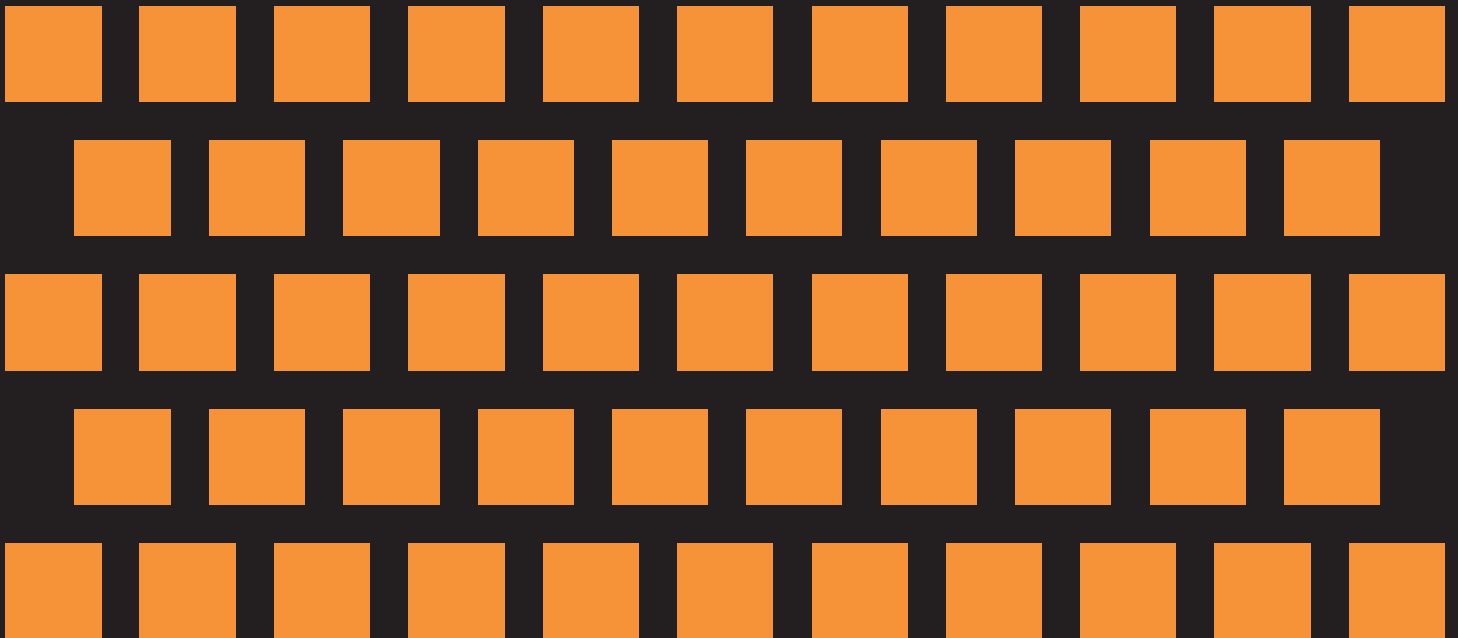


STP-NU-042

NEW MATERIALS FOR ASME SUBSECTION NH



STP-NU-042

NEW MATERIALS FOR ASME SUBSECTION NH

Prepared by:

Kazuhiko Suzuki and Tai Asayama

Japan Atomic Energy Agency

Robert W. Swindeman

Cromtech Inc

Douglas L. Marriott

Stress Engineering Services Inc



Date of Issuance: June 30, 2011

This report was prepared as an account of work sponsored by the U.S. Department of Energy (DOE) and the ASME Standards Technology, LLC (ASME ST-LLC).

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer or otherwise does not necessarily constitute or imply its endorsement, recommendation or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Neither ASME, ASME ST-LLC, the authors nor others involved in the preparation or review of this report, nor any of their respective employees, members or persons acting on their behalf, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe upon privately owned rights.

Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer or otherwise does not necessarily constitute or imply its endorsement, recommendation or favoring by ASME ST-LLC or others involved in the preparation or review of this report, or any agency thereof. The views and opinions of the authors, contributors and reviewers of the report expressed herein do not necessarily reflect those of ASME ST-LLC or others involved in the preparation or review of this report, or any agency thereof.

ASME ST-LLC does not take any position with respect to the validity of any patent rights asserted in connection with any items mentioned in this document, and does not undertake to insure anyone utilizing a publication against liability for infringement of any applicable Letters Patent, nor assumes any such liability. Users of a publication are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, is entirely their own responsibility.

Participation by federal agency representative(s) or person(s) affiliated with industry is not to be interpreted as government or industry endorsement of this publication.

ASME is the registered trademark of the American Society of Mechanical Engineers.

No part of this document may be reproduced in any form,
in an electronic retrieval system or otherwise,
without the prior written permission of the publisher.

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

ISBN No. 978-0-7918-3388-9

Copyright © 2011 by
ASME Standards Technology, LLC
All Rights Reserved

TABLE OF CONTENTS

Foreword	vii
Abstract	viii
PART I	1
1 SELECTION OF CANDIDATE MATERIALS AND CORRESPONDING TIME AND TEMPERATURE OPERATING CONDITIONS	2
1.1 Considerations in Selecting the Candidate Materials	2
1.1.1 Corrosive Oxidation	2
1.1.2 High Temperature Strength	3
1.1.3 Low Temperature Strength and Other Properties.....	3
1.1.4 Workability and Weldability	3
1.2 Operating Time and Temperature Conditions	4
2 REVIEW OF AVAILABLE JAPANESE DATA ON HASTELLOY XR AND INCONNEL 617 AND REQUIRED R&D	5
2.1 Review of Japanese information on Hastelloy XR and Inconel 617	5
2.1.1 Environmental Effects.....	5
2.1.2 Unique Tensile Stress-Strain Relationship Due To Dynamic Recrystallization	10
2.1.3 Very significant creep	14
2.1.4 Creep Analysis Method: Creep Constitutive Equation and Related Hardening/Flow Rules, and a Creep Analysis-Based Method of Evaluating Creep Damage and Creep Strain.....	19
2.1.5 Thermal Aging Effect on Low Temperature Strength	20
2.2 Required R&D.....	23
3 ESTIMATION OF STRENGTH CHARACTERISTICS	24
3.1 Creep rupture strength data on Hastelloy XR.....	24
3.2 Extrapolation Technique	25
3.3 Estimation of Creep Rupture Strength at 800°C and 100,000h.....	26
References - Part I	27
PART II	28
1 SELECTION OF CANDIDATE MATERIALS	29
1.1 Identification of Metallic Components and Operational Requirements	29
1.2 Required Properties for Construction of Section III Class 1 Components for Elevated Temperature Service.....	33
1.3 A Brief Review of Development of the Primary and Alternative Alloys Considered for Structural HTGR Components	33
1.4 Selection of Candidate Materials and Code Status.....	34
1.4.1 Currently Approved Materials.....	34
1.4.2 Primary Candidate Materials.....	34
1.4.3 Alternate Materials	34
1.5 Summary	35
References - PART II, Section 1	36
2 REVIEW OF AVAILABLE DATA FOR CANDIDATE MATERIALS	42

2.1 Needed Properties for Construction of Section III Subsection NH Components for Elevated Temperature Service	42
2.1.1 Current Requirements for ASME III-NH	42
2.1.2 Other Considerations Regarding Current and Future Data Needs for ASME III-NH	42
2.1.3 Summary of materials properties needs for modern design analysis:.....	45
3 ESTIMATE OF STRENGTH CHARACTERISTICS	47
3.1 Benchmark Comparison of Candidate Materials with Respect to Creep-Rupture Strength	47
3.2 Review of Available Data for New Materials Relative to the Needs for Incorporation into ASME III-NH	48
3.2.1 Cold Work Effects	48
3.2.2 Tensile Properties	48
3.2.3 Tensile Reduction Factors.....	50
3.2.4 Creep and Stress-Rupture	50
3.2.5 Tensile Stress-Strain Curves	54
3.2.6 Creep Strain versus Time Data	55
3.2.7 Relaxation Data.....	57
3.2.8 Strain-Controlled Fatigue Data	59
3.2.9 Creep-Fatigue Interaction	60
3.2.10 Multiaxial Stress And Strain.....	62
3.2.11 Stress-Rupture Factors for Weldments	62
3.2.12 Fine-Grained Strip Products for Compact Heat Exchangers	63
3.3 Overview of the Estimates for Data Needs.....	65
3.3.1 Suggested Testing of Alloy 800H to Support ASME III-NH.....	65
3.3.2 Suggested Testing for Alloy 617	66
3.4 Summary	69
References - Part II, Sections 2&3	70
Appendix A - U. S. Patent of Hastelloy XR	76
Appendix B - Tests and Estimated Costs.....	89
Acknowledgments.....	94

LIST OF TABLES

Table 1 - Chemical Composition of Hastelloy XR and Hastelloy X	3
Table 2 - Operating Conditions of the Main Components in an HTGR-IS Hydrogen Production System [3]	4
Table 3 - Impurities Levels of JAERI-B Type Helium.....	6
Table 4 - Candidate Materials Listed for Intermediate and High-Temperature Components for the Very High Temperature NGNP	31
Table 5 - Potential Candidate Materials for Intermediate and High-Temperature Metallic Components in the VHTR Concept of the NGNP Reactor.....	32

LIST OF FIGURES

Figure 1 - Environmental Effects on the Creep Rupture Strength of Inconel 617 and Hastelloy XR at HTGR.....	7
---	---

Figure 2 - Environmental Effect and Test Specimen Configuration Dependence on Low Cycle Fatigue Strength within a Fast-Fast Type Waveform for Inconel 617 at 1000°C [6]	8
Figure 3 - Environmental Effect on Low Cycle Fatigue Strength Under Fast-Fast Type Waveform for Hastelloy XR at 950°C [6]	9
Figure 4 - Environmental Effect on the Cyclic Stress-Strain Relationship of Inconel 617 and Hastelloy XR at HGTR Temperatures [6]	9
Figure 5 - Illustration of Reduced Creep Rupture Strength of Inconel 617 in HTGR-He Environment at 1000°C and Corresponding Unaffected Strength of Hastelloy XR	10
Figure 6 - Tensile Stress-Strain Curves of Hastelloy XR at Various Temperatures at the Strain Rate Specified in JIS Standards [5]	11
Figure 7 - Tensile Stress-Strain Curves of Hastelloy XR at 950°C at Various Extension Rates [5]....	11
Figure 8 - Extension Rate Dependence of Yield Strength and Tensile Strength of Hastelloy XR at 800 and 1000°C [4]	12
Figure 9 - Schematic Illustration of Extension Rate (Strain Rate) Dependence of Yield Strength and Tensile Strength at the Very High Temperature where Extremely Significant Creep Occurs	12
Figure 10 - Hysteresis Loop of Hastelloy XR at 950°C and a Strain Rate of 0.1%/s [5].....	13
Figure 11 - Effect of Strain Hold Time on Low-Cycle-Fatigue Lives Within the Strain Hold Waveform for Inconel 617 at 1000°C in 99.99% Helium [6]	15
Figure 12 - Effects of Strain Hold Time and Strain Rate on Low Cycle Fatigue Lives in the so-called Creep Fatigue Interaction Testing for Hastelloy XR in an HTGR-He Environment [4], [9].....	15
Figure 13 - Effects of Strain Hold Time and Strain Rate on Low-Cycle-Fatigue Lines in Creep Fatigue Interaction Testing of SS 304 [10]	16
Figure 14 - Practically Full Relaxation of Inconel 617 at the High Temperature of 900°C and Comparison of the Observed Relaxation Curve with One Estimated Using Creep Data [6]	16
Figure 15 - Temperature and Stress Dependences of Reciprocal Time Constant in Primary Creep Regime τ for Hastelloy XR in the High Temperature Region of 800°C and Above [4]	17
Figure 16 - Time to Onset of Tertiary Creep for Hastelloy XR [4].....	18
Figure 17 - Creep Curve Fitting Using the Garofalo Equation [4].....	20
Figure 18 - Comparison of Low-Cycle Fatigue Strength at Very High Temperature as Received and Aged at the Same Temperature [6].....	21
Figure 19 - Changes in Range of Stress with Increasing Number of Cycles for Inconel 617 [6]	22
Figure 20 - Monotonic and Cyclic Stress-Strain Relationship for Hastelloy XR at 950°C in an HTGR-He Environment [6].....	23
Figure 21 - Creep Rupture Strength Data on Hastelloy XR	24
Figure 22 - Helium Pressure Effect on Creep Rupture Strength of Hastelloy XR [4]	25
Figure 23 - Probability Distribution of Creep Rupture Data for Hastelloy XR [4].....	26

Figure 24 - Comparisons of the Strength Based on 100,000 Hours for Alloys Intended for Service at Temperatures Around 800°C	47
Figure 25 - Typical Yield Strength vs. Temperature for Several Candidate Alloys	49
Figure 26 - Typical Ultimate Strength vs. Temperature for Several Candidate Alloys	49
Figure 27 - Temperature-Time-Precipitation (TTP) Diagram for Alloy 617 by Wu et. al. [17]. Long-Time Aging at ORNL by McCoy [21]	50
Figure 28 - Stress vs. the Larson-Miller Parameter for Rupture of Alloy 617 (Arrows show the Larson-Miller parameter at 100,000 hours)	51
Figure 29 - Stress vs. Larson-Miller parameter for Rupture of Alloy 230	52
Figure 30 - Stress vs. the Larson-Miller Parameter for Rupture of Alloy X	52
Figure 31 - Stress vs. Larson-Miller Parameter for Rupture of Alloy 556	53
Figure 32 - Stress vs. Larson-Miller Parameter for Rupture of NF 709	53
Figure 33 - Stress vs. Larson-Miller Parameter for Rupture of Alloy 800H	54
Figure 34 - Tensile Yield Curves for Alloy 230 at 871°C (1600°F) and Above [34]	55
Figure 35 - Two Creep Curves for Alloy 617 Showing the Variability in Primary Creep	56
Figure 36 - Creep Curves for Alloy 230 at 871°C	56
Figure 37 - Creep Curves for Alloy 556 at Three Temperatures	57
Figure 38 - Relaxation Behavior for Alloy 556 near 871°C	58
Figure 39 - Start of a 0.50 Hour Relaxation-Hold C-F Test on Alloy 556 at 871°C and 0.62% Strain Range	58
Figure 40 - Comparison of Continuous Cycling Low Cycle Fatigue Data for some Nickel Base Alloys	59
Figure 41 - Typical Stress vs. Cycles Behavior for Alloy 556	60
Figure 42 - Damage Interaction Diagram for Alloy 800 and Alloy 800H Determined from Three Analyses	61
Figure 43 - Stress vs. Larson-Miller Parameter for 0.08 to 0.13 mm Foils	64
Figure 44 - Comparison of Creep Curves for Alloy 625 and Alloy 214 Foils at 800°C	64

FOREWORD

This document is the result of work resulting from Cooperative Agreement DE-FC07-05ID14712 between the U.S. Department of Energy (DOE) and ASME Standards Technology, LLC (ASME ST-LLC) for the Generation IV (Gen IV) Reactor Materials Project. The objective of the project is to provide technical information necessary to update and expand appropriate ASME materials, construction and design codes for application in future Gen IV nuclear reactor systems that operate at elevated temperatures. The scope of work is divided into specific areas that are tied to the Generation IV Reactors Integrated Materials Technology Program Plan. This report is the result of work performed under Task 11 titled “New Materials for ASME Subsection NH.”

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

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

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

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

ABSTRACT

When selecting candidate materials, their resistance to environmental degradation caused by exposure to an HTGR helium atmosphere is a key factor. Improving the resistance of commercially available Nickel base super alloys to corrosive oxidation in low oxidizing potential atmospheres such as HTGR-He was discussed in Part I of this report, with reference to, for example, the improved Hastelloy X resulting in Hastelloy XR. With regard to the operating temperature, the required primary helium coolant temperature in the SI process (or IS process) was identified as being 950°C at the reactor outlet.

Review of the available information on Hastelloy XR and Inconel 617 as candidate materials was made in Part I of this report, and several critical issues discussed. Information on Inconel 617 is from a Japanese project. Those issues were identified with help from the author's experiences in developing the HTTR high temperature structural design guide. Some R&D needed to obtain approval for Subsection NH construction was then pointed out.

With estimating the strength characteristics, the design creep rupture strength was identified as being 14MPa for Hastelloy XR, even in the HTGR-He atmosphere. The OSDP (Orr-Sherby-Dorn Parameter) method was applied to Hastelloy XR as an extrapolation technique to gain creep rupture strength values, primarily because of scarcity of data on the longer rupture life region.

In Part II of this report, the bounding conditions were briefly summarized for the Next Generation Nuclear Plant (NGNP) that is the leading candidate in the Department of Energy Generation IV reactor program. Metallic materials essential to the successful development and proof of concept for the NGNP were identified. The literature bearing on the materials technology for high-temperature gas-cooled reactors was reviewed with emphasis on the needs identified for the NGNP. Several materials were identified for a more thorough study of their databases and behavioral features relative to the requirements ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NH.

Material properties required for the design and construction of components meeting the rules of ASME Section III Subsection NH (ASME III-NH) were reviewed in Part II. An overview of the data available for candidate "new materials" for the Next Generation Nuclear Plant (NGNP) was undertaken with respect to meeting the needs for incorporation of the materials into ASME III-NH. These materials included alloy 617, alloy 230 and alloy 556 for service to 800°C and above. For service below 800°C, an "enhanced strength" stainless steel typical of a new group of such steels was included. Although not a new material, alloy 800H was included in the review. The data needs identified in the National Laboratories testing plans for the NGNP were considered. In these plans, emphasis was placed on alloy 617 which is the leading candidate for the high-temperature metallic components in the NGNP for components operating above 800°C. It was found that the plans were very comprehensive and identified the data needs for both incorporation of a new alloy into ASME III-NH and the complementary database needed for the application of the Code. A comparison of the strength of several candidate alloys approved for ASME Section I or Section VIII, Division 1 construction was made and this comparison supported the selection of alloy 617 as the leading candidate on the basis of strength. With respect to compact heat exchangers, some concerns about the behavioral features of these alloys as fine-grained strip products were developed, and some comparisons were made between candidate alloys developed for high-temperature recuperators.