonstration plant establishes a sound foundation for future commercial deployments. The NGNP challenge is to achieve a significant advancement in nuclear technology while setting the stage for an economically viable deployment of the new technology in the commercial sector soon after 2020.

Studies of potential Reactor Pressure Vessel (RPV) steels have been carried out as part of the pre-conceptual design studies. These design studies have generally focused on American Society of Mechanical Engineers (ASME) Code status of the steels, temperature limits, and allowable stresses. Initially, three candidate materials were identified by this process: conventional light water reactor (LWR) RPV steels A 508/A 533, 2¼Cr-1Mo in the annealed condition, and Grade 91 steel. The low strength of 2¼Cr-1Mo at elevated temperature has eliminated this steel from serious consideration as the NGNP RPV candidate material.

Discussions with the very few vendors that can potentially produce large forgings for nuclear pressure vessels indicate a strong preference for conventional LWR steels. This preference is based in part on extensive experience with forging these steels for nuclear components. It is also based on the inability to cast large ingots of the Grade 91 steel due to segregation during ingot solidification, thus restricting the possible mass of forging components and increasing the amount of welding required for completion of the RPV. The Grade 91 steel is also prone to weld cracking and must be post-weld heat treated to ensure adequate high-temperature strength. There are also questions about the ability to produce, and very importantly, verify the through thickness properties of thick sections of the Grade 91 material.

The availability of large components, ease of fabrication, and nuclear service experience with the A 508/A 533 steels strongly favor their use in the RPV for the NGNP. Lowering the gas outlet temperature for the NGNP to 750°C from 950 to 1000°C, proposed in early concept studies, strengthens the justification for this material selection further. Selection of RPV steel reduces the need for further research and development and the associated technical risk to the project. Availability of vendors with experience fabricating nuclear components with these steels minimizes the schedule risk to the project as well.

This technology development plan details the additional research and development (R&D) required to design and license the NGNP RPV, assuming that A 508/A 533 is the material of construction. The majority of additional information that is required is related to long-term aging behavior at NGNP vessel temperatures, which are somewhat above those commonly encountered in the existing database from LWR experience. Additional data are also required for the anticipated NGNP environment.

An assessment of required R&D for a Grade 91 vessel has been retained from the first revision of the R&D plan in Appendix B in somewhat less detail. Considerably more development is required for this steel compared to A 508/A 533 including additional irradiation testing for expected NGNP operating temperatures, high-temperature mechanical properties, and extensive studies of long-term microstructural stability.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of the following: D. Vandel, J. Cox, and D. Kunerth from INL; and W. R. Corwin, D. F. Wilson, J. P. Shingledecker, M. A. Sokolov, and R. L. Battiste from ORNL. We would also like to thank R. I. Jetter, Chair, ASME Boiler and Pressure Vessel Code, SC-D, Subgroup Elevated Temperature Design; R. W. Swindeman of Cromtech Inc.; D. Eno of Consulting Statistician; V. K. Vasudevan, Professor, Department of Chemical and Materials Engineering, University of Cincinnati; and W. J. O’Donnell of O’Donnell Consulting Engineers, Inc.

CONTENTS

SUMMARY vii

ACKNOWLEDGMENTS ix

ACRONYMS xvii

1. INTRODUCTION AND PURPOSE 1
   - 1.1 Mission Statement 1
   - 1.2 Assumptions 2
   - 1.3 Approach 2

2. BACKGROUND 4
   - 2.1 Previous and Current Research Planning Documents 4
     - 2.1.1 FY-08 Research and Technology Plan 4
     - 2.1.2 RPV Acquisition Plan 4
   - 2.2 Reactor Preconceptual Designs and Vendor Reports 4
     - 2.2.1 General Atomics—GT-MHR Concept 5
     - 2.2.2 AREVA ANTARES Concept 6
     - 2.2.3 PBMR Concept 7
   - 2.3 Complementary Programs 8
     - 2.3.1 Generation IV International Forum 8
     - 2.3.2 International Nuclear Energy Research Initiative Programs 9
     - 2.3.3 University Nuclear Engineering Research Initiative Programs 9
     - 2.3.4 Nuclear Energy University Program Research and Development Awards 9

3. OPERATIONAL REQUIREMENTS 10
   - 3.1 Base Case Definition 10
     - 3.1.1 Reactor Design 10
     - 3.1.2 Temperature 10
     - 3.1.3 Candidate Materials 10
     - 3.1.4 Dimensions 11
   - 3.2 Plant Transient Definitions 11
     - 3.2.1 Anticipated Operational Occurrences 11
     - 3.2.2 Design Basis Events 11
     - 3.2.3 Beyond Design Basis Events 12

4. CURRENT STATE-OF-THE-ART 13
   - 4.1 Materials Research to Date 13
     - 4.1.1 Existing Data 13
     - 4.1.2 New Results 13
   - 4.2 ASME Boiler and Pressure Vessel Code 13
     - 4.2.1 Section III, Subsection NB 14
     - 4.2.2 Code Case N-499-2 15
     - 4.2.3 Section III, Subsection NH 15

4.2.4 Recent Code Activities 16
4.2.5 DOE Initiative to Address ASME Code Issues 17
4.2.6 NRC-sponsored Tasks 21

5. RESEARCH ISSUES 23
5.1 Code Compliance/Licensing 23
5.1.1 Baseline Case 23
5.1.2 NRC Structural Integrity Issues 23
5.2 Procurement and Fabricability 29
5.2.1 Transportation 29
5.2.2 Forging/Rolling 29
5.2.3 On-site Fabrication 29
5.3 Welding 34
5.4 Damage Sources 34
5.4.1 Radiation 34
5.4.2 Oxidation/Corrosion 34
5.4.3 Emissivity 34
5.5 Inspection 36

6. RESEARCH AND TECHNOLOGY PLAN 38
6.1 Required Actions for Code/Licensing Issues 38
6.1.1 Material Procurement 38
6.1.2 Welding 38
6.1.3 Testing 39
6.2 Cost 47

7. REFERENCES 50

Appendix A—Test Matrices for A 508/A 533 Steels 53

Appendix B—Hot Vessel Option 111

Appendix C—Test Matrices for Hot Vessel Option 149

FIGURES

Figure 1. Extrapolated time-dependent primary stress limits for A 533B rolled plate. 25

Figure 2. Extrapolated time-dependent primary stress limits for A 533B at 340°C, 350°C, and 371°C. 25

Figure 3. Extrapolated lower bound creep rupture stress for A 533B at 340°C, 350°C, and 371°C. 26

Figure 4. Effect of environment and temperature on the emissivity of SA 508 steel. 35

Figure B-1. Variation of primary membrane stress intensity and allowable primary membrane stress intensities as functions of temperature and time. 115

TABLES

Table 1. Key operating parameters for the NGNP designs and the Fort St. Vrain HTGR. 6
Table 2. Applicability of rules in Section III of the ASME Code to component construction. 13
Table 3. Division 1 Code cases that were developed for elevated temperature service.......... 14
Table 4. Potential licensing issues for RPVs. 18
Table 5. Lower bound rupture stress given by factor *s* multiplied by $\left.S_y\right)_{T_i}$ 27
Table 6. Comparison of rupture stress predictions from Code Case N-499-2 and statistical re-analysis. 27
Table 7. Rupture data at 371ºC from Code Case N-499 database. 27
Table 8. NRC "cold" vessel issues list from CRBR review – assessment relative to the "cold" and "hot" vessel options. 30
Table 9. Article NB-5300 Inspection Acceptance Standards.......... 36
Table 10. Summary of mandatory post-weld heat treatment according to ASME Table NB-4622.1-1. 39
Table 11. Summary of test plan for A 508/A 533 material – cold vessel. 40
Table 12. Costs associated with sample preparation and testing for A 508/A 533. 48
Table 13. Estimated total cost for testing and analysis for A 508/A 533.......... 49
Table A-1. A 508/533B Creep Rupture Tests in air to Address Creep Effects on Cold Vessel. 55
Table A-2. SAW Cross-Weld Creep Rupture Tests in Air to Address Creep Effects on Cold Vessel. 58
Table A-3. A 508/533B Creep Rupture Tests in NGNP He to Address Creep Effects on Cold Vessel. 59
Table A-4. SAW Creep Rupture Tests in NGNP He to Address Creep Effects on Cold Vessel.......... 60
Table A-5. Creep Rupture Tests in Air on Fatigue-SRX Damaged A 508/533B Material.......... 61
Table A-6. Creep Rupture Tests in Air on Fatigue-SRX Damaged SAW. 62
Table A-7. A 508/533B Long-Term Qualifying Creep Rupture Tests in Air to Address Creep Effects on Cold Vessel. 63
Table A-8. SAW Long-Term Qualifying Creep Rupture Tests in Air to Address Creep Effects on Cold Vessel.......... 64
Table A-9. A 508/533B Relaxation Strength in Air to Address Creep Effects on Cold Vessel. 65
Table A-10. SAW Relaxation Strength in Air to Address Creep Effects on Cold Vessel. 67
Table A-11. Relaxation Strength Tests of fatigue-SRX damaged A 508/533B in Air to Address Creep Effects on Cold Vessel. 68
Table A-12. Relaxation Strength Tests of Fatigue-SRX Damaged SAW in Air to Address Creep Effects on Cold Vessel. 70

Table A-13. A 508/533B Fatigue-SRX Tests in Air to Address Creep Effects on Cold Vessel. 71

Table A-14. SAW Fatigue-SRX Tests in Air to Address Creep Effects on Cold Vessel. 72

Table A-15. Baseline Tensile Tests of A 508/533B in Air to Address Creep Effects on Cold Vessel. 73

Table A-16. Baseline Tensile Tests of SAW in Air to Address Creep Effects on Cold Vessel. 74

Table A-17. Tensile Tests of Fatigue-SRX Damaged A 508/533B in Air to Address Creep Effects on Cold Vessel. 75

Table A-18. Tensile Tests of Fatigue-SRX Damaged SAW in Air to Address Creep Effects on Cold Vessel. 76

Table A-19. Tensile Tests of Thermally Aged A 508/533B in Air to Address Creep Effects on Cold Vessel. 77

Table A-20. Tensile Tests Thermally Aged SAW in Air to Address Creep Effects on Cold Vessel. 78

Table A-21. Tensile Tests of Long-Term Thermally Aged A 508/533B in Air to Address Creep Effects on Cold Vessel. 79

Table A-22. Tensile Tests of Long-Term Thermally Aged SAW in Air to Address Creep Effects on Cold Vessel. 80

Table A-23. Baseline Toughness Measurement (Master Curve To and J-R Curve) for A 508/533B. 81

Table A-24. Toughness Measurement (Master Curve To and J-R Curve) for Fatigue-SRX Damaged A 508/533B Material. 85

Table A-25. Toughness Measurement (Master Curve To and J-R Curve) for Thermally Aged (20,000 hr) A 508/533B Material. 89

Table A-26. Toughness Measurement (Master Curve To and J-R Curve) for Thermally Aged (70,000 hr) A 508/533B Material. 93

Table A-27. Baseline Toughness Measurement (Master Curve To and J-R Curve) for SAW. 97

Table A-28. Baseline Toughness Measurement (Master Curve To and J-R Curve) for Heat Affected Zone of SAW. 99

Table A-29. Cyclic Stress-Strain Curves for 508/533. 101

Table A-30. A 508/533B Creep Rupture Tests in Air to Support Code Case N-499. 104

Table A-31. SAW Creep Rupture Tests in Air to Support Code Case N-499. 106

Table A-32. A 508/533B Fatigue-SRX Tests in Air to Support Code Case N-499. 107

Table A-33. SAW Fatigue-SRX Tests in Air to Support Code Case N-499 109

Table B-1. Allowable stress intensity values for Cr-Mo steels for a maximum design time of 300,000h, extracted from ASME Section III, Subsection NH, Table I-14.3. 114

Table B-2. Variations of 2¼Cr-1Mo alloy, applications and data needs. 116

Table B-3. Temperature limits for NH code materials. 118

Table B-4. NRC “hot” vessel issues list from CRBR review – assessment relative to the “cold” and “hot” vessel options. 128

Table B-5. Forging capability of Grade 91 for NGNP RPV (~8-m dia. × 24-m high × 100–300-mm thick). 134

Table B-6. Summary of test plan for Grade 91 steel 140

Table B-7. Estimated costs for specimen fabrication and testing of the Grade 91 steel 145

Table B-8. Estimated cost for testing and analysis of the Grade 91 steel instead of the A 508/533 146

Table C-1. Creep Tests at 425°C to Support Determination of Negligible Creep Temperature for Grade 91 Steel. 151

Table C-2. Creep Tests at 450°C to Support Determination of Negligible Creep Temperature for Grade 91 Steel. 155

Table C-3. Creep Tests at 475°C to Support Determination of Negligible Creep Temperature for Grade 91 Steel. 159

Table C-4. Creep Tests to Extend Grade 91 Steel Database. 163

Table C-5. Creep-Fatigue Tests to Support Negligible Creep Temperature Determination. 169

Table C-6. Fatigue-Relaxation Tests for Grade 91 steel at 500ºC. 178

Table C-7. Creep-Fatigue Tests for Grade 91 Steel at 500ºC. 186

Table C-8. Fatigue-Relaxation Tests for Grade 91 Steel at 550ºC. 190

Table C-9. Creep-Fatigue Tests for Grade 91 Steel at 550ºC. 194

Table C-10. Fatigue-Relaxation Tests at 500ºC for Aged Grade 91 Steel. 196

Table C-11. Creep-Fatigue Tests at 500ºC for Aged Grade 91 Steel 200

Table C-12. Fatigue-Relaxation Tests at 550ºC for Grade 91 Cross Welds. 202

Table C-13. Test Matrix to Determine Weld Stress Rupture Factor for Grade 91 Cross Welds. 206

Table C-14. Short and Medium Term Creep Tests for Creep-Fatigue Softened Grade 91 Steel at 550°C 209

Table C-15. Tensile Tests for Creep-Fatigue Softened Grade 91 Steel at 550°C 210

Table C-16. Test Matrix for Grade 91 Steel Fatigue Design Curve at 650ºC, AR = As Received. 211

ACRONYMS

ACRS	Advisory Committee on Reactor Safeguards
AOO	Anticipated Operational Occurrence
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AVR	Albeitsgemeinschaft Versuchsreaktor (German reactor)
BDBE	Beyond Design Basis Events
BPVC	Boiler and Pressure Vessel Code
CPD	Conceptual and Preliminary Design
CRBR	Clinch River Breeder Reactor
DBE	Design Basis Events
DHI	Doosan Heavy Industries, South Korea
DOE	Department of Energy
FSV	Fort St. Vrain
FY	fiscal year
GA	General Atomics
GIF	Generation IV International Forum
GT-MHR	Gas Turbine-Modular Helium Reactor
HAZ	Heat Affected Zone
HPCC	High pressure conduction cooldown
HTGR	High-Temperature Gas Reactor
HTR	High-Temperature Reactor
HTR-10	High-Temperature Reactor (China)
HTTR	High-Temperature Engineering Test Reactor (Japan)
IHX	Intermediate/Input Heat Exchanger
INERI	International Nuclear Energy Research Initiative
INL	Idaho National Laboratory (formerly the Idaho National Engineering and Environmental Laboratory)
LPCC	Low pressure conduction cooldown
LWR	Light-Water Reactor
NDMAS	NGNP Data Management Analysis System
NE	DOE Office of Nuclear Energy
NERI	Nuclear Energy Research Initiative

NEUP	Nuclear Energy University Program
NGNP	Next Generation Nuclear Plant
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PA	Project Arrangement
PBMR	Pebble Bed Modular Helium Reactor
PBR	Pebble Bed Reactor
PBMR	Pebble Bed Modular Reactor (South Africa)
PCHE	Printed Circuit Heat Exchangers
PCS	Primary Cooling System
PCU	Power Conversion Unit
PMR	Prismatic Modular Reactor
PRISM	Power Reactor Innovative Small Module
PWR	Pressurized Water Reactor
PWHT	Post Weld Heat Treatment
QA	Quality Assurance
R&D	Research and Development
RCS	Reactor Control System
RES	NRC Office of Nuclear Regulatory Research
RPV	Reactor Pressure Vessel
SAW	Submerged Arc Weld
SG	steam generator
SMAW	shielded-metal arc welding
SSC	Safety Significant Components
SSR	Simulated Stress Relief
THTR	Thorium Hochtemperatur Reaktor (German reactor)
TRISO	Tri-isotopic (fuel)
VHTR	Very High-Temperature Reactor

1. INTRODUCTION AND PURPOSE

The U.S. Department of Energy (DOE) has selected the High-Temperature Gas-cooled Reactor (HTGR) design for the Next Generation Nuclear Plant (NGNP) project. The NGNP will demonstrate the use of nuclear power for electricity, process heat, and hydrogen production. The reactor design will be a graphite moderated, helium-cooled, prismatic or pebble bed, thermal neutron spectrum reactor. The NGNP will use very high burn-up, low-enriched uranium, Tri-Isotopic (TRISO)-coated fuel, and have a projected plant design service life of 60 years. The HTGR concept is considered to be the nearest-term reactor design that has the capability to efficiently produce hydrogen. The plant size, reactor thermal power, and core configuration will ensure passive decay heat removal without fuel damage or radioactive material releases during accidents.

The basic technology for the NGNP was established in former HTGRs such as DRAGON, Peach Bottom, Albeitsgemeinschaft Versuchsreaktor (AVR), Thorium Hochtemperatur Reaktor (THTR), and Fort St. Vrain (FSV). These reactor designs represent two design categories: the Pebble Bed Reactor (PBR) and the Prismatic Modular Reactor (PMR). Commercial examples of potential NGNP candidates are the Gas Turbine-Modular Helium Reactor (GT-MHR) from General Atomics (GA), the high-temperature reactor concept (ANTARES) from AREVA, and the Pebble Bed Modular Reactor (PBMR) from the PBMR consortium. The Japanese High-Temperature Engineering Test Reactor (HTTR) and Chinese High-Temperature Reactor (HTR-10) are currently in operation demonstrating the feasibility of the reactor components and materials needed for NGNP. Therefore, NGNP is focused on building a first-of-its-kind demonstration plant, rather than simply confirming the basic feasibility of the concept.

The operating conditions for NGNP represent a major departure from existing water-cooled reactor technologies. Few choices exist for metallic alloys for use at NGNP conditions and the design lifetime considerations for the metallic components impact the maximum operating temperature. Qualification of materials for successful application at the high-temperature conditions and 60-year-design life planned for the NGNP is a large portion of the effort in the NGNP Materials Research and Development (R&D) Program.

Selection of the technology and design configuration for the NGNP must consider both the cost and risk profiles to ensure that the demonstration plant establishes a sound foundation for future commercial deployments. The NGNP challenge is to achieve a significant advancement in nuclear technology while setting the stage for an economically viable deployment of the new technology in the commercial sector soon after 2020. This document discusses the technical issues that must be resolved for successful design and licensing of the pressure vessel for the NGNP and presents a detailed R&D plan, with associated cost and schedule, to resolve these issues.

1.1 Mission Statement

The objective of the NGNP Materials R&D Program is to provide the essential materials R&D needed to support the design and licensing of the reactor and balance of plant, excluding the hydrogen plant. The Materials R&D Program was initiated prior to the design effort to ensure that materials R&D activities are initiated early enough to support the design process. The thermal, environmental, and service life conditions of the NGNP will make selection and qualification of the high-temperature materials a significant challenge. The mission of the NGNP Materials R&D Program supports the objectives associated with NGNP in the *Energy Policy Act of 2005* and provides any materials related support required during the development of the NGNP Project.

A number of NGNP materials research objectives are specifically related to materials for high-temperature applications such as the intermediate heat exchanger (IHX), steam generator, core barrel, and core internals such as the control rod sleeves. These activities are described in a separate technology development plan. Research is needed to develop improved high-temperature design methodologies for high-temperature metallic alloys for the heat exchanger, and it is possible similar issues will arise for the reactor pressure vessel (RPV). Currently, the data and models for high-temperature design are inadequate for some of the alloys and the codes and standards need to be re-evaluated. An improved understanding and new models are needed for the environmental effects and thermal aging of the high-temperature alloys and possibly the RPV alloys as well. There are potential issues specific to the pressure vessel. Improved inspection methods and procedures must be developed. There are also potential irradiation effects to be considered for both the vessel and some of the core internals. The R&D Plan also includes activities of selected university materials related R&D activities and international materials related collaboration activities that would be of direct benefit to the NGNP Project.

1.2 Assumptions

The following assumptions are incorporated into the mission statements and are fundamental to estimating the scope, cost, and schedule for completing the materials R&D processes:

- NGNP will be a full-sized reactor plant capable of producing process heat for various applications.
- The reactor design will be a helium-cooled, graphite-moderated core design fueled with TRISO-design fuel particles in carbon-based compacts or pebbles.
- The design, materials, and construction will need to meet appropriate Quality Assurance (QA) methods and criteria and other nationally recognized codes and standards. NGNP must demonstrate the capability to obtain a Nuclear Regulatory Commission (NRC) operating license.
- The demonstration plant will be designed to operate for a nominal 60 years.
- The NGNP Program, including the materials program, will continue to be directed by Idaho National Laboratory (INL) based on the guidelines given in the Energy Policy Act of 2005. The scope of work will be adjusted to reflect the level of congressional appropriations.
- Application for an NRC operating license and fabrication of the NGNP will occur with direct interaction and involvement of one or more commercial organizations.

1.3 Approach

Beyond the general assumptions listed above, this research plan will primarily address a baseline design case for the first NGNP that incorporates the following most likely design features and conditions:

- An outlet gas temperature of 750°C
- The "cold" vessel option, meaning a cooled pressure vessel fabricated from conventional pressure vessel steels A 508 Grade 3 Class 1 for forgings and A 533 Grade B Class 1 for rolled plate (referred to as "A 508/A 533" in this report)
- A steam generator
- Possibly a heat exchanger with He as both the primary and secondary coolant.

Although these are the operating conditions of the NGNP, subsequent VHTRs may incorporate variations of this baseline design to allow eventual operation at gas outlet temperatures up to 950°C. One of the primary design changes could be an RPV that is not actively cooled during normal operation, referred to as the "hot" vessel option. Either higher gas temperatures or the hot vessel option could require the use of higher alloy steels for the RPV that are not currently in the nuclear codes and may not be of sufficient technical maturity to incorporate in the design of the first plant. Information on these variations can be found in Appendix B.

2. BACKGROUND

2.1 Previous and Current Research Planning Documents

2.1.1 FY-08 Research and Technology Plan

The Fiscal Year (FY)-08 "Next Generation Nuclear Plant Reactor Pressure Vessel Materials Research and Development Plan," PLN 2803 Rev 0, is the basis for this document (Revision 1). The core gas outlet temperature for the NGNP was 900–950°C at the time that Revision 0 was prepared. One vendor recommended conventional A 508/A 533 pressure vessel steel, used for LWRs, while another recommended 2¼Cr-1Mo steel and another recommended Grade 91 for the pressure vessel steel. PLN-2803 was written under the primary assumption that a cooled pressure vessel would be fabricated from conventional pressure vessel steels A 508/A 533; however, Grade 91 steel was discussed in some detail. Information on the hot vessel option was also included. Information on these topics has been moved to Appendix B since all vendors are currently recommending an A 508/A 533 RPV.

2.1.2 RPV Acquisition Plan

An acquisition plan, INL/EXT 08-13951,(Mizea 2008) has been developed for the RPV that considers, in detail, issues that have significant bearing on RPV technology development planning. Principal among these issues are the large size and restricted availability of forgings for NGNP. The very large size of NGNP RPV components dictates that onsite fabrication will likely be necessary. This consideration motivates the discussion below on welding, heat treatment, and inspection methods. It is also clear that the worldwide capability to produce very large forgings is limited. Direct experience with forgings of the size required for NGNP is restricted to conventional pressure vessel steels. Furthermore, limitations on forging capacity, even with these conventional steels, suggest that welded structures from rolled heavy plate must be considered.

2.2 Reactor Preconceptual Designs and Vendor Reports

Preconceptual design work was initiated in FY-07 by the NGNP Project at INL.(2007) This work was completed by three contractor teams with extensive experience in HTGR technology, nuclear power applications, and hydrogen production(AREVA NP Inc. 2007; Caspersson 2007; General Atomics 2007) and later updated to reflect lower core gas outlet temperature.(Crozier 2009; Koekemoer 2009; Saurwein 2009) Each contractor developed a recommended design for NGNP and a commercial version of the HTGR. R&D, data needs, and future studies required to achieve operation of the NGNP were identified as part of the work. A number of special studies were also requested: Reactor Type Trade Study,(Weaver 2007) Preconceptual Heat Transfer and Transport Studies,(Sherman 2007) Primary and Secondary Cycle Trade Study,(Vandel 2007) and Power Conversion System Trade Study.(Schultz 2007) Three designs were developed:

1. The **GT-MHR** concept; team led by **General Atomics** teamed with: Washington Group International; Rolls-Royce (United Kingdom); Toshiba Corporation and Fuji Electric Systems (Japan); Korean Atomic Energy Research Institute and DOOSAN Heavy Industries and Construction (Korea); and OKB Mechanical Design (Russia).
2. The **ANTARES** concept; team led by **AREVA NP, Inc.** teamed with: Burns & Roe; Washington Group International, BWXT, Dominion Engineering, Air Products, Hamilton-Sundstrand-Rocketdyne, Mitsubishi Heavy Industries, Nova Tech, and Energy.

3. **The PBMR** concept team led by **Westinghouse Electric Company**, LLC teamed with: Pebble Bed Modular Reactor (Pty) Ltd. and M-Tech Industrial (Pty) Ltd. (South Africa); The Shaw Group; Technology Insights; Air Products and Chemicals, Inc.; Nuclear Fuel Services; and Kadak Associates.

All three designs use TRISO fuel, graphite moderation, and high-temperature helium coolant in the primary system in the 750°C temperature range. All of the concepts have various passive neutronic design features that result in a core with relatively low power density and a negative temperature coefficient of neutron reactivity. The shut-down cooling system, the secondary reactivity shut-down system, and the control rod design are similar in all three designs. All of the reactor concepts could be used as a basis for the NGNP. Although the designs will not be presented in detail here, the features that relate to RPV material selection and challenges will be discussed. The key operating parameters and design features for all three designs are listed in Table 1 along with information for the Fort St. Vrain high-temperature gas reactor, the largest and most recent gas-cooled reactor to operate in the U.S., for comparison.

2.2.1 General Atomics—GT-MHR Concept

GA recommends a 600-MWt prismatic reactor design that is essentially a larger version of the GT-MHR,(GA Technologies Inc. 1987; Turner, Baxter et al. 1988; Shenoy 1996; General Atomics 2007) operating at a system pressure of about 7 MPa.(Crozier 2009) The core consists of graphite blocks with an annular-fueled region of 1,020 prismatic fuel blocks arranged in three columns. They argue that a prismatic reactor inherently allows higher reactor power density levels, resulting in better plant economics, and involves fewer uncertainties (and therefore less risk).(2007; Weaver 2007)

The temperature rise of the coolant in the various flow paths through the core varies over a wide range. Good mixing of the outlet coolant is needed to avoid excessive thermal stresses in the downstream components resulting from large temperature gradients and fluctuations, and to assure that the gas entering the turbine has a uniform mixed mean temperature.

This test plan assumes a co-generation application. Steam passes from the steam generator (SG) to both turbine-type generators and directly to the application requiring process heat.

2.2.1.1 Reactor Pressure Vessel

The RPV for the NGNP must be fabricated from A 508/A 533 steel in this design. GA has also concluded that with the NGNP reactor operating with core outlet and inlet helium temperatures of 750°C and less than 350°C, respectively, the nominal RPV temperature during normal operation can be limited to ~320°C. This is well below the ASME code limit of 371°C for A 508/A 533 steel. GA does not consider long-term creep effects to be a potential problem for the NGNP RPV; a direct vessel cooling system will not be needed. Furthermore, GA does not believe that there are likely to be any significant deleterious effects of impure helium on the mechanical properties of the A 508/A 533 RPV based on the experience with 2.25Cr-1Mo steel in the HTTR, although some testing will be needed for confirmation and licensing purposes. GA foresees a test plan where some, but not all, of the testing proposed in INL PLN-2803 is needed.(Crozier 2009)

The RPV design, including the wall thicknesses, will be developed to meet ASME code stress allowable with adequate margin, based on the mechanical properties testing for A 508/A 533. The RPV for a 600-MWt prismatic NGNP will be larger in diameter than most LWR vessels, but the wall thickness should be comparable, and it has been determined that forgings of the required size are within the capabilities of a major forging supplier (Japan Steel Works).

Table 1. Key operating parameters for the NGNP designs and the Fort St. Vrain HTGR.

Condition or Feature	Fort St. Vrain HTGR	General Atomics GT-MHR	AREVA ANTARES	Westinghouse PBMR
Power Output [MW(t)]	842	550–600	565	500
Average power density (w/cm^3)	6.3	6.5	–	4.8
Moderator	Graphite	Graphite	Graphite	Graphite
Core Geometry	Cylindrical	Annular	Annular	Annular
Reactor type	Prismatic	Prismatic	Prismatic	Pebble Bed
Safety Design Philosophy	Active	Passive	Passive	Passive
Plant Design Life (Years)	30	60	60	60
Core outlet temperature (°C)	785	750	750	750
Core inlet temperature (°C)	406	322	325	280
Coolant Pressure (MPa)	4.8	7	5	9
Coolant Flow Rate (kg/s)	428	–	282	204
Secondary outlet temperature (°C)	538	540	550	700/541
Secondary inlet temperature (°C)	NA	200	–	267/217
Secondary Fluid	Steam	Steam	Steam	He, Steam
Secondary Coolant Flow Rate (kg/s)	–	–	141	204
RPV Material	Prestressed concrete	A 508/A 533	A 508/A 533	A 508/A 533
RPV Outside Diameter (m)		8.2*	7.5*	6.8
RPV Height (m)		31*	25*	30
RPV Thickness (mm)		281*	150*	>200
*Value based on preconceptual designs for 950°C gas outlet temperature.				

2.2.2 AREVA ANTARES Concept

The AREVA design(Hittner 2004; AREVA NP Inc. 2007; 2009) is also based in part on the GT-MHR concept, with 1020 fuel blocks arranged in three columns. AREVA recommends that the NGNP be a 565-MWt prismatic reactor, citing advantages over a pebble bed reactor design, in part because the concept was previously licensed for FSV.(Natesan, Purohit et al. 2003; AREVA NP Inc. 2007) The secondary loop currently uses steam rather than a 20% He/80% N_2 gas mixture originally proposed.

AREVA suggests a conventional steam cycle with two parallel primary coolant loops feeding one turbine generator. Each loop includes a SG, a main helium circulator, and a hot duct. The IHX and a number of other elements were removed from the initial design when the reactor outlet temperature was lowered to 750°C from their original suggestion of 900°C. The system pressure is about 5 MPa, somewhat less than specified by the other vendors. They believe the small operational losses resulting from the lower pressure would be offset by reduced capital costs associated with using thinner vessel walls for pressure containment.(AREVA NP Inc. 2007)

2.2.2.1 Reactor Pressure Vessel

The conventional steam cycle NGNP with a 750°C reactor outlet temperature allows the use of LWR steels (A 508/A 533) for the RPV. The selection of this material greatly simplifies design data needs and RPV qualification due to extensive nuclear industry experience with this type of steel. They have determined that currently available technology and materials data exist for developing ASME Code rules for the currently envisioned design; therefore, this technology is ready for use in the NGNP without further technology development. However, AREVA concluded that a seal weld is preferable over the sealing devices used in LWRs and earlier gas reactors.

The Vessel System (RPV, cross vessels and steam generator [SG] vessel) is fabricated both in the vendor shop and at the NGNP site. Due to its size, the RPV must be shipped to the reactor site in four packages and field-welded together. Connecting welds between the RPV and cross vessel, and the cross vessel and SG vessel must also be done on site.(2009)

2.2.3 PBMR Concept

Until recently, a reactor was being developed in South Africa by PBMR (Pty), Ltd., through a world-wide development effort.(Ion, Nicholls et al. 2003; Fazluddin, Smit et al. 2004; Koster, Matzie et al. 2004; Matzner 2004; Caspersson 2007) The program included testing of mechanical systems and components and a testing and verification program to support the licensing process. The PBMR design utilizes graphite-based spherical fuel elements, called pebbles, which are approximately 6 centimeters in diameter. Pebbles proceed vertically downward through the reactor vessel until they are removed at the bottom. On removal they are inspected, and if they are intact and not past the burn-up limit, they are circulated to the input queue again. Otherwise, they are replaced with fresh pebbles. This on-line refueling feature makes refueling shutdowns unnecessary, and it also allows the reactor to operate with almost no excess reactivity.(Caspersson 2007)

Westinghouse recommends the use of an IHX operating in the range of 750–800°C(Koekemoer 2009) to transfer thermal energy between the primary and secondary heat transport systems. The IHX vessel is part of the helium pressure boundary, and considered part of the primary loop which has a pressure of 9 MPa. A compact heat exchanger is recommended as Westinghouse believes that tubular heat exchangers would be too large and costly to be economical. The IHX is expected to transfer 500 MWt from the primary working fluid to the secondary fluid (steam), with the primary and secondary loops being essentially pressure balanced. For a reactor outlet temperature of 800°C, the exit temperatures from the IHX have been calculated as 267°C and 217°C for the primary and secondary side of the IHX, respectively.

2.2.3.1 Reactor Pressure Vessel

The PBMR design utilized readily available materials included in the ASME code, concluding that these materials will not need significant development or data base generation for use with NGNP system design conditions. However, testing is required to address ASME Code and NRC licensing issues related to the long design lifetime and normal operating temperatures that are very near the transition region where long-term creep and creep-fatigue effects need to be considered in the design.

The vessel design consists of a welded cylindrical shell welded to the bottom head. The top head, containing numerous penetrations for fuel handling and reactor control systems, will be bolted to the cylindrical section. The dimensions are 6.8 m in diameter by 30 m high.

The RPV design configuration is such that its normal operating temperature range is from 300 to 350°C. The steel specified is A 508 (forgings), A 533 (plates), and A 04 Grade 24B Class 3 (bolts). A separate stream of helium actively cools the RPV. The IHX vessel, made from the same steel as the RPV, connects the primary system to the secondary heat transport loop and contains the heat exchanger.

2.3 Complementary Programs

2.3.1 Generation IV International Forum

The primary mechanism for international collaboration for materials R&D activities in support of a HTGR is through the Generation IV International Forum (GIF). The GIF is an international effort working to advance nuclear energy to meet future energy needs. It includes eight partners that have now signed the treaty-level GIF International Framework Agreement: Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, the United States, and the European Union, with China's application to join under final negotiation. These partners have agreed on a framework for international cooperation in research necessary to build a future generation of nuclear energy systems.

Generation I nuclear reactor systems are early prototype plants such as Magnox. Generation II plants are the current generation of electricity-producing commercial nuclear plants. Generation III plants are advanced LWRs including Advanced Boiling Water Reactors. Generation IV plants are envisioned as highly economical and proliferation resistant, and feature enhanced safety and minimal waste; however they have yet to be commercially operated. The objective is to have HTGR systems available for international deployment by about 2030 when many of the world's currently operating nuclear plants will be at or near the end of their operating lifetimes.

Gen IV collaboration is underway. The specific international vehicle that governs the exchange of GIF information on structural materials relevant to the NGNP is the Project Arrangement (PA) on Materials for the International Research and Development of the Very High-Temperature Reactor (VHTR) Nuclear Energy System. This PA, established by the VHTR Materials Project Management Board, covers both individual and cooperative contributions by the international partners. The initial PA covers the exchange of materials information generated during 2007–2012, as well as historical information that has heretofore not been publicly available. Information is generated and exchanged on three major classes of materials: graphite for core components; metals for pressure boundaries, reactor internals, piping, heat exchangers, and balance of plant; and ceramics and ceramic composites for special needs, such as control rods, insulation, reactor internals, etc. All materials data identified within the PA that is produced by any partner shall be shared with all other partners for use in their national programs. Currently, about $120M in VHTR materials data has been committed as contributions by the GIF partners, including about $52M in generated metals data, plus significant amounts of proprietary historical data. Detailed assessments will be made of the portion of the GIF VHTR materials data that will be available to meet the data needs of the NGNP and reduce the resources required by the project.

2.3.2 International Nuclear Energy Research Initiative Programs

The International Nuclear Energy Research Initiative (INERI) programs are designed to allow a free exchange of ideas and data between U.S. and international researchers working in similar research areas. This international agreement encourages strong collaboration between research institutions where a benefit to both countries is anticipated. There are currently no active INERI programs addressing RPV materials issues.

2.3.3 University Nuclear Engineering Research Initiative Programs

Nuclear Engineering Research Initiative (NERI) programs facilitate technical cooperation between the NGNP Materials Program and universities. There is one NERI project at the University of Wisconsin-Madison that is addressing emissivity of candidate RPV core internal materials. Emissivity is being determined as a function of the time and temperature of exposure to impure helium and air. These experiments address materials behavior on the interior and exterior surface of the reactor system.

2.3.4 Nuclear Energy University Program Research and Development Awards

Nuclear Energy University Programs (NEUP) Research and Development Awards are the current mechanism for cooperative research with universities on NGNP topics. Three of these programs are related to RPV materials research:

- Prediction and Monitoring Systems of Creep-Fracture Behavior of 9Cr-1Mo Steels for Reactor pressure Vessels – University of Idaho – Gabriel Potirniche
- Corrosion and Creep Candidate Alloys in High-Temperature Helium and Steam Environments for the NGNP – University of Michigan – Gary Was
- Effect of Post-Weld Heat Treatment on Creep rupture Properties of Grade 91 Steel heavy Section Welds – Utah State university – Leijun Li.

3. OPERATIONAL REQUIREMENTS

3.1 Base Case Definition

This R&D plan details the materials issues that result from the base case discussed in this section which will be executed for the first generation NGNP. Eventually the goals are to increase the outlet temperature of the reactor or allow the pressure vessel to operate at higher temperature with active cooling reduced or eliminated. If pursued, these will apply to subsequent VHTRs. Any additional materials R&D needs that result from this alternative case are specifically identified in Appendix B.

3.1.1 Reactor Design

The NGNP program has not yet determined whether the reactor will be of the pebble bed or prismatic type. Modeling and analysis of the two different configurations has indicated that there are small differences in the expected operating conditions of the RPV depending on which type is selected. However, for purposes of this development plan, the base case adequately addresses either configuration.

3.1.2 Temperature

Base case conditions assume an outlet gas temperature of 750°C. The maximum operating temperature of the RPV will depend on the NGNP design, outlet gas temperature, and power level selected. The PBMR design calculated an RPV nominal operating range of 260 to 300°C, achieved by using an independent cooling stream. GA estimated the nominal operating temperature for the GT-MHR concept at ~320°C.

3.1.3 Candidate Materials

For these operating conditions the RPV structural material selection is A 508 (forgings) and A 533 (plates). There is extensive use of these materials in LWR RPVs for application at about 290°C. As a result these pressure vessel steels provide the following benefits:

- The A 508 Grade 3 and A 533 materials are in the nuclear pressure vessel section of the ASME Code for temperatures less than 371°C. Confirmatory testing is required to address issues with long-term creep and creep-fatigue behavior.
- ASME design rules in the form of a nuclear code case for limited use of these materials are available in the temperature range of 371 to 538°C.
- There is manufacturing experience in forging large-diameter, thick-ring sections, thus ensuring predictable through-thickness material properties.
- There is welding experience with these materials.
- There is an extensive irradiation response database at the normal operating temperatures incorporated in the NRC licensing guidelines (NRC Regulatory Guide 1.99) and other international standards (American Society for Testing and Materials E 900).

3.1.4 Dimensions

Although the NGNP RPV dimensions vary somewhat with the particular design, it is on the order of 20 m or more in height, 8 to 9 m in diameter and 200 to 300 mm thick. Vessels with this diameter present challenges for both fabrication and transportation to the reactor site. The likelihood of assembling the pressure vessel on site introduces potential technical difficulties. These issues are discussed in Sections 5.2–5.3, and in greater detail in the NGNP RPV Acquisition Strategy(Mizea 2008).

3.2 Plant Transient Definitions

The plant transient definitions below are borrowed from the PBMR white paper on Licensing Basis Event (LBE) selection for the purposes of discussing various scenarios.(PBMR 2006) These definitions have not yet been endorsed by the NRC, and formal definitions for a HTGR have not been determined. The frequencies of LBEs are expressed in units of events per plant-year where a plant is defined as a collection of up to eight reactor modules having certain shared systems.

3.2.1 Anticipated Operational Occurrences

An anticipated operational occurrence (AOO) encompasses planned and anticipated events. AOOs are used to set operating limits for normal operation modes and states. AOOs are event sequences with a mean frequency greater than 10^{-2} per plant-year. Startup/shutdown is an example of a relatively frequent AOO.

PBMR gives an AOO example as the loss of the power conversion system (PCS) where one of the active core heat removal systems works as specified. Since the heat is successfully removed from the core, this occurrence would have little impact on the RPV.

3.2.2 Design Basis Events

Design basis events (DBEs) encompass unplanned, off-normal events not expected in the plant's lifetime, but which might occur in the lifetimes of a fleet of plants. DBEs are the basis for the design, construction, and operation of the safety significant components (SSCs) during accidents. Separate from the design certification, DBEs are also evaluated in developing emergency planning measures. DBEs have event sequences with mean frequencies less than 10^{-2} per plant-year and greater than 10^{-4} per plant-year. Any of a number of small break scenarios in the helium pressure boundary are examples of DBEs given by PBMR.

It is likely that a loss of flow leading to a high pressure conduction cooldown (HPCC) and loss of coolant leading to a low pressure conduction cooldown (LPCC) will be defined as DBEs. The HPCC results in decay heat that is more uniformly distributed within the core and vessel than during an LPCC because the system remains at high pressure. The LPCC is typically initiated by a small leak of the primary coolant, resulting in depressurization and initiating a reactor trip. In both events, the shut-down cooling system fails to start and decay heat is removed passively by thermal radiation and natural convection from the reactor vessel.(General Atomics 2007) Peak temperatures for these events have been reported for the fuel, the control rods, and the RPV. The calculated vessel temperature for this case is well above the 371°C normal operating condition. Higher vessel temperatures resulting from an LPCC may affect the properties of A 508/A 533. These possible degradation mechanisms are considered in detail in this report and accounted for in the R&D plan.

3.2.3 Beyond Design Basis Events

Beyond Design Basis Events (BDBEs) are rare, off-normal events of lower frequency than DBEs. BDBEs are evaluated to ensure that they do not pose an unacceptable risk to the public. Separate from the design certification, BDBEs are also evaluated in developing emergency planning measures. Loss of the primary cooling system (PCS), where the reactor control system (RCS) does not shut down the reactor is the example given by PBMR. BDBEs are defined as event sequences with mean frequencies less than 10^{-4} per plant-year and greater than 5×10^{-7} per plant-year. BDBEs will not be considered in this report.

4. CURRENT STATE-OF-THE-ART

4.1 Materials Research to Date

Based on the vendor recommendations, three primary candidate alloys were considered for the RPV: low-alloy steel A 508 (UNS K12042), Fe-2¼Cr-1Mo steel (UNS K21590), and Grade 91 steel (UNS K90901). A 508/A 533 has been selected as the RPV material for the NGNP now that the gas outlet temperature has been lowered to 750°C. Only the annealed version (2¼Cr-1Mo) is incorporated in the nuclear section of the ASME Code because the properties of modified versions of the steel are not stable for extended periods at elevated temperature. It has become clear that the mechanical properties of the annealed version of 2¼Cr-1Mo steel are so poor at the temperatures of interest, that it cannot be considered for the NGNP pressure vessel. Potential welding difficulties, a lack of forging capability for the very large ring forgings required for this large RPV, difficulties with field fabrication, and limited operating experience with the Grade 91 steel contributed to its elimination. More information on these two alternate steels can be found in Appendix B.

4.1.1 Existing Data

A sufficient database is available to validate the mechanical properties of A 508/A 533 steel. Data supporting the thermal aging effects on mechanical properties is promising, but additional information on long-term aging effects is needed. Data are also needed on the effects of impure helium on the long-term corrosion and mechanical properties of the material.

4.1.2 New Results

A 508/A 533 plate has been procured and heat treated, but testing has not yet begun.

4.2 ASME Boiler and Pressure Vessel Code

The general requirements for Divisions 1 and 2 rules for construction of nuclear facility components are given in Section III, Subsection NCA of the ASME Boiler and Pressure Vessel Code (BPVC).

Section III, Division 1 of the BPVC contains specific rules for the construction of different nuclear facility components. The coverage of these construction rules by various subsections in Section III is shown in Table 2. Section III, Division 1 Code cases that were developed for elevated temperature service are listed in Table 3. NGNP RPV is a Class 1 component and the relevant rules of construction are covered under Subsections NB and Code Case N-499 for operating temperatures below 371°C, and Subsection NH for the hot vessel option.

Table 2. Applicability of rules in Section III of the ASME Code to component construction.

Subsection of Section III, Div 1, BPVC	Coverage
NB	Class 1 Components
NC	Class 2 Components
ND	Class 3 Components
NE	Class MC Components
NF	Supports
NG	Core Support Structures
NH	Class 1 Components in Elevated Temperature Service

Table 3. Division 1 Code cases that were developed for elevated temperature service.

Code Case, Section III, Div 1	Coverage
N-201-5	Class CS (Core Support) Components in Elevated Temperature Service
N-290-1	Expansion Joints in Class 1, Liquid Metal Piping
N-253-14	Construction of Class 2 or Class 3 Components for Elevated Temperature Service
N-254	Fabrication and Installation of Elevated Temperature Components, Class 2 and 3
N-257	Protection Against Overpressure of Elevated Temperature Components, Classes 2 and 3
N-467	Testing of Elevated Temperature Components, Classes 2 and 3
N-499-2	Use of A 533 Plate and A 508 Forgings and their Weldments for Limited Elevated Temperature Service

4.2.1 Section III, Subsection NB

The rules of construction in Subsection NB are based on the design-by-analysis approach in which detailed stress analysis is required to demonstrate that stress intensities through sections in the component do not exceed the allowable limits.

The Design-by-Analysis approach requires categorizing stresses into primary (load controlled), secondary (displacement controlled), and peak (local stress elevation) stresses with different stress limits. Different stress limits are used for design conditions; operating conditions grouped into Service Level A (normal), B (upset), C (emergency), and D (faulted) events; and test conditions. The various stress limits are developed to guard against the structural failure modes of ductile rupture from short-term loading, gross distortion due to incremental collapse and ratcheting, loss of function due to excessive deformation, and buckling due to short-term loadings. Additional considerations in setting the stress limits are the consequence of failure and the probability of occurrence.

The design conditions include design pressure, design temperature, and design mechanical loads. Sizing of component dimensions is established by using the design conditions. Per Subsection NCA, the design temperature is the expected maximum mean metal temperature through the thickness of the part considered for which Level A (normal) service limits are specified.

The maximum temperature limit permitted by Subsection NB for Class 1 components is 371°C (700°F) for ferritic steels. The values for the stress limit, S_m, for Subsection NB code materials are tabulated in Section II, Part D, Table 2A. Table 4 of Part D gives the stress limits for bolting materials. The Subsection NB rules shall not be used for materials at metal and design temperatures that exceed the maximum temperature limits listed in the applicability columns of these tables. These maximum temperature limits are adopted to ensure that creep deformation is negligible and does not negatively impact the fatigue performance of a component.

Fracture toughness requirements are specified in Subsection NB for pressure-retaining materials and material welded thereto. A list of materials that are exempted from the fracture toughness requirements is provided. RPV materials are not among the exempted list.

Rules that govern the deterioration of material caused by service are not covered by Subsection NB. The owner is responsible to account for such effects. Procedures for calculating the effects of neutron irradiation embrittlement of the low-alloy steels in LWRs are provided in NRC Regulatory Guide 1.99.

The criteria for design my analysis for Class 1 components covered by Subsection NB is given in a separate document(ASME 1969). A detailed summary of the Subsection NB rules is given in the Companion Guide to the BPVC(2002). A recent overview of the Subsection NB rules is given in an NRC NUREG report.(Shah, Majumdar et al. 2003)

Significance to NGNP: For the NGNP cold vessel concept, the reactor vendor needs to limit the RPV design temperature, which bounds the maximum through-wall average metal temperature for Service Level A (normal) conditions, to a maximum of 371°C (700°F) in order to apply the Subsection NB rules to the RPV design.

4.2.2 Code Case N-499-2

Code case N-499-2 was developed to provide rules of construction for two specific low-alloy steels: A 533 (UNS K12539) and A 508 forgings (UNS K12042) and their weldments for short-term temperature excursions above the temperature limit of 371°C (700°F).

Only Level B (upset), C (emergency), and D (faulted) service events are allowed. Metal temperatures are limited to 427°C (800°F) during Level B events, and 538°C (1000°F) during Level C and D events. The total duration of such temperature excursions is limited to 3,000 hours in the temperature range of 371°C (700°F) to 427°C (800°F) and 1,000 hours in the range of 427°C (800°F) to 538°C (1000°F). The number of Level C and D events above 427°C (800°F) is limited to three. Even for these few cycles, hold time effects reduce design margin. For the events permitted by this code case, Subsection NH rules of construction shall be used with the design data provided in the code case to perform design evaluations.

Significance to NGNP: The use of A 533 plates and/or A 508 forgings and their weldments as the RPV materials in the cold vessel concept permits short-term off-normal temperature excursions above 371°C (700°F). This provides design flexibility in the RPV cold vessel concept. However, elevated temperature design rules in Subsection NH have to be used for these permitted temperature excursions.

4.2.3 Section III, Subsection NH

Subsection NH provides component design rules that cover vessels, pumps, valves, and piping operating at service temperatures above those permitted in Subsection NB. Subsection NH provides numerous restrictions on the use of Subsection NB component rules, charts, and formulas for meeting the design and service limits. These component rules generally require that creep effects are not significant.

Subsection NH also provides analysis requirements for the design and location of all pressure retaining and other primary structural welds under elevated temperature service. Special examination requirements are included for welded joints. Guidance on welding and brazing qualifications is provided by reference to Subsection NB, which invokes Section IX. Subsection NH further provides special limits on weld regions by limiting the weld strains and the allowable number of design cycles for weldments to be one-half of those permitted for the parent material. The allowable time for creep rupture damage is also reduced by multiplying the stress by the weld strength reduction factor. Creep stress-rupture reduction factors for weldments are given as a function of temperature and time. Subsection NH also imposes additional examination requirements on weld joints.

Guidance on fabrication and installation, examination, and overpressure protection is also provided in Subsection NH to supplement Subsection NB. Guidance on testing is provided in Subsection NH to replace that in Subsection NB.

Similar to Subsection NB, rules that govern the deterioration of material caused by service are not covered by Subsection NH. The owner is responsible to account for such effects. Currently, design correlations to account for the environmental effects due to neutron irradiation or impure helium coolant are unavailable.

Significance to NGNP: Vendor preconceptual design reports, produced when the gas outlet temperature was targeted at 950°C, predicted the metal temperatures for the RPV designs from AREVA and GA designs exceed the Subsection NB limit of 371°C (700°F). Thus, the use of the design procedures from Subsection NH would be required. With the lower gas outlet temperature of 750°C, design procedures from Subsection NB should apply. Further information related to NH requirements can be found in Appendix B.

4.2.4 Recent Code Activities

4.2.4.1 Section III

The topic that generated the most controversy in the Section III design and analysis area is the impact of coolant environments (primary water) on fatigue performance of LWR structural materials. It has been demonstrated from laboratory data that LWR environments have a significant adverse impact on the fatigue life of reactor structural materials. Section III fatigue design curves are based on laboratory data tested in air and at ambient temperatures. Due to the inability of the ASME Section III code committees to arrive at a consensus to resolve the matter, NRC has mandated in Regulatory Guide 1.207, the so-called "Fen" approach, to account for LWR environments. This places a severe penalty on fatigue usage, which affects low-alloy steels and stainless steels.

Currently, three different Code Cases are being developed by ASME Code committees to address this issue. The first and farthest along is a somewhat revised version of the O'Donnell design curve approach. The next is a "Fen" approach, similar to but not the same as the NRC approach. The last is a procedure based on crack growth that is similar to procedures in Section XI. These Code Cases are slowly getting through the ASME Code committees, putting in place procedures for environmental effects on fatigue in LWRs.

Significance to NGNP: This issue has raised significant visibility within NRC, ASME, and the industry on environmental effects. While this is related to LWR coolant environments, it would be prudent for the NGNP project to proactively collect necessary data to demonstrate that this is not an issue for low-alloy steels in impure He environments.

4.2.4.2 Section III, Subsection NH

The task activities carried out in the DOE initiative to address ASME code issues have had significant and positive impact on the Subsection NH code rules. Further discussion of NH appears in Appendix B.

4.2.4.3 Section III, Division 5

With the recent interest in HTGRs and Liquid Metal Reactors (LMRs), a new division, the Division 5, was formed within Section III to address the Code rule needs of these high-temperature reactors. Division 5 shall be responsible for the development of rules for the HTGR and the LMR. The rules of Division 5 shall constitute the requirements for materials, design, fabrication, examination, testing, inspection, overpressure protection, certification and stamping. Division 5 shall also establish a liaison to facilitate the exchange of technical information with other Sections of the ASME Codes and Standards. It is also a long-term objective to develop rules that may be used and adopted by jurisdictional authorities.

The Code structure and rules for Division 5 are currently being developed. The vision is to have a section that contains rules common to HTGR and LMR, e.g., design by analysis, and Parts 1 and 2 that would contain specific requirements for HTGR and LMR, respectively. Such a new division would provide more flexibility for ASME to address the specific needs of HTGRs and LMRs via Code rules or Code Cases as they are developed, at either low or elevated temperatures. It can accommodate a different safety basis, and can address issues related to different coolant environment and operating conditions, as compared with the current light water reactors addressed by Division 1. It can also address different material needs, e.g., graphite components for HTGR.

As the development of a new Code structure for Division 5 would require a longer time horizon, a draft code structure that makes reference to Subsections NB, NC, NF, NG, and NH of Division 1, and relevant Code Cases, is being considered by the Code committees in order to support the short-term needs of NGNP. Code rules for graphite will be included in this short-term Code structure. Two safety classifications are envisioned: Class A, safety-related, and Class B, non-safety related with special treatment. Safety-related structures, systems, and components (SSCs) are similar to Class 1 components in Division 1. Non-safety related SSCs, with alternative safety function capability contributing to defense-in-depth, will be addressed by Code rules that are similar to Class 2 components in Division 1. Non-safety related SSCs, designated as Commercial, will be treated as balance of plant items similar to the current LWR fleet where Code rules such as Section VIII, B31, etc., will be used, as appropriate.

The target of this Code committee effort is to publish the Division 5 Code book by mid 2011, which is the next scheduled ASME publication date, to support NGNP.

Subsection NH would remain in Division 1 for the foreseeable future.

4.2.5 DOE Initiative to Address ASME Code Issues

Nuclear structural component construction in the U.S. complies with Section III of the ASME Boiler and Pressure Vessel Code, although licensing is granted by the NRC. A number of technical topics were identified by DOE, Oak Ridge National Laboratory (ORNL), INL, and ASME to have particular value with respect to the ASME Code. A collaboration between DOE and ASME Standards Technology (ST), LLC was established that addressed twelve topics in support of an industrial stakeholder's application for licensing of a Generation IV nuclear reactor. The majority of these tasks are relevant to action items within ASME Section III Subsection NH, and the nature of the topics inherently includes significant overlap, and in some cases parallel activities on the same issue.

The original twelve topics developed in the DOE Initiative to address ASME Code issues were drafted in 2006 and five topics were funded in the first round of this initiative. The remaining topics from the original list have been re-prioritized, some work scopes have been modified, and new work scopes have been added as the NGNP design has evolved. The work effort for this second phase has been completed and final reports are being prepared by the investigators. Tasks for a third phase are being developed. Two tasks were funded by NRC and administered by ASME ST, LLC in parallel to the other DOE-funded tasks. Only RPV relevant tasks are discussed here, and a number of these concern Grade 91 steel, so the discussion appears in Appendix B.

4.2.5.1 Task 2: Regulatory Safety Issues in Structural Design Criteria for ASME Section III Subsection NH

The objective of Task 2 was to identify issues relevant to ASME Section III Subsection NH, and related Code Cases that must be resolved for licensing purposes for VHTR concepts and to identify the material models, design criteria, and analysis methods that need to be added to the ASME Code to cover the unresolved safety issues.

The task report included the description of (1) NRC and Advisory Committee on Reactor Safeguards (ACRS) safety concerns raised during the licensing process of the Clinch River Breeder Reactor (CRBR), and other subsequent high-temperature reactor concepts, (2) how some of these issues are addressed by the current Subsection NH of the ASME Code; and (3) the material models, design criteria, and analysis methods that need to be added to the ASME Code and Code Cases to cover unresolved regulatory issues for very high-temperature service.

The NRC and ACRS issues which were raised in conjunction with the licensing of CRBR and the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor, and more recent NRC/RES (Office of Nuclear Regulatory Research) efforts on licensing issues for high-temperature reactors were summarized.

The CRBR license application for a construction permit was approved by NRC, subject to project R&D activities to address concerns identified by NRC and ACRS. However, due to the abrupt cancellation of the project that led to the cessation of all activities, NRC had not progressed to a point to either approve or disapprove the ASME Code Case N-47, a precursor to Subsection NH, which was the basis for the design of Class 1 pressure-retaining components for elevated temperature service for CRBR. This remains the status of Subsection NH to date.

Table 4, which is being prepared by the NRC staff in the draft form, summarizes the current understanding of the licensing concerns by the task investigators, based on the elevated temperature structural integrity issues identified by the NRC licensing review of CRBR. The order is not ranked.

Table 4. Potential licensing issues for RPVs.

Elevated temperature Structural Integrity Issues	Priority Level: (1) Issue to be of higher concern or safety significance (2) Issue addressed by ASME BPV Code or of a lower concern (3) Issue beyond scope of Subsection NH (4) Issue considered to be of no concern			
	CRBR	Pebble Bed Reactor (& cold vessel option for VHTR)	VHTR (hot vessel option)	GEN IV
#1 Transition joints	(1)	(4)	(1)	(1)
#2 Weld residual stresses	(1)	(4)	(1)	(1)
#3 Design loading combinations	(1)	(3)	(3)	(3)
#4 Creep-rupture and fatigue damage	(1)	(2)	(1)	(1)
#5 Simplified bounds for creep ratcheting	(1)	(2)	(1)	(1)
#6 Thermal striping	(1)	(2)	(2)	(1)
#7 Creep-fatigue analysis of Class 2 and 3 piping	(1)	(2)	(2)	(2)
#8 Are limits of Case N-253 for elevated temperature Class 2 and 3 components met?	(1)	(2)	(2)	(2)

Table 4. (continued).

Elevated temperature Structural Integrity Issues	Priority Level: (1) Issue to be of higher concern or safety significance (2) Issue addressed by ASME BPV Code or of a lower concern (3) Issue beyond scope of Subsection NH (4) Issue considered to be of no concern			
	CRBR	Pebble Bed Reactor (& cold vessel option for VHTR)	VHTR (hot vessel option)	GEN IV
#9 Creep buckling under axial compression – design margins	(1)	(2)	(2)	(2)
#10 Identify areas where Appendix T rules are not met	(1)	(2)	(1)	(1)
#11 Rules for component supports at elevated temperature	(1)	(2)	(2)	(2)
#12 Strain and deformation limits at elevated temperature	(1)	(2)	(4)	(1)
#13 Evaluation of weldments	(1)	(1)	(1)	(1)
#14 Material acceptance criteria for elevated temperature	(1)	(2)	(2)	(1)
#15 Creep-rupture damage due to forming and welding	(1)	(2)	(1)	(1)
#16 Mass transfer effects	(1)	(2)	(2)	(2)
#17 Environmental effects	(1)	(1), (3)	(1), (3)	(1), (3)
#18 Fracture toughness criteria	(1)	(2)	(1)	(1)
#19 Thermal aging effects	(1)	(1)	(1)	(1)
#20 Irradiation effects	(1)	(1), (3)	(1), (3)	(1), (3)
#21 Use of simplified bounding rules at discontinuities	(1)	(1)	(1)	(1)
#22 Elastic follow-up	(1)	(4)	(4)	(4)
#23 Design criteria for elevated temperature core support structures and welds	(1)	(2)	(2)	(1)
#24 Elevated temperature data base for mechanical properties	(1)	(1)	(1)	(1)
#25 Basis for leak-before-break at elevated temperatures	(1)	(4)	(1)	(1)

The task investigators provided an account of the manner in which NRC licensing issues for the structural design of VHTR and Gen IV systems are addressed in the current ASME Subsection NH and Code Cases. The creep behavior, creep-fatigue, and environmental effects are addressed in Subsection NH and Code Cases largely in terms of design criteria and allowable stress and strain values. The detailed material properties needed for cyclic finite element creep design analyses are generally not provided in the Code. The minimum strength properties given in the Code are used as anchor values for the more comprehensive material suppliers' average properties. The NRC perspective is that the Code and/or Code Cases currently do not adequately cover the material behavior under cyclic loads in the creep regime, and creep-fatigue, and creep-rupture interaction effects.

It is noted that for CRBR, the guidance on inelastic finite element analyses, external to the Code, was provided in NE F9-5T, Nuclear Standard, Guidelines and Procedures for Design of Class 1 Elevated Temperature Nuclear System Components.

Subsection NH has rules for the design of welded joints separated into categories A through D. The permissible types of welded joints and their dimensional requirements are specified. Paragraph 3353 of Subsection NH provides analysis requirements for the design and location of all pressure retaining welds operating at temperatures where creep effects are significant. Reduction factors for creep stress rupture are given as a function of time and temperature. Permissible weld metals are limited and special examination requirements are imposed.

Probably the most restrictive Subsection NH requirement for welds is that the inelastic accumulated strains are limited to one-half the allowable strain limits for the base metal. This has forced designers to keep welds out of high stress areas. The allowable fatigue at weldments is limited to one-half the design cycles allowed for the base metal. The allowable creep rupture damage at weldments is limited in Subsection NH by requiring that the rupture strength be reduced by the weld strength reduction factor when determining the time-to-rupture. The Code also imposes additional examination requirements on Category A through D welded joints. The adequacy of these and other Code weldment structural design requirements has been questioned by the NRC, even for the temperatures currently covered, which are lower than the VHTR and Gen IV High-Temperature Systems.

The task report also provided a discussion on the material models, design criteria, and analysis methods that need to be added to the ASME Code and Code Cases to cover unresolved regulatory issues for very high-temperature service. The identified needs are summarized below.

Needs for material creep behavior, creep-fatigue and environmental effects include:

- Extension of temperature and/or time for current code materials to cover VHTR conditions
- New code materials to cover VHTR applications
- Appropriate databases for calculating fatigue, creep, creep-fatigue, and stress corrosion cracking (SCC) lifetimes, including environmental effects of impure helium and crevice concentration
- Aging behavior of alloys
- Degradation by carburization, decarburization, and oxidation
- Sensitization of austenitic alloys and weldments.

Needs for design methods include:

- Treatment of connecting pipe as a vessel for code application
- In-service inspection plans and methods
- Probabilistic risk assessment methodologies for vessels, pipes, and components.

4.2.5.1.1 Structural integrity of welds

Because of the importance of potential elevated temperature cracking of weldments, NRC wanted the designer to account for potential creep strain concentrations due to metallurgical notch effects. Subsection NH does not include methods for analyzing the effects of varying properties between the base metal, weld metal, and Heat Affected Zone (HAZ), or even how to determine these properties after welding and post weld heat treatment. Moreover, NRC expressed concern with potential early crack initiation at the inside wall surface in the HAZ, how crack propagation can be quantified, and the stability of the remaining uncracked wall section.

Methods of evaluating such weldment integrity issues and the corresponding safety margins are needed in the ASME Code to satisfy regulatory concerns. These methods will require:

- Materials models
- Cyclic creep analysis methods
- Crack growth analyses
- Remaining ligament enhanced creep stability analysis methods.

Such methods essentially parallel Section XI flaw evaluation methods which are only applicable below the creep regime.

The NRC has also requested confirmation of the creep rupture, creep-fatigue, and interaction evaluation procedures at weldments, accounting for load sequence effects.

4.2.5.1.2 Development and verification of simplified design analysis methods

Existing simplified design analysis methods have proven to be very valuable in providing assurance of structural integrity in the moderate creep regime and have been used in France, Germany, Japan, and the U.S. for this purpose. These methods can be further developed to include higher temperatures where creep effects control the design margins, and where structural discontinuity notches and defects need to be evaluated. Cyclic finite element creep analysis results are difficult to trust without having comparative results of simplified design analysis methods.

4.2.5.1.3 Verification testing

Verification testing was carried out on representative structural features of CRBR as part of the licensing effort. VHTR temperatures are much higher than the CRBR temperatures; consequently, additional verification testing is desired to validate the elevated temperature designs of VHTRs.

Such tests include validation of the material models needed to perform cyclic creep analyses, and validation of the finite element software capabilities to handle cyclic creep at structural discontinuities, elastic follow-up, creep rupture at notches, weldment behavior, and possibly flaw tolerance evaluation methods.

4.2.6 NRC-sponsored Tasks

4.2.6.1 HTGR Roadmap

A task to develop a HTGR roadmap for Code rule development was sponsored by NRC and managed by ASME Standards Technology (ST), LLC. The objective was to develop a guide to the R&D and Code development tasks that should be considered in developing rules for HTGRs. The HTGR Roadmap was divided into Phases 1 and 2. Phase 1 was further divided into Parts A and B. Phase 1A corresponded to the development of interim design rules, by referencing existing code rules, when appropriate, to support the short-terms needs of NGNP. The focus of Phase 1B was on the development of a complete set of rules for the design and operating conditions that are being proposed for NGNP. Phase 2 corresponded to the development of Code rules for the nth-of-a-kind NGNP that are expected to operate at higher temperatures.

This task is currently in the final comment resolution phase and will be published by ST, LLC when completed.

4.2.6.2 NDE and ISI

This task involves the development of a technical basis document to update and expand codes and standards for non-destructive evaluation (NDE) and in-service inspection (ISI) methods and monitoring in HTGRs. The scope of work consists of two parts. Part 1 is involved with a technology assessment of advanced monitoring, diagnostic and prognostics systems that can support regulatory needs for HTGRs. Past experience from the current LWR industry is included. Technology gaps where future research is needed should also be identified. Part 2 is involved with identifying appropriate new construction and in-service NDE methods for examination of metallic materials. Studies should be based upon NGNP-relevant considerations.

The work effort for this task has been completed. Final report will be published by ASME ST, LLC.

5. RESEARCH ISSUES

This section addresses issues with code qualification of RPV materials. It also addresses application of the ASME code to the design of RPV. Detailed test plans to address the code compliance/licensing issues are given in Section 6.

5.1 Code Compliance/Licensing

The NGNP RPV needs to be designed using the ASME Section III Code rules. If the RPV wall temperature can be maintained at a sufficiently low temperature (≤371°C = 700°F) with only limited excursions as defined under Code Case N-499, Subsection NB of the Code can be used. Otherwise Subsection NH must be applied; however, the maximum design lifetime data provided in Subsection NH is ≈34 yrs (300,000 h) for the steel, which is less than the NGNP design lifetime of 60 yrs.

5.1.1 Baseline Case

A 508/A 533 steels are ASME Code approved for Class 1 nuclear components and Subsection NB rules apply. With a gas outlet temperature of 750°C, the inlet temperature will likely be low enough that the use temperature of the RPV should be ≤371°C.

There is extensive experience with these alloys as RPV materials in the U.S. LWR fleet of commercial plants. Fabrication and welding are not expected to represent significant technical issues and the irradiation effects are well known in the temperature range of LWR vessels. Although NGNP temperatures are expected to differ from LWR temperatures, the fluence is estimated to be roughly an order of magnitude less. Therefore, studies of irradiation effects on long-term creep and creep-fatigue are not planned at this time.

5.1.2 NRC Structural Integrity Issues

The ASME BPVC Section III, Division 1, Subsections NB, NC, ND, NE, NF, and NG, are incorporated by reference into Section 50.55a of Title 10 of the Code of Federal Regulations (10 CFR 50.55a) as the rules of construction for LWR nuclear power plant components. Section III Code Cases, which provide alternatives to the Section III, Division 1 Code requirements under special circumstances, are reviewed by the NRC staff and its findings are published in the regulatory guides. The acceptable and conditionally acceptable Section III Code Cases listed in the regulatory guides are then incorporated by reference into 10 CFR 50.55a.

While the rules of construction of the ASME Code and Code Cases cover many aspects related to structural integrity, they do not explicitly address issues such as degradation of properties due to service conditions or environment. However, these structural integrity issues are highlighted in the Code and it is the responsibility of the "Owner" to demonstrate to NRC that these additional issues are adequately addressed.

Due to a lack of VHTR operational experience in using A 508/A 533 pressure vessel steels at ~350°C for 60 years and under impure helium environment, confirmatory data on thermal aging and environmental effect are required to support licensing. Efforts are proposed in Section 6.1 to address these issues.

In contrast, the behavior of irradiated A 508/A 533 is well known based on about forty years of operating experience in LWRs. The base materials and weld metals have good fracture toughness in the unirradiated condition, and major factors in irradiation sensitivity for these materials are well understood.

5.1.2.1 Issues Related to Code Case N-499

The creep data that supported Code Case N-499 were mainly based on data from A 533B rolled plates. Confirmatory tests are planned in Section 6.1.3.7 to extend the database in order to build higher confidence in ensuring the structural integrity of the NGNP RPV.

5.1.2.1.1 Negligible Creep

Current consideration of the “cold” vessel option by reactor vendors appears to be based on the logical assumption that if the temperature is within the bounds of Subsection NB (371°C for RPV materials) then creep effects do not need to be considered. While this is undoubtedly true for typical LWR operating temperatures, it may not be true for the higher NGNP operating temperature and a 60-year design life, and in particular, with the consideration of localized high stress areas. The reason is that creep deformation depends on stress, time, and temperature and does not have a strict temperature cut-off that separates creep from non-creep regimes. This could potentially affect the primary stress limits and impact RPV sizing. The potential impact could also likely show up at structural or metallurgical discontinuities. If there is a real problem in the RPV due to creep effects, it is not likely to show up until the component is well into its operating life.

Such a concern was prompted by a recent statistical re-analysis(Sham and Eno 2008) of the A 533B database reported in the data package(Brinkman and transmitter 1990) that was used to support the development of Code Case N-499. This database consists of 51 creep data from four heats of A 533B plates, with temperatures ranging from 371°C to 593°C and applied stresses from 7 MPa to 517 MPa. Both rupture data and run-out data (where tests were stopped before rupture occurred) are contained in the database. The rupture data were less than 3,500 hours while one run-out datum at 482°C and 207 MPa reached ~11,500 hours and another at 593°C and 28 MPa reached ~26,000 hours. Only the rupture data were used in establishing the rupture stress and time-dependent primary stress limits for Code Case N-499 as the objective of the code case was to develop code rules for limited, short-term temperature excursions beyond the Subsection NB temperature limit of 371ºC.

The Code Case N-499 database is the only currently available data that could provide limited information in framing the issue of whether or not the consideration of creep is needed for the RPV in the “cold” vessel option. A statistical methodology similar to that employed in analyzing the Alloy 617 and Alloy 230 creep data(Eno, Young et al. 2008) was used to re-analyze the Code Case N-499 creep data. This method allows the inclusion of run-out data in the statistical analysis, and hence makes full use of the information from the database. Best estimate and 95% confidence limit lower bounds were developed for stress to one-percent strain, stress to onset of tertiary creep, and stress to rupture. Extrapolations to 100,000 hours, 300,000 hours, and 600,000 hours in the temperature range of 340°C to 390°C were made. The Subsection NH procedure for establishing the time-dependent primary stress limit S_t was used and the results are shown in Figure 1 and Figure 2. The Subsection NB time-independent primary stress limit S_m is also included in these two figures for reference.

It should be noted that sizing methods in Subsections NB and NH are somewhat different. In Subsection NB, the wall thickness is based on the design condition while Subsection NH uses both design condition (based on 100,000-hour allowables as in Section VIII) and operating conditions. Further, in Subsection NB the limit on P_m is S_m and on $P_L + P_b$ is 1.5 S_m, while in Subsection NH the limit on P_m is S_{mt}, and on $P_L + P_b$ is 1.5 S_m, and in addition, the limit on $P_L + (P_b/1.25)$ is S_t. Since the Subsection NH limit of S_{mt} is the lesser of S_m and S_t, the limits on the general membrane stress intensity P_m from Subsections NB and NH can be compared by considering the relative magnitudes of S_m and S_t.

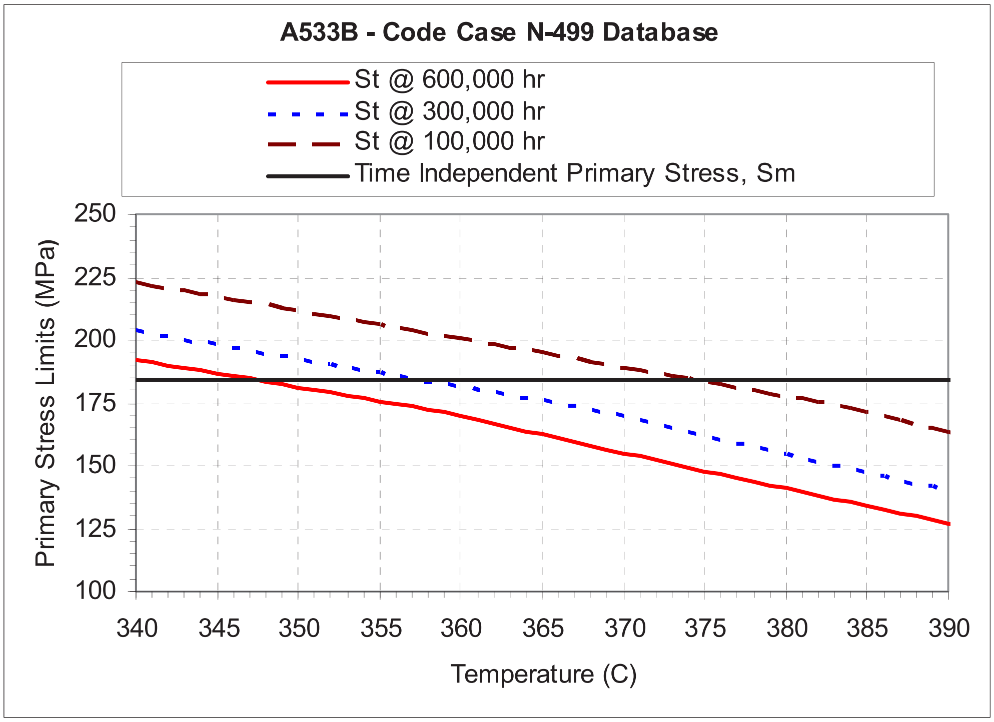


Figure 1. Extrapolated time-dependent primary stress limits for A 533B rolled plate.

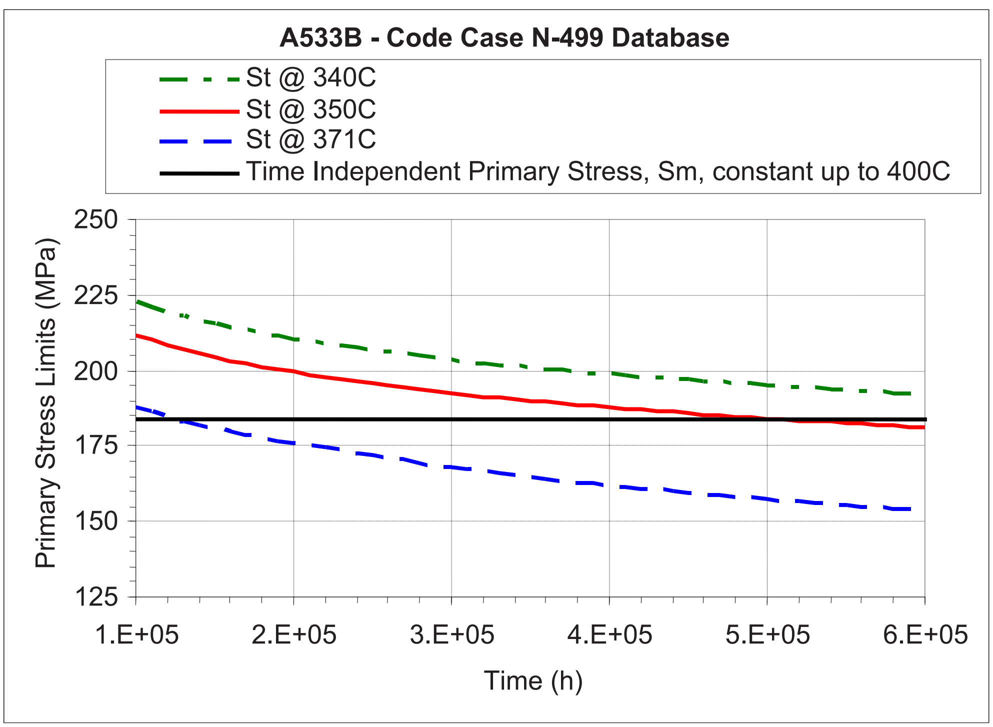


Figure 2. Extrapolated time-dependent primary stress limits for A 533B at 340°C, 350°C, and 371°C.

The extrapolated results in the plots show that the time-independent primary stress limit S_m is lower, and hence more conservative, than the time-dependent primary stress limit S_t for times below 500,000 hours at 350°C, and slightly non-conservative relative to S_t for times between 500,000 and 600,000 hours. For a temperature of 340°C, the extrapolated values of S_t are higher than those for S_m in the range of time considered; hence, the use of S_m is conservative for at least up to 600,000 hours. At the Subsection NB cut-off temperature of 371°C, S_m is non-conservative for lifetimes beyond ~125,000 hours.

Figure 3 shows the extrapolated lower bound creep rupture stress at 340°C, 350°C, and 371°C as a function of time. One of the negligible creep criteria in Subsection NH, Article T-1324 is:

$$\sum_i \frac{t_i}{t_{id}} \leq 0.1$$

where t_i is total duration of time during the service lifetime that the metal is at temperature T_i and t_{id} is the rupture time given by the lower bound rupture stress that is equal to $\left.S_y\right)_{T_i}$, the minimum yield strength at temperature T_i, multiplied by a factor s which is equal to 1.5. The factor s is based on a factor of 1.25 to bring the minimum yield strength at temperature to the average value and a factor of 1.2 to account for cyclic hardening of austenitic stainless steel in order to approximate the achievable stress state at geometric discontinuities.

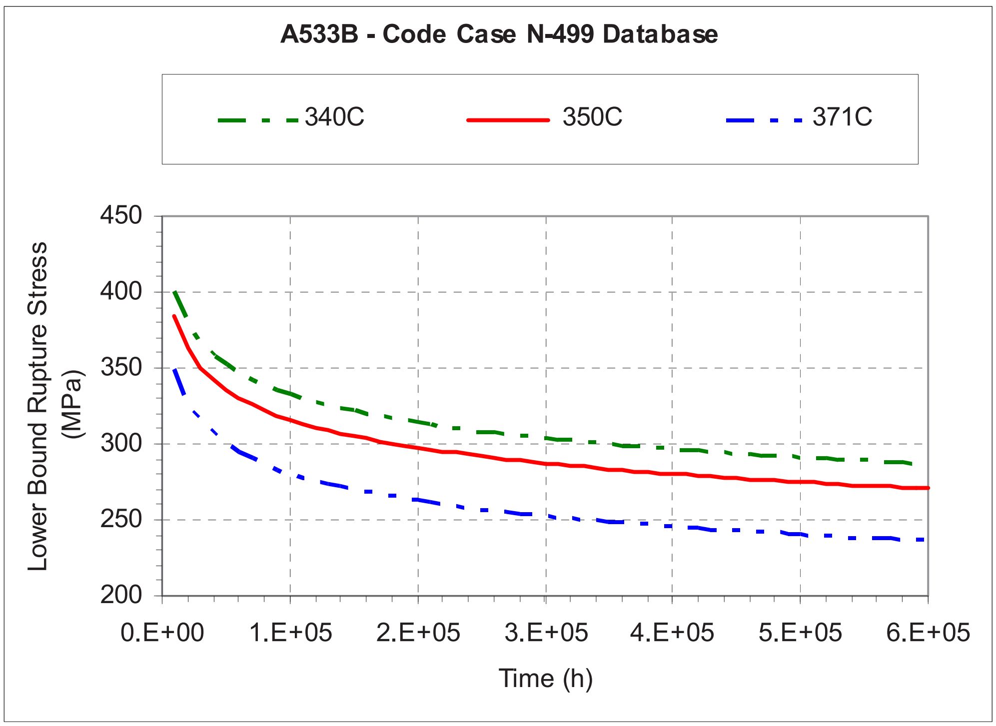


Figure 3. Extrapolated lower bound creep rupture stress for A 533B at 340°C, 350°C, and 371°C.

The lower bound rupture stress that is required to evaluate the rupture time t_{id} in the negligible creep criterion as a function of the factor s is tabulated in Table 5. It is seen from Table 5 and the curves in Figure 3 that the rupture time t_{id} obtained from the rupture stresses given in Table 5 would not satisfy the negligible creep criterion of Subsection NH for t_i equal to 60 years.

Table 5. Lower bound rupture stress given by factor *s* multiplied by $\left.S_y\right)_{T_i}$.

Factor *s*	Lower Bound Rupture Stress to Determine t_{id} (MPa)		
	340°C	350°C	371°C
1	287	285	281
1.25	358	356	351
1.5	430	428	421

It is noted that the current re-analysis of the Code Case N-499 database gives values of lower bound creep rupture stress at 371°C that are much lower than those given in Code Case N-499-2 for the expected minimum rupture stress. The comparison is shown in Table 6. An inspection of the Code Case N-499 database showed the following two ruptured data in Table 7.

Table 6. Comparison of rupture stress predictions from Code Case N-499-2 and statistical re-analysis.

Time to Rupture (h)	Code Case N-499-2 (Table 4)		Statistical Re-analysis	
	Rupture Stress at 371°C (ksi)	Rupture Stress at 371°C (MPa)	Rupture Stress at 371°C (ksi)	Rupture Stress at 371°C (MPa)
1,000	77	531	62	425
10,000	70	483	51	349

Table 7. Rupture data at 371ºC from Code Case N-499 database.

Heat No.	Measured Creep Rupture Time (h)	Applied Stress at 371°C	
		ksi	MPa
5795	956	65	448
9583A	1004	75	517

It is concluded from the results shown in these two tables that the values of the creep rupture stress given in Code Case N-499-2 are non-conservative relative to the rupture data at 371°C, and the results from the statistical re-analysis give adequately conservative lower bounds to the rupture data. This provides a level of confidence in the results presented in Figure 1 to Figure 3 from the statistical re-analysis. As the emphasis of Code Case N-499 was on creep-fatigue rules at higher temperatures, it could very well be that the discrepancy at the lower temperatures was over looked. As Code Case N-499 is an important code case for the NGNP "cold" vessel option, testing and re-evaluation of the Code Case are recommended to ascertain the design information is adequately conservative.

To put the results presented in Figure 1 to Figure 3 into perspective, it is well to recognize that the extrapolations are based on a small database with relatively short-term creep data as compared with the extrapolated times of 500,000 to 600,000 hours. Thus definitive conclusions could not be drawn based on these results. However, the results shown in these figures do underscore the need to develop longer-term confirmatory creep rupture data, and to follow-up on the creep-fatigue issue to ensure that creep effects are properly accounted for in design for very long operating lives.

In light of the above results, the areas that need particular attention for A 508/A 533 steels and their weldments for NGNP RPV application are creep-rupture and fatigue damage, which is closely related to the definition of when creep effects become significant. This issue is discussed further for Grade 91 steel in the "hot" vessel option covered in Appendix B.

5.1.2.2 Creep-Fatigue and Ratcheting

Simplified bounds for creep ratcheting, strain and deformation limits, and use of simplified boundary rules at discontinuities are related issues that also need to be considered. To address these issues, it is important to understand how ratcheting, strain limits and creep fatigue affect the integrity of a structure differently.

Creep-fatigue is a localized issue whereas ratcheting is based, conceptually, on the interaction of the core stress and linearized through-wall stress (in the Bree model). Also, creep-fatigue is a direct failure mode whereas ratcheting is not. Cyclic life can, conceptually, be influenced directly by creep rupture damage at lower temperatures, whereas ratcheting would most likely be influenced by degraded tensile properties due to aging, or potentially cyclic softening, either from long-term exposure at normal operation and/or short-term, higher temperatures. Within the negligible creep regime, Subsection NH relies on $3\overline{S}_m$ where the limit is based on S_m and the relaxation strength to ensure shakedown. Relaxation strength tests are proposed in Section 6.1.3.2.

There is a potential risk that the wall thickness might not be sufficient near the end of RPV design life if long-term test data do show that creep-fatigue is an issue. One problem in developing creep data at the lower temperatures is the long test times involved. A typical new reactor project cycle would generally involve the following sequential events:

1. RPV sizing per Subsection NB rules based on time-independent primary stresses
2. Placement of long-lead forging orders per sizing dimensions
3. Detailed design analyses that would include fatigue analysis.

Reactor vendors must take creep-fatigue into their design consideration early on. Subsection NB, article NB 3222.4 (d) provides guidelines on conditions that would exempt components from fatigue analysis for cyclic service.

No creep-fatigue data were generated from A 533B plates in support of the Code Case N-499 development. The intersection point in the creep-fatigue interaction diagram of the code case was presumably taken from 2¼ Cr-1 Mo steel. Creep-fatigue tests for the conditions covered by the code case are proposed in Section 6.1.3.3 to confirm the adequacy of the intersection point.

5.1.2.2.1 Elevated Temperature Excursions

Another code/licensing issue related to the use of Code Case N-499 deals with off-normal, limited temperature excursions beyond 371°C. N-499 permits excursions up to 427°C for a total of 3000 accumulated hours, while excursions beyond 427°C and within 538°C are limited to three occurrences. There is a concern that creep-fatigue damage accumulated during these excursions would degrade the creep rupture strengths of the base metals and their weldments, if it is concluded that creep effects need to be considered at the normal operating temperature of 350°C. Test programs are proposed in Sections 6.1.3.1 and 6.1.3.7 to address creep rupture and creep-fatigue, and the issues of whether or not the material properties at normal operating temperatures are compromised by short-term, higher temperature off normal conditions. Data on the relaxation strength under these conditions will also be developed (see Section 6.1.3.2).

5.1.2.3 NRC Issues List

Code Case N-47, a precursor to Subsection NH, had been reviewed by NRC during the application of a construction permit by the CRBR Project in the late 70s and early 80s. The licensing process was stopped due to the abrupt cancellation of the CRBR project. However, a list of safety related issues were identified by NRC. NRC also performed a pre-application safety evaluation of the PRISM LMR design in the mid 90s and similar issues were raised. These NRC issues have been documented in Task 2 of the DOE/ASME ST collaboration and the task report was summarized in 4.2.5.

It is important to note that there are added burdens in licensing NGNP, as Subsection NH and Code Case N-499 have not been approved by NRC.

The CRBR safety related issues identified by NRC are discussed with respect to the “cold” and “hot” vessel options separately. The corresponding assessment and recommended actions for the cold vessel option are given in Table 8. It is noted that the NRC issues list is not ranked relative to the severity of the concerns.

5.2 Procurement and Fabricability

These topics are only addressed briefly in this report to frame the discussion of the related R&D needs. The current schedule for the NGNP plant requires that the design be completed by calendar year 2015. The selection of material for the NGNP RPV is one of the critical items to meet the schedule.

5.2.1 Transportation

Transportation issues are discussed in detail in the Acquisition Strategy.(Mizea 2008) The maximum diameter of ring that can be delivered to the INL site is considerably less than 8 m. This will drive the need to fabricate the vessel on site from rolled plate or forged sections, or result in a decision to site the reactor in a location with direct access to a seaport for delivery of large forged components by barge.

5.2.2 Forging/Rolling

In order to fabricate the huge RPV, vendors are needed who can produce seamless rings (forged) or plates (forged or rolled), achieving uniform through-thickness properties with the candidate materials. Japan Steel Works has capability and experience with forging 8 m diameter rings from A 508 pressure vessel steel. They are willing to forge sections for NGNP; however, the lead time is substantial and an early decision to purchase these forgings will be necessary.

At present, several vendors around the world have substantial experience in fabrication of RPVs from A 508/A 533. Procurement of a vessel of this material may depend primarily on the availability of a vendor to meet the schedule and not on the technical issues with the material.

5.2.3 On-site Fabrication

Fabricating a vessel from conventional A 508/A 533 steel would be somewhat complicated compared to a fossil fired plant due to the heavy section thickness. However, there appear to be few issues that arise from this process that will require R&D.

Table 8. NRC "cold" vessel issues list from CRBR review – assessment relative to the "cold" and "hot" vessel options.

Issue #	Structural Integrity Issues identified by NRC for CRBR	"Cold" Vessel Option	
		Assessment	Required Actions
1	Transition joints (i.e., dissimilar metals)	Effects could be minimized if materials are a close match in thermal expansion coefficient. There is some experience in LWR to draw on, e.g., pressurizer nozzles at a slightly lower temperature. However, this could be a possible long-term problem with the long NGNP design lifetime.	This issue needs to be addressed if such transition joints are present in the down-selected vendor design concept.
2	Weld residual stresses	Weld residual stress is considered in Section XI flaw evaluation procedure in connection with in-service inspection. This is a lower level concern.	Information on through thickness weld residual stress profiles for A 508/A 533 steels is available in connection with LWR applications. Any additional data required for NGNP application is judged to be confirmatory in nature and will be proposed when is necessary.
3	Design loading combinations	This is an owner/regulator issue that is beyond the scope of Subsection NB.	This is an action for the reactor vendor.
4	Creep-rupture and fatigue damage	Creep and creep-fatigue interaction are not the applicable failure modes for Subsection NB. However, this could be a potential problem. The combination of high localized stress levels and very long-term operation could cause localized cyclic creep damage below the Subsection NB to Subsection NH temperature boundary. This possibility is not addressed in the current Subsection NB rules because creep is presumed to be insignificant and Subsection NH does not apply below 371°C.	Creep rupture tests are proposed in Section 6 to address this potential problem.
5	Simplified bounds for creep ratcheting	Creep ratcheting is not considered in Subsection NB. However, ratcheting can likely be influenced by degraded tensile properties due to aging, or, potentially, cyclic softening, either from long-term exposure at normal operation and/or short-term, higher temperatures.	Confirmatory testing to determine tensile and cyclic properties of materials aged for long-term at normal operating and higher temperatures is proposed in Section 6.

Table 8. (continued).

Issue #	Structural Integrity Issues identified by NRC for CRBR	"Cold" Vessel Option	
		Assessment	Required Actions
6	Thermal striping	Thermal striping has been a concern for Pares. Input from reactor vendors on the potential threat from thermal striping due to NGNP thermal transients is needed.	No action is recommended at this point. Future testing will be proposed if thermal striping is judged to be a threat.
9	Creep buckling under axial compression design margins	The buckling design margins are high and creep is unlikely to be an issue at low permitted stress levels. NGNP has thicker RPV wall than the thin-walled fast breeder reactor vessels.	No action is required.
10	Identify areas where Appendix T rules are not met	Issue is not relevant to "cold" vessel option. However, based on the discussion in Section 5.1.1, further investigation is needed as the negligible creep criterion of Subsection NH might not be satisfied for the full design life and temperature. This will affect failure modes such as creep and creep-fatigue which are "local" in nature (e.g., at stress riser).	Testing is recommended in Section 6 to address issues related to Code case N-499.
12	Strain and deformation limits at elevated temperature	This is not an issue for the "cold" vessel option for sustained loading. For sustained loading this is a through-thickness issue, thus the allowable primary stress limits from Subsection NB would limit creep, if any, to insignificant levels. However, at localized high stress areas it is a potential problem as discussed under Issue #5.	No action is required. However, see issues #5 for localized, high stress areas.
13	Evaluation of weldments	Weldment evaluation is considered in the flaw evaluation procedure of Section XI in connection with in-service inspection. Can draw on LWR practice.	Effort to assess fatigue crack growth data for A 508/A 533 at 350°C is proposed in Section 6. Test will be proposed if there is a data gap.
14	Material acceptance criteria for elevated temperature	This probably is not a concern but long-term data at 350°C is needed to verify and to support licensing.	Long-term confirmatory creep test is proposed in Section 6.

Table 8. (continued).

Issue #	Structural Integrity Issues identified by NRC for CRBR	"Cold" Vessel Option	
		Assessment	Required Actions
17	Environmental effects	NGNP helium environment is not covered by specific code rules in Subsection NB. This is an owner/regulator issue.	Effect of NGNP helium environment on allowable stresses and fatigue performance needs to be investigated. Also, residual damage after off normal temperature excursions needs to be investigated.
18	Fracture toughness criteria	Fracture performance of A 508/A 533 steels and associated weldments in air is well characterized.	Confirmatory fracture toughness data on materials exposed to NGNP helium environment are needed to support licensing. Similar data are needed for materials that are thermally aged for a long time as well as materials that have received creep-fatigue damage since some temperature excursions beyond 371°C, but within the limits of Code Case N-499, are anticipated.
19	Thermal aging effects	Data from surveillance materials consisting of A 508 Class 2, Mn-Mo-Ni Linde 80 submerged-arc weld, and A 533B, exposed to temperature of about 260°C for 209,000 hours show that there is no statistically significant degradation on impact property and upper shelf and transition region toughness. However, the intended NGNP application is at higher temperature (~350°C) and longer time (60 years). Thermal aging is a time-at-temperature process. While this is not judged to be a significant concern, there is no LWR experience to draw on under these conditions. A potential effect would be degradation of yield and tensile strength which could compromise design margins, particularly for off normal or faulted conditions near the end of the design life. It could also impact facture toughness, particularly at the end of design life.	Confirmatory long-term thermal aging tests are proposed in Section 6 to support licensing.

Table 8. (continued).

Issue #	Structural Integrity Issues identified by NRC for CRBR	"Cold" Vessel Option	
		Assessment	Required Actions
20	Irradiation effects	There is an extensive database for LWR incorporated in the NRC licensing guidelines (NRC Regulatory Guide 1.99) and other international standards (ASTM E 900). Neutron irradiation embrittlement is less severe at the higher normal operating temperature of the cold vessel option.	Effort on obtaining confirmatory irradiation data is needed to support licensing.
21	Use of simplified bounding rules at discontinuities	Covered by Subsection NB. Can draw on LWR practice. However, as for #5, creep rate data at yield or near yield should be obtained to confirm that this is not a concern.	Action from #5 applies here.
22	Elastic follow-up	Not a significant concern at low temperature for the "cold" vessel option. Possible long-term problem at local stress risers.	This is a lower-tier concern. Effort will be proposed in the future.
24	Elevated temperature data base for mechanical properties	Code case N-499 permits limited short-term temperature excursions beyond 371°C for Service Level B, C, and D.	Confirmatory creep rupture test is proposed in Section 6.
25	Basis for leak-before-break at elevated temperatures	This is closely related to Issues #13 and #18. Can draw on LWR practice.	J-R curve testing covering temperatures that include the temperature limits of Code Case N-499 is proposed in Section 6.

5.3 Welding

The RPV will be much larger than the current LWR vessels, requiring field welding of either ring forgings or plates of the selected material. While ring forgings are preferred, since they would result in fewer welds (no longitudinal welds) to assemble the RPV, this may not be possible. Welding procedures may include pre- and post-weld heat treatment in the field.

Pressure vessels of low-alloy steels have been fabricated and used in U.S. LWRs and there is substantial experience in welding of both plates and rings to form the vessels. Vessels with wall thicknesses varying between 203 to 254 mm (8 to 10 inch) and diameter-to-thickness ratios of ~20 have been fabricated for Pressurized Water Reactors (PWR). In contrast, Boiling Water Reactor vessels with much larger diameter and a wall thickness of 152-mm (6-inch) have been fabricated.

Both rolled A 508 and forged A 533B steels were investigated to great extents in U.S. nuclear reactor programs for LWR RPV applications. Extensive field data suggest that current welding procedures and vendor welding practice are adequate to support NGNP RPV applications.

5.4 Damage Sources

5.4.1 Radiation

A sufficient database exists of radiation effects on the A 508/A 533 steels and their weldments from LWR experience. The NGNP lifetime fluence is anticipated to be approximately an order of magnitude lower than that for LWR vessels. The Westinghouse preconceptual design provides a maximum end-of-life fast fluence of 2×10^{18} n/cm^2 (>0.1 MeV); this estimate is based on PBMR documents. This is a very low fluence, approximately an order of magnitude less than that for the 40-year end-of-life fluence for current LWR RPVs. Assuming that the radiation exposure for the RPV is relatively low for all the NGNP conceptual designs, irradiation embrittlement is not anticipated to be a major issue based on current knowledge accumulated for 250–300°C irradiation temperatures for these steels. The temperature at which the exposure occurs in the NGNP is expected to be above that for LWR vessels and there is less concern about the potential for embrittlement at moderately higher temperatures. Therefore, an extensive irradiation program is not planned for these materials or weldments at this time. However, if analysis indicates areas where the RPV temperature is lower, this issue may need to be re-examined.

5.4.2 Oxidation/Corrosion

Data for oxidation and corrosion of alloys in NGNP helium atmosphere are very limited. Long-term aging in air will be required to investigate the potential for environmental degradation on the exterior of the vessel. Experimental characterization of the behavior in NGNP He will be required in both quasi-static environments for scoping studies and using He with the expected levels of impurities at velocities on the order of 50 m/s that are thought to characterize flow in some sections of the NGNP. The potential for particle erosion at high velocity must also be examined.

5.4.3 Emissivity

For the passive heat removal system to function properly, it is necessary that the reactor pressure vessel be able to radiate heat to the external environment under accident conditions. While a target emittance has not yet been finalized, it is necessary to have a stable, high-emissivity layer on the proposed pressure vessel material. Haque et al.(Haque, Feltes et al.) assumed emittance of 0.6 to 0.8 in their sensitivity analysis of the peak fuel temperature for depressurized cooldown (inlet/outlet temperature 490/850°C). Preliminary results, shown in Figure 4, indicate that an emittance of > 0.85 can be established in air for SA 508.(Sridharan and Anderson 2010) While, the emissivities of steel can be increased by the formation of an oxide film,(Pawel, McElroy et al. 1986) the conditions under which this film can be created and the stability of this film in air (including the effect of humidity) at operating temperature needs to be established. In addition the effects of field welding on the emissivity layer must be evaluated.

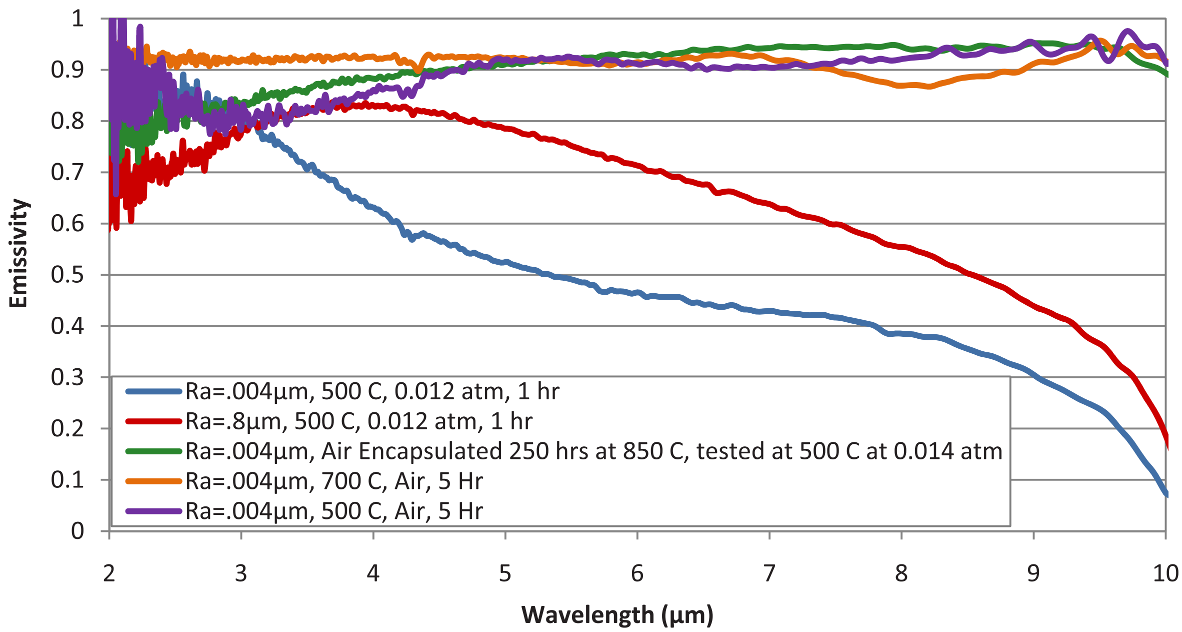


Figure 4. Effect of environment and temperature on the emissivity of SA 508 steel.

Additionally, unlike LWRs, the interior surface of the reactor vessel needs an effective emissivity layer in order to absorb the internal radiant energy, which is then radiated to the external environment, especially under accident conditions. It will be even more difficult to establish an emittance of >0.85 on the interior of the RPV, should such a high value be required, because of the much lower oxygen partial pressure and humidity in the NGNP helium environment. Thus, an understanding of the formation and stability of this emissivity layer film in the operating environment needs to be established. Again, the effects of field welding on the formation and stability of this layer need to be evaluated.

To ensure the capability of passive heat removal throughout the design lifetime of 60 years, the long-term stability of the emissivity layers must be established. While there is significant LWR experience with A 508/A 533, the higher temperature involved in the NGNP requires an evaluation of the rate of formation and long-term stability of the emissivity layer on the outer surface of the reactor pressure vessel, which is exposed to air. There is considerably less information available for the proposed chrome variant reactor vessel materials at the proposed temperatures; however, standard tabulations of emissivity values suggest that alloy composition does not significantly impact the emissivity of oxidized steel. In fact, most steels with surface oxidation have emissivity values that are acceptable for the NGNP. Testing of emissivity of candidate materials for the NGNP is currently ongoing at University of Wisconsin under a NERI project.

5.5 Inspection

As noted previously, Section III, Division 1, Subsection NB of the ASME BPVC applies to the design and fabrication of the RPV (see Table 2). Article NB-2000, “Material,” in this subsection specifies mechanical testing and examination requirements for material acceptance while NB-5000, “Examination,” specifies examinations required during fabrication and assembly. Article NB-6000, “Testing,” specifies required pressure testing of the completed components and systems.

Other than special instructions and acceptance criteria included in the NB code, nondestructive examinations are performed using the requirements stated in Section V.

Examinations are divided into surface inspections performed using visual, liquid penetrant, magnetic particle, or eddy current and volumetric inspections using radiography or ultrasonic techniques. Current code provides acceptance criteria that define what type and size of indications are deemed relevant and ultimately rejectable as shown in Table 9.

Table 9. Article NB-5300 Inspection Acceptance Standards.

Sub Article of Subsection NB, Section III, Div 1, BPVC	Acceptance Standard
NB-5320	RADIOGRAPHIC
NB-5330	ULTRASONIC
NB-5331	Fabrication
NB-5340	MAGNETIC PARTICLE
NB-5341	Evaluation of Indications
NB-5342	Acceptance Standards
NB-5350	LIQUID PENETRANT
NB-5351	Evaluation of Indications
NB-5352	Acceptance Standards

The primary circumferential and longitudinal welds (Categories A, B, and C, Figure NB-3351-1) call for radiographic volumetric examination and surface examination using liquid penetrant or magnetic particle (Article NB-5200). Attachment welds for branch, piping, and nozzles (Category D weld joints, Figure NB-3351-1) require radiographic or ultrasonic examination and surface examination using liquid penetrant or magnetic particle.

Radiographic examination of thick sections is viable using portable linear accelerators (6 MeV can penetrate up to 406 mm of steel) when there is sufficient room to set up and meet code sensitivity requirements (HESCO in Alameda, CA, is a commercial company that performs code based radiographic inspections of thick section components). However, Section V, T-274.2 allows a maximum geometric unsharpness of 1.78 mm for material thickness greater than 101.6 mm. This means a defect on the order of 1.78 mm can be missed. Similarly, ultrasonic inspections of the attachments welds use calibration blocks that contain sensitivity notches having dimensions based on test specimen thickness. As a result, the size of defect deemed relevant during ultrasonic examination changes with thickness. Surface inspections, which are not affected by specimen thickness, utilize the acceptance criteria as stated in the code.

In general, code inspections can be performed for the fabrication of new reactor pressure vessels using A 508 and A 533 materials up to the possible thicknesses of 250 mm. However, the applicability of the BPVC will be determined by the design of the pressure vessel, section thickness, and weld joint designs, as well as the operating conditions that define critical flaw size. If actual critical flaw sizes are smaller than what is defined in the code as being rejectable, application of the code does not assure integrity. It is also important to consider inspectability issues such as weld joint design, access, etc., that may prevent reliable inspections from being performed during fabrications or later during in-service monitoring.

6. RESEARCH AND TECHNOLOGY PLAN

6.1 Required Actions for Code/Licensing Issues

This section discusses the detailed plans to address the code and licensing issues highlighted in Section 5.

6.1.1 Material Procurement

Approximately 1400 kg of A 508/A 533 178-mm-thick steel plate has been procured for material testing. The material has been both forged and rolled during its processing, resulting in dual certification for ASTM A508 Grade 3 Class 1 and ASME SA533 Grade B Class 1. The dual certification has reduced the projected number of test specimens substantially from that predicted in the 2008 (Rev. 0) version of this report.

All procured material is from a single heat. Many of the test matrices require test specimens from two or three heats; therefore, material from additional heats will be needed to complete required testing. It is unknown if additional heats procured will also have the dual certification. Test matrices in this revision of the plan assume that it will. If not, additional test specimens may need to be added to characterize the properties of the two grades of steel.

6.1.2 Welding

Welding these conventional pressure vessel steels is mature technology. There is no additional weld procedure development proposed for the NGNP program, and acceptable weldments are adequately defined in the ASME Code.

6.1.2.1 Define Testing Schemes for Prototypical Weldments

Test specimens for welds can be obtained from weld cradles (deposited weld metal), weld plates from procedural qualification, and weldments obtained by welding together base metals of prototypical section thickness. Testing schemes for prototypical A 508/A 533 weldments are well established for LWRs. All proposed tensile, creep, creep-fatigue, and fracture toughness tests for A 508/A 533 welds in support of the more challenging NGNP condition are based on weldments manufactured from prototypical section thickness. The submerged arc welding (SAW) process will be used. Originally, shielded-metal arc welding (SMAW) was included in the welding test matrices. This type of welding is typically used in repair operations and it is not necessary for design to characterize this process. Elimination of SMAW has reduced the required amount of testing substantially.

6.1.2.2 Post-Weld Heat Treatment

During construction of a RPV, stress relief heat treatments are typically applied after welding the conventional pressure vessel steels to produce a stress relieved state before operation. This is mature technology and there is no additional development required for the NGNP program.

In order to develop property data, the practice in LWR is to select a time that would bound the total stress relief time, and subject the as-received RPV material to a “simulated” stress relief (SSR) heat treatment. Any degradations such as thermal aging or irradiation embrittlement occur subsequent to this stress relief treatment; therefore, SSR will be applied to all A 508/A 533 metals and associated weldments before specimens are machined. This will ensure that the properties measured are appropriate for RPV applications.

In accordance with the ASME III NB requirements (Table NB-4622.1-1) summarized in Table 10, all RPV welds are to receive a post-weld heat treatment with a holding time commensurate with the thickness. Any weld repair will require an additional cycle of the heat treatment. Assuming the RPV plate will be 181 mm (7.128 in) thick, a post-weld heat treat time of 3.28 hours is required based on this table. Allowing for 6 cycles of post-weld heat treatment, the SSR has been set at 607 ± 13°C (~1125°F) for a total of 19 hours, 40 minutes. The ASME code also limits the rate of heating and cooling above 425°C to no more than 220÷plate thickness °C/hr., but not less than 56°C/hr. The SSR treatment average selected 66°C /hr during heating and 77°C/hr during cooling.

Table 10. Summary of mandatory post-weld heat treatment according to ASME Table NB-4622.1-1.

	Minimal holding time for nominal section thickness (t, inches)		
Temperature Range (°F)	≤½	½ < t ≤ 2	2 < t ≤ 5
1100–1250	30 minutes	1 hour/inch	2 hours + 15 minutes/inch over 2 inches

6.1.3 Testing

Details of the required testing to support the use of A 508/A 533 for the RPV within the operating conditions assumed for this plan are contained in a series of tables in Appendix A. A summary table (Table 11) is included here; discussion of the motivation and anticipated results of this testing is contained in the sections below. Data from this project will be archived in the NGNP Data Management Analysis System (NDMAS).

Table 11. Summary of test plan for A 508/A 533 material – cold vessel.

Test Matrix Table (A1-A33) Shown in detail in Appendix A	Specimen Type	Number Specimens	Environment	Temperature (°C)	Sample Condition Time (h)	Notes
A1 Creep Rupture Tests	Creep	54	Air	350-390	SSR	3 heats of each product form
A2 SAW Cross-Weld Creep Rupture Tests	Creep	18	Air	350-390	SSR	
A3 Creep Rupture Tests in NGNP He	Creep	6	NGNP He	350-390	SSR	
A4 SAW Creep Rupture Tests of Cross-Welds in NGNP He	Creep	6	NGNP He	350-390	SSR	
A5 Creep Rupture Tests on Fatigue-SRX Damaged Material	Creep	6	Air	350-390	SSR Damaged[1]	[1]By fatigue-SRX 180 cycles, 427°C with 1% strain range, tensile hold 1000 min.
A6 SAW Creep Rupture Tests of Cross-Welds on Fatigue-SRX Damaged Material	Creep	6	Air	350-390	SSR Damaged[1]	[1]By fatigue-SRX 180 cycles, 427°C with 1% strain range, tensile hold 1000 min.
A7 Long-Term Qualifying Creep Rupture Tests	Creep	4	Air	350	SSR	[2]Test to Rupture. [3]Stop test at 200,000 h if not ruptured
A8 SAW Long-Term Qualifying Creep Rupture Tests	Creep	4	Air	350	SSR	[2]Test to Rupture. [3] Stop test at 200,000 h if not ruptured
A9 Relaxation Strength to Address Creep Effects	SRX	32	Air	350-538	SSR	
A10 SAW Relaxation Strength to Address Creep Effects	SRX	8	Air	350-538	SSR	

Table 11. (continued).

Test Matrix Table (A1-A33) Shown in detail in Appendix A	Specimen Type	Number Specimens	Environment	Temperature (°C)	Sample Condition Time (h)	Notes
A11 Relaxation Strength Tests of fatigue-SRX Damaged A 508/A 533	SRX	32	Air	350-538	SSR Damaged[1]	Initial stress 214-414 MPa 2 heats of each product form [1]By fatigue-SRX 180 cycles, 427°C with 1% strain range, tensile hold 1000 min.
A12 Relaxation Strength Tests of Fatigue-SRX Damaged SAW Cross-Welds	SRX	8	Air	350-538	SSR Damaged[1]	Initial stress of 214 or 276 MPa [1]By fatigue-SRX 180 cycles, 427°C with 1% strain range, tensile hold 1000 min.
A13 Fatigue-SRX Tests	Fatigue-SRX	21	Air	350	SSR	Both tensile and compressive hold tests
A14 SAW Fatigue-SRX Tests	Fatigue-SRX	15	Air	350	SSR	Both tensile and compressive hold tests
A15 Baseline Tensile Tests	Tensile	24	Air	20-550	SSR	
A16 Baseline Tensile Tests of SAW Cross-Welds	Tensile	12	Air	20-550	SSR	
A17 Tensile Tests of Fatigue-SRX Damaged A 508/A 533	Tensile	24	Air	20-550	SSR Damaged[1]	[1]By fatigue-SRX 180 cycles, 427°C with 1% strain range, tensile hold 1000 min.
A18 Tensile Tests of Fatigue-SRX Damaged Cross-Welds	Tensile	12	Air	20-550	SSR Damaged[1]	[1]By fatigue-SRX 180 cycles, 427°C with 1% strain range, tensile hold 1000 min.
A19 Tensile Tests of Thermally Aged A 508/A 533	Tensile	24	Air	20-550	SSR Aged[4]	[4]Aged at 450°C for 20,000 h
A20 Tensile Tests of Thermally Aged Cross-Welds	Tensile	12	Air	20-550	SSR Aged[4]	[4]Aged at 450°C for 20,000 h

Table 11. (continued).

Test Matrix Table (A1-A33) Shown in detail in Appendix A	Specimen Type	Number Specimens	Environment	Temperature (°C)	Sample Condition Time (h)	Notes
A21 Tensile Tests of Long-Term Thermally Aged A 508/A 533	Tensile	24	Air	20-550	SSR + Aged[5]	[5]Aged at 450°C for 70,000 h
A22 Tensile Tests of Long-Term Thermally Aged SAW Cross-Welds	Tensile	12	Air	20-550	SSR + Aged[5]	[5]Aged at 450°C for 70,000 h
A21 Baseline Toughness Measurements (Master Curve T_o and J-R Curve) Base Metals	Compact tension	84	Air	20-518[6]	SSR	2 heats of each product form [6]Some test temperatures TBD
A24 Toughness Measurement (Master Curve T_o and J-R Curve) for Fatigue-SRX Damaged Material	Compact tension	84	Air	20-538[6]	SSR Damaged[1]	2 heats of each product form [1]By fatigue-SRX 180 cycles, at 427°C with 1% strain range, tensile hold 1000 min. [6]Some test temperatures TBD
A25 Toughness Measurement (Master Curve T_o and J-R Curve) for Thermally Aged Material	Compact tension	84	Air	20-538[6]	SSR Aged[4]	2 heats of each product form [4]Aged at 450°C for 20,000 h [6]Some test temperatures TBD
A26 Toughness Measurement (Master Curve T_o and J-R Curve) for Thermally Aged Material	Compact tension	84	Air	20-538	SSR Aged[7]	2 heats of each product form [6]Some test temperatures TBD [7]Aged at 450°C for 70,000 h
A27 SAW Baseline Toughness Measurements (Master Curve T_o and J-R Curve) Weldment	Compact tension	42	Air	20-538[6]	SSR	[6]Some test temperatures TBD

Table 11. (continued).

Test Matrix Table (A1-A33) Shown in detail in Appendix A	Specimen Type	Number Specimens	Environment	Temperature (°C)	Sample Condition Time (h)	Notes
A28 SAW Baseline Toughness Measurements (Master Curve T_o and J-R Curve) Weldment HAZ	Compact tension	42	Air	20-538[6]	SSR	[6]Some test temperatures TBD
A29 Cyclic Stress-Strain Curves for A 508	Cyclic	75	Air	20-538	SSR	3 heats of forged A 508
A30 Creep Rupture Tests in Air	Creep	36	Air	350-593	SSR	3 heats of F and 1 heat of RP
A31 SAW Cross-Weld Creep Rupture Tests	Creep	12	Air	350-593	SSR	
A32 Fatigue-SRX Tests	Fatigue-SRX	36	Air	427-538	SSR	Both tensile and compressive hold tests
A33 SAW Cross-Weld Fatigue-SRX Tests	Fatigue-SRX	15	Air	427-538	SSR	Both tensile and compressive hold tests

6.1.3.1 Creep Effects on RPV Under Normal Operating Conditions

As discussed in Section 5.1.2.1, the Code Case N-499 database does not provide adequate creep rupture data to address the issue of whether or not creep effects for the RPV need to be considered under normal a operating temperature of 350ºC. Longer-term creep rupture data are needed and testing is proposed to address this issue. The base metal and weldment creep rupture test plans are developed to generate data in time to support conceptual and preliminary design (CPD) activities, and final design/licensing efforts. To meet this goal, parallel test efforts are required.

Testing to support CPD activities is given in Tables A1 and A2 of Appendix A for base metals and weldments, respectively. The test temperatures are 350, 371, and 390°C, to cover the normal operating temperature of 350°C, and to provide some acceleration of the creep process. These are air tests. Two heats are required for the base metal test plan (A1). The welds to be tested are cross-welds and creep test specimens should be machined from thick section welds. The longest average creep rupture time is estimated to be about two years. This estimation is based on the best estimate statistical correlation (i.e., without accounting for data scatter) developed from the Code Case N-499 database, as discussed in Section 5.1.2.1.1.

Environmental creep rupture tests are also planned to assess the potential impact of NGNP helium on the creep rupture strengths of A 508/A 533 steels and their weldments. The test matrices are shown in Tables A3 and A4. The temperature and applied stress conditions are designed to be a subset of those used in the air tests of Tables A1 and A2 so that an assessment of the potential impact of NGNP helium on the creep rupture strengths can be made.

Limited temperature excursions above the subsection NB cut-off temperature of 371°C but within the time-and-temperature restrictions of Code Case N-499 could occur for the RPV as discussed in Section 5.1.2.2.1. The creep specimens in the SSR condition will be given a "damage" treatment by subjecting the specimen to strain-controlled cycling, with a tensile strain hold of 1000 minutes, for 180 cycles at 427°C. This will accumulate creep-fatigue damage for about 3000 hours. Since the stress relaxes during the strain hold, this form of cycling is called fatigue-stress relaxation. Creep rupture tests are then performed on the "damaged" specimens per the temperature and applied stress conditions given in Tables A5 and A6 for the base metal and weldments, respectively.

The tests listed in Tables A1 through A6 can be completed in about two years if testing capacity is available to test all of the testing in parallel. The data assembled from these tests will be used to assess whether the creep effects need to be considered for the RPV during normal operations.

Longer-term creep rupture tests in air are proposed in Tables A7 and A8 for the A 508/A 533 steels and their weldments, respectively. Both 5-year and 20-year data are targeted for these tests at 350°C. The temperature and applied stress combinations are selected based on the best estimate of the statistical model developed from the Code Case N-499 database. The tests to generate the five-year data can be performed using standard laboratory equipment but the 20-year creep rupture tests are best performed in a dedicated Long-term Aging Laboratory. The five-year data will be used to check the adequacy of the extrapolation based on the statistical analysis of the shorter-term data developed from Tables A1 and A2. This is to support final design/licensing. The 20-year tests are designed to lead the reactor operations. This would provide lead time to develop mitigation strategy if an unanticipated rupture event occurs in one of the tests.

6.1.3.2 Relaxation Strengths

As discussed in Section 5.1.2.2, the relaxation strength is required to provide the limit to ensure that shakedown takes place so ratcheting does not occur. Stress relaxation curves will be developed from the testing listed in Tables A9 and A10. The relaxation strengths will be determined at 350, 371, 427, and 538°C, covering the normal operating temperature and the temperatures permitted in Code Case N-499. Longer relaxation durations are selected for the two lower temperatures as the relaxation process is slower at those temperatures, while shorter durations are selected for the two higher temperatures. Adjustment to the initial stress and relaxation period will be made before the commencement of the tests if necessary.

Tables A11 and A12 provide the test conditions for determining the relaxation strengths for creep-fatigue damaged base metals and their associated weldments. The test conditions are the same as those in Tables A9 and A10. The same "damage" treatment of strain-controlled cycling, with a tensile strain hold of 1000 minutes, for 180 cycles at 427°C will be used. Any change to the initial stress and relaxation period for the tests in Tables A9 and A10 will also be made in these tests so that comparison of the relaxation strengths of "undamaged" and "damaged" materials can be made.

6.1.3.3 Creep-Fatigue Tests

To assist the assessment of whether creep needs to be considered for the RPV under normal operating temperature, creep-fatigue tests at 350°C are proposed in Tables A13 and A14. These tests will measure fatigue-stress relaxation behavior for A 508/A 533 steels and their associated weldments. The strain hold times will be adjusted after initial results are obtained, if deemed necessary. The continuous cycling tests discussed in Section 6.1.3.6 will be compared with these tests with strain hold times to provide additional information on the assessment of the creep effects at 350°C.

6.1.3.4 Effects on Tensile Properties

Thermal aging and creep-fatigue damage accumulated during short-term high-temperature excursions would potentially degrade tensile properties and thus impact the ratcheting resistance. Tensile tests are proposed to determine the baseline tensile properties in the SSR condition (Tables A15 and A16), the creep-fatigue damaged condition (Tables A17 and A18), and the thermally aged conditions (Tables A19, A20, A21, and A22).

Each table is will generate test data at 20, 150, 250, 350, 450, and 550°C. Two heats of A 508/A 533 steels are involved in all the base metal tests. The damaged condition is the same as described in Section 6.1.3.1. Two thermal aging protocols, 20,000 hours at 450°C and 70,000 hours at 450°C, are employed. The aging temperature of 450°C is selected to accelerate the aging process. Adjustment to this aging condition will be made, if needed.

In addition to providing data to assess the potential tensile property degradation, these tensile data will be needed in the analysis of the fracture toughness data described in Section 6.1.3.5.

6.1.3.5 Fracture Toughness

A 508/A 533 steels and their associated weldments are body-centered cubic materials that exhibit ductile-brittle transition behavior. In the transition and lower shelf regions where the temperatures are low, the fracture mechanism is a brittle failure mode of transgranular cleavage, while the fracture mechanism changes to a void nucleation and growth type of ductile tearing mode at higher temperatures. In the brittle regime, the toughness of the material can be characterized by the "Master Curve" reference temperature T_0 while the resistance to ductile tearing and tearing instability are characterized by J_{IC} and the resistance curve, or the J-R curve. It is reiterated that the ASME Code does not provide detailed guidance in dealing with fracture and this issue is traditionally handled between NRC and the nuclear plant "owner" for LWRs. Fracture toughness and J-R curve have been studied extensively for these LWR pressure vessel materials. However, the LWR temperatures of interest are 300°C and below and these data do not cover the conditions that the NGNP RPV would likely encounter.

There are two fracture issues of concern for the NGNP RPV in the low temperature, brittle regime. First, very long-term thermal aging accumulated during the normal operations at 350°C for the ~60 year service life may result in embrittlement resulting in potential negative impact on the fracture toughness. This is of concern for transients (such as shutdown) towards the end of design life of the reactor, as it takes a very long time to accrue thermal embrittlement. Second, creep-fatigue damage accumulated during the short-term high-temperature excursions that are permitted by Code Case N-499. This also is primarily of concern towards the latter part of the reactor design life, as more creep-fatigue damage is accumulated.

The high-temperature toughness, as characterized by J_{IC} and the J-R curve, decreases as the temperature is increased. The decrease is small to about 400°C and it is expected to drop more rapidly as the yield and tensile strengths of these materials drop more significantly beyond this temperature. This could be a potential threat to NGNP RPV as Code Case N-499 permits short-term high-temperature excursions up to 473°C and 538°C with certain restrictions. Thus J_{IC} and J-R curve data are needed to address this issue which is related to the leak-before-break issue on the NRC concerns list discussed in Section 5.1.2.

Testing efforts to address these issues are proposed in Tables A23 to A26 for A 508/A 533 and their associated weldments. Two heats are included. The testing protocols for these four tables are the same, but the material conditions are different. Table A-23 will generate baseline data with no pre-conditioning except the SSR. Tables A24, A25, and A26 correspond to pre-conditioning of creep-fatigue damage, thermal aging for 20,000 hours at 450°C, and 70,000 hours at 450°C, respectively. The creep-fatigue damage protocol is the same as described in Section 6.1.3.1. For each table, both Master Curve T_0 , and J-R curves at 20, 50, 350, 427, and 538°C, are determined. Due to the constraint in the amount of material from creep-fatigue pre-conditioning, 0.5T disk-shaped compact tension specimens will be used. If it is determined at the commencement of this test program that more pre-conditioned materials can be made available, the use of 0.6T or 0.7T disk-shaped compact tension specimens will be considered.

The details for the testing of weldments are given in Tables A27 and A28. For Table A-27 the crack is aligned within the weldment, and with the crack propagation direction to be the same as the welding direction. For the testing in Table A-28, the crack is also propagated in the direction of welding, but is aligned within the HAZ. Testing is in the SSR condition, with the intent of providing baseline toughness values for the weldment and HAZ. Any degradation in the base metal toughness due to creep-fatigue damage (A24) and thermal embrittlement (A 25 and A26) will be applied to the baseline toughness value of the weldment and HAZ.

As noted in the Section 6.1.3.4, tensile data are required to process the toughness data. The heats of base metal and weld consumables, and the pre-conditioning for the disk-shaped compact tension specimens, shall be the same as those used in the tensile testing described in Tables A15 to A22. If circumstances arise that this is not the case, tensile tests for the same material heats and material conditions as the disk-shaped compact tension specimen will be required.

6.1.3.6 Cyclic Stress-Strain Curve

Cyclic stress-strain curves are required to determine the cyclic response. Cyclic hardening, cyclic softening, or cyclic neutral material behavior is important in establishing the negligible creep criterion. Cyclic stress-strain curves have been determined for A 533B (rolled material) to support the Code Case N-499 effort and they are available for use. Table A-29 proposes testing to develop cyclic stress-strain curves at 20, 350, 371, 427, and 538°C for A 508 steel (forged material). Three heats of A 508 are involved.

6.1.3.7 Testing to Support Re-evaluation of Code Case N-499

As described in Section 5.1.2.1, data that supported this code case were from A 533B (rolled) steel. However, the intersection point of the creep-fatigue damage interaction diagram was not determined using A 508/A 533 and associated weldment creep-fatigue data. Thus, in order to address these database issues, tests are proposed in Tables A30 to A33. Short-term creep rupture tests that cover the applicable durations of the code case for base metal and weldment are presented in Tables A30 and A31. Test temperatures are 350, 371, 427, 482, 538, and 593°C, selected to match the Code Case N-499 database. Creep-fatigue tests for base metals and weldment are proposed in Tables A32 and A33. Strain hold times of 30, 150, and 300 minutes will be applied during strain-controlled cycling, to determine if increasing hold time will degrade the fatigue performance. These data will also be used to verify the intersection point of the creep-fatigue interaction diagram in Code Case N-499.

6.2 Cost

Table 12 details costs associated with sample preparation and testing for A 508/A 533. Table 13 details the estimated total cost for testing and analysis for A 508/A 533.

Table 12. Costs associated with sample preparation and testing for A 508/A 533.

Test Type	# Tests	Product Form	Sample Form	Cost/ Sample[a]	Sample Cost[b]	Time/ Test (H)	Total Test Time	Post Test Time[c]	Testing Cost[d]	Grand Total
Tensile	148	plate	tensile	150	43,200	5	720	720	216,000	259,200
Creep	148	plate	tensile	150	43,200	7	1,008	1,008	302,400	345,600
Fracture Toughness	420	plate	CT	300	252,000	8	3,360	3,360	1,008,000	1,260,000
Fatigue	75	plate	fatigue	200	30,000	7	525	525	157,500	187,500
Fatigue-Relaxation	87	plate	fatigue	200	34,800	7	609	609	182,700	217,500
Stress Relaxation	80	plate	tensile	150	24,000	7	560	560	168,000	192,000
Long-term Creep	4	plate	SMT	150	2,400	15	120	120	36,000	38,400
Damaged Samples	172					7	1,204	1,204	361,200	
Welded	224					1	224	224	67,200	
Subtotals	958				429,600				2,499,900	**2,928,600**

a. Does not include cost of raw material.

b. Multiplied by a factor of 2.0 to account for drafting, pre-test purchasing, inspections, welding, and aging.

c. Post-test metallurgical, fracture, and data analysis.

d. Average burdened labor cost of $150/h used.

Table 13. Estimated total cost for testing and analysis for A 508/A 533.

FY09-FY14	*(All values in FY10 burdened $)*	Cost ($)	Subtotals
Material Cost			948,600
Raw Material		100,000	
Cost to Machine Samples [a]		429,600	
Consumables		200,000	
Adder for Purchasing (30%)		218,880	
Labor for Testing			3,249,900
Test Method Development and Validation		250,000	
Mechanical Property Testing a		2,499,900	
Corrosion Testing		500,000	
Equipment Purchase			4,322,500
Load Frames		1,500,000	
Fixtures		75,000	
Furnaces		250,000	
Repair, Upgrade, and Refurbishing		1,500,000	
Adder for Purchasing (30%)		997,500	
Other Labor			4,000,000
Analysis and Reporting		900,000	
Engineering Design Support		600,000	
Project Engineer		900,000	
ASME Code Interface		1,600,000	
Subtotal for Labor			7,249,900
Subtotal for Materials & Equipment			5,271,100
Subtotal			12,521,000
Quality Assurance (10%)		1,252,100	
Program Management (10%)		1,252,100	
Total			15,025,200

a. Value from Table 12.

7. REFERENCES

1. Mizea R. E., INL, *Next Generation Nuclear Plant Reactor Pressure Vessel Acquisition Strategy*; INL/EXT-08-13951; April 2008.
2. INL, *Next Generation Nuclear Plant Pre-Conceptual Design Report*; INL/EXT-07-12967 Revision 1; November 2007.
3. AREVA NP Inc., *NGNP with Hydrogen Production Preconceptual Design Studies Report Executive Summary*; 12-9052076-000; June 2007.
4. Caspersson S. A., Westinghouse Electric Company LLC, Nuclear Power Plants, *NGNP and Hydrogen Production Preconceptual Design Report Executive Summary Report;* NGNP-ESR-RPT-001 Revision 1; June 2007.
5. General Atomics, *Preconceptual Engineering Services for the Next Generation Nuclear Plant (NGNP) with Hydrogen Production*; PC-000544; 7/10/2007.
6. Koekemoer W., *Westinghouse Electric Company LLC, Next Generation Nuclear Plant Report on Update of Technology Development Roadmaps for NGNP Steam Production at 750°C-800°C*; NGNP-TDI-TDR-RPT-G- 00003 Revision 0; April 2009.
7. Crozier J., General Atomics, *Engineering Services for the Next Generation Nuclear Plant (NGNP) with Hydrogen Production Test Plan-Steam Generator for 750°C Reactor Outlet Helium Temperature*; 911174, Revision 0; December 16, 2008.
8. Saurwein, General Atomics, *Technology Development Road Mapping Report for NGNP with 750°C Reactor Outlet Helium Temperature*; PC-000586/0; November 2009.
9. Weaver K. D., Idaho National Laboratory, *NGNP Engineering White Paper: Reactor Type Trade Study;* INL/EXT-07-12729.
10. Sherman S. R., Idaho National Laboratory, INL, *NGNP Engineering White Paper: NGNP Project Pre-Conceptual Heat Transfer and Transport Studies*; INL/EXT-07-12730; April 2007.
11. Vandel D. S., Idaho National Laboratory, INL, *NGNP Engineering White Paper: Primary and Secondary Cycle Trade Study;* INL/EXT-07-12732; April 2007.
12. Schultz R. R., Idaho National Laboratory, INL, *NGNP Engineering White Paper: Power Conversion System Trade Study;* INL/EXT-07-12727; April 2007.
13. GA Technologies Inc., DOE, *Reactor Core Subsystem Design Description (Modular HTGR Plant)*; DOE-HTGR-86-036; July 1987.
14. Shenoy A. S., General Atomics, *Gas Turbine - Modular Helium Reactor (GT-MHR) Conceptual Design Description Report*; RGE-910720; July 1996.
15. Turner R. F., et al., “Annular Core for the Modular High-Temperature Gas-Cooled Reactor (MHTGR),” *Nuclear Engineering and Design,* Vol. 109, 1988, p. 227-231.
16. Crozier J., General Atomics, *Test Plan – Reactor Pressure Vessel for 750°C Reactor Outlet Helium Temperature*; 911173 Revision 0; June 11, 2009.
17. Hittner D., “The European Programme of Development of HTR/VHTR Technology,” *Proceedings of the Conference on High Temperature Reactors HTR-2004*, *Beijing, China*, *22-24 September 2004*, International Atomic Energy Agency, Vienna, Austria: v., p. 1-17.

18. AREVA Federal Services, LLC, *NGNP Technology Development Road Mapping Report;* TDR-3001031-002; April 2009.

19. Natesan K., et al., Argonne National Laboratory, *Materials Behavior in HTGR Environments;* ANL-02/37 NUREG/CR-6824; February 2003.

20. Fazluddin S., et al., "The Use of Advanced Materials in VHTR's," *2nd International Topical Meeting on High Temperature Reactor Technology, Beijing, China, September 22-24, 2004: v.*

21. Ion S., et al. "Pebble Bed Modular Reactor the First Generation IV Reactor to Be Constructed," http://www.world-nuclear.org/sym/2003/matzie.htm.

22. Matzner D., "PBMR Project Status and the Way Ahead," *Proceedings of the 2nd International Topical Meeting on High Temperature Reactor Technology, Beijing China, September 22-24, 2004*, International Atomic Energy Agency: v., p. 1-13.

23. Koster A., et al., "PBMR: A Generation IV High Temperature Gas Cooled Reactor," *Proc. Instn Mech. Engrs, J. Power and Energy*, *2004*: v. Vol. 218, Part A.

24. PBMR, PBMR, *Licensing Basis Event Selection for the Pebble Bed Modular Reactor*; PBMR-040251.

25. Sections III and VIII, Division 2, *Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis In ASME*, 1969.

26. *Companion Guide to the ASME Boiler & Pressure Vessel Code*. New York, NY: ASME Press, 2002.

27. Shah V. N., et al., Argonne National Laboratory, *Review and Assessment of Codes and Procedures for HTGR Components;* NUREG/CR-6816; June 2003.

28. Sham T.-L. and Eno D. R., Re-Analysis of Code Case N-499 Sa-533 Grade B, Class 1 Creep Data Preliminary Analysis, to Be Reported, 2008, unpublished work.

29. Brinkman C. R. and transmitter, Data Package for Sa-533 Grade B, Class 1 Plates, Sa-508 Class 3 Forgings, and Their Weldments ORNL, Oak Ridge, TN, 1990, personal communication with ASME: A.W. Dalcher (SG-ETC) M. G. S.-S., SC-II), R. I. Jetter (SG-ETD, SC-D).

30. Eno D. R., et al., ASME, *A Unified View of Engineering Creep Parameters*; PVP2008-61129.

31. Haque H., et al., "Thermal Response of a High Temperature Reactor During Passive Cooldown under Pressurized and Depressurized Conditions," *September 22-24, 2004*: v.

32. Sridharan K. and Anderson M., Emissivity Data, 2010, unpublished work.

33. Pawel R. E., et al., Oak Ridge National Laboratory, *The Emittance of an Oxidized 304 Stainless Steel;* ORNL/TM-9858.

Appendix A

Appendix A

Test Matrices for A 508/A 533 Steels

Appendix A

Table A-1. A 508/533B Creep Rupture Tests in air to Address Creep Effects on Cold Vessel.

Spec. Type	Spec. #	Material	Product Form (~250 mm thick)	Mat Cond.	Heat	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture Time (h)	LB Rupture Time (h)
Creep	1	508/533	Plate	SSR	Ht-1	air	350	552	1238	33
Creep	2	508/533	Plate	SSR	Ht-1	air	350	552	1238	33
Creep	3	508/533	Plate	SSR	Ht-1	air	350	517	4151	128
Creep	4	508/533	Plate	SSR	Ht-1	air	350	517	4151	128
Creep	5	508/533	Plate	SSR	Ht-1	air	350	483	15128	440
Creep	6	508/533	Plate	SSR	Ht-1	air	350	483	15128	440
Creep	7	508/533	Plate	SSR	Ht-1	air	371	517	1154	39
Creep	8	508/533	Plate	SSR	Ht-1	air	371	517	1154	39
Creep	9	508/533	Plate	SSR	Ht-1	air	371	483	3752	148
Creep	10	508/533	Plate	SSR	Ht-1	air	371	483	3752	148
Creep	11	508/533	Plate	SSR	Ht-1	air	371	448	13316	490
Creep	12	508/533	Plate	SSR	Ht-1	air	371	448	13316	490
Creep	13	508/533	Plate	SSR	Ht-1	air	390	483	1147	45
Creep	14	508/533	Plate	SSR	Ht-1	air	390	483	1147	45
Creep	15	508/533	Plate	SSR	Ht-1	air	390	448	3667	169
Creep	16	508/533	Plate	SSR	Ht-1	air	390	448	3667	169
Creep	17	508/533	Plate	SSR	Ht-1	air	390	414	12871	539
Creep	18	508/533	Plate	SSR	Ht-1	air	390	414	12871	539
Creep	19	508/533	Plate	SSR	Ht-2	air	350	552	1238	33
Creep	20	508/533	Plate	SSR	Ht-2	air	350	552	1238	33
Creep	21	508/533	Plate	SSR	Ht-2	air	350	517	4151	128
Creep	22	508/533	Plate	SSR	Ht-2	air	350	517	4151	128
Creep	23	508/533	Plate	SSR	Ht-2	air	350	483	15128	440
Creep	24	508/533	Plate	SSR	Ht-2	air	350	483	15128	440
Creep	25	508/533	Plate	SSR	Ht-2	air	371	517	1154	39

Table A-1. (continued).

Spec. Type	Spec. #	Material	Product Form (~250 mm thick)	Mat Cond.	Heat	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture Time (h)	LB Rupture Time (h)
Creep	26	508/533	Plate	SSR	Ht-2	air	371	517	1154	39
Creep	27	508/533	Plate	SSR	Ht-2	air	371	483	3752	148
Creep	28	508/533	Plate	SSR	Ht-2	air	371	483	3752	148
Creep	29	508/533	Plate	SSR	Ht-2	air	371	448	13316	490
Creep	30	508/533	Plate	SSR	Ht-2	air	371	448	13316	490
Creep	31	508/533	Plate	SSR	Ht-2	air	390	483	1147	45
Creep	32	508/533	Plate	SSR	Ht-2	air	390	483	1147	45
Creep	33	508/533	Plate	SSR	Ht-2	air	390	448	3667	169
Creep	34	508/533	Plate	SSR	Ht-2	air	390	448	3667	169
Creep	35	508/533	Plate	SSR	Ht-2	air	390	414	12871	539
Creep	36	508/533	Plate	SSR	Ht-2	air	390	414	12871	539
Creep	37	508/533	Plate	SSR	Ht-3	air	350	552	1238	33
Creep	38	508/533	Plate	SSR	Ht-3	air	350	552	1238	33
Creep	39	508/533	Plate	SSR	Ht-3	air	350	517	4151	128
Creep	40	508/533	Plate	SSR	Ht-3	air	350	517	4151	128
Creep	41	508/533	Plate	SSR	Ht-3	air	350	483	15128	440
Creep	42	508/533	Plate	SSR	Ht-3	air	350	483	15128	440
Creep	43	508/533	Plate	SSR	Ht-3	air	371	517	1154	39
Creep	44	508/533	Plate	SSR	Ht-3	air	371	517	1154	39
Creep	45	508/533	Plate	SSR	Ht-3	air	371	483	3752	148
Creep	46	508/533	Plate	SSR	Ht-3	air	371	483	3752	148
Creep	47	508/533	Plate	SSR	Ht-3	air	371	448	13316	490
Creep	48	508/533	Plate	SSR	Ht-3	air	371	448	13316	490
Creep	49	508/533	Plate	SSR	Ht-3	air	390	483	1147	45
Creep	50	508/533	Plate	SSR	Ht-3	air	390	483	1147	45
Creep	51	508/533	Plate	SSR	Ht-3	air	390	448	3667	169

Table A-1. (continued).

Spec. Type	Spec. #	Material	Product Form (~250 mm thick)	Mat Cond.	Heat	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture Time (h)	LB Rupture Time (h)
Creep	52	508/533	Plate	SSR	Ht-3	air	390	448	3667	169
Creep	53	508/533	Plate	SSR	Ht-3	air	390	414	12871	539
Creep	54	508/533	Plate	SSR	Ht-3	air	390	414	12871	539

Table A-2. SAW Cross-Weld Creep Rupture Tests in Air to Address Creep Effects on Cold Vessel.

Spec. Type	Spec #	Weld Con-sumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond.	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture time (h)	LB Rupture time (h)
Creep	1	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	350	552	1238	33
Creep	2	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	350	552	1238	33
Creep	3	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	350	517	4151	128
Creep	4	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	350	517	4151	128
Creep	5	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	350	483	15128	440
Creep	6	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	350	483	15128	440
Creep	7	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	371	517	1154	39
Creep	8	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	371	517	1154	39
Creep	9	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	371	483	3752	148
Creep	10	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	371	483	3752	148
Creep	11	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	371	448	13316	490
Creep	12	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	371	448	13316	490
Creep	13	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	390	483	1147	45
Creep	14	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	390	483	1147	45
Creep	15	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	390	448	3667	169
Creep	16	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	390	448	3667	169
Creep	17	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	390	414	12871	539
Creep	18	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	390	414	12871	539

Table A-3. A 508/533B Creep Rupture Tests in NGNP He to Address Creep Effects on Cold Vessel.

Spec. Type	Spec #	Mat	Product Form (~250 mm thick)	Mat Cond.	Heat #	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture time (h)	LB Rupture time (h)
Creep	1	508/533	Plate	SSR	Ht-1	NGNP He	350	483	15128	440
Creep	2	508/533	Plate	SSR	Ht-1	NGNP He	350	483	15128	440
Creep	3	508/533	Plate	SSR	Ht-1	NGNP He	371	448	13316	490
Creep	4	508/533	Plate	SSR	Ht-1	NGNP He	371	448	13316	490
Creep	5	508/533	Plate	SSR	Ht-1	NGNP He	390	414	12871	539
Creep	6	508/533	Plate	SSR	Ht-1	NGNP He	390	414	12871	539

Table A-4. SAW Creep Rupture Tests in NGNP He to Address Creep Effects on Cold Vessel.

Spec. Type	Spec #	Weld Con-sumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond.	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture time (h)	LB Rupture time (h)
Creep	1	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	NGNP He	350	483	15128	440
Creep	2	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	NGNP He	350	483	15128	440
Creep	3	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	NGNP He	371	448	13316	490
Creep	4	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	NGNP He	371	448	13316	490
Creep	5	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	NGNP He	390	414	12871	539
Creep	6	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	NGNP He	390	414	12871	539

Table A-5. Creep Rupture Tests in Air on Fatigue-SRX Damaged A 508/533B Material.

Spec. Type	Spec. #	Mat	Product Form (~250 mm thick)	Mat Cond. (1)	Heat	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture time (h)	LB Rupture time (h)
Creep	1	508/533	Plate	SSR + Damaged	Ht-1	air	350	483	15128	440
Creep	2	508/533	Plate	SSR + Damaged	Ht-1	air	350	483	15128	440
Creep	3	508/533	Plate	SSR + Damaged	Ht-1	air	371	448	13316	490
Creep	4	508/533	Plate	SSR + Damaged	Ht-1	air	371	448	13316	490
Creep	5	508/533	Plate	SSR + Damaged	Ht-1	air	390	414	12871	539
Creep	6	508/533	Plate	SSR + Damaged	Ht-1	air	390	414	12871	539

Note (1) Damaged by fatigue-SRX
Fatigue-SRX condition: 1% strain range, strain rate = 1.E-3 m/m/s, tensile hold, hold time =1000 min., 180 cycles, at 427ºC

Table A-6. Creep Rupture Tests in Air on Fatigue-SRX Damaged SAW.

Spec. Type	Spec #	Weld Con-sumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond (1)	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture time (h)	LB Rupture time (h)
Creep	1	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	Air	350	483	15128	440
Creep	2	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	Air	350	483	15128	440
Creep	3	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	Air	371	448	13316	490
Creep	4	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	Air	371	448	13316	490
Creep	5	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	Air	390	414	12871	539
Creep	6	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	Air	390	414	12871	539

Note (1) Damaged by fatigue-SRX
Fatigue-SRX condition: 1% strain range, strain rate = 1.E-3 m/m/s, tensile hold, hold time =1000 min., 180 cycles, at 427ºC

Table A-7. A 508/533B Long-Term Qualifying Creep Rupture Tests in Air to Address Creep Effects on Cold Vessel.

Test Prgm	Spec. Type	Spec #	Mat	Product Form (~ 250 mm thick)	Mat Cond.	Heat	Env	Temp, (ºC)	Applied Stress (MPa)	Best Est. Rupture time (h)	Remark
Creep-QUAL	Creep	1	508/533	Plate	SSR	Ht-1	air	350	456	43844	Note (1)
Creep-QUAL	Creep	2	508/533	Plate	SSR	Ht-1	air	350	456	43844	Note (1)
Creep-QUAL	Creep	3	508/533	Plate	SSR	Ht-1	air	350	423	179253	Note (2)
Creep-QUAL	Creep	4	508/533	Plate	SSR	Ht-1	air	350	423	179253	Note (2)
Note (1) Test to Rupture. Note (2) Stop test at 200,000 h if not ruptured											

Table A-8. SAW Long-Term Qualifying Creep Rupture Tests in Air to Address Creep Effects on Cold Vessel.

Test Prgm	Spec. Type	Spec #	Weld Con-sumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond.	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture time (h)	Remark
Creep-QUAL	Creep	1	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	350	456	43844	Note (1)
Creep-QUAL	Creep	2	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	350	456	43844	Note (1)
Creep-QUAL	Creep	3	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	350	423	179253	Note (2)
Creep-QUAL	Creep	4	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	air	350	423	179253	Note (2)

Note (1) Test to Rupture. Note (2) Stop test at 200,000 h if not ruptured

Table A-9. A 508/533B Relaxation Strength in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Mat	Product Form	Mat Cond	Heat	Loading Stress Rate (MPa/s)	Env	Temp. (ºC)	Initial Stress (MPa)	Relaxation Time (h)
1	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	350	276	12000
2	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	350	276	12000
3	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	350	414	12000
4	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	350	414	12000
5	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	371	276	12000
6	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	371	276	12000
7	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	371	414	12000
8	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	371	414	12000
9	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	427	276	4000
10	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	427	276	4000
11	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	427	414	4000
12	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	427	414	4000
13	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	538	214	2000
14	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	538	214	2000
15	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	538	320	2000
16	SRX	508/533	Plate (thick)	SSR	Ht-1	0.5	air	538	320	2000
17	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	350	276	12000
18	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	350	276	12000
19	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	350	414	12000
20	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	350	414	12000
21	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	371	276	12000
22	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	371	276	12000
23	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	371	414	12000
24	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	371	414	12000
25	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	427	276	4000

Table A-9. (continued).

Spec. #	Test Type	Mat	Product Form	Mat Cond	Heat	Loading Stress Rate (MPa/s)	Env	Temp. (ºC)	Initial Stress (MPa)	Relaxation Time (h)
26	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	427	276	4000
27	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	427	414	4000
28	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	427	414	4000
29	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	538	214	2000
30	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	538	214	2000
31	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	538	320	2000
32	SRX	508/533	Plate (thick)	SSR	Ht-2	0.5	air	538	320	2000

Table A-10. SAW Relaxation Strength in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Weld Con-sumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond	Loading Stress Rate (MPa/s)	Env	Temp. (ºC)	Initial Stress (MPa)	Relaxation Time (h)
1	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	0.5	air	350	276	12000
2	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	0.5	air	350	276	12000
3	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	0.5	air	371	276	12000
4	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	0.5	air	371	276	12000
5	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	0.5	air	427	276	4000
6	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	0.5	air	427	276	4000
7	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	0.5	air	538	214	2000
8	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	0.5	air	538	214	2000

Table A-11. Relaxation Strength Tests of fatigue-SRX damaged A 508/533B in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Material	Product Form	Mat Cond (1)	Heat	Loading Stress Rate (MPa/s)	Env	Temp. (ºC)	Initial Stress (MPa)	Relaxation Time (h)
1	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	350	276	12000
2	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	350	276	12000
3	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	350	414	12000
4	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	350	414	12000
5	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	371	276	12000
6	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	371	276	12000
7	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	371	414	12000
8	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	371	414	12000
9	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	427	276	4000
10	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	427	276	4000
11	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	427	414	4000
12	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	427	414	4000
13	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	538	214	2000
14	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	538	214	2000
15	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	538	320	2000
16	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-1	0.5	air	538	320	2000
17	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	350	276	12000
18	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	350	276	12000
19	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	350	414	12000
20	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	350	414	12000
21	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	371	276	12000
22	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	371	276	12000
23	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	371	414	12000
24	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	371	414	12000
25	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	427	276	4000

Table A-11. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond [(1)]	Heat	Loading Stress Rate (MPa/s)	Env	Temp. (ºC)	Initial Stress (MPa)	Relaxation Time (h)
26	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	427	276	4000
27	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	427	414	4000
28	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	427	414	4000
29	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	538	214	2000
30	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	538	214	2000
31	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	538	320	2000
32	SRX	508/533	Plate (thick)	SSR + Damaged	Ht-2	0.5	air	538	320	2000

Footnote (1) Damage produced by fatigue-SRX, with 1% strain range, strain rate = 1.E-3 m/m/s, tensile hold, hold time =1000 min., 180 cycles, at 427ºC

Table A-12. Relaxation Strength Tests of Fatigue-SRX Damaged SAW in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Weld Con-sumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond (1)	Loading Stress Rate (MPa/s)	Env	Temp. (ºC)	Initial Stress (MPa)	Relaxation Time (h)
1	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	0.5	air	350	276	12000
2	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	0.5	air	350	276	12000
3	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	0.5	air	371	276	12000
4	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	0.5	air	371	276	12000
5	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	0.5	air	427	276	4000
6	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	0.5	air	427	276	4000
7	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	0.5	air	538	214	2000
8	SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	0.5	air	538	214	2000

Footnote (1) Damage produced by fatigue-SRX

Fatigue-SRX condition: 1% strain range, strain rate = 1.E-3 m/m/s, tensile hold, hold time =1000 min., 180 cycles, at 427ºC

Table A-13. A 508/533B Fatigue-SRX Tests in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Mat	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Strain Hold Time (min)
1	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	N/A	350	1.0	0
2	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	N/A	350	1.0	0
3	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	N/A	350	1.0	0
4	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	350	1.0	30
5	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	350	1.0	30
6	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	350	1.0	30
7	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	350	1.0	150
8	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	350	1.0	150
9	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	350	1.0	150
10	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	350	1.0	300
11	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	350	1.0	300
12	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	350	1.0	300
13	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	350	1.0	30
14	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	350	1.0	30
15	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	350	1.0	30
16	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	350	1.0	150
17	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	350	1.0	150
18	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	350	1.0	150
19	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	350	1.0	300
20	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	350	1.0	300
21	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	350	1.0	300

Table A-14. SAW Fatigue-SRX Tests in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Weld Con-sumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond.	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Strain Hold Time (min)
1	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	N/A	350	1.0	0
2	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	N/A	350	1.0	0
3	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	N/A	350	1.0	0
4	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	350	1.0	30
5	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	350	1.0	30
6	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	350	1.0	30
7	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	350	1.0	150
8	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	350	1.0	150
9	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	350	1.0	150
10	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	350	1.0	30
11	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	350	1.0	30
12	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	350	1.0	30
13	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	350	1.0	150
14	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	350	1.0	150
15	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	350	1.0	150

Table A-15. Baseline Tensile Tests of A 508/533B in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Mat	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Temp. (ºC)
1	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	20
2	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	20
3	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	150
4	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	150
5	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	250
6	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	250
7	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	350
8	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	350
9	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	450
10	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	450
11	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	550
12	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	550
13	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	20
14	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	20
15	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	150
16	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	150
17	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	250
18	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	250
19	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	350
20	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	350
21	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	450
22	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	450
23	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	550
24	Tensile-Baseline	508/533	Plate (thick)	SSR	Ht-2	1E-03	air	550

Table A-16. Baseline Tensile Tests of SAW in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Weld Consumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond	Strain Rate (m/m/s)	Env	Temp. (ºC)
1	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	20
2	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	20
3	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	150
4	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	150
5	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	250
6	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	250
7	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	350
8	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	350
9	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	450
10	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	450
11	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	550
12	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	550

Table A-17. Tensile Tests of Fatigue-SRX Damaged A 508/533B in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Mat	Product Form	Mat Cond (1)	Heat	Strain Rate (m/m/s)	Env	Temp. (ºC)
1	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	20
2	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	20
3	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	150
4	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	150
5	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	250
6	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	250
7	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	350
8	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	350
9	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	450
10	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	450
11	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	550
12	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-1	1E-03	air	550
13	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	20
14	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	20
15	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	150
16	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	150
17	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	250
18	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	250
19	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	350
20	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	350
21	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	450
22	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	450
23	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	550
24	Tensile	508/533	Plate (thick)	SSR + Damaged	Ht-2	1E-03	air	550

Footnote (1) Damage produced by fatigue-SRX

Fatigue-SRX condition: 1% strain range, strain rate = 1.E-3 m/m/s, tensile hold, hold time =1000 min., 180 cycles, at 427ºC

Table A-18. Tensile Tests of Fatigue-SRX Damaged SAW in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Weld Consumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond (1)	Strain Rate (m/m/s)	Env	Temp. (ºC)
1	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	20
2	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	20
3	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	150
4	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	150
5	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	250
6	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	250
7	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	350
8	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	350
9	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	450
10	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	450
11	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	550
12	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Damaged	1E-03	air	550

Footnote (1) Damage produced by fatigue-SRX

Fatigue-SRX condition: 1% strain range, strain rate = 1.E-3 m/m/s, tensile hold, hold time =1000 min., 180 cycles, at 427ºC

Table A-19. Tensile Tests of Thermally Aged A 508/533B in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Mat	Product Form	Mat Cond	Aging Temp. (ºC)	Aging Time (h)	Heat	Strain Rate (m/m/s)	Env	Temp. (ºC)
1	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	20
2	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	20
3	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	150
4	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	150
5	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	250
6	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	250
7	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	350
8	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	350
9	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	450
10	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	450
11	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	550
12	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-1	1E-03	air	550
13	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	20
14	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	20
15	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	150
16	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	150
17	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	250
18	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	250
19	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	350
20	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	350
21	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	450
22	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	450
23	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	550
24	Tensile	508/533	Plate (thick)	SSR + Aged	450	20000	Ht-2	1E-03	air	550

Table A-20. Tensile Tests Thermally Aged SAW in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Weld Con-sumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond	Aging Temp. (ºC)	Aging Time (h)	Strain Rate (m/m/s)	Env	Temp. (ºC)
1	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	20
2	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	20
3	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	150
4	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	150
5	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	250
6	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	250
7	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	350
8	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	350
9	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	450
10	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	450
11	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	550
12	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	20000	1E-03	air	550

Table A-21. Tensile Tests of Long-Term Thermally Aged A 508/533B in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Material	Product Form	Mat Cond	Aging Temp. (ºC)	Aging Time (h)	Heat	Strain Rate (m/m/s)	Env	Temp. (ºC)
1	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	20
2	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	20
3	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	150
4	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	150
5	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	250
6	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	250
7	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	350
8	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	350
9	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	450
10	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	450
11	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	550
12	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-1	1E-03	air	550
13	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	20
14	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	20
15	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	150
16	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	150
17	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	250
18	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	250
19	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	350
20	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	350
21	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	450
22	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	450
23	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	550
24	Tensile	508/533	Plate (thick)	SSR + Aged	450	70000	Ht-2	1E-03	air	550

Table A-22. Tensile Tests of Long-Term Thermally Aged SAW in Air to Address Creep Effects on Cold Vessel.

Spec. #	Test Type	Weld Con-sumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond	Aging Temp. (ºC)	Aging Time (h)	Strain Rate (m/m/s)	Env	Temp. (ºC)
1	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	20
2	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	20
3	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	150
4	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	150
5	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	250
6	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	250
7	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	350
8	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	350
9	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	450
10	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	450
11	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	550
12	Tensile	TBD	~ 250	SAW	Ht-1	X-Weld	SSR + Aged	450	70000	1E-03	air	550

Table A-23. Baseline Toughness Measurement (Master Curve To and J-R Curve) for A 508/533B.

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond.	Env.	Test Temp. (ºC)
1	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
2	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
3	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
4	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
5	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
6	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
7	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
8	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
9	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
10	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
11	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
12	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	TBD
13	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	20
14	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	20
15	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	20
16	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	20
17	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	20
18	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	20
19	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	150
20	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	150
21	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	150
22	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	150
23	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	150
24	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	150
25	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	350
26	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	350

Table A-23. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond.	Env.	Test Temp. (ºC)
27	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	350
28	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	350
29	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	350
30	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	350
31	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	427
32	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	427
33	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	427
34	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	427
35	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	427
36	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	427
37	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	538
38	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	538
39	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	538
40	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	538
41	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	538
42	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR	Air	538
43	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
44	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
45	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
46	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
47	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
48	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
49	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
50	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
51	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
52	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
53	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD

Table A-23. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond.	Env.	Test Temp. (ºC)
54	MC To baseline	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	TBD
55	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	20
56	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	20
57	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	20
58	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	20
59	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	20
60	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	20
61	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	150
62	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	150
63	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	150
64	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	150
65	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	150
66	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	150
67	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	350
68	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	350
69	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	350
70	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	350
71	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	350
72	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	350
73	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	427
74	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	427
75	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	427
76	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	427
77	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	427
78	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	427
79	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	538
80	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	538

Table A-23. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond.	Env.	Test Temp. (ºC)
81	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	538
82	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	538
83	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	538
84	J-R baseline	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR	Air	538

Table A-24. Toughness Measurement (Master Curve To and J-R Curve) for Fatigue-SRX Damaged A 508/533B Material.

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
1	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
2	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
3	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
4	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
5	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
6	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
7	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
8	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
9	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
10	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
11	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
12	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	TBD
13	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	20
14	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	20
15	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	20
16	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	20
17	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	20
18	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	20
19	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	150
20	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	150
21	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	150
22	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	150
23	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	150
24	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	150
25	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	350
26	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	350

Table A-24. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
27	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	350
28	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	350
29	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	350
30	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	350
31	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	427
32	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	427
33	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	427
34	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	427
35	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	427
36	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	427
37	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	538
38	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	538
39	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	538
40	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	538
41	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	538
42	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Damaged	Air	538
43	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
44	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
45	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
46	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
47	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
48	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
49	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
50	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
51	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
52	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
53	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD

Table A-24. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
54	MC To, Damaged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	TBD
55	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	20
56	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	20
57	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	20
58	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	20
59	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	20
60	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	20
61	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	150
62	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	150
63	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	150
64	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	150
65	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	150
66	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	150
67	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	350
68	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	350
69	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	350
70	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	350
71	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	350
72	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	350
73	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	427
74	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	427
75	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	427
76	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	427
77	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	427
78	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	427
79	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	538
80	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	538

Table A-24. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
81	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	538
82	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	538
83	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	538
84	J-R, Damaged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Damaged	Air	538

Note (1) Damaged by fatigue-SRX

Fatigue-SRX condition: 1% strain range, strain rate = 1.E-3 m/m/s, tensile hold, hold time =1000 min., 180 cycles, at 427ºC

Table A-25. Toughness Measurement (Master Curve To and J-R Curve) for Thermally Aged (20,000 hr) A 508/533B Material.

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
1	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
2	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
3	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
4	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
5	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
6	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
7	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
8	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
9	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
10	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
11	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
12	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	TBD
13	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	20
14	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	20
15	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	20
16	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	20
17	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	20
18	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	20
19	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	150
20	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	150
21	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	150
22	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	150
23	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	150
24	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	150
25	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	350
26	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	350

Table A-25. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
27	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	350
28	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	350
29	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	350
30	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	350
31	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	427
32	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	427
33	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	427
34	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	427
35	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	427
36	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	427
37	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	538
38	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	538
39	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	538
40	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	538
41	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	538
42	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 20k h	Air	538
43	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
44	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
45	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
46	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
47	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
48	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
49	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
50	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
51	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
52	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
53	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD

Table A-25. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
54	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	TBD
55	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	20
56	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	20
57	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	20
58	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	20
59	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	20
60	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	20
61	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	150
62	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	150
63	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	150
64	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	150
65	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	150
66	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	150
67	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	350
68	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	350
69	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	350
70	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	350
71	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	350
72	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	350
73	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	427
74	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	427
75	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	427
76	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	427
77	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	427
78	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	427
79	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	538
80	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	538

Table A-25. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
81	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	538
82	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	538
83	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	538
84	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 20k h	Air	538

Note (1) Thermal Aging Condition: 450ºC for 20,000 hours

Table A-26. Toughness Measurement (Master Curve To and J-R Curve) for Thermally Aged (70,000 hr) A 508/533B Material.

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
1	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
2	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
3	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
4	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
5	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
6	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
7	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
8	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
9	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
10	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
11	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
12	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	TBD
13	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	20
14	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	20
15	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	20
16	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	20
17	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	20
18	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	20
19	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	150
20	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	150
21	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	150
22	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	150
23	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	150
24	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	150
25	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	350
26	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	350

Table A-26. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
27	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	350
28	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	350
29	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	350
30	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	350
31	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	427
32	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	427
33	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	427
34	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	427
35	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	427
36	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	427
37	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	538
38	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	538
39	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	538
40	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	538
41	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	538
42	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-1	SSR + Aged 70k h	Air	538
43	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
44	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
45	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
46	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
47	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
48	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
49	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
50	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
51	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
52	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
53	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD

Table A-26. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
54	MC To, Aged	E-1921	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	TBD
55	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	20
56	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	20
57	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	20
58	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	20
59	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	20
60	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	20
61	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	150
62	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	150
63	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	150
64	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	150
65	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	150
66	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	150
67	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	350
68	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	350
69	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	350
70	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	350
71	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	350
72	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	350
73	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	427
74	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	427
75	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	427
76	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	427
77	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	427
78	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	427
79	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	538
80	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	538

Table A-26. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Mat	Product Form (~250 mm thick)	Heat #	Mat Cond. (1)	Env.	Test Temp. (ºC)
81	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	538
82	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	538
83	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	538
84	J-R, Aged	E-1820	0.5T D-CT	508/533	Plate	Ht-2	SSR + Aged 70k h	Air	538

Note (1) Thermal Aging Condition: 450ºC for 70,000 hours

Table A-27. Baseline Toughness Measurement (Master Curve To and J-R Curve) for SAW.

Spec. #	Test Type	Test Method	Spec. Type	Weld Consumable	Section Thickness (mm)	Weld Process	Base Metal Heat #	Weld Location to be Tested	Mat Cond.	Env.	Test Temp. (ºC)
1	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
2	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
3	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
4	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
5	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
6	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
7	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
8	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
9	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
10	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
11	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
12	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	TBD
13	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	20
14	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	20
15	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	20
16	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	20
17	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	20
18	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	20
19	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	150
20	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	150
21	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	150
22	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	150
23	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	150
24	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	150
25	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	350

Table A-27. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Weld Consumable	Section Thickness (mm)	Weld Process	Base Metal Heat #	Weld Location to be Tested	Mat Cond.	Env.	Test Temp. (ºC)
26	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	350
27	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	350
28	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	350
29	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	350
30	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	350
31	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	427
32	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	427
33	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	427
34	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	427
35	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	427
36	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	427
37	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	538
38	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	538
39	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	538
40	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	538
41	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	538
42	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	X Weld	SSR	Air	538

Table A-28. Baseline Toughness Measurement (Master Curve To and J-R Curve) for Heat Affected Zone of SAW.

Spec. #	Test Type	Test Method	Spec. Type	Weld Consumable	Section Thickness (mm)	Weld Process	Base Metal Heat #	Weld Location to be Tested	Mat Cond.	Env.	Test Temp. (ºC)
1	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
2	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
3	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
4	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
5	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
6	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
7	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
8	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
9	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
10	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
11	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
12	MC To	E-1921	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	TBD
13	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	20
14	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	20
15	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	20
16	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	20
17	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	20
18	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	20
19	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	150
20	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	150
21	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	150
22	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	150
23	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	150
24	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	150
25	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	350

Table A-28. (continued).

Spec. #	Test Type	Test Method	Spec. Type	Weld Consumable	Section Thickness (mm)	Weld Process	Base Metal Heat #	Weld Location to be Tested	Mat Cond.	Env.	Test Temp. (ºC)
26	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	350
27	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	350
28	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	350
29	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	350
30	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	350
31	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	427
32	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	427
33	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	427
34	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	427
35	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	427
36	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	427
37	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	538
38	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	538
39	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	538
40	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	538
41	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	538
42	J-R	E-1820	0.5T D-CT	TBD	~ 250	SAW	Ht-1	HAZ	SSR	Air	538

Table A-29. Cyclic Stress-Strain Curves for 508/533.

Spec. #	Test Type	Material	Product Form (~ 250 mm thick)	Mat Cond	Heat #	Strain Rate (± m/m/s)	Env	Temp. (ºC)
1	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	20
2	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	20
3	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	20
4	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	20
5	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	20
6	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	350
7	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	350
8	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	350
9	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	350
10	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	350
11	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	371
12	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	371
13	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	371
14	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	371
15	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	371
16	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	427
17	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	427
18	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	427
19	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	427
20	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	427
21	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	538
22	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	538
23	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	538
24	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	538
25	Cyclic	508/533	Plate	SSR	Ht-1	1E-03	air	538
26	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	20

Table A-29. (continued).

Spec. #	Test Type	Material	Product Form (~ 250 mm thick)	Mat Cond	Heat #	Strain Rate (± m/m/s)	Env	Temp. (ºC)
27	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	20
28	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	20
29	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	20
30	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	20
31	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	350
32	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	350
33	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	350
34	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	350
35	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	350
36	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	371
37	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	371
38	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	371
39	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	371
40	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	371
41	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	427
42	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	427
43	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	427
44	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	427
45	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	427
46	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	538
47	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	538
48	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	538
49	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	538
50	Cyclic	508/533	Plate	SSR	Ht-2	1E-03	air	538
51	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	20
52	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	20
53	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	20

Table A-29. (continued).

Spec. #	Test Type	Material	Product Form (~ 250 mm thick)	Mat Cond	Heat #	Strain Rate (± m/m/s)	Env	Temp. (ºC)
54	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	20
55	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	20
56	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	350
57	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	350
58	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	350
59	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	350
60	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	350
61	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	371
62	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	371
63	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	371
64	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	371
65	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	371
66	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	427
67	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	427
68	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	427
69	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	427
70	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	427
71	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	538
72	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	538
73	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	538
74	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	538
75	Cyclic	508/533	Plate	SSR	Ht-3	1E-03	air	538

Table A-30. A 508/533B Creep Rupture Tests in Air to Support Code Case N-499.

Spec. Type	Spec. #	Mat	Product Form (~250 mm thick)	Mat Cond.	Heat	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture time (h)	LB Rupture time (h)
Creep	1	508/533	Plate	SSR	Ht-1	air	350	524	3238	98
Creep	2	508/533	Plate	SSR	Ht-1	air	350	524	3238	98
Creep	3	508/533	Plate	SSR	Ht-1	air	371	483	3752	148
Creep	4	508/533	Plate	SSR	Ht-1	air	371	483	3752	148
Creep	5	508/533	Plate	SSR	Ht-1	air	427	414	1044	43
Creep	6	508/533	Plate	SSR	Ht-1	air	427	414	1044	43
Creep	7	508/533	Plate	SSR	Ht-1	air	482	296	1056	38
Creep	8	508/533	Plate	SSR	Ht-1	air	482	296	1056	38
Creep	9	508/533	Plate	SSR	Ht-1	air	538	172	998	34
Creep	10	508/533	Plate	SSR	Ht-1	air	538	172	998	34
Creep	11	508/533	Plate	SSR	Ht-1	air	593	62	974	30
Creep	12	508/533	Plate	SSR	Ht-1	air	593	62	974	30
Creep	13	508/533	Plate	SSR	Ht-2	air	350	524	3238	98
Creep	14	508/533	Plate	SSR	Ht-2	air	350	524	3238	98
Creep	15	508/533	Plate	SSR	Ht-2	air	371	483	3752	148
Creep	16	508/533	Plate	SSR	Ht-2	air	371	483	3752	148
Creep	17	508/533	Plate	SSR	Ht-2	air	427	414	1044	43
Creep	18	508/533	Plate	SSR	Ht-2	air	427	414	1044	43
Creep	19	508/533	Plate	SSR	Ht-2	air	482	296	1056	38
Creep	20	508/533	Plate	SSR	Ht-2	air	482	296	1056	38
Creep	21	508/533	Plate	SSR	Ht-2	air	538	172	998	34
Creep	22	508/533	Plate	SSR	Ht-2	air	538	172	998	34
Creep	23	508/533	Plate	SSR	Ht-2	air	593	62	974	30
Creep	24	508/533	Plate	SSR	Ht-2	air	593	62	974	30
Creep	25	508/533	Plate	SSR	Ht-3	air	350	524	3238	98

Table A-30. (continued).

Spec. Type	Spec. #	Mat	Product Form (~250 mm thick)	Mat Cond.	Heat	Env	Temp. (ºC)	Applied Stress (MPa)	Best Est. Rupture time (h)	LB Rupture time (h)
Creep	26	508/533	Plate	SSR	Ht-3	air	350	524	3238	98
Creep	27	508/533	Plate	SSR	Ht-3	air	371	483	3752	148
Creep	28	508/533	Plate	SSR	Ht-3	air	371	483	3752	148
Creep	29	508/533	Plate	SSR	Ht-3	air	427	414	1044	43
Creep	30	508/533	Plate	SSR	Ht-3	air	427	414	1044	43
Creep	31	508/533	Plate	SSR	Ht-3	air	482	296	1056	38
Creep	32	508/533	Plate	SSR	Ht-3	air	482	296	1056	38
Creep	33	508/533	Plate	SSR	Ht-3	air	538	172	998	34
Creep	34	508/533	Plate	SSR	Ht-3	air	538	172	998	34
Creep	35	508/533	Plate	SSR	Ht-3	air	593	62	974	30
Creep	36	508/533	Plate	SSR	Ht-3	air	593	62	974	30

Table A-31. SAW Creep Rupture Tests in Air to Support Code Case N-499.

Spec. Type	Spec. #	Weld Con-sumable	Product Form (~250 mm thick)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond	Env	Temp. (º C)	Applied Stress (MPa)	Best Est. Rupture time (h)	LB Rupture time (h)
Creep	1	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	350	524	3238	98
Creep	2	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	350	524	3238	98
Creep	3	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	371	483	3752	148
Creep	4	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	371	483	3752	148
Creep	5	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	427	414	1044	43
Creep	6	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	427	414	1044	43
Creep	7	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	482	296	1056	38
Creep	8	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	482	296	1056	38
Creep	9	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	538	172	998	34
Creep	10	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	538	172	998	34
Creep	11	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	593	62	974	30
Creep	12	TBD	Thick Section Weld	SAW	Ht-1	X-Weld	SSR	air	593	62	974	30

Table A-32. A 508/533B Fatigue-SRX Tests in Air to Support Code Case N-499.

Spec. #	Test Type	Mat	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Strain Hold Time (min)
1	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	N/A	427	1.0	0
2	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	N/A	427	1.0	0
3	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	N/A	427	1.0	0
4	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	427	1.0	30
5	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	427	1.0	30
6	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	427	1.0	30
7	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	427	1.0	150
8	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	427	1.0	150
9	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	427	1.0	150
10	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	427	1.0	300
11	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	427	1.0	300
12	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	427	1.0	300
13	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	427	1.0	30
14	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	427	1.0	30
15	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	427	1.0	30
16	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	427	1.0	150
17	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	427	1.0	150
18	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	427	1.0	150
19	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	427	1.0	300
20	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	427	1.0	300
21	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	427	1.0	300
22	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	N/A	538	1.0	0
23	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	N/A	538	1.0	0
24	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	N/A	538	1.0	0
25	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	538	1.0	30

Table A-32. (continued).

Spec. #	Test Type	Mat	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Strain Hold Time (min)
26	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	538	1.0	30
27	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	538	1.0	30
28	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	538	1.0	150
29	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	538	1.0	150
30	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	tension	538	1.0	150
31	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	538	1.0	30
32	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	538	1.0	30
33	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	538	1.0	30
34	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	538	1.0	150
35	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	538	1.0	150
36	Fatigue-SRX	508/533	Plate (thick)	SSR	Ht-1	1E-03	air	strain	comp.	538	1.0	150

Table A-33. SAW Fatigue-SRX Tests in Air to Support Code Case N-499

Spec. #	Test Type	Weld Con-sumable	Section Thickness (mm)	Weld Process	Base Metal Heat	Weld to be Tested	Mat Cond.	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Strain Hold Time (min)
1	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	N/A	427	1.0	0
2	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	N/A	427	1.0	0
3	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	N/A	427	1.0	0
4	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	427	1.0	30
5	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	427	1.0	30
6	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	427	1.0	30
7	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	427	1.0	150
8	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	427	1.0	150
9	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	tension	427	1.0	150
10	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	427	1.0	30
11	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	427	1.0	30
12	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	427	1.0	30
13	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	427	1.0	150
14	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	427	1.0	150
15	Fatigue-SRX	TBD	~ 250	SAW	Ht-1	X-Weld	SSR	1E-03	air	strain	comp.	427	1.0	150

Appendix B

Appendix B

Hot Vessel Option

Appendix B

Appendix B

Hot Vessel Option

As discussed in the main body of this report, current preconceptual designs for the NGNP assume a gas outlet temperature of 750°C and incorporate a pressure vessel fabricated from conventional pressure vessel steels A 508 Grade 3 Class 1 forgings and/or A 533 Grade B Class 1 rolled plate. These designs assume the RPV operating temperature is ≤371°C.

B-1. Operational Requirements

B-1.1 Hot Vessel Definition

The secondary design case for the NGNP is the "hot vessel option." This design option minimizes active cooling of the vessel and requires the RPV to operate at a somewhat higher temperature. For this case design temperatures may be >371°C but less than the maximum allowable temperature specified in Section III, Subsection NH, for the RPV steels likely to be used for this design option.

Subsequent very high temperature reactors (VHTRs) may operate at gas outlet temperatures up to 950°C. The higher gas outlet temperature would likely increase the operating temperature of the RPV. Active cooling of the pressure vessel may be required, even for higher allowable temperatures. Furthermore, simulations have suggested that the vessel temperature is increased for a prismatic design compared to a pebble bed design, which may have to be taken into account for the hot vessel option.(Gougar and Davis 2006)

B-1.2 Plant Transient Definitions

Plant transient definitions are given in Section 3.2.

B-1.2.1 Normal Operating Temperature

The normal operating temperature for the hot vessel condition has not been finalized. GA suggested a normal operating temperature for the vessel in their preconceptual prismatic design (950°C outlet gas) of 440°C. However, if the design is constrained to have negligible creep in the vessel, this temperature will be limited to about 425°C (see Section B-2).

B-1.2.2 Anticipated Operational Occurrences

As mentioned in Section 3.2.1, forseen AOOs would have little impact on the RPV.

B-1.2.3 Design Basis Events

It is possible that the temperature excursion resulting from a design basis event will not exceed the capability of the higher alloy vessel materials for a significant period of time. Therefore, the design basis event may be of less concern for the hot vessel option compared to the cooled vessel option.

B-2. Material Options

The hot vessel option could require the use of higher alloy steels for the RPV. The reference/baseline material for the hot vessel option is Grade 91 steel (9Cr-1Mo-V). A somewhat lower temperature material, 2¼Cr-1Mo, has also been considered.

B-2.1 Design Allowables

In the current ASME Code, Section III, Subsection NB, the design temperature limits for the RPV are <371°C for A 508/A 533, and 2¼Cr-1Mo. For the elevated temperature rules in Section III, Subsection NH, the design temperature limits for the RPV are <575°C for 2¼Cr-1Mo and <650°C for Grade 91. However, the allowable stress intensity values for these Cr-Mo steels decrease with increasing temperature, such that the stress intensity values at the maximum temperatures allowed (for the maximum design time 300,000 h operation) are very low, as shown in Table B-1. Thus, as the design temperature increases, a thicker RPV will be required to accommodate the lower allowable stress intensity values. The maximum design temperature will be determined by the need to avoid the thermal creep regime, which is about 425°C for the Cr-Mo steels in the hot vessel option.

Table B-1. Allowable stress intensity values for Cr-Mo steels for a maximum design time of 300,000h, extracted from ASME Section III, Subsection NH, Table I-14.3.

Temperature (°C)	Grade 91 (MPa)	2¼Cr-1Mo (MPa)
400	179	123
425	172	112
450	165	89
500	131	56
550	85	33
575	66	25
650	17	---

Figure B-1 shows the allowable primary membrane stress intensities versus temperature for each material and the maximum calculated primary stress intensity/maximum wall temperature data points for the pebble bed and prismatic RPV designs, assuming a gas outlet temperature of 950°C. (Gougar and Davis 2006) Figure B-1 indicates that while Fe-2¼Cr-1Mo (without V) does not have adequate strength for either RPV design, Fe-2¼Cr-1Mo-V has sufficient strength up to 400°C, and limited creep-rupture data in the literature indicates it may have adequate high temperature strength for either design. However, at present, Fe-2¼Cr-1Mo-V steel is approved under ASME Code Section VIII (non-nuclear applications) but is not approved under Section III for nuclear service. The upper temperature limit of 400°C is only about 30°C above the temperature for which the A 508/A 533 alloys can be used. Consequently, Fe-2¼Cr-1Mo (without V) is highly unlikely as a RPV candidate material.

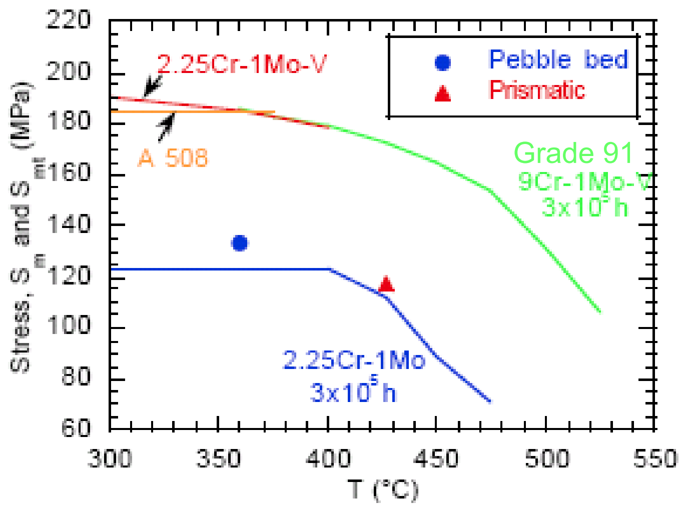


Figure B-1. Variation of primary membrane stress intensity and allowable primary membrane stress intensities as functions of temperature and time.

Grade 91 steel is approved in Section III of the ASME Code for nuclear applications; however, the creep-fatigue limits for the steel in the code are highly conservative. Calculations performed for the Grade 91 steel showed that the peak membrane stress for the pebble bed design RPV is within the ASME Code Subsection NB (elastic) allowable stress for the steel (see Figure B-1). The peak membrane stress for the prismatic design RPV is allowed in ASME Code, Subsection NH (plastic). Stress analysis of the depressurized conduction cool down condition for both pebble bed and prismatic designs showed the peak temperatures to be within the creep range for the steel, but the stresses are too low to cause any significant creep deformation ($<10^{-6}$).

B-2.2 Materials Research to Date

SA 508/533 has been selected as the RPV material for the NGNP as discussed above. Below is a review of information on high alloy RPV candidates Grade 91 steel (UNS K90901) and Fe-2¼Cr-1Mo steel (UNS K21590), based largely on existing literature.

B-2.2.1 Grade 91 Steel

The primary reference material for the hot vessel RPV option is Grade 91. Grade 91 is classified as a martensitic steel. After proper heat treatment that results in the desired tempered ferritic-matensitic microstructure, it was developed for relatively high temperature applications. With its superior high temperature strength, the thickness of the RPV wall can be significantly reduced in comparison with other candidate materials, resulting in lower through-wall thermal stresses during transient events. The reduced mass and weight would also allow smaller and less expensive supporting structures for the RPV.

Grade 91 is a relatively mature material, as indicated by its inclusion in Section III of the ASME Boiler and Pressure Vessel Code (BPVC), including subsection NH on high temperature materials. Subsection NH applies for service up to 300,000 h, whereas the current design concept of 60 years would require over 420,000 h, if operated at 80% efficiency.

A large database exists on mechanical properties for this material, including the effects of long-term thermal aging. However, additional data are needed for the mechanical properties of thick sections, where there is the possibility of retained ferrite that can lead to embrittlement in this martensitic steel. In addition, data on creep-fatigue are needed to evaluate the extremely conservative limits that currently exist for this material. Properties in impure helium must also be explored.

A substantial amount of data exists relative to irradiation effects at relatively high dose levels, indicating that this ferritic-martensitic steel is quite radiation resistant at temperatures above 400°C. At lower temperatures, the steel is more sensitive and subject to embrittlement, dependent on the specific temperature and the dose. Assuming the irradiation level is low for the cold vessel option as discussed above, radiation effects are not expected to present a major issue for this material under the hot vessel option. For regulatory purposes, however, experimental data relevant to NGNP conditions may be required to demonstrate this.

B-2.2.2 2¼Cr-1Mo Steel

Alloy 2¼Cr-1Mo is in the nuclear section of the ASME code for steel in the annealed condition because the properties of modified versions of the steel are not stable for extended periods at elevated temperatures. This was the primary steel of choice for the initial GA preconceptual design, primarily because of potential welding difficulties and lack of manufacturing and operating experience with the Grade 91 steel. There is an extensive database for the 2¼Cr-1Mo alloy, including data in different operating environments such as helium. Another advantage is the extensive industrial experience with this alloy in various applications around the world. It is commonly used in the petroleum industry for thick and heavy section vessels. However, it has become clear that the mechanical properties of the annealed version of the steel are so poor that its use is highly unlikely for the NGNP pressure vessel, as discussed in Section B-2.1. Other versions and modified chemistries of this steel exist that have higher strength, as shown in Table B-2, but more data would be needed for codification in NH.

Table B-2. Variations of 2¼Cr-1Mo alloy, applications and data needs.

Modification	Application	Data needed for NH
Normalized and tempered or quenched and tempered condition	HTTR in Japan, RPV operates at a nominal temperature of about 400 to 440°C	More relevant data regarding irradiation effects
~0.25% vanadium, copper and quite high phosphorus levels (contribute to relatively high radiation sensitivity)	LWRs in Eastern European countries, such as the VVER-440 reactors in Russia	Evaluation of the irradiation data from about 265 to 290°C
2¼Cr-1Mo-¼V	Extensive use in petrochemical industry, developed to increase the fabricability in thick sections for pressure vessels	Some creep data, substantial creep fatigue properties, performance in impure helium, and properties of thick section material, especially at elevated temperatures (DCC). Additional long-term test data to qualify the welded components.

B-3. ASME Code Status

B-3.1 Section III, Subsection NH

As part of the liquid-metal reactor (LMR) program in the late 1960s, the Atomic Energy Commission initiated a Materials and Structures Technology program and simultaneously asked the ASME B&PV Committee to charge an expanded Subgroup on Elevated Temperature Design with developing the design rules that eventually provided the basis for Subsection NH. The purpose of the early code cases for elevated temperature service was to provide rules for construction that account for the effects of deformation and damage due to creep with the same rigor that Subsection NB addressed the temperature regime, below which creep effects are significant.

The structural failure modes covered by Subsection NH for elevated temperature service include the following time-independent, structural failure modes of Subsection NB:

1. ductile rupture from short-term loading
2. gross distortion due to incremental collapse and ratcheting
3. loss of function due to excessive deformation
4. buckling due to short-term loading
5. and new time-dependent structural failure modes
6. creep rupture from long-term loading
7. creep-fatigue failure
8. creep-buckling due to long-term loading.

At elevated temperatures, some stresses that would have been considered as secondary per Subsection NB take on the characteristics of primary stresses due to elastic follow-up. To account for differing loads, times and temperatures, the stress allowable S_m from Subsection NB is retained for time-independent loads, and a new time-dependent stress allowable S_t, which is based on the time to 1% total strain, time to start of tertiary creep, and creep rupture strength, is introduced for time-dependent loads. The stress S_{mt} defined as the lower of S_m and S_t is also introduced.

These allowable stresses are used to set different primary stress limits for Level A (normal), B (upset), C (emergency), and D (faulted) service events, similar to Subsection NB. But time-of-loading is an additional variable that needs to be considered due to the time dependency. A different criterion adopted from Sections I and VIII and based on 100,000-hr creep rupture properties and a creep rate of 0.01% per 1,000 hr is used to set the primary stress limits for design conditions. Only elastic analysis results are required to satisfy the primary stress limits.

Acceptable deformation-controlled limits are given in Appendix T of Subsection NH and they cover strain limits/ratcheting, creep-fatigue damage, and buckling and welds. Strain limits and creep-fatigue damage rules can be satisfied using either elastic or inelastic analysis methods. In addition, Appendix T also includes rules for general loading conditions evaluated with inelastic analysis, including the time-dependent effects of creep.

The number of Subsection NH code materials for elevated temperature service is much smaller than that of Subsection NB. The temperature limits for NH code materials (other than bolting) at 300,000 hr and the maximum temperatures at which fatigue curves are provided are listed in Table B-3.

Table B-3. Temperature limits for NH code materials.

NH Code Materials, Other Than Bolting	Maximum Temperature	
	For Stress Allowables S_o, S_{mt}, S_t, S_r up to 300,000 hrs[a]	For Fatigue Curves
304 stainless steels (UNS S30400, S30409)	816°C (1,500°F)	704°C (1,300°F)
316 stainless steel (UNS S31600, S31609)	816°C (1,500°F)	704°C (1,300°F)
Alloy 800H (UNS N08810)	760°C (1,400°F)	760°C (1,400°F)
2¼Cr 1Mo steel, annealed condition (UNS K21590)	593°C (1,100°F)[b]	593°C (1,100°F)
Grade 91 steel (UNS K90901)[c]	649°C (1,200°F)	538°C (1,000°F)

a. The primary stress limits are very low at 300,000 hr and the maximum temperature limit.

b. Temperatures up to 649°C (1,200°F) are allowed up to 1,000 hours.

c. *The specifications for Grade 91 steel covered by Subsection NH are* A182 (forgings), A213 (small tube), A335 (small pipe), and A387 (plate). The forging size for A182 is not to exceed 4540 kg.

The delta ferrite limits of 5-FN minimum in Subsection NB are changed to a range of 3-FN to 10-FN in Subsection NH. Ferrite numbers refer to the volume fraction of delta ferrite in the microstructure. Reduction in the yield and tensile strength due to aging is required in Subsection NH. In addition to meeting other materials acceptance requirements specified in Subsection NB, creep-fatigue acceptance test is required for 304 and 316 stainless steels. The creep-fatigue acceptance test involves fatigue test in air at 595°C (1,100°F) at an axial strain range of 1.0% with a one-hour hold period at the maximum positive strain point in each cycle. Test should be performed to ASTM Standard E 606. The material lot is acceptable if the test exceeds 200 cycles without fracture or a 20% drop in the load range.

The criteria documents for Class 1 components covered by Subsection NH are given in the literature(1976; Berman and Gupta 1976; Jakub 1976; Jetter 1976) and a detailed summary of the Subsection NH rules is given in the *Companion Guide* to the BPVC.(2002) A recent overview of the Subsection NH rules is given in a NRC NUREG report(Shah, Majumdar et al. 2003).

B-3.2 DOE Initiative to Address ASME Code Issues

Nuclear structural component construction in the U.S. complies with Section III of the ASME Boiler and Pressure Vessel Code, although licensing is granted by the NRC. A number of technical topics were identified by DOE, Oak Ridge National Laboratory (ORNL), INL, and ASME to have particular value with respect to the ASME Code. A three-year collaboration between DOE and ASME was established that addressed twelve topics in support of an industrial stakeholder's application for licensing of a Generation IV nuclear reactor.

The majority of these tasks are relevant to action items within ASME Section III Subsection NH, and the nature of the topics inherently include significant overlap, and in some cases parallel activities on the same issue. A number of the tasks concern Grade 91 steel and are discussed here.

B-3.2.1 Task 1: Verification of Allowable Stresses—

The ASME Section III Subsection NH criteria for estimating the time-dependent allowable stress S_t include the average strength for 1% total strain, 80% of the minimum strength for tertiary creep, and 67% of the minimum rupture strength values. Part III of this task was to review the allowable stresses for Grade 91 steel and to perform a data gap analysis for conditions of interest to VHTR.

- **Results and Recommendations**

The creep-rupture data for Grade 91 steel were collected and reviewed to determine if it met the needs for recommending time-dependent strength values, S_t, for coverage in ASME Section III Subsection NH to 650°C (1200°F) and 600,000 hours.

The accumulated database included over 300 tests for 1% total strain, nearly 400 tests for tertiary creep, and nearly 1700 tests to rupture. Procedures for analyzing creep and rupture data for Subsection NH were reviewed and compared to the procedures used to develop the current allowable stress values for Grade 91 steel for Section II, Part D.

Time-temperature-stress parametric formulations were selected to correlate the data and make predictions of the long-time strength. It was found that the stress corresponding to 1% total strain and the initiation of tertiary creep were not the controlling criteria over the temperature-time range of concern. It was found that small adjustments to the current values in Subsection NH could be introduced but that the existing values were conservative and could be retained. The existing database was found to be adequate to extend the coverage to 600,000 hours for temperatures <u>below</u> 650°C (1200°F). A model was developed to extend the allowable stress values to 600,000 hours.

- **Significance to NGNP**

The extension in temperature and/or time for the stress allowables established in Task 1 is of significance to the NGNP project. Per the vendor pre conceptual design reports, Alloy 800H is used as a control rod cladding material for the Westinghouse and GA designs, as a core barrel material for the AREVA design, and as the material of construction for the lower temperature IHX. Grade 91 steel is the candidate material for the RPV in the AREVA and GA designs (the hot vessel concept).

B-3.2.2 Task 3: Improvement of ASME Subsection NH Rules for Grade 91 Steel – Negligible Creep and Creep-Fatigue

B-3.2.2.1 Part I. Negligible creep regime

The objective of Part I of this task was to examine current approaches available to define negligible creep, to check their applicability to Grade 91 steel, and to identify tests required to support the definition of negligible creep for Grade 91 steel.

- **Results and Recommendations**

Creep data for Grade 91 steel from the Commissariat à l'Énergie Atomique, France (CEA, 450–500°C or 842–932°F), U.S. (ORNL, 427–500°C or 800–932°F), and Japan (NIMS [National Institute of Material Science] and JNC [Japan Nuclear Cycle Development Institute], 450°C and 500°C or 842°F and 932°F) were assembled. A review was performed on the creep-stress-to-rupture data and the different creep strain laws developed by RCC-MR, ORNL and Japanese researchers. Based on the assembled data, a revised creep strain law with a formulation similar to that of the RCC-MR code was developed in order to provide more reliable results in the low temperature range (below 500°C or 932°F).

It was concluded that negligible creep criteria developed for austenitic stainless steels used in Subsection NH are not directly applicable to Grade 91 steel and the definition of negligible creep conditions is very dependent on the creep properties that are taken into account (either creep strain laws or creep-stress-to-rupture data).

Creep-stress-to-rupture results were re-analyzed to evaluate if improved design data could be obtained at lower temperatures. The number of available stress-to-rupture data at temperatures lower than 500°C (932°F) is small and the data cover a limited range of stress (for example, 450–360 MPa at 450°C or 842°F). It was shown that different equations for average values of stress-to-rupture derived from different databases do not describe the time dependence of stress-to-rupture at 450°C (842°F) correctly. However, the Subsection NH minimum curves seem to provide a conservative estimate of the creep-stress-to-rupture at 450°C (842°F) and below for long-term time durations (beyond 10,000 hours).

The negligible creep criteria from Subsection NH and from RCC-MR were evaluated. It was found that three criteria seem to be applicable to Grade 91 steel:

1. Time-fraction criterion with S_y as a reference stress
2. Strain criterion with S_y as reference stress and 0.2% creep strain
3. Relaxation of 1.5 S_m by 20%.

The first two criteria are those from Subsection NH but are modified to take account of cyclic softening.

The time-fraction and 0.2% creep-strain criteria would allow up to 535,000 hours and 158,000 hours of operation in the negligible creep regime, respectively, at 400°C (752°F). The criterion based on stress relaxation would provide more favorable negligible creep conditions below 450°C (842°F).

The RCC-MR and Japanese approaches that rely on creep-strain criteria in the order of 0.01 to 0.03% were shown to be not applicable to Grade 91 steel. Reference stresses would have to be reduced to about the allowable stress S_m to achieve negligible creep conditions similar to what were given by the three other criteria listed above.

It was concluded that for further confirmation of the negligible creep limits, more creep strain data at 475°C (887°F), 450°C (842°F) and, if possible, at 425°C (797°F) will be needed. Further tests should also be performed to improve the creep-stress-to-rupture curves below 500°C (932°F).

Creep tests on Grade 91 steel were proposed to increase the knowledge of creep behavior at moderate temperatures of 425°C to 525°C (797°F to 977°F) in order to improve the evaluation of negligible creep conditions from different criteria.

Creep-fatigue tests on Grade 91 steel were proposed to evaluate the margin between negligible creep conditions at the moderate temperatures of 450°C and 500°C (842°F and 932°F) and conditions that produce a significant reduction in fatigue life.

B-3.2.2.2 Part II. Creep-fatigue procedure

The objective of Part II of this task was to compare the Subsection NH and RCC-MR creep-fatigue procedures for Grade 91 steel, to explore the extent to which data for Grade 91 steel presently available in Subsection NH and RCC-MR are thought to be validated, to recommend improvements to existing

Subsection NH creep-fatigue procedure for Grade 91 steel, and to define a test program to validate the improved creep-fatigue procedure for Grade 91 steel.

- **Results and Recommendations**

A total of 103 creep-fatigue test results for Grade 91 steel were assembled from the sources of: the JAPC-USDOE joint study, the JNC study, the CEA studies, the Electric Power Research Institute (EPRI) /Central Research Institute of Power Industry in Japan (CRIEPI) joint studies, the IGCAR studies, and the University of Connecticut. The Subsection NH and RCC-MR creep-fatigue procedures for Grade 91 steel were analyzed using these assembled creep-fatigue data.

It was concluded that the Subsection NH creep-fatigue procedure for Grade 91 steel is very conservative. For the test conditions studied, the Subsection NH design approach was shown to be not executable. With the best-fit approach where the design factor was set to one, the life prediction is very conservative as compared with experimental results when the hold times are non-zero.

It was found that the values of the predicted stresses at the beginning of hold times are far too high. Results could be improved by modifying the procedure for calculating the stress at the beginning of the hold time by taking into account cyclic softening and symmetrization effects for Grade 91 steel. This could be implemented by applying a reduction factor to the stress calculated using the isochronous stress-strain curves.

It was found that the prediction of stress relaxation using the isochronous stress-strain curves is overly conservative (the stress relaxation is under-predicted as compared with the experimental results). Unnecessary conservatism could be reduced in Subsection NH by performing systematic cyclic stress relaxation analyses using a creep-strain law as in the RCC-MR procedure. For that purpose, it was recommended that Subsection NH provides additional creep-strain laws so that such analyses could be performed. It was further recommended that guidance to address elastic follow-up effects be added to Subsection NH for code improvement.

It was concluded that the large safety factor used in the calculation of the creep damage (1/K'=1/0.67) is too conservative in comparison with data. It was recommended that a K' value of 0.9 instead of 0.67 be adopted for the elastic analysis route in the Subsection NH procedure, as currently employed in RCC-MR. It is noted that a proposal for modifying Subsection NH in this manner for all Subsection NH code materials had been made. The proposal was approved by the Code committees.

It was concluded that the Subsection NH creep-fatigue damage envelope is very conservative for Grade 91 steel (bi-linear damage lines with (0.1, 0.01) intersection). On the basis of existing results, this diagram does not seem to be fully justified. It was recommended that for the investigation of true creep-fatigue interaction, tests where environment plays a role (tests with hold time in compression) should not be included. At 593°C (1099°F) or 600°C (1112°F), true creep-fatigue interaction can probably be studied. But at lower temperatures, 550°C (1022°F) or 500°C (932°F), it seems that there is a lack of creep-fatigue data in vacuum from which to select relevant data for the investigation of true creep-fatigue interaction. In the absence of such critical data, it was recommended conservatively that the (0.3, 0.3) intersection point in the creep-fatigue damage envelope of RCC-MR be adopted in Subsection NH for Grade 91 steel.

It was concluded that when the environment effects on fatigue life at elevated temperatures must be treated, as is the case for cycling in air or non-inert gas, the fatigue dependences on frequency, tensile and compressive strain rates instead of creep damage evaluation are probably more appropriate to improve the design rules.

It was pointed out that the RCC-MR creep-fatigue procedure provides results that are consistent with experimental data and could be used to help improve the Subsection NH creep-fatigue procedure. However, when used under combined primary and secondary stresses, the RCC-MR creep-fatigue procedure could be very conservative. The stress calculated at the beginning of the hold time by the RCC-MR procedure is higher than that calculated by using the Subsection NH rules. Improvement of this part of the RCC-MR creep-fatigue procedure, when supported by specific test results, is needed.

An extensive creep-fatigue and fatigue-relaxation test program on Grade 91 steel was proposed. The test program contains the following elements:

1. Tests at 500°C (932°F) or 525°C (977°F) for comparison with data at 550°C (1022°F)
2. Extension of the database at 550°C (1022°F) with tests with longer hold times
3. Characterization of cyclically softened material and comparison with thermally aged material
4. Effect of reactor environment with priority on testing in impure helium
5. Tests after post-weld heat treatment and comparison with data from as-received material
6. Screening tests on cross-weld specimens.

- **Significance to NGNP**

Per the vendor pre-conceptual design reports, Grade 91 steel is a RPV candidate material for the AREVA and GA designs (the hot vessel concept). Results on negligible creep temperature and creep-fatigue procedure for Grade 91 steel from Task 3 directly support the RPV design option from AREVA and GA.

B-3.2.3 Task 5: Collect Available Creep-Fatigue Data and Study Existing Creep-Fatigue Evaluation Procedures for Grade 91 Steel and Hastelloy XR

The object of Task 5 was to collect creep, creep-fatigue and fatigue (when available) data for Grade 91 steel in air, vacuum, and sodium environments and Hastelloy XR (not relevant for RVPs) in air and helium environments, and to evaluate creep-fatigue procedures from Subsection NH, RCC-MR and the Japanese HTGR Code.

B-3.2.3.1 Part I. Grade 91 steel

Grade 91 steel data were collected from the Japan Atomic Energy Agency (JAEA), EPRI, ORNL, CRIEPI, and NIMS. They included 205 creep data, 281 fatigue data, and 78 creep-fatigue data. Product forms included plates, forgings and pipes.

These data were analyzed from the perspective of (i) general trend and sodium environmental effect for the creep properties; (ii) general trend, effect of thermal aging, effect of environment, and stress-strain relationship for the fatigue properties; and (iii) reduction of creep-fatigue life due to strain hold, and effect of strain hold period for creep-fatigue properties.

While there was a fair amount of creep-fatigue data collected, it was pointed out that most of the data were originally obtained for application to fast breeder reactors and the temperature range was limited to 400°C (752°F) to 650°C (1202°F). Within this temperature range, creep-fatigue data had been accumulated to the extent that they served to clarify the mechanisms of creep-fatigue life reduction of Grade 91 steel, even if the data were not sufficient in quantity. Data from tests that included tensile hold time, compressive hold time and both tensile and compressive hold times had been collected. Most of the data were obtained in an air environment but data in sodium and vacuum environments were also available, providing valuable information. For the effect of aging, available data were not necessarily sufficient to clarify the effects on stress-strain response and creep-fatigue life.

Comparison of the creep-fatigue procedures from Subsection NH, RCC-MR and the Japanese HTGR Code was made, with emphasis on the method of determination of strain range, initial stress of stress relaxation, stress relaxation behavior and formulation of creep damage. These creep-fatigue procedures were then applied to the collected data. Specific focus was given to the determination of the initial stress of stress relaxation, the description of stress relaxation behavior during strain hold period, and the creep-fatigue damage diagram. The creep-fatigue evaluations were performed both with and without safety factors employed by each code. It was concluded that the creep-fatigue evaluation procedure of Subsection NH is very conservative.

It was recommended that the use of cyclic stress-strain curve, use of creep-strain law in conjunction with the strain hardening law, or the combination of both be adopted in the creep-fatigue procedure of Subsection NH. It was also recommended that the current intersection point of (0.1, 0.01) in the damage envelope of Subsection NH be changed to (0.3, 0.3). Recommendations on (i) long-term material testing, (ii) evaluation method for welded joints, (iii) extrapolation of experimental data to the design regime, and (iv) structural testing for validation were made.

B-3.2.4 Task 6: Operating Condition Allowable Stress Values

A spot check of minimum stress-to-rupture values provided in NH revealed disagreement between the minimum stress-to-rupture values, S_r, at 100,000 hours and the values of design condition stress intensity, S_o. The current operating condition allowable stresses provided in ASME Section III, Subsection NH were reviewed for consistency with the criteria used to establish the stress allowables and with the allowable stresses provided in ASME Section II, Part D. It was found that the S_o values in ASME III-NH were consistent with the S values in ASME IID for the five materials of interest. However, it was found that $0.80S_r$ was less than S_o for some temperatures for four of the materials, including Grade 91 steel. The expectation is that the values of S_r are lower than would be expected if they were derived from the same data as the values for S_o. Further, the values of S_t, the allowable stresses for operating conditions, appear consistent with the values of S_r, thus throwing in doubt all the allowable operating condition stress values for both load controlled stress limits and displacement controlled limits in NH.

The database(s) used to establish S_r, S_t and S_o for the five materials were reviewed and augmented databases were assembled. In Part II these assembled databases will be reviewed for completeness and consistency, identifying areas of inconsistency and recommending a course of action to resolve them. This should include additional testing if required.

The stress allowables (including S, S_o, S_t, and S_r) for 9Cr-1Mo-V steel were compared for temperatures in the time-dependent range covered by ASME Section III-NH (700 to 1200°F). The values for S_o at 700 and 900°F correspond to the S_{mt} values at 300,000 hr (NH-3221). Other than this difference, S and S_o are identical. However, the S values for 1150 and 1200°F are greater than the values in the 0.80 S_r column. This inconsistency should be resolved.

The values for S_t are equal to or less than the values of 0.67 S_r. This trend suggests that the minimum rupture strength at 100,000 hr controls S_t. It is not clear that the S_r values in the ASME Section III-NH pertain to products thicker than 3 inches. It is known, however, that the S_o values represent the thick product stress line and that the difference in the allowable stresses for the product size difference only occurs at 1100 and 1150°F.

The original database for 9Cr-1Mo-V steel was well documented at the time of the submittal for inclusion in ASME Section III and III-N-47 in 1989. In the early 1990s, however, European producers became concerned about the stress allowables in ASME for Section I and Section VIII construction. A new database was assembled by the MPC. The expanded database produced modifications of ASME Section II Part D Table 1A stresses including a separate stress line for products thicker than 3 inches. Eventually, the "thick product" stress line was provided as a singular set of S_o values when 9Cr-1Mo-V steel was incorporated into ASME III-N-47.

Because of its world-wide usage in Section I and VIII components, the 9Cr-1Mo-V steel database has grown substantially in the last fifteen years. Unfortunately, most of the "new" data are not freely available. Nevertheless, the data have been used to assess the adequacy of the stress allowables in the ASME and overseas construction codes for boilers, pressure vessels, and piping.

The database for the creep-rupture of 9Cr-1Mo-V (Grade 91) steel was reviewed to determine if it met the needs for recommending time-dependent strength values, St, for coverage in BPV IIII-NH to 650°C and 500,000 or 600,000 hours. The accumulated database included over 300 tests for 1% strain, nearly 400 tests for tertiary creep, and nearly 1700 tests to rupture. Procedures for analyzing creep and rupture data for BPV III-NH were reviewed and compared to the procedures used to develop the current allowable stress values for Gr 91 for BPV II-D. The criteria in BPV III-NH for estimating St included the average strength for 1% strain for times up to 600,000 hours, 80% of the minimum strength for tertiary creep for times up to 600,000 hours, and 67% of the minimum stress-to-rupture values for times up to 600,000 hours. Time-temperature-stress parametric formulations were selected to correlate the data and make predictions of the long-time strength. It was found that the stress corresponding to 1% strain and the initiation of tertiary creep were not the controlling criteria over the temperature-time range of concern. Small adjustments to the current values in BPV III-NH could be introduced; however the existing values are conservative and can be retained. The existing database was found to be adequate to extend the coverage to at least 500,000 hours for temperatures below 600°C and perhaps continue coverage at 649°C to 100,000 hours.

B-3.2.5 TASK 10: Alternative Simplified Creep-Fatigue Design Methods

Tasks 3 and 5 have assessed the creep-fatigue rules in NH for Grade 91 steel and concluded that the creep-fatigue interaction rules in NH have a number of deficiencies. Various areas of improvement have been recommended. Task 10 was initiated to assess other creep-fatigue methodologies other than the time fraction method employed in NH. The focus of the assessment is on Grade 91 steel, using the creep-fatigue database assembled in Tasks 3 and 5. The creep-fatigue methodologies that were examined in this task include:

- Modified Ductility Exhaustion Method by Takahashi
- Modified Strain Range Separation (SRS) Method by Hoffelner
- Omega-Based Creep-Fatigue Method by Prager
- Hybrid Method of Time-Fraction and Ductility Exhaustion by the High Pressure Institute of Japan
- Simplified Model Test (SMT) Approach by Jetter

The focus of the first four methodologies is on different approaches to evaluate creep damage, while the SMT approach involves a novel method to address total damage due to creep-fatigue. The results of the assessment of these methods are summarized below.

B-3.2.5.1 Modified Ductility Exhaustion Method

The advantage of the modified ductility exhaustion method is that the creep-fatigue life prediction result is insensitive to creep rupture time, initial stress of relaxation and description of stress relaxation behavior (i.e., creep strain equation, steady state creep rate and elastic follow-up parameter). However, this method is very sensitive to the values of creep rupture elongation and tensile rupture elongation. This presents a challenge in applying this method as the scatter of creep rupture elongation is generally large and the determination of the temperature dependency is difficult. This method gives good creep-fatigue life predictions under accelerated test conditions. But predictions for longer times under prototypical operating conditions tend to be unconservative compared to the time fraction rule of NH. The complexity of this method is comparable to the time fraction approach.

B-3.2.5.2 Modified SRS Method

In the modified SRS method, the creep damage is calculated based on the Monkman-Grant relationship only, and with the effects of cyclic softening on the stress relaxation behavior accounted for by using the concept of "additive stress." The method results in a procedure very similar to that of the time fraction rule when the creep life fraction is evaluated as the reciprocal of the creep damage accumulated during a hold time. It was found that the creep-fatigue life prediction is affected significantly by the choice of the additive stress. Further, the prediction is sensitive to the initial value of the stress during a hold time, but not sensitive to creep rupture elongation, tensile rupture elongation, creep rupture time, steady state creep rate, creep strain equation and elastic follow-up parameter. This method emphasizes the importance of the influence of cyclic softening in creep-fatigue life prediction. The complexity of the method is comparable to the time-fraction approach.

B-3.2.5.3 Omega-Based Creep-Fatigue Method

This method focuses on the effect of cyclic plastic strain on creep rupture life but not on the effect of creep damage on cyclic life. The application of this approach to plants whose design is basically performed by referencing stress allowable S (conceptually stress level corresponding to creep rupture time of 100,000 hours) would be fairly practical. However, for applications in which creep-fatigue is accompanied by significant stress relaxation under strain controlled conditions, a step-by-step procedure to apply this method is yet to be established. A novelty of this method is that the creep-fatigue interaction depends on loading conditions such as strain range and hold time. For other creep-fatigue evaluation methods, the creep-fatigue interaction is expressed uniquely by the ratio of creep damage to fatigue damage, regardless of loading conditions. This method is simpler than the time-fraction approach.

B-3.2.5.4 Hybrid Method

The hybrid method accounts for both stress and strain in evaluating creep damage through the weighted contributions from the time fraction and ductility exhaustion methods. However, there are some technical difficulties associated with determining the weighting factor. The determination of the weighting factor that is most appropriate for prototypical operating conditions could be an issue.

This method is more complex than the time fraction method because a ductility exhaustion term is added.

B-3.2.5.5 SMT Approach

The current NH creep-fatigue procedure and the four methods discussed above were all established by the steps of (1) analytically obtaining a detailed stress-strain history, (2) comparing the stress and strain components to cyclic test results deconstructed into stress and strain quantities, and (3) recombining the results to obtain a damage function. Instead of these steps, the SMT approach is predicated on testing simplified models of structures that include the elastic follow-up to determine the cyclic life experimentally. Since no parsing of the creep-fatigue damage into purely creep and fatigue components, the creep-fatigue design procedure resulting from the SMT approach is very similar to that below the creep regime such as in Subsection NB. However, additional work needs to be done before its implementation in NH is considered. This includes additional representations of actual geometry, materials and operating conditions to verify the conservatism of the approach.

This is the simplest method among those investigated in this task and the time fraction rule.

- **Conclusion and Recommendation**

It was concluded that these five methods all give reasonable predictions in the short-term region where experimental results are available. But differences in the predictions become significant in the long-term region where the conditions are more prototypical. Time fraction rule tends to give conservative predictions in the long-term region. It was also concluded that the SMT approach is much more robust and simpler because it does not parse fatigue and creep damage.

It was recommended that in the near term the current time fraction rule in NH be modified, using the insights gained from this task. In the long term, the NH creep-fatigue procedure should be changed to that based on the SMT approach when the method is verified and validated and the necessary database developed.

B-4. RESEARCH ISSUES

This section addresses issues with code qualification of alternative NGNP RPV materials. It also addresses application of the ASME code to design of RPVs.

B-4.1 NRC Structural Integrity Issues for "Hot" Vessel Option

Grade 91 steel is the candidate RPV material for the "hot" vessel option. As discussed in the previous sections, the major concern on Grade 91 steel for NGNP RPV application is the adequacy of thick section properties of the base metal (as-received and post-weld heat treated), and weldments. The current specification for Grade 91 forgings is A182. Products made to this specification are limited to a maximum weight of 4540 kg, which is too small for NGNP RPV applications. Addition of specification A336 for Grade 91 steel, which permits weight greater than 4540 kg, in Subsections NB and NH is required to support the NGNP RPV application.

The concept on the design of the RPV for the hot vessel option is to restrict the RPV metal temperature to be below the negligible creep temperature for Grade 91 steel. This does not necessarily imply that the Subsection NH rules of construction can be completely exempted. However, it does reduce the design analysis burden, as creep-fatigue interaction is no longer a structural integrity issue within the negligible creep regime. The criteria to be satisfied in that case are specified in Subsection NH, article T-1324, which includes (i) NB-3222.2 on primary plus secondary stress intensity, NB-3222.3 on expansion stress intensity, and NB-3222.5 on thermal stress ratchet, by reference; and (ii) restrictions on creep rupture time and accumulated creep strain. For the $3S_m$ limit in NB-3222.2 and NB-3222.3, the lesser of $3S_m$ and $3\overline{S}_m$ is to be used. Whether staying within the negligible creep regime will lessen any surveillance requirement for monitoring creep and creep-fatigue damage remains to be determined through discussions between the regulators and reactor vendors.

Other code issues related to allowable stresses, negligible creep temperature, and creep-fatigue for Grade 91 steel have been addressed by Tasks 1, 3, and 5 of the DOE/ASME ST collaboration, as summarized in Section B-3.2. Tests recommended by Task 3 for determining the negligible creep temperature, to extending the Grade 91 database, and to addressing creep-fatigue issues are proposed in Section B-5.1. Thick section forgings, rolled plates and weldments are selected in the test matrix so that thick section properties can also be addressed.

As mentioned in Section 4.2.5.1, a list of safety related issues were identified by NRC during the CRBR project and these NRC issues have been documented in Task 2 of the DOE/ASME ST collaboration.

The CRBR safety related issues identified by NRC are discussed with respect to the "cold" and "hot" vessel options separately. Table B-4 lists the hot-vessel issues (not ranked relative to the severity of the concerns).

Table B-4. NRC "hot" vessel issues list from CRBR review – assessment relative to the "cold" and "hot" vessel options.

Issue #	Structural Integrity Issues identified by NRC for CRBR	"Hot" Vessel Option	
		Assessment	Required Actions
1	Transition joints (i.e., dissimilar metals)	The Code specified approach is to model the joint with base metal properties to the weld centerline and then include differences in the connecting base metal properties in the weldment stress analysis.	This issue needs to be addressed if such transition joints are present in the down-selected vendor design concept.
2	Weld residual stresses	Not considered in current Subsection NH methodology. Subsection NH approach implies that the selection of weld wires and welding process produce ductile welds and subsequent load cycling and creep reduce residual stresses, particularly at very high temperatures. For NGNP RPV applications, relaxation of weld residual stress due to creep deformation is not as effective because of the lower temperature. Weld residual stresses, when combined with operation stresses, could reduce brittle fracture margin.	Characterization of weld residual stress through thickness profiles, by a combination of measurements and weld residual stress finite element simulation, is required.
3	Design loading combinations	This is an owner/regulator issue that is beyond the scope of Subsection NH.	This is an action for the reactor vendor.

Table B-4. (continued).

Issue #	Structural Integrity Issues identified by NRC for CRBR	"Hot" Vessel Option	
		Assessment	Required Actions
4	Creep-rupture and fatigue damage	This is a valid concern. Extrapolation of creep-fatigue data is a challenge, particularly at the extremes of the creep regime. At the low temperature end the concern involves the definition of negligible creep and at the very high temperature end one of the issues is whether or not plasticity and creep can be separated. The major issues identified for Subsection NH is that NH is too conservative for materials such as Grade 91 steel, particularly with respect to other international codes. DOE/ASME ST Tasks 3 and 5 have assessed the creep-fatigue issues for Grade 91 with respective to the current Subsection NH time fraction rules. There is proposed new work (Task 10) in DOE/ASME ST that will address this issue by exploring other creep-fatigue technology.	Creep and creep-fatigue testing for Grade 91 was recommended by Task 3 of the DOE/ASME ST to support the determination of negligible creep regime, to improve the understanding of cyclic behavior, and to validate the creep-fatigue procedures. These test plans are proposed in Section 6. Recommended testing from Task 10 will be assessed and testing will be proposed when necessary.
5	Simplified bounds for creep ratcheting	This is a valid concern. Proposed new work (Task 9) in DOE/ASME ST addresses this issue.	Recommended testing from Task 9 will be assessed and relevant testing will be proposed.
6	Thermal striping	Current Subsection NH rules provide a framework for assessment of structural response. Generally, the issue is determining thermal hydraulic response. This is not considered to be an issue for gas-cooled reactors. Recent R&D in Japan that should be assessed for relevance and incorporation.	No action is recommended.
7	Creep-fatigue analysis of Class 2 and 3 piping	Issue is not relevant to vessels.	No action is required.

Table B-4. (continued).

Issue #	Structural Integrity Issues identified by NRC for CRBR	"Hot" Vessel Option	
		Assessment	Required Actions
8	Are limits of Case N-253 for Elevated temperature Class 2 and 3 components met?	Issue is not relevant to vessels that are Class 1 pressure boundary components.	No action is required.
9	Creep buckling under axial compression design margins	Code committee responsible for Subsection NH is not aware of any generic issues or inconsistencies within the creep-buckling rules, particularly for thick-walled components. Should consider French concerns; it may be a local crimpling issue for very large diameter, thin-walled vessels.	This is a lower tier issue. No immediate action is recommended.
10	Identify areas where Appendix T rules are not met	Appendix T provides procedures to determine strain range using elastic analysis. If these rules cannot be satisfied, additional rules are provided, presumably less conservative, based on the results of inelastic analyses. However, inelastic analysis requires detailed constitutive models of material behavior under time varying loading conditions. For the CRBR these behavioral models were based on Nuclear Standard NE F9-5T. These standards are no longer maintained and there have been numerous technical developments in this area since. Development of material models for materials not currently covered or for temperatures beyond their original range of verification will be a considerable effort.	There are a number of constitutive equations developed for Grade 91 in the literature. Assessment of long-term creep and stress relaxation predictions of these models is required. If improvement to the predictive capability of the model is needed, testing to support such effort will be identified. Establishment of guidelines similar to Nuclear Standard NE F9-5T, developed specifically for high temperature design of liquid metal fast breeder reactor components, is recommended in Section 6.
12	Strain and deformation limits at elevated temperature	This is a valid concern. Proposed new work (Task 9) in DOE/ASME ST addresses this issue.	Recommended testing from Task 9 will be assessed and relevant testing will be proposed.

Table B-4. (continued).

Issue #	Structural Integrity Issues identified by NRC for CRBR	"Hot" Vessel Option	
		Assessment	Required Actions
13	Evaluation of weldments	A number of provisions in Subsection NH and related documents assure reliable weld joints. Subsection NH methods exceed current requirements for non-nuclear applications as well as nuclear applications below the creep regime.	Type IV cracking of Grade 91 welds is a concern. The issue of creep and creep-fatigue crack growth in geometric (notches) and material (welds) discontinuities will be addressed in the new Task 8 of the DOE/ASME ST. Recommended testing from this task will be assessed and relevant testing will be proposed. Task 3 of the DOE/ASME ST has proposed creep-fatigue tests for Grade 91 weldments. This test plan is proposed in Section 6.
14	Material acceptance criteria for elevated temperature	Developing data for a 60-year design life at elevated temperatures is very challenging. The ability to demonstrate confidence in using accelerated test data to predict performance for NGNP design life time is paramount for licensing success.	Task 1 of the DOE/ASME ST concluded that the existing database for Grade 91 is adequate for extending the coverage of allowable stresses to 600,000 hours for temperatures below 650°C. Effort is required to ensure that Code action on the Task 1 recommendation is taken.
15	Creep-rupture damage due to forming and welding	This issue is also covered under Issue #2.	No immediate action is recommended.
17	Environmental effects	This is an important area that is not covered by specific code rules in Subsection NH. This is an Owner/regulator issue.	Effect of NGNP helium on the mechanical properties and allowable stresses of Grade 91 steel needs to be investigated. (Irradiation effect is discussed in Item #20.)

Table B-4. (continued).

Issue #	Structural Integrity Issues identified by NRC for CRBR	“Hot” Vessel Option	
		Assessment	Required Actions
18	Fracture toughness criteria	Grade 91 steel exhibits ductile/brittle transition behavior. Thus its fracture toughness needs to be characterized. This should include the effect of long-term thermal aging on the fracture toughness, with emphasis on the targeted RPV metal temperature. Since this temperature is lower than the maximum allowable Code temperature, there is room to accelerate the thermal aging process in testing in order to gain confidence in extrapolating the fracture toughness data of aged materials to end of design life under service conditions.	ASTM E1921 master curve testing is proposed in Section 6 to establish the master curve transition temperatures for stress-relieved and stress-relieved plus thermally aged Grade 91 steel.
19	Thermal aging effects	Thermal aging effects on allowable stresses are addressed in Subsection NH. Yield and tensile strength reductions are not required of Grade 91 steel for temperatures below 480°C and service time less than 300,000 hours. Per vendor report, RPV metal temperature is below 480°C.	Long-term thermal aging tests are proposed in Section 6 to qualify the Subsection NH strength reduction factors of Grade 91 steel for the RPV metal temperature and NGNP design life.
20	Irradiation effects	This is an important area that is not covered by specific Code rules in Subsection NH. This is an Owner/regulator issue. Per information provided by reactor vendors, the dpa for the RPV is low and hence irradiation embrittlement is not a significant concern in terms of fracture performance. But confirmatory irradiation data are needed to support licensing.	Irradiation data on tensile properties and fracture toughness of Grade 91 steel need to be assembled or developed.
21	Use of simplified bounding rules at discontinuities	This is an important issue that is the subject of ongoing R&D efforts.	Similar to Issue #5, this will be addressed by the proposed work (Task 9) in the DOE/ASME ST. Recommended testing will be assessed and relevant testing will be proposed.

Table B-4. (continued).

Issue #	Structural Integrity Issues identified by NRC for CRBR	"Hot" Vessel Option	
		Assessment	Required Actions
22	Elastic follow-up	This is part of Issue #21 as accounting for the effects of elastic follow-up is a significant part of simplified bounding rules.	Similar to Issues #5 and #21, this will be addressed by the new proposed work (Task 9) in the DOE/ASME ST. Recommended testing from this task will be assessed and relevant testing will be proposed. A test plan for SMT creep-fatigue testing of Grade 91 steel is proposed in Section 6. The SMT specimen will be designed to have a significant elastic follow-up.
24	Elevated temperature data base for mechanical properties	This issue is similar to Issues #13, #14, #18, and #19. This issue is particularly important for Grade 91 thick section forgings and thick section welds. Forging thickness currently covered by Subsection NH does not support NGNP pressure vessel applications.	This and the related issues need to be addressed in an integrated manner. Testing for thick section base metal and associated weldments is required.
25	Basis for leak-before-break at elevated temperatures	This is closely related to Issues #13 and #18.	This needs to be addressed together with Issues #13 and #18 in an integrated manner. Creep and creep-fatigue crack growth rates and J-R curve data are required to support the development of leak-before-break design methodology.

B-4.2 Irradiation Effects

Irradiation embrittlement is not anticipated to be a major issue based on current knowledge accumulated for 250–300°C irradiation temperatures for these steels. However, there is an obvious gap in knowledge regarding potential synergism between low flux irradiation and long-time aging at temperatures as high as 370°C. There is a very limited number of studies, mostly performed by Russians on VVER-type steels, that indicated that irradiation may enhance thermal aging through irradiation-enhanced segregation of impurities (for example phosphorus) on grain boundaries. Unfortunately, short-term irradiation experiments at ~370°C will not be able to resolve this concern. There is a need to perform a longer term study (at least two years of irradiation exposure) to address this issue.

B-4.3 Procurement and Fabricability

In order to fabricate the huge RPV, vendors are needed who can produce seamless rings (forged) or plates (forged or rolled), achieving uniform through-thickness properties with the candidate materials. Grade 91 steel has overall superior mechanical properties (compared to A 508/A 533 and Fe-2¼Cr-1Mo) that would enable manufacture of an RPV with thinner walls, thereby reducing thermally induced stresses, minimizing eventual thermal fatigue, and making it a primary candidate for use in the NGNP RPV. However, information is lacking on fabrication experience of this material.

B-4.3.1 Forging/Rolling

Ring forging of RPV using Grade 91 steel does not appear to be a feasible option at present. Axial welding of plates/ring segments is the alternate choice; however, none of the vendors has experience in manufacturing thick section plates. Saarschmeide of Germany is confident they can manufacture such plates; about 55 plates would be required to construct the NGNP RPV.

An assessment of the potential vendors from all over the world showed that capability and experience to fabricate a Grade 91 vessel of the size required for NGNP are severely lacking (see Table B-5).(Mizea 2008) At that time it was apparent that none of the vendors were willing to upgrade their existing capabilities to facilitate forging of this steel unless an incentive is offered in terms of assured market/customers to order RPV of the Grade 91 steel, or in some other form.

Table B-5. Forging capability of Grade 91 for NGNP RPV (~8-m dia. × 24-m high × 100–300-mm thick).

Manufacturer	Current Ring Forging Capability	Future/Upgrade Plans	Viability to forge Grade 91
Japan Steel Works, Japan	8 m OD	May be inclined to try 2¼Cr-Mo steel but not Grade 91 steel	Rings? No Plates? No
Bruck Forgings, Germany	5.2 m OD (max)	8 m rings in 2 to 3 years[a]	Rings? No Plates? No
Saarschmeide, Germany	<5 m	Probable investment in large forging press by 2009[a]	Rings? No Plates? Yes[b]
Scot Forge, Illinois	6 m OD (max)	None	Rings? No Plates? No

Table B-5. (continued).

Doosan Heavy Industries (DHI), South Korea	Experience with Grade 91 for non-nuclear applications.	KAERI[c] in talks with DHI to fabricate thick section vessel using Grade 91.	?

a. Not necessarily for Grade 91

b. ≈6 m × 2.5-m plates, but no experience in manufacturing Grade 91 or 2¼Cr-1Mo-V.

c. Korean Atomic Energy Research Institute (KAERI) is interested in investing/funding DHI for this project.

B-4.3.2 On-site Fabrication

Fabricating a vessel from Grade 91 steel is considerably more difficult than conventional steels due to the welding and heat treating issues discussed in Section B-4.4. In addition to solving technical issues associated with onsite welding and heat treating, post-fabrication heat treatment of Grade 91 structures is likely to require sophisticated inspection methods that are not currently available and may be particularly challenging for field fabrication.

B-4.4 Welding

The superior mechanical properties of the Grade 91 weldment strongly depend on creation of a precise microstructure and maintaining it throughout the service life of the welded component. Welding procedure and post-weld heat treatment play critical roles in creating the desired microstructure and producing a stress-free weld. Welding this steel requires more care in fabrication procedure and joint design than lower alloy steels, being sensitive to temperature variations both during welding and post-weld heat treatment. The most significant problem with welding of Grade 91 steel is its propensity to Type IV cracking in the heat affected zone (see Section B-4.4.4). Over-tempering, under-tempering, cold-work, dissimilar metal welds and stress corrosion cracking are also potential problems encountered in Grade 91 weldments.

Creep-fatigue data show that the number of cycles to failure decreases with the introduction of hold time, and the effect is more severe for the Grade 91 weldment than for the base metal. Significant additional data are needed to quantify this effect and establish the maximum reduction in life, if any.

Repair welding may become necessary for Grade 91. Repair welding usually faces even more technical and operational difficulties than standard welding. Consequently, repair welds are normally not as high quality as the original welds. The issues of avoiding repair welding in fabrication and optimizing its quality during maintenance repair must be studied.

B-4.4.1 Weldability of Vessel Materials

Experience in welding Grade 91 in heavy section components the size of the NGNP RPV for nuclear application is lacking. Grade 91 is a ferritic/martensitic Cr-Mo alloy that requires special consideration and should not be considered just another Cr-Mo material. To obtain the expected superior strength at elevated temperatures, specific microstructures must be obtained and maintained, which requires rigorous control and great care when processing and heat treating the material. During welding, the solidification of the weld pool is virtually a small casting process and many thermal-mechanical processing measures cannot be used or precisely controlled to obtain the desired microstructure. The heavy section for the intended RPV application further adds difficulties to the control of the thermal-mechanical process during welding. R&D activities are needed to investigate and address welding issues.

The presence of delta ferrite is generally undesirable in Grade 91 steels because it may be detrimental to toughness and creep properties. Some compositions within the standard specifications of Grade 91 have delta ferrite, which is stable at all temperatures. In addition, chemical micro-segregation during welding could produce conditions in weld deposits that effectively stabilize the delta ferrite. The influence of delta ferrite on the properties of weld deposits and weldments should be thoroughly characterized, and delta ferrite minimizing measures should be developed.

The phase transformations of the steel are very sensitive to the chemical compositions, and the critical points can change significantly as the composition varies. For example, the M_s can decrease from approximately 400 to 340°C, and the M_f from 210 to 150°C, at the low and high ends of the standard chemistry specification. It is well known that chemical microsegregation inevitably occurs during welding and casting of all alloys. Segregation of elements such as C, Cr, Mo, Si, and V etc. in heavy section welding can significantly influence weld deposit microstructures by creating local variations in phase transformation behavior. Unfortunately little systematic study has been done of microsegregation in martensitic steels. More detailed studies of the effects of chemical micro-segregation on microstructures and properties should be conducted. Further, since chemical micro-segregation is related to welding parameters and is unavoidable, the relationship of chemical micro-segregation in Grade 91 steel to welding parameters should be established.

B-4.4.2 Maintaining Properties for Thick Section Welds

Although the high strength of Grade 91 allows relatively thinner wall designs compared to low-alloy candidate materials, the RPV still requires a heavy section wall and large size. Controlling residual stresses could therefore be an important fabrication issue in the thick section weldment. Recent studies indicate that local application of auxiliary heating or cooling during welding can have beneficial effects on residual stresses in weldment. The need for residual stress control should be established for critical components. Strategies for controlling residual stresses should be developed and verified.

The current experimental testing and weld design approach often oversimplifies the effect of the complex weld microstructure and property gradients in the design and assessment of structural performance and integrity of such large welded structural components. Grade 91 steel includes alloying elements of V, Nb, N, Al, and Ni. Elements such as Nb are prone to segregation in heavy section product forms. This macro-segregation can further complicate the property gradient in the welded region. New or improved design approaches that can realistically incorporate the complex microstructure and property gradients of the weld joint should be developed and verified. Advanced computational models to predict the microstructural changes and their impact on the fracture behavior and long-term creep resistance should also be developed.

During fabrication, heavy section weldments may be held at temperatures below those used for post-weld heat treatments for extended time periods (possibly days). This may be done to maintain preheating temperatures and for hydrogen bake-out treatments. Depending on their temperatures and chemical compositions, weld deposits could contain metastable austenite when low-temperature holds begin. This austenite could then transform during the long holding periods, resulting in different microstructures from those expected under conditions where extended low-temperature holds are not used. Existing data also suggest that hold times may reduce fatigue life of the Grade 91 weldment. The need for extended low-temperature holds should be established and their effects on microstructures and properties determined.

Hydrogen-induced cold cracking is always a concern for heavy section components. To ensure RPV safety, the material susceptibility to cold cracking needs to be investigated. This information will provide crucial guidance for developing temperature control procedures before, during, and after the welding process.

Limited existing data on Grade 91 suggest that creep may become negligible in the temperature range of 425 to 450°C. Designing the RPV in a negligible creep regime could eliminate the need for expensive creep and creep crack monitoring programs throughout the reactor operation life of 60 years. If this design approach is taken, negligible creep behavior of heavy section welds must be thoroughly investigated in order to define the desired operation temperature.

B-4.4.3 Post-Weld Heat Treatment

Post weld heat treatment (PWHT) has a great impact on the final microstructure and long-term mechanical properties of the welds. Grade 91 steel requires great care in PWHT because the material air-hardens and exhibits very little ductility in the as-welded condition. Experience with fossil energy applications has shown that variation of heat chemistry within the ASTM specification can alter critical phase transformation temperatures, as mentioned in Section B-4.4.1. The heavy section of the RPV and the necessity for onsite welding impart additional difficulties in controlling the PWHT parameters.

Customized PWHT procedures must be developed in detail, and the PWHT process should be closely monitored with an array of thermal couples and other types of sensors. To achieve optimum microstructures and high temperature strength, not only the PWHT, but the entire thermal progression for fabricating the weld must be strictly controlled. This usually includes proper preheating, inter-pass temperature control, post weld hydrogen bake-out, and PWHT. Detailed procedures for each step of the thermal processing should be developed, with special considerations for onsite welding of thick sections in various weather conditions. Tabulated continuous cooling transformation diagrams can only be considered as approximate and the heat treating temperatures may need adjustment depending on the actual heat chemistry.

B-4.4.4 Type IV Cracking

Type IV cracking can lead to a shortened creep rupture time in the HAZ compared to that of the base metal. Type IV cracking of transversely loaded weldments may be unavoidable in a Grade 91 steel RPV. Furthermore, as the transverse load decreases the difference between the creep rupture times of the weldment and base metal may actually increase due to Type IV cracking.

Type IV cracking occurs as a result of an accelerated formation rate of creep voids in the fine-grained region of the weld, close to the intercritically annealed zone of the HAZ. The accelerated void formation rate may result from a combination of the fine-grained microstructure and coarse carbide particles contained in the region. The coarse carbide particles can serve as void nucleation sites. The high diffusion rate along the abundant grain boundaries of the fine-grained region can greatly accelerate the formation and growth of creep voids, leading to premature creep failure.

Although Type IV cracking arises from the heterogeneous microstructure in the HAZ, it is usually impractical to eliminate it by a reaustenitization and tempering heat treatment, especially for the large scale and onsite RPV construction. It may be pragmatic to define a creep strength reduction factor for design through creep testing of cross-welds. Known factors that affect propensity to Type IV cracking include service temperature, heat treatment (preheating, tempering, and normalization) temperature, and boron composition. The PWHT time, energy input, and other chemical components may also have limited effects. Investigations are needed to study these factors and develop means to minimize or ideally eliminate the propensity to Type IV cracking.

Material that has exceeded the minimum transformation temperature during the welding process can partially reaustenitize and coarsen, resulting in substantially reduced creep-rupture strength and leading to cracking at relatively low operating temperatures and early component lifetimes. Boron addition seems to reduce cracking susceptibility but additional data are needed to quantify the effect over the long term.

B-4.4.5 Welding Irradiation Effects

As noted in Section B-4.2, some gaps exist in understanding the irradiation behavior of Grade 91. This will be particularly true of weldments, if post-weld heat treatment to re-austenitize and quench the fabricated components to eliminate Type IV cracking prove to be impractical. The fine-grained region of mixed austenite/ferrite microstructure close to the intercritically annealed zone of the HAZ may have quite a different response to irradiation compared to the tempered martensite microstructure in optimally quenched and tempered Grade 91 steel.

B-4.5 Inspection

In general, the inspection requirements for Grade 91 will be similar to those for A 508/A 533. Acceptance criteria defined in the BPVC are well defined for A 508/A 533 pressure vessels and will be broadly similar for Grade 91, but specific flaw sizes will need to be defined. The toughness of a material will affect its critical flaw size: the lower the toughness, the smaller the flaw that must be detected. Grade 91 weldments, which may have nonoptimal heat treatment and properties, are a concern.

An issue that is specific to Grade 91 is the need to develop an additional criterion to ensure that the proper heat treatment has been carried out, resulting in a tempered martensite microstructure that yields the required properties. The Code currently requires a maximum hardness value to ensure that tempering of the brittle martensite has occurred. However, there is, no minimum hardness value specified. Without a minimum hardness value, a mixed microstructure containing ferrite and coarse carbides from an insufficiently rapid quench (with the resulting diminished properties) could exist in the material. It should be noted that hardness measurements characterize the near-surface condition of the steel. There is currently no way to assess the through-thickness microstructure for components of any appreciable size.

B-5. RESEARCH AND TECHNOLOGY PLAN

B-5.1 Required Actions for Code/Licensing Issues

This section discusses the detailed plans to address the code and licensing issues highlighted for the "hot" vessel options. A summary table (Table B-6) and discussion of the required testing for this option is included in this section.

B-5.1.1 Materials Procurement

Forged heavy section Grade 91 steel with a thickness of at least 120 mm would be required for the R&D program to adequately reflect the behavior of heavy pressure vessel sections if it is determined that the hot vessel option requires development.

B-5.1.2 Negligible Creep Temperature for Grade 91 Steel

Section B-3.2.2 described the DOE/ASME ST collaboration Task 3 effort on the investigation of the negligible creep criteria for Grade 91 steel. The following test program is recommended, based on the Task 3 reports,(Riou 2007; Riou 2007) to support NGNP if the "hot" vessel option is pursued for RPV. Tables C1 to C5 of Appendix C present the test matrices for the creep, creep rupture, and creep-fatigue tests to (i) support the assessment of negligible creep conditions, (ii) expand the Grade 91 creep database, and (iii) provide creep-fatigue data to validate the negligible creep temperature recommended in the Task 3 reports.

Tables C1-C3 present creep rupture tests for test temperatures of 425°C, 450°C, and 475°C. The as-received (AR) condition is the default material condition for the testing. Other pre-conditionings include simulated post weld heat treatment (PWHT), thermally aged and cyclically softened (or damaged). The simulated PWHT consists of 20 hours at 750°C. The cyclically softened protocol consists of strain controlled continuous cycling with 0.5% strain range until the stress-strain conditions are consistent with the cyclic stress-strain curve at temperature. For the aging protocol, it is recommended that the condition of 10,000 hours at 475°C proposed by Task 3 be changed to 20,000 hours at 650°C to accelerate the aging process as the intended RPV application is for 60 years.

The test matrix to expand the creep database is presented in Table C-4. The material conditions include AR, simulated PWHT and cyclic softening. The test temperatures are 500°C and 525°C. The creep-fatigue text matrix is shown in Table C-5. Tests with only tension hold and with only compression hold are included. The test temperatures are 450°C and 500°C and the strain range is 0.7%.

Table B-6. Summary of test plan for Grade 91 steel.

Test Matrix Table (C1-C16)	Specimen Type	Number Specimens	Environment	Temperature (°C)	Product Form	Strain Rate (m/m/s)	Time	Specimen Condition	Notes
C1 Creep Tests at 425°C to Support Determination of Negligible Creep Temperature for Grade 91 Steel	Creep Rupture	96	Air	425	F RP	1E-03		AR, Aged, Sim. PWHT combinations	3 heats of each product form 375 or 400 MPa applied stress
C2 Creep Tests at 450°C to Support Determination of Negligible Creep Temperature for Grade 91 Steel	Creep Rupture	108	Air	450	F RP	1E-03		AR, C-F soft., Sim. PWHT combinations	3 heats of each product form 325-425 MPa applied stress
C3 Creep Tests at 475°C to Support Determination of Negligible Creep Temperature for Grade 91 Steel	Creep Rupture	108	Air	475	F RP	1E-03		AR, C-F soft, Sim. PWHT combinations	3 heats of each product form Strain range 0.15-2.0%
C4 Creep to Extend Grade 91 Steel Database	Creep Rupture	144	Air	500, 525	F RP	1E-03		AR, C-F soft., Sim. PWHT combinations	3 heats of each product form Strain range 0.7%
C5 Creep-Fatigue Tests to Support Negligible Creep Temperature Determination	Creep-Fatigue	216	Air	450 or 500	F RP	1E-03	0-300m hold time	AR	2 heats of each product form Coth tensile and compressive hold tests
C6 Fatigue-Relaxation Tests at 500°C	Fatigue-Relaxation	198	Air NGNP-He	500	F	1E-03	0-120m hold time	AR	Coth tensile and compressive hold tests Strain range 0.5-1.0%
C7 Creep-Fatigue Tests at 500°C (stress control)	Creep-Fatigue	90	Air NGNP-He	500	F	1E-03	0-120 m hold time	AR	Coth tensile and compressive hold tests Strain range 0.5-1.0%

Table B-6. (continued).

Test Matrix Table (C1-C16)	Specimen Type	Number Specimens	Environment	Temperature (°C)	Product Form	Strain Rate (m/m/s)	Time	Specimen Condition	Notes
C8 Fatigue-Relaxation Tests for Grade 91 Steel at 550°C	Fatigue-Relaxation	90	Air	550	F	1E-03	0-180 m hold time	AR, Sim. PWHT	Coth tensile and compressive hold tests Strain range 0.4-0.7%
C9 Creep-Fatigue Tests for Grade 91 Steel at 550°C	Creep-Fatigue	27	Air	550	F	1E-03	0-180 m hold time	AR	Coth tensile and compressive hold tests Strain range 0.4-0.7%
C10 Fatigue-Relaxation Tests at 500°C for Aged Grade 91 Steel	Fatigue-Relaxation	99	Air	500	F	1E-03	0-120 m hold time	Aged at 650 20,000 h	Coth tensile and compressive hold tests Strain range 0.4-1.0%
C11 Creep-Fatigue Tests at 500°C for Aged Grade 91 Steel	Creep-Fatigue	45	Air	500	F	1E-03	0-120 m hold time	Aged at 650 20,000 h	Coth tensile and compressive hold tests Strain range 0.5-1.0%
C12 Fatigue-Relaxation Tests at 550°C for SAW, GTAW and SMAW Cross-Welds	Fatigue-Relaxation	135	Air	550	W F	1E-03	0-180 m hold time	PWHT	Coth tensile and compressive hold tests Strain range 0.4-0.7%
C13 Weld Stress Rupture Factor for SAW, GTAW and SMAW Cross-Welds	Creep Rupture	84	Air	425-650	W F	1E-03	1000-100,000 h	PWHT	52-460 MPa applied stress
C14 Short & Medium Term Creep Tests on Creep Fatigue Softened Samples	Creep	6	Air	550	F	1E-03	1000-10,000 h	Crp-Fatigue Softened	
C15 Tensile Tests for Creep Fatigue Softened Samples at 550°C	Tensile	16	Air	20-700	F	1E-03		Crp-Fatigue Softened	
C16 Test Matrix for Grade 91 Steel Fatigue Design Curve at 650°C	Fatigue	54	Air	650	F	4E-03			3 heats of each product form Strain range 0.15-2.07%

B-5.1.3 Creep-Fatigue Testing

The objectives of the Grade 91 testing effort recommend by Task 3 are to improve the understanding of the cyclic behavior at high temperature and to validate creep-fatigue procedure. The test program proposed by Task 3(Riou 2007; Riou 2007) was assessed, and it is recommended that this test program be executed to support NGNP if the “hot” vessel option is pursued for RPV.

There are two “creep-fatigue” protocols recommended by Task 3. One involves keeping the strain constant during hold time and hence the stress relaxes during hold time. This is referred to as fatigue-relaxation test. The other involves keeping the stress constant during hold time and the material will creep. This is called a creep-fatigue test.

Tables C-6 to C-9 present the test matrices for the fatigue-relaxation and creep-fatigue tests at 500°C, with strain ranges of 0.5%, 0.7% and 1%, and 550°C, with strain ranges of 0.4%, 0.5% and 0.7%, respectively. Tension hold only tests and compression hold only tests are both included in the tables. All the tests have AR as the material pre-condition, except one set at 550°C where the pre-condition is simulated PWHT. Some tests are performed in air while others are in NGNP helium.

Tables C10 and C11 present the fatigue-relaxation and creep-fatigue test matrices at 500°C for aged material where the aging protocol is 20,000 hours at 650°C from the AR condition. The aging temperature of 650°C is selected to accelerate the aging process so that the equivalent thermal embrittlement at temperatures lower than 650°C would correspond to times longer than 20,000 hours.

Fatigue-relaxation tests for thick section cross-welds, produced by SA and GTA welding processes, are given in Table C-12. The weldments will be given a simulated PWHT before test specimens are machined.

Table C-13 presents the creep rupture tests of thick section welds, again produced by SA and GTA welding processes. All weldments will receive a simulated PWHT. The applied stresses are sized to get rupture time targets of 1000, 3000 and 10000 hours. However, there are 12 tests that have been sized for 100,000-hour rupture tests to provide qualification data. The data from Table C-13 can be used to develop a weld stress rupture factor to support the code qualification of thick section welds.

Creep rupture tests on Grade 91 specimens that have been softened by creep-fatigue pre-conditioning are given in Table C-14 while Table C-15 presents tensile tests on similarly creep-fatigue softened Grade 91 specimens.

Table C-16 presents testing to support the development of a design continuous cycling fatigue curve at 650°C for use in Subsection NH.

B-5.1.4 Irradiation Effects

As discussed in Section B-4.2, longer term (~two years) and low flux irradiation data are needed to address the concern of synergistic effect of irradiation enhanced segregation of embrittling impurities on grain boundaries. The following irradiation program is proposed. It will include irradiation of tensile specimens, 0.5T compact tension specimens for fracture toughness evaluation, and coupons for microstructural characterization at 325 and 375°C. It is anticipated that irradiation will be performed on simulated stress relieved and thermally aged steels and welds.

As more and more research reactors are shut down, the list of facilities capable of performing such experiments has diminished significantly. In fact, there are probably only three reactors left in North America (the MURR reactor at the University of Missouri in Columbia, Missouri; the MNR at McMaster University in Hamilton, Ontario, Canada; and the MITR-2 at Massachusetts Institute of Technology in Cambridge, Massachusetts) and two reactors in Europe (The BR2 reactor, located at the Studie Centrum Voor Kernenergie - Centre D'etude De L'Energie Nucleaire (SCK-CEN), Mol, Belgium and the LVR-15, located at the Nuclear Research Institute in Rez, Czech Republic) that are capable of performing such irradiation experiments. However, their availability for performing such irradiations is unclear at this point.

B-5.1.5 Welding

B-5.1.5.1 Define Adequate Weldments

Unlike the A 508/533 steel, Grade 91 steel requires post-weld quench and temper heat treatment to achieve maximum high temperature properties. In addition to standard specifications for post-weld examination (e.g., inspection for lack of fusion), the microstructure must be characterized. The current ASME Code rules specify a maximum hardness in order to ensure that proper tempering treatment has been carried out. An additional specification will be required for minimum hardness to ensure that the quench from the austenitizing temperature was sufficient to avoid formation of ferrite and coarse carbides.

B-5.1.5.2 Define Testing Schemes for Prototypical Weldments

The testing schemes for prototypical Grade 91 weldments should consist of three parts. The first part is to characterize the microstructure of the welds to determine whether the desired microstructures are achieved, and delta ferrite is limited within the allowable standards stipulated by ASME Code Section III Division 1 Subsection NH. The second part is to evaluate the integrity of the fabricated weldment in optimizing the filler metals and processing parameters. The third part is to generate some verification data for the Weld Strength Factor (WSF), such as the stress-rupture factor for welds needed for Tables I-14.10 of Mandatory Appendix I-14 of ASME Code Section III Division 1 Subsection NH. The current NH already contains factor values for some specified filler metals. If new filler metals are developed, some data would be needed for verification of the existing factor values. Verification data is especially needed for large forgings not currently covered by the Code.(Ren) Computational modeling will be required for extrapolation of the experimental data to cover the long-term data requirements.

B-5.1.5.3 Post-Weld Heat Treatment

Customized PWHT procedures must be developed for Grade 91 as discussed in Section B-4.4.3. PWHT must be adjusted, depending on the filler metal employed, to achieve the desired microstructure and mechanical properties. Normally, PWHT may be conducted at 760°C ± 15°C over 1 hour for walls less than 13-mm thick. If the thickness is greater than 13 mm, the hold time should be at least 2 hours. For walls thicker than 50 mm, every additional 25 mm may add 1 hour of hold time. Special considerations are needed for onsite welding of thick sections in various weather conditions, including the effects on humidity, heating rate, and cooling rate. For the NGNP RPV, a specific PWHT scheme should be developed based on these suggested parameters.

B-5.1.5.4 Irradiation Effects

Some additional irradiation testing at elevated temperatures will be required for Grade 91 weldments. Evaluation of scoping studies carried out under the Gen IV program must be completed in order to adequately plan the necessary additional irradiation characterization required.

B-5.2 Cost

Table B-7 gives estimated costs for specimen fabrication and testing of the Grade 91 steel and Table B-8 provides the total estimated cost of about $18.5M for testing and analysis of the Grade 91 steel.

Table B-7. Estimated costs for specimen fabrication and testing of the Grade 91 steel

Test Type	# Tests	Product Form	Sample Form	Cost/ Sample[1]	Sample Cost[2]	Time/ Test (H)	Total Test Time	Post Test Time[3]	Testing Cost[4]	Grand Total
Tensile	16	plate	tensile	150	4,800	5	80	80	24,000	28,800
Creep	518	plate	tensile	150	155,400	7	3,626	3,626	1,087,800	1,243,200
Creep-Fatigue	378	plate	crp-fatigue	250	189,000	20	7,560	7,560	2,268,000	2,457,000
Fatigue	54	plate	fatigue	200	21,600	7	378	378	113,400	135,000
Fatigue-Relaxation	477	plate	fatigue	200	190,800	7	3,339	3,339	1,001,700	1,192,500
3,169,800									4,494,900	5,056,500
Pre-treatment										
Damage	70					20	1,400	1,400	420,000	
Welded	146					1	146	146	43,800	
Subtotals	1443				561,600				4,958,700	5,520,300

1. Does not include cost of raw material
2. Multiplied by a factor of 2.0 to account for pre-test purchasing, inspections, welding, and aging
3. Post-test metallurgical, fracture, and data analysis
4. Average burdened labor cost of $150/h used

Table B-8. Estimated cost for testing and analysis of the Grade 91 steel instead of the A 508/533.

FY-09 to FY-14	*(All values in FY-08 burdened $)*	Cost ($)	Subtotals
Material Cost			1,152,580
	Grade 91 raw material	125,000	
	Cost To Machine Samples[a]	561,600	
	Consumables	200,000	
	Adder For Purchasing (30%)	265,980	
Labor For Testing			5,954,570
	Mechanical Property Testing[a]	4,958,700	
	Test Method Development and Validation (10%)	495,870	
	Corrosion Testing	500,000	
Equipment Purchase			4,322,500
	Load Frames	1,500,000	
	Fixtures	75,000	
	Furnaces	250,000	
	Repair, Upgrade, And Refurbishing	1,500,000	
	Adder For Purchasing (30%)	997,500	
Other Labor			4,000,000
	Analysis And Reporting	900,000	
	Engineering Design Support	600,000	
	Project Engineer	900,000	
	ASME Code Interface	1,600,000	
	Subtotal For Labor		9,954,570
	Subtotal For Materials & Equipment		5,475,080
Subtotal			15,429,650
	Quality Assurance (10%)	1,542,965	
	Program Management (10%)	1,542,965	
Total		18,515,580	

a. Value from Table B-7.

Based on previous experience with irradiating RPV steels for the U.S. NRC program, it is estimated that design, instrumentation, assembly, and installation of an instrumented capsule for an irradiation experiment as described in Section B-5.1.4 would be ~$1M and the irradiation facility operating cost would be around $0.5M per year. The operating cost should be considered as a very rough estimate since the reactor site for this experiment has not been selected. The post irradiation examination cost would be ~ $0.6M. Thus the total cost is $3M, which includes a 15% contingency.

B-5.3 References

1. Gougar H. D., and C.B. Davis, 2006, *Reactor Pressure Vessel Temperature Analysis for Prismatic and Pebble-Bed VHTR Designs,* INL/EXT-06-11057, April 2006.
2. *Criteria for Design of Elevated Temperature Class 1 Components in Section III, Division 1, of the ASME Boiler and Pressure Vessel Code*. ASME, 1976.
3. Berman, I., and G. D. Gupta, 1976, "Buckling Rules for Nuclear Components," *Journal of Pressure Vessel Technology,* Vol. 98, p. 229–231.
4. Jakub, M. T., 1976, "New Rules for Construction of Section III, Class 1 Components for Elevated Temperature Service," *Journal of Pressure Vessel Technology,* Vol. 98, p. 214–222.
5. Jetter, R. I., 1976, "Elevated Temperature Design – Development and Implementation of Code Case 1592," *Journal of Pressure Vessel Technology,* Vol. 98, p. 222–229.
6. *Companion Guide to the ASME Boiler & Pressure Vessel Code*. New York, NY: ASME Press, 2002.
7. Shah, V. N., et al., 2003, *Review and Assessment of Codes and Procedures for HTGR Components,* Argonne National Laboratory, NUREG/CR-6816, June 2003.
8. Mizea, R. E., 2008, *Next Generation Nuclear Plant Reactor Pressure Vessel Acquisition Strategy,* INL/EXT-08-13951, April 2008,.
9. Riou, B., YEAR, *Task 3. Improvement of ASME NH for Grade 91 (Negligible Creep,* AREVA NP Inc., an AREVA and Siemens company, 12-9040130-001.
10. Riou, B., 2007, *Task 3. Proposed Test Program to Assess Negligible Creep Conditions of Modified 9cr1mo Grade,* AREVA NP Inc., an AREVA and Siemens company, 12--9047093-001, October 9, 2001.
11. Riou, B., 2007, *Task 3. Improvement of ASME NH for Grade 91 (Creep Fatigue),* AREVA NP Inc., an AREVA and Siemens company, 12-9045964-001, September 27, 2007.
12. Riou, B., 2007, *Task 3. Proposed Test Program to Validate Creep-Fatigue Procedures for Modified 9cr1mo,* AREVA NP Inc., an AREVA and Siemens company, 12-9061054-001, October 9, 2007.
13. Ren, W., 2008, "Preliminary Considerations of Grade 91 Steel for Gen IV Nuclear Reactor Application," *PVP2008-61004*, *Chicago, Il*, *July 27–31, 2008*: v.

Appendix B

Appendix C

Test Matrices for Hot Vessel Option

Appendix C

Table C-1. Creep Tests at 425°C to Support Determination of Negligible Creep Temperature for Grade 91 Steel.

Spec. #	Test Type	Material	Product Form	Mat Cond (1)	Heat	Env	Temp. (°C)	Applied Stress (MPa)
1	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	425	400
2	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	425	400
3	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	425	375
4	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	425	375
5	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-1	air	425	400
6	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-1	air	425	400
7	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-1	air	425	375
8	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-1	air	425	375
9	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	425	400
10	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	425	400
11	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	425	375
12	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	425	375
13	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-1	air	425	400
14	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-1	air	425	400
15	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-1	air	425	375
16	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-1	air	425	375
17	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	425	400
18	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	425	400
19	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	425	375
20	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	425	375
21	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-2	air	425	400
22	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-2	air	425	400
23	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-2	air	425	375
24	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-2	air	425	375
25	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	425	400
26	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	425	400
27	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	425	375

Table C-1. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond [1]	Heat	Env	Temp. (°C)	Applied Stress (MPa)
28	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	425	375
29	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-2	air	425	400
30	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-2	air	425	400
31	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-2	air	425	375
32	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-2	air	425	375
33	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	425	400
34	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	425	400
35	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	425	375
36	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	425	375
37	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-3	air	425	400
38	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-3	air	425	400
39	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-3	air	425	375
40	Creep Rupture	Grade 91	Forging (thick)	AR + Aged	Heat-3	air	425	375
41	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	425	400
42	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	425	400
43	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	425	375
44	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	425	375
45	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-3	air	425	400
46	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-3	air	425	400
47	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-3	air	425	375
48	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT + Aged	Heat-3	air	425	375
49	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	425	400
50	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	425	400
51	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	425	375
52	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	425	375
53	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-1	air	425	400
54	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-1	air	425	400
55	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-1	air	425	375

Table C-1. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond (1)	Heat	Env	Temp. (°C)	Applied Stress (MPa)
56	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-1	air	425	375
57	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	425	400
58	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	425	400
59	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	425	375
60	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	425	375
61	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-1	air	425	400
62	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-1	air	425	400
63	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-1	air	425	375
64	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-1	air	425	375
65	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	425	400
66	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	425	400
67	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	425	375
68	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	425	375
69	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-2	air	425	400
70	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-2	air	425	400
71	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-2	air	425	375
72	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-2	air	425	375
73	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	425	400
74	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	425	400
75	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	425	375
76	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	425	375
77	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-2	air	425	400
78	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-2	air	425	400
79	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-2	air	425	375
80	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-2	air	425	375
81	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	425	400
82	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	425	400
83	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	425	375

Table C-1. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond (1)	Heat	Env	Temp. (°C)	Applied Stress (MPa)
84	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	425	375
85	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-3	air	425	400
86	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-3	air	425	400
87	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-3	air	425	375
88	Creep Rupture	Grade 91	Rolled Plate (thick)	AR + Aged	Heat-3	air	425	375
89	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	425	400
90	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	425	400
91	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	425	375
92	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	425	375
93	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-3	air	425	400
94	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-3	air	425	400
95	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-3	air	425	375
96	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT + Aged	Heat-3	air	425	375

Footnote (1): AR = As Received, Aged = Aging at 650C for 20,000 h

Table C-2. Creep Tests at 450°C to Support Determination of Negligible Creep Temperature for Grade 91 Steel.

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
1	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	450	425
2	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	450	425
3	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	450	425
4	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	450	425
5	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	450	400
6	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	450	400
7	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	450	400
8	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	450	400
9	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-1	air	450	400
10	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-1	air	450	400
11	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	450	375
12	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	450	375
13	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	450	350
14	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	450	350
15	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	450	350
16	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	450	350
17	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	450	325
18	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	450	325
19	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	450	425
20	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	450	425
21	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	450	425
22	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	450	425
23	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	450	400
24	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	450	400
25	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	450	400
26	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	450	400
27	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-2	air	450	400
28	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-2	air	450	400

Table C-2. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
29	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	450	375
30	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	450	375
31	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	450	350
32	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	450	350
33	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	450	350
34	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	450	350
35	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	450	325
36	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	450	325
37	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	450	425
38	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	450	425
39	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	450	425
40	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	450	425
41	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	450	400
42	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	450	400
43	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	450	400
44	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	450	400
45	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-3	air	450	400
46	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-3	air	450	400
47	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	450	375
48	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	450	375
49	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	450	350
50	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	450	350
51	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	450	350
52	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	450	350
53	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	450	325
54	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	450	325
55	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	450	425
56	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	450	425
57	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	450	425

Table C-2. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
58	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	450	425
59	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	450	400
60	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	450	400
61	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	450	400
62	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	450	400
63	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-1	air	450	400
64	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-1	air	450	400
65	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	450	375
66	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	450	375
67	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	450	350
68	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	450	350
69	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	450	350
70	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	450	350
71	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	450	325
72	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	450	325
73	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	450	425
74	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	450	425
75	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	450	425
76	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	450	425
77	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	450	400
78	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	450	400
79	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	450	400
80	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	450	400
81	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-2	air	450	400
82	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-2	air	450	400
83	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	450	375
84	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	450	375
85	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	450	350
86	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	450	350

Table C-2. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
87	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	450	350
88	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	450	350
89	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	450	325
90	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	450	325
91	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	450	425
92	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	450	425
93	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	450	425
94	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	450	425
95	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	450	400
96	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	450	400
97	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	450	400
98	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	450	400
99	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-3	air	450	400
100	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-3	air	450	400
101	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	450	375
102	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	450	375
103	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	450	350
104	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	450	350
105	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	450	350
106	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	450	350
107	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	450	325

Table C-3. Creep Tests at 475°C to Support Determination of Negligible Creep Temperature for Grade 91 Steel.

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
1	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	475	375
2	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	475	375
3	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	475	375
4	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	475	375
5	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	475	350
6	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	475	350
7	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	475	350
8	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	475	350
9	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-1	air	475	350
10	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-1	air	475	350
11	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	475	325
12	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	475	325
13	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	475	300
14	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	475	300
15	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	475	300
16	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	475	300
17	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	475	275
18	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	475	275
19	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	475	375
20	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	475	375
21	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	475	375
22	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	475	375
23	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	475	350
24	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	475	350
25	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	475	350
26	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	475	350
27	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-2	air	475	350
28	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-2	air	475	350

Table C-3. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
29	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	475	325
30	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	475	325
31	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	475	300
32	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	475	300
33	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	475	300
34	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	475	300
35	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	475	275
36	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	475	275
37	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	475	375
38	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	475	375
39	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	475	375
40	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	475	375
41	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	475	350
42	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	475	350
43	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	475	350
44	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	475	350
45	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-3	air	475	350
46	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-3	air	475	350
47	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	475	325
48	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	475	325
49	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	475	300
50	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	475	300
51	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	475	300
52	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	475	300
53	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	475	275
54	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	475	275
55	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	475	375
56	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	475	375
57	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	475	375

Table C-3. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
58	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	475	375
59	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	475	350
60	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	475	350
61	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	475	350
62	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	475	350
63	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-1	air	475	350
64	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-1	air	475	350
65	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	475	325
66	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	475	325
67	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	475	300
68	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	475	300
69	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	475	300
70	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	475	300
71	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	475	275
72	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	475	275
73	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	475	375
74	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	475	375
75	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	475	375
76	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	475	375
77	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	475	350
78	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	475	350
79	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	475	350
80	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	475	350
81	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-2	air	475	350
82	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-2	air	475	350
83	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	475	325
84	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	475	325
85	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	475	300
86	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	475	300

Table C-3. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
87	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	475	300
88	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	475	300
89	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	475	275
90	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	475	275
91	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	475	375
92	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	475	375
93	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	475	375
94	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	475	375
95	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	475	350
96	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	475	350
97	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	475	350
98	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	475	350
99	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-3	air	475	350
100	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-3	air	475	350
101	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	475	325
102	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	475	325
103	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	475	300
104	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	475	300
105	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	475	300
106	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	475	300
107	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	475	275
108	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	475	275

Table C-4. Creep Tests to Extend Grade 91 Steel Database.

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
1	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	500	330
2	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	500	330
3	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	500	330
4	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	500	330
5	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	500	290
6	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	500	290
7	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-1	air	500	290
8	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-1	air	500	290
9	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	500	260
10	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	500	260
11	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	500	260
12	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	500	260
13	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	525	280
14	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	525	280
15	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	525	280
16	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	525	280
17	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	525	250
18	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	525	250
19	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-1	air	525	250
20	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-1	air	525	250
21	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	525	220
22	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-1	air	525	220
23	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	525	220
24	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-1	air	525	220
25	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	500	330
26	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	500	330
27	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	500	330

Table C-4. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
28	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	500	330
29	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	500	290
30	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	500	290
31	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-2	air	500	290
32	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-2	air	500	290
33	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	500	260
34	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	500	260
35	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	500	260
36	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	500	260
37	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	525	280
38	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	525	280
39	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	525	280
40	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	525	280
41	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	525	250
42	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	525	250
43	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-2	air	525	250
44	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-2	air	525	250
45	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	525	220
46	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-2	air	525	220
47	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	525	220
48	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-2	air	525	220
49	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	500	330
50	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	500	330
51	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	500	330
52	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	500	330
53	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	500	290
54	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	500	290
55	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-3	air	500	290

Table C-4. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
56	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-3	air	500	290
57	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	500	260
58	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	500	260
59	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	500	260
60	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	500	260
61	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	525	280
62	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	525	280
63	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	525	280
64	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	525	280
65	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	525	250
66	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	525	250
67	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-3	air	525	250
68	Creep Rupture	Grade 91	Forging (thick)	Creep-Fatigue Softened	Heat-3	air	525	250
69	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	525	220
70	Creep Rupture	Grade 91	Forging (thick)	AR	Heat-3	air	525	220
71	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	525	220
72	Creep Rupture	Grade 91	Forging (thick)	Sim. PWHT	Heat-3	air	525	220
73	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	500	330
74	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	500	330
75	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	500	330
76	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	500	330
77	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	500	290
78	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	500	290
79	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-1	air	500	290
80	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-1	air	500	290
81	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	500	260
82	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	500	260
83	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	500	260

Table C-4. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
84	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	500	260
85	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	525	280
86	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	525	280
87	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	525	280
88	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	525	280
89	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	525	250
90	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	525	250
91	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-1	air	525	250
92	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-1	air	525	250
93	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	525	220
94	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-1	air	525	220
95	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	525	220
96	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-1	air	525	220
97	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	500	330
98	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	500	330
99	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	500	330
100	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	500	330
101	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	500	290
102	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	500	290
103	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-2	air	500	290
104	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-2	air	500	290
105	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	500	260
106	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	500	260
107	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	500	260
108	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	500	260
109	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	525	280
110	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	525	280
111	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	525	280

Table C-4. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
112	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	525	280
113	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	525	250
114	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	525	250
115	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-2	air	525	250
116	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-2	air	525	250
117	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	525	220
118	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-2	air	525	220
119	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	525	220
120	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-2	air	525	220
121	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	500	330
122	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	500	330
123	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	500	330
124	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	500	330
125	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	500	290
126	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	500	290
127	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-3	air	500	290
128	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-3	air	500	290
129	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	500	260
130	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	500	260
131	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	500	260
132	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	500	260
133	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	525	280
134	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	525	280
135	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	525	280
136	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	525	280
137	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	525	250
138	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	525	250
139	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-3	air	525	250

Table C-4. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Heat	Env	Temp. (°C)	Applied Stress (MPa)
140	Creep Rupture	Grade 91	Rolled Plate (thick)	Creep-Fatigue Softened	Heat-3	air	525	250
141	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	525	220
142	Creep Rupture	Grade 91	Rolled Plate (thick)	AR	Heat-3	air	525	220
143	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	525	220
144	Creep Rupture	Grade 91	Rolled Plate (thick)	Sim. PWHT	Heat-3	air	525	220

Table C-5. Creep-Fatigue Tests to Support Negligible Creep Temperature Determination.

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Stress Hold in T/C	Temp. (°C)	Strain Range (%)	Stress Hold Time (min)
1	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	450	0.7	0
2	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	450	0.7	0
3	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	450	0.7	0
4	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	1
5	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	1
6	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	1
7	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	10
8	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	10
9	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	10
10	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	60
11	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	60
12	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	60
13	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	300*
14	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	300*
15	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	300*
16	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	1
17	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	1
18	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	1
19	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	10
20	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	10
21	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	10
22	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	60
23	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	60
24	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	60
25	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	300*

Table C-5. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Stress Hold in T/C	Temp. (°C)	Strain Range (%)	Stress Hold Time (min)
26	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	300*
27	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	300*
28	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.7	0
29	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.7	0
30	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.7	0
31	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	1
32	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	1
33	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	1
34	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	10
35	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	10
36	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	10
37	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	60
38	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	60
39	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	60
40	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	300*
41	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	300*
42	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	300*
43	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	1
44	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	1
45	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	1
46	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	10
47	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	10
48	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	10
49	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	60
50	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	60
51	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	60

Table C-5. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Stress Hold in T/C	Temp. (°C)	Strain Range (%)	Stress Hold Time (min)
52	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	300*
53	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	300*
54	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	300*
55	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	N/A	450	0.7	0
56	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	N/A	450	0.7	0
57	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	N/A	450	0.7	0
58	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	1
59	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	1
60	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	1
61	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	10
62	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	10
63	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	10
64	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	60
65	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	60
66	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	60
67	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	300*
68	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	300*
69	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	300*
70	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	1
71	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	1
72	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	1
73	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	10
74	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	10
75	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	10
76	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	60
77	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	60

Table C-5. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Stress Hold in T/C	Temp. (°C)	Strain Range (%)	Stress Hold Time (min)
78	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	60
79	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	300*
80	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	300*
81	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	300*
82	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	N/A	500	0.7	0
83	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	N/A	500	0.7	0
84	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	N/A	500	0.7	0
85	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	1
86	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	1
87	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	1
88	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	10
89	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	10
90	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	10
91	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	60
92	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	60
93	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	60
94	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	300*
95	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	300*
96	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	300*
97	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	1
98	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	1
99	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	1
100	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	10
101	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	10
102	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	10
103	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	60

Table C-5. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Stress Hold in T/C	Temp. (°C)	Strain Range (%)	Stress Hold Time (min)
104	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	60
105	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	60
106	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	300*
107	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	300*
108	Creep-Fatigue	Grade 91	Forging (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	300*
109	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	N/A	450	0.7	0
110	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	N/A	450	0.7	0
111	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	N/A	450	0.7	0
112	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	1
113	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	1
114	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	1
115	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	10
116	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	10
117	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	10
118	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	60
119	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	60
120	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	60
121	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	300*
122	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	300*
123	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	450	0.7	300*
124	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	1
125	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	1
126	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	1
127	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	10
128	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	10
129	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	10

Table C-5. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Stress Hold in T/C	Temp. (°C)	Strain Range (%)	Stress Hold Time (min)
130	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	60
131	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	60
132	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	60
133	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	300*
134	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	300*
135	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	450	0.7	300*
136	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.7	0
137	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.7	0
138	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.7	0
139	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	1
140	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	1
141	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	1
142	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	10
143	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	10
144	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	10
145	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	60
146	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	60
147	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	60
148	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	300*
149	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	300*
150	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	300*
151	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	1
152	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	1
153	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	1
154	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	10
155	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	10

Table C-5. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Stress Hold in T/C	Temp. (°C)	Strain Range (%)	Stress Hold Time (min)
156	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	10
157	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	60
158	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	60
159	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	60
160	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	300*
161	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	300*
162	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	300*
163	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	N/A	450	0.7	0
164	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	N/A	450	0.7	0
165	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	N/A	450	0.7	0
166	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	1
167	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	1
168	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	1
169	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	10
170	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	10
171	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	10
172	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	60
173	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	60
174	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	60
175	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	300*
176	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	300*
177	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	450	0.7	300*
178	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	1
179	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	1
180	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	1
181	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	10

Table C-5. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Stress Hold in T/C	Temp. (°C)	Strain Range (%)	Stress Hold Time (min)
182	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	10
183	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	10
184	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	60
185	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	60
186	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	60
187	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	300*
188	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	300*
189	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	450	0.7	300*
190	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	N/A	500	0.7	0
191	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	N/A	500	0.7	0
192	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	N/A	500	0.7	0
193	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	1
194	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	1
195	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	1
196	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	10
197	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	10
198	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	10
199	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	60
200	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	60
201	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	60
202	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	300*
203	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	300*
204	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	tension	500	0.7	300*
205	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	1
206	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	1
207	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	1

Table C-5. (continued).

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Stress Hold in T/C	Temp. (°C)	Strain Range (%)	Stress Hold Time (min)
208	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	10
209	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	10
210	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	10
211	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	60
212	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	60
213	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	60
214	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	300*
215	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	300*
216	Creep-Fatigue	Grade 91	Rolled Plate (thick)	AR	heat-2	1E-03	air	stress	comp.	500	0.7	300*

Footnote * Test Can Stop Cefore Failure

Table C-6. Fatigue-Relaxation Tests for Grade 91 steel at 500ºC.

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
1	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	500	0.5	0
2	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	500	0.5	0
3	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	500	0.5	0
4	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	10
5	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	10
6	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	10
7	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	30
8	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	30
9	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	30
10	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	60
11	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	60
12	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	60
13	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	90
14	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	90
15	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	90
16	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	120
17	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	120
18	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.5	120
19	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	500	0.7	0
20	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	500	0.7	0
21	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	500	0.7	0
22	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	10
23	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	10
24	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	10
25	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	30

Table C-6. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
26	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	30
27	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	30
28	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	60
29	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	60
30	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	60
31	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	90
32	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	90
33	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	90
34	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	120
35	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	120
36	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	0.7	120
37	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	500	1.0	0
38	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	500	1.0	0
39	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	500	1.0	0
40	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	10
41	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	10
42	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	10
43	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	30
44	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	30
45	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	30
46	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	60
47	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	60
48	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	60
49	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	90
50	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	90
51	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	90

Table C-6. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
52	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	120
53	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	120
54	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	500	1.0	120
55	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	10
56	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	10
57	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	10
58	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	30
59	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	30
60	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	30
61	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	60
62	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	60
63	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	60
64	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	90
65	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	90
66	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	90
67	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	120
68	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	120
69	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.5	120
70	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	10
71	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	10
72	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	10
73	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	30
74	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	30
75	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	30
76	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	60
77	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	60

Table C-6. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
78	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	60
79	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	90
80	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	90
81	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	90
82	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	120
83	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	120
84	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	0.7	120
85	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	10
86	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	10
87	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	10
88	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	30
89	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	30
90	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	30
91	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	60
92	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	60
93	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	60
94	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	90
95	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	90
96	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	90
97	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	120
98	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	120
99	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	500	1.0	120
100	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	N/A	500	0.5	0
101	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	N/A	500	0.5	0
102	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	N/A	500	0.5	0
103	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	10

Table C-6. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
104	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	10
105	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	10
106	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	30
107	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	30
108	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	30
109	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	60
110	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	60
111	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	60
112	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	90
113	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	90
114	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	90
115	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	120
116	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	120
117	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.5	120
118	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	N/A	500	0.7	0
119	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	N/A	500	0.7	0
120	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	N/A	500	0.7	0
121	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	10
122	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	10
123	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	10
124	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	30
125	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	30
126	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	30
127	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	60
128	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	60
129	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	60

Table C-6. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
130	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	90
131	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	90
132	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	90
133	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	120
134	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	120
135	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	0.7	120
136	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	N/A	500	1.0	0
137	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	N/A	500	1.0	0
138	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	N/A	500	1.0	0
139	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	10
140	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	10
141	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	10
142	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	30
143	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	30
144	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	30
145	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	60
146	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	60
147	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	60
148	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	90
149	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	90
150	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	90
151	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	120
152	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	120
153	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	tension	500	1.0	120
154	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	10
155	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	10

Table C-6. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
156	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	10
157	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	30
158	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	30
159	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	30
160	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	60
161	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	60
162	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	60
163	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	90
164	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	90
165	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	90
166	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	120
167	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	120
168	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.5	120
169	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	10
170	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	10
171	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	10
172	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	30
173	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	30
174	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	30
175	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	60
176	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	60
177	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	60
178	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	90
179	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	90
180	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	90
181	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	120

Table C-6. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
182	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	120
183	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	0.7	120
184	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	10
185	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	10
186	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	10
187	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	30
188	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	30
189	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	30
190	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	60
191	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	60
192	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	60
193	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	90
194	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	90
195	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	90
196	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	120
197	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	120
198	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	strain	comp.	500	1.0	120

Table C-7. Creep-Fatigue Tests for Grade 91 Steel at 500ºC.

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Stress Hold in T/C	Temp. (ºC)	Strain Range (%)	Total Strain During Stress Hold (%)
1	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.5	0
2	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.5	0
3	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.5	0
4	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.5	0.1
5	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.5	0.1
6	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.5	0.1
7	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.5	0.3
8	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.5	0.3
9	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.5	0.3
10	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.7	0
11	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.7	0
12	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	0.7	0
13	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	0.1
14	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	0.1
15	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	0.1
16	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	0.3
17	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	0.3
18	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	0.7	0.3
19	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	1.0	0
20	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	1.0	0
21	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	500	1.0	0
22	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	1.0	0.1
23	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	1.0	0.1
24	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	1.0	0.1
25	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	1.0	0.3

Table C-7. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Stress Hold in T/C	Temp. (ºC)	Strain Range (%)	Total Strain During Stress Hold (%)
26	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	1.0	0.3
27	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	500	1.0	0.3
28	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.5	0.1
29	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.5	0.1
30	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.5	0.1
31	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.5	0.3
32	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.5	0.3
33	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.5	0.3
34	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	0.1
35	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	0.1
36	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	0.1
37	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	0.3
38	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	0.3
39	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	0.7	0.3
40	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	1.0	0.1
41	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	1.0	0.1
42	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	1.0	0.1
43	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	1.0	0.3
44	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	1.0	0.3
45	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	500	1.0	0.3
46	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	N/A	500	0.5	0
47	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	N/A	500	0.5	0
48	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	N/A	500	0.5	0
49	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.5	0.1
50	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.5	0.1
51	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.5	0.1

Table C-7. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Stress Hold in T/C	Temp. (ºC)	Strain Range (%)	Total Strain During Stress Hold (%)
52	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.5	0.3
53	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.5	0.3
54	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.5	0.3
55	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	N/A	500	0.7	0
56	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	N/A	500	0.7	0
57	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	N/A	500	0.7	0
58	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.7	0.1
59	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.7	0.1
60	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.7	0.1
61	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.7	0.3
62	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.7	0.3
63	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	0.7	0.3
64	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	N/A	500	1.0	0
65	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	N/A	500	1.0	0
66	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	N/A	500	1.0	0
67	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	1.0	0.1
68	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	1.0	0.1
69	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	1.0	0.1
70	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	1.0	0.3
71	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	1.0	0.3
72	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	tension	500	1.0	0.3
73	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.5	0.1
74	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.5	0.1
75	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.5	0.1
76	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.5	0.3
77	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.5	0.3

Table C-7. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Stress Hold in T/C	Temp. (ºC)	Strain Range (%)	Total Strain During Stress Hold (%)
78	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.5	0.3
79	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.7	0.1
80	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.7	0.1
81	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.7	0.1
82	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.7	0.3
83	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.7	0.3
84	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	0.7	0.3
85	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	1.0	0.1
86	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	1.0	0.1
87	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	1.0	0.1
88	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	1.0	0.3
89	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	1.0	0.3
90	Grade 91	Forging (thick)	AR	heat-1	1E-03	NGNP-He	stress	comp.	500	1.0	0.3

Table C-8. Fatigue-Relaxation Tests for Grade 91 Steel at 550ºC.

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
1	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	550	0.4	0
2	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	550	0.4	0
3	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	550	0.4	0
4	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.4	90
5	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.4	90
6	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.4	90
7	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.4	180
8	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.4	180
9	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.4	180
10	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	550	0.5	0
11	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	550	0.5	0
12	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	550	0.5	0
13	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.5	90
14	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.5	90
15	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.5	90
16	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.5	180
17	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.5	180
18	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.5	180
19	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	550	0.7	0
20	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	550	0.7	0
21	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	N/A	550	0.7	0
22	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.7	90
23	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.7	90
24	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.7	90
25	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.7	180

Table C-8. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
26	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.7	180
27	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	tension	550	0.7	180
28	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.4	90
29	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.4	90
30	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.4	90
31	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.4	180
32	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.4	180
33	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.4	180
34	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.5	90
35	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.5	90
36	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.5	90
37	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.5	180
38	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.5	180
39	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.5	180
40	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.7	90
41	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.7	90
42	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.7	90
43	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.7	180
44	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.7	180
45	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	strain	comp.	550	0.7	180
46	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	N/A	550	0.4	0
47	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	N/A	550	0.4	0
48	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	N/A	550	0.4	0
49	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.4	90
50	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.4	90
51	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.4	90

Table C-8. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
52	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.4	180
53	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.4	180
54	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.4	180
55	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	N/A	550	0.5	0
56	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	N/A	550	0.5	0
57	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	N/A	550	0.5	0
58	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.5	90
59	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.5	90
60	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.5	90
61	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.5	180
62	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.5	180
63	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.5	180
64	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	N/A	550	0.7	0
65	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	N/A	550	0.7	0
66	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	N/A	550	0.7	0
67	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.7	90
68	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.7	90
69	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.7	90
70	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.7	180
71	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.7	180
72	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	tension	550	0.7	180
73	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.4	90
74	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.4	90
75	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.4	90
76	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.4	180
77	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.4	180

Table C-8. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
78	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.4	180
79	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.5	90
80	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.5	90
81	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.5	90
82	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.5	180
83	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.5	180
84	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.5	180
85	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.7	90
86	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.7	90
87	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.7	90
88	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.7	180
89	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.7	180
90	Grade 91	Forging (thick)	Sim. PWHT	heat-1	1E-03	air	strain	comp.	550	0.7	180

Table C-9. Creep-Fatigue Tests for Grade 91 Steel at 550ºC.

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Stress Hold in T/C	Temp. (ºC)	Strain Range (%)	Total Strain During Stress Hold (%)
1	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	550	0.4	0
2	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	550	0.4	0
3	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	550	0.4	0
4	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	550	0.4	0.5
5	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	550	0.4	0.5
6	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	550	0.4	0.5
7	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	550	0.5	0
8	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	550	0.5	0
9	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	550	0.5	0
10	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	550	0.5	0.5
11	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	550	0.5	0.5
12	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	550	0.5	0.5
13	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	550	0.7	0
14	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	550	0.7	0
15	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	N/A	550	0.7	0
16	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	550	0.7	0.3
17	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	550	0.7	0.3
18	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	tension	550	0.7	0.3
19	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	550	0.4	0.5
20	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	550	0.4	0.5
21	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	550	0.4	0.5
22	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	550	0.5	0.5
23	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	550	0.5	0.5
24	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	550	0.5	0.5
25	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	550	0.7	0.3

Table C-9. (continued).

Spec. #	Material	Product Form	Mat Cond	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Stress Hold in T/C	Temp. (ºC)	Strain Range (%)	Total Strain During Stress Hold (%)
26	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	550	0.7	0.3
27	Grade 91	Forging (thick)	AR	heat-1	1E-03	air	stress	comp.	550	0.7	0.3

Table C-10. Fatigue-Relaxation Tests at 500ºC for Aged Grade 91 Steel.

Spec. #	Material	Product Form	Aging Temp. (ºC)	Aging Time (h)	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
1	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	N/A	500	0.5	0
2	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	N/A	500	0.5	0
3	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	N/A	500	0.5	0
4	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	10
5	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	10
6	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	10
7	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	30
8	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	30
9	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	30
10	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	60
11	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	60
12	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	60
13	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	90
14	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	90
15	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	90
16	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	120
17	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	120
18	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.5	120
19	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	N/A	500	0.7	0
20	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	N/A	500	0.7	0
21	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	N/A	500	0.7	0
22	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	10
23	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	10
24	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	10
25	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	30
26	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	30

Table C-10. (continued).

Spec. #	Material	Product Form	Aging Temp. (ºC)	Aging Time (h)	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
27	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	30
28	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	60
29	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	60
30	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	60
31	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	90
32	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	90
33	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	90
34	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	120
35	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	120
36	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	0.7	120
37	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	N/A	500	1.0	0
38	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	N/A	500	1.0	0
39	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	N/A	500	1.0	0
40	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	10
41	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	10
42	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	10
43	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	30
44	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	30
45	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	30
46	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	60
47	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	60
48	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	60
49	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	90
50	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	90
51	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	90
52	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	120
53	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	120

Table C-10. (continued).

Spec. #	Material	Product Form	Aging Temp. (ºC)	Aging Time (h)	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
54	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	tension	500	1.0	120
55	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	10
56	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	10
57	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	10
58	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	30
59	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	30
60	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	30
61	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	60
62	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	60
63	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	60
64	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	90
65	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	90
66	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	90
67	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	120
68	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	120
69	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.5	120
70	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	10
71	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	10
72	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	10
73	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	30
74	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	30
75	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	30
76	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	60
77	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	60
78	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	60
79	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	90
80	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	90

Table C-10. (continued).

Spec. #	Material	Product Form	Aging Temp. (ºC)	Aging Time (h)	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
81	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	90
82	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	120
83	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	120
84	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	0.7	120
85	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	10
86	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	10
87	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	10
88	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	30
89	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	30
90	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	30
91	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	60
92	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	60
93	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	60
94	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	90
95	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	90
96	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	90
97	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	120
98	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	120
99	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	strain	comp.	500	1.0	120

Table C-11. Creep-Fatigue Tests at 500ºC for Aged Grade 91 Steel.

Spec. #	Material	Product Form	Aging Temp. (ºC)	Aging Time (h)	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Stress Hold in T/C	Temp. (ºC)	Strain Range (%)	Total Strain During Stress Hold (%)
1	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	N/A	500	0.5	0
2	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	N/A	500	0.5	0
3	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	N/A	500	0.5	0
4	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.5	0.1
5	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.5	0.1
6	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.5	0.1
7	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.5	0.3
8	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.5	0.3
9	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.5	0.3
10	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	N/A	500	0.7	0
11	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	N/A	500	0.7	0
12	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	N/A	500	0.7	0
13	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.7	0.1
14	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.7	0.1
15	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.7	0.1
16	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.7	0.3
17	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.7	0.3
18	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	0.7	0.3
19	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	N/A	500	1.0	0
20	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	N/A	500	1.0	0
21	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	N/A	500	1.0	0
22	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	1.0	0.1
23	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	1.0	0.1
24	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	1.0	0.1
25	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	1.0	0.3

Table C-11. (continued).

Spec. #	Material	Product Form	Aging Temp. (ºC)	Aging Time (h)	Heat	Strain Rate (m/m/s)	Env	Hold Cntrl (stress/strain)	Stress Hold in T/C	Temp. (ºC)	Strain Range (%)	Total Strain During Stress Hold (%)
26	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	1.0	0.3
27	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	tension	500	1.0	0.3
28	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.5	0.1
29	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.5	0.1
30	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.5	0.1
31	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.5	0.3
32	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.5	0.3
33	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.5	0.3
34	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.7	0.1
35	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.7	0.1
36	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.7	0.1
37	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.7	0.3
38	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.7	0.3
39	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	0.7	0.3
40	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	1.0	0.1
41	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	1.0	0.1
42	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	1.0	0.1
43	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	1.0	0.3
44	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	1.0	0.3
45	Grade 91	Forging (thick)	650	20000	heat-1	1E-03	air	stress	comp.	500	1.0	0.3

Table C-12. Fatigue-Relaxation Tests at 550ºC for Grade 91 Cross Welds.

Spec. #	Weld Wire	Product Form	Weld Process	Mat Cond	G91 Thick Section Heat #	Weld to be Tested	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
1	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.4	0
2	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.4	0
3	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.4	0
4	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	90
5	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	90
6	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	90
7	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	180
8	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	180
9	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	180
10	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.5	0
11	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.5	0
12	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.5	0
13	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	90
14	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	90
15	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	90
16	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	180
17	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	180
18	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	180
19	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.7	0
20	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.7	0
21	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.7	0
22	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	90
23	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	90
24	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	90
25	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	180

Table C-12. (continued).

Spec. #	Weld Wire	Product Form	Weld Process	Mat Cond	G91 Thick Section Heat #	Weld to be Tested	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
26	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	180
27	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	180
28	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	90
29	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	90
30	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	90
31	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	180
32	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	180
33	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	180
34	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	90
35	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	90
36	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	90
37	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	180
38	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	180
39	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	180
40	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	90
41	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	90
42	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	90
43	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	180
44	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	180
45	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	180
46	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.4	0
47	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.4	0
48	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.4	0
49	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	90
50	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	90
51	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	90

Table C-12. (continued).

Spec. #	Weld Wire	Product Form	Weld Process	Mat Cond	G91 Thick Section Heat #	Weld to be Tested	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
52	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	180
53	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	180
54	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.4	180
55	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.5	0
56	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.5	0
57	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.5	0
58	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	90
59	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	90
60	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	90
61	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	180
62	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	180
63	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.5	180
64	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.7	0
65	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.7	0
66	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	N/A	550	0.7	0
67	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	90
68	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	90
69	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	90
70	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	180
71	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	180
72	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	tension	550	0.7	180
73	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	90
74	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	90
75	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	90
76	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	180
77	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	180

Table C-12. (continued).

Spec. #	Weld Wire	Product Form	Weld Process	Mat Cond	G91 Thick Section Heat #	Weld to be Tested	Strain Rate (m/m/s)	Env	Hold Cntrl (stress or strain)	Strain Hold in T/C	Temp. (ºC)	Strain Range (%)	Time During Strain Hold (min)
78	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.4	180
79	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	90
80	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	90
81	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	90
82	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	180
83	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	180
84	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.5	180
85	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	90
86	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	90
87	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	90
88	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	180
89	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	180
90	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	1E-03	air	strain	comp.	550	0.7	180

Table C-13. Test Matrix to Determine Weld Stress Rupture Factor for Grade 91 Cross Welds.

Test Prgm	Spec. #	Weld Wire	Product Form	Weld Process	Mat Cond	G91 Thick Section Heat #	Weld to be Tested	Env	Temp. (ºC)	Stress (MPa)	Est. Rupture Time (h)
Tk-Weld	1	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	425	460	1000
Tk-Weld	2	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	425	460	1000
Tk-Weld	3	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	425	436	3000
Tk-Weld	4	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	425	436	3000
Tk-Weld	5	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	425	415	10000
Tk-Weld	6	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	425	415	10000
Tk-Weld	7	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	500	285	1000
Tk-Weld	8	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	500	285	1000
Tk-Weld	9	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	500	265	3000
Tk-Weld	10	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	500	265	3000
Tk-Weld	11	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	500	250	10000
Tk-Weld	12	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	500	250	10000
Tk-Weld	13	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	575	165	1000
Tk-Weld	14	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	575	165	1000
Tk-Weld	15	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	575	150	3000
Tk-Weld	16	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	575	150	3000
Tk-Weld	17	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	575	135	10000
Tk-Weld	18	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	575	135	10000
Tk-Weld	19	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	650	82	1000
Tk-Weld	20	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	650	82	1000
Tk-Weld	21	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	650	72	3000
Tk-Weld	22	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	650	72	3000
Tk-Weld	23	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	650	52	10000
Tk-Weld	24	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	650	52	10000
Tk-Weld	25	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	425	460	1000

Table C-13. (continued).

Test Prgm	Spec. #	Weld Wire	Product Form	Weld Process	Mat Cond	G91 Thick Section Heat #	Weld to be Tested	Env	Temp. (ºC)	Stress (MPa)	Est. Rupture Time (h)
Tk-Weld	26	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	425	460	1000
Tk-Weld	27	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	425	436	3000
Tk-Weld	28	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	425	436	3000
Tk-Weld	29	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	425	415	10000
Tk-Weld	30	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	425	415	10000
Tk-Weld	31	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	500	285	1000
Tk-Weld	32	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	500	285	1000
Tk-Weld	33	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	500	265	3000
Tk-Weld	34	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	500	265	3000
Tk-Weld	35	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	500	250	10000
Tk-Weld	36	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	500	250	10000
Tk-Weld	37	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	575	165	1000
Tk-Weld	38	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	575	165	1000
Tk-Weld	39	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	575	150	3000
Tk-Weld	40	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	575	150	3000
Tk-Weld	41	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	575	135	10000
Tk-Weld	42	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	575	135	10000
Tk-Weld	43	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	650	82	1000
Tk-Weld	44	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	650	82	1000
Tk-Weld	45	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	650	72	3000
Tk-Weld	46	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	650	72	3000
Tk-Weld	47	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	650	52	10000
Tk-Weld	48	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	650	52	10000
Tk-Weld-QUAL	73	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	425	370	100000
Tk-Weld-QUAL	74	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	425	370	100000
Tk-Weld-QUAL	75	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	500	215	100000

Table C-13. (continued).

Test Prgm	Spec. #	Weld Wire	Product Form	Weld Process	Mat Cond	G91 Thick Section Heat #	Weld to be Tested	Env	Temp. (ºC)	Stress (MPa)	Est. Rupture Time (h)
Tk-Weld-QUAL	76	TBD	Thick Sect. Weld	SAW	PWHT	heat-1	X-Weld	air	500	215	100000
Tk-Weld-QUAL	77	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	425	370	100000
Tk-Weld-QUAL	78	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	425	370	100000
Tk-Weld-QUAL	79	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	500	215	100000
Tk-Weld-QUAL	80	TBD	Thick Sect. Weld	GTAW	PWHT	heat-1	X-Weld	air	500	215	100000

Table C-14. Short and Medium Term Creep Tests for Creep-Fatigue Softened Grade 91 Steel at 550°C

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Env	Temp. (°C)	Applied Stress (MPa)	Creep Time (h)
1	Creep	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	550	240	1000
2	Creep	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	550	240	1000
3	Creep	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	550	227	3000
4	Creep	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	550	227	3000
5	Creep	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	550	209	10000
6	Creep	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	550	209	10000

Table C-15. Tensile Tests for Creep-Fatigue Softened Grade 91 Steel at 550°C

Spec. #	Test Type	Material	Product Form	Mat Cond	Grade 91 Heat #	Env	Strain Rate (m/m/s)	Temp. (°C)
1	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	20
2	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	20
3	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	100
4	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	100
5	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	200
6	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	200
7	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	300
8	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	300
9	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	400
10	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	400
11	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	500
12	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	500
13	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	600
14	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	600
15	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	700
16	Tensile	Grade 91	Forging (thick)	Creep-Fatigue Softened	heat-1	air	1E-03	700

Table C-16. Test Matrix for Grade 91 Steel Fatigue Design Curve at 650ºC, AR = As Received.

Test Program	Specimen Type	Spec. #	Material	Product Form	Mat Cond	Grade 91 Heat #	Env.	Temp. (ºC)	Strain Rate Magnitude (m/m/s)	Strain Range (%)
Design Curve	Fatigue	1	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.15
Design Curve	Fatigue	2	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.15
Design Curve	Fatigue	3	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.15
Design Curve	Fatigue	4	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.25
Design Curve	Fatigue	5	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.25
Design Curve	Fatigue	6	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.25
Design Curve	Fatigue	7	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.40
Design Curve	Fatigue	8	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.40
Design Curve	Fatigue	9	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.40
Design Curve	Fatigue	10	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.60
Design Curve	Fatigue	11	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.60
Design Curve	Fatigue	12	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	0.60
Design Curve	Fatigue	13	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	1.00
Design Curve	Fatigue	14	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	1.00
Design Curve	Fatigue	15	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	1.00
Design Curve	Fatigue	16	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	2.00
Design Curve	Fatigue	17	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	2.00
Design Curve	Fatigue	18	Grade 91	Forging (thick)	AR	heat-1	air	650	4E-03	2.00
Design Curve	Fatigue	19	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.15
Design Curve	Fatigue	20	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.15
Design Curve	Fatigue	21	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.15
Design Curve	Fatigue	22	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.25
Design Curve	Fatigue	23	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.25
Design Curve	Fatigue	24	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.25
Design Curve	Fatigue	25	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.40

Table C-16. (continued).

Test Program	Specimen Type	Spec. #	Material	Product Form	Mat Cond	Grade 91 Heat #	Env.	Temp. (ºC)	Strain Rate Magnitude (m/m/s)	Strain Range (%)
Design Curve	Fatigue	26	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.40
Design Curve	Fatigue	27	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.40
Design Curve	Fatigue	28	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.60
Design Curve	Fatigue	29	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.60
Design Curve	Fatigue	30	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	0.60
Design Curve	Fatigue	31	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	1.00
Design Curve	Fatigue	32	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	1.00
Design Curve	Fatigue	33	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	1.00
Design Curve	Fatigue	34	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	2.00
Design Curve	Fatigue	35	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	2.00
Design Curve	Fatigue	36	Grade 91	Forging (thick)	AR	heat-2	air	650	4E-03	2.00
Design Curve	Fatigue	37	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.15
Design Curve	Fatigue	38	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.15
Design Curve	Fatigue	39	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.15
Design Curve	Fatigue	40	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.25
Design Curve	Fatigue	41	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.25
Design Curve	Fatigue	42	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.25
Design Curve	Fatigue	43	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.40
Design Curve	Fatigue	44	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.40
Design Curve	Fatigue	45	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.40
Design Curve	Fatigue	46	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.60
Design Curve	Fatigue	47	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.60
Design Curve	Fatigue	48	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	0.60
Design Curve	Fatigue	49	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	1.00
Design Curve	Fatigue	50	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	1.00
Design Curve	Fatigue	51	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	1.00

Table C-16. (continued).

Test Program	Specimen Type	Spec. #	Material	Product Form	Mat Cond	Grade 91 Heat #	Env.	Temp. (ºC)	Strain Rate Magnitude (m/m/s)	Strain Range (%)
Design Curve	Fatigue	52	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	2.00
Design Curve	Fatigue	53	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	2.00
Design Curve	Fatigue	54	Grade 91	Forging (thick)	AR	heat-3	air	650	4E-03	2.00