CREEP-FATIGUE DATA AND EXISTING EVALUATION PROCEDURES FOR GRADE 91 AND HASTELLOY XR
STP-NU-018

CREEP-FATIGUE DATA AND EXISTING EVALUATION PROCEDURES FOR GRADE 91 AND HASTELLOY XR

Prepared by:

Tai Asayama and Yukio Tachibana
Japan Atomic Energy Agency
# TABLE OF CONTENTS

**Foreword** ............................................................................................................................... xi

**Executive Summary** ................................................................................................................ xii

**PART I GRADE 91** .................................................................................................................... 1

## 1 COLLECTION OF AVAILABLE DATA .................................................................................... 2

### 1.1 Outline of Collected Data ................................................................................................... 2

### 1.2 Evaluation of Collected Data ............................................................................................ 2

#### 1.2.1 Creep Properties ...................................................................................................... 2

#### 1.2.2 Fatigue Properties .................................................................................................... 2

#### 1.2.3 Creep-Fatigue Properties ........................................................................................ 3

#### 1.2.4 Points to be Addressed ............................................................................................ 3

## 2 CREEP-FATIGUE EVALUATION METHOD ........................................................................... 15

### 2.1 Procedures of ASME-NH, DDS and RCC-MR ................................................................ 15

#### 2.1.1 ASME-NH .............................................................................................................. 15

#### 2.1.2 DDS .......................................................................................................................... 17

#### 2.1.3 RCC-MR .................................................................................................................... 20

### 2.2 Comparison of the Procedures ........................................................................................ 21

#### 2.2.1 Determination of Strain Range ................................................................................ 21

#### 2.2.2 Initial Stress of Stress Relaxation ............................................................................ 21

#### 2.2.3 Estimation of Stress Relaxation Behavior ............................................................... 22

#### 2.2.4 Formulation of Creep Damage ................................................................................. 22

### 2.3 Creep-Fatigue Evaluation Without Safety Margins ............................................................ 22

#### 2.3.1 Conditions of Evaluation ......................................................................................... 22

#### 2.3.2 Description of Stress Relaxation Behavior ............................................................... 23

#### 2.3.3 Creep-Fatigue Damage Evaluation and Life Prediction ........................................... 23

#### 2.3.4 Discussions ............................................................................................................. 25

### 2.4 Creep-Fatigue Evaluation According to Code Procedures ................................................ 27

#### 2.4.1 Purpose .................................................................................................................... 27

#### 2.4.2 Conditions for Evaluation ....................................................................................... 27

#### 2.4.3 Discussions ............................................................................................................. 27

### 2.5 Other Factors to be Considered ....................................................................................... 28

#### 2.5.1 Environmental Effects on Tensile and Compressive Hold Tests ............................... 28

#### 2.5.2 Effect of Thermal Aging .......................................................................................... 28

#### 2.5.3 Conceptual Investigation of the Relationship between Time Fraction and Ductility Exhaustion Methods ................................................................................................... 29

## 3 SUGGESTIONS TO IMPROVE ASME-NH PROCEDURE AND R&D ITEMS ............... 64

### 3.1 Suggestions to Improve ASME-NH Procedure ................................................................. 64

#### 3.1.1 Evaluation of Creep Damage .................................................................................... 64

#### 3.1.2 Evaluation of Creep-Fatigue Life Based on Creep-Damage ....................................... 65

### 3.2 Necessary R&D Items .................................................................................................... 65

#### 3.2.1 Short-Term Items ..................................................................................................... 65

#### 3.2.2 Long-Term Items .................................................................................................... 66

**References** .................................................................................................................................. 75

**PART II HASTELLOY XR** ...................................................................................................... 77
1 DATA COLLECTION ON HASTELLOY XR .................................................................78
   1.1 Development of Hastelloy XR .................................................................78
   1.2 Data of Hastelloy XR .............................................................................81
      1.2.1 Creep fatigue ...............................................................................81
      1.2.2 Creep .........................................................................................81
      1.2.3 Fatigue ......................................................................................81

2 CREEP-FATIGUE CRITERIA ON HASTELLOY XR .........................................................95
   2.1 High Temperature Structural Design Guideline for HTGR ............................95
      2.1.1 Introduction ..............................................................................95
      2.1.2 Identification of Failure Modes .................................................95
      2.1.3 Developments of Design Limits and Rules ..............................96
      2.1.4 Material Characterization on Hastelloy XR ...............................96
   2.2 Inelastic Analysis of the Intermediate Heat Exchanger (IHX) for HTTR ..........105
      2.2.1 Intermediate Heat Exchanger (IHX) for the HTTR ..................105
      2.2.2 Structural Integrity Evaluation of the HTTR IHX ......................106
   2.3 Summary of Creep-Fatigue Criteria on Hastelloy XR .................................117

3 NECESSARY RESEARCH AND DEVELOPMENT ITEMS IN RELATION TO CREEP-
   FATIGUE EVALUATION FOR GEN IV AND VHTR REACTORS .............................118
   3.1 Linear Summation Rule of Cycle and Time Fractions .............................118
   3.2 Inelastic Constitutive Equations .........................................................118
   3.3 Helium Environmental Effect ............................................................118

References ..............................................................................................................119

Appendix A ..............................................................................................................120
Appendix B ..............................................................................................................142
Appendix C ..............................................................................................................148
Acknowledgments ..................................................................................................149
Abbreviations And Acronyms ...............................................................................150

LIST OF TABLES
Table 1 - Mod. 9Cr-1Mo Material Data Source List (Temp is 400°C or higher.) ..........4
Table 2 - Chemical Composition of Mod. 9Cr-1Mo ..............................................5
Table 3 - Factor K’ (TABLE T-1411.1) .................................................................30
Table 4 - Average Material Properties ...............................................................30
Table 5 - Creep Fatigue Evaluation Conditions on Elastic Design Base ..............31
Table 6 - Material Properties and Design Values ...............................................31
Table 7 - Suggested Options for the Improvement of Creep-Fatigue Evaluation Procedure in ASME-NH .................................................................67
Table 8 - Recommended Creep Test Conditions ...............................................67
Table 9 - Recommended Creep-Fatigue Test Conditions ....................................68
Table 10 - Specifications for Chemical Composition of Hastelloy XR and X .......79
Table 11 - Results of Low Cycle Fatigue Tests with Symmetric Triangular Strain Waveform on Hastelloy X and Hastelloy XR at 900°C In JAERI-Type B Helium Environment ........... 82
Table 12 - Results of Low Cycle Fatigue Tests with Trapezoidal Strain Waveform on Hastelloy XR at 900°C in JAERI-Type B Helium Environment ....................................................... 82
Table 13 - Impurity Levels of Simulated HTGR Helium Called JAERI-Type B Helium ........... 83
Table 14 - Chemical Composition of the Materials Hastelloy X and Hastelloy XR .................... 84
Table 15 - Results of Creep Tests for Hastelloy XR in Air (Tube) ...................................................... 86
Table 16 - Results of Creep Tests for Hastelloy XR in Air (Plate) ...................................................... 87
Table 17 - Results of Creep Tests for Hastelloy XR in Air (Bar) ........................................................ 87
Table 18 - Results of Creep Tests for Hastelloy XR in Air (Subsize Specimen Machined from Tube) ............................................................................................................................... ... 88
Table 19 - Results of Creep Tests for Hastelloy XR in JAERI-Type B Helium Environment ............ 88
Table 20 - Chemical Composition of Hastelloy XR for Creep Tests ................................................... 89
Table 21 - Results of Creep Tests for Hastelloy XR-II in Air (Plate: φ 10mm) .................................... 90
Table 22 - Results of Creep Tests for Hastelloy XR-II in Air (Plate: φ 6mm) ...................................... 91
Table 23 - Results of Creep Tests for Hastelloy XR-II in Air (Tube) .................................................. 91
Table 24 - Results of Creep Tests for Hastelloy XR-II In JAERI-Type B Helium Environment (Plate: φ 6mm) ..................................................................................................................... 92
Table 25 - Chemical Composition of Hastelloy XR-II for Creep Tests ............................................... 92
Table 26 - HTGR High Temperature Structural Design Guideline Features ....................................... 99
Table 27 - Mechanical Properties Data on Hastelloy XR Obtained for High Temperature Structural Design Guideline .............................................................. 99
Table 28 - Major Specifications of the Intermediate Heat Exchanger for HTTR .............................. 110
Table 29 - Material Constants of the Creep Constitutive Equation for Hastelloy XR .................... 111
Table 30 - Cumulative Principal Creep Strain, Cumulative Creep and Fatigue Damage Factors of the Heat Transfer Tubes at First Layer in the Intermediate Heat Exchanger ................... 112
Table 31 - Cumulative Principal Creep Strain, Cumulative Creep and Fatigue Damage Factors of the Lower Reducer of the Center Pipe in the Intermediate Heat Exchanger ............ 112
Table 32 - Mod. 9Cr-1Mo Creep Data (Temperature is 400°C or more) ........................................... 120
Table 33 - Mod. 9Cr-1Mo Fatigue Data of JAEA (Temperature is 400°C or more).......................... 127
Table 34 - Mod. 9Cr-1Mo Creep Fatigue Data (Temperature is 400°C or more) .............................. 138

LIST OF FIGURES
Figure 1 - Creep Rupture: Average Curves and Experimental Values................................................... 6
Figure 2 - Fatigue Life: Average Curves and Experimental Values at 400°C........................................... 6
Figure 3 - Fatigue Life: Average Curves and Experimental Values at 450°C........................................... 7
Figure 4 - Fatigue Life: Average Curves and Experimental Values at 500°C........................................... 7
Figure 5 - Fatigue Life: Average Curves and Experimental Values at 550°C ........................................8
Figure 6 - Fatigue Life: Average Curves and Experimental Values at 600°C ........................................8
Figure 7 - Fatigue Life: Average Curves and Experimental Values at 650°C ........................................9
Figure 8 - Cyclic Stress-Strain Curve: Average Curve and Experimental Values at 450°C ...................9
Figure 9 - Cyclic Stress-Strain Curve: Average Curve and Experimental Values at 500°C ..............10
Figure 10 - Cyclic Stress-Strain Curve: Average Curve and Experimental Values at 550°C ............10
Figure 11 - Cyclic Stress-Strain Curve: Average Curve and Experimental Values at 600°C .............11
Figure 12 - Cyclic Stress-Strain Curve: Average Curve and Experimental Values at 650°C ...........11
Figure 13 - Creep-Fatigue Life: Average Curves and Experimental Values at 500°C .....................12
Figure 14 - Creep-Fatigue Life: Average Curves and Experimental Values at 550°C .....................12
Figure 15 - Creep-Fatigue Life: Average Curves and Experimental Values at 600°C .....................13
Figure 16 - Creep-Fatigue Life: Average Curves and Experimental Values at 500°C .....................13
Figure 17 - Creep-Fatigue Life: Average Curves and Experimental Values at 550°C .....................14
Figure 18 - Creep-Fatigue Life: Average Curves and Experimental Values at 600°C .....................14
Figure 19 - Stress-Strain Relationship (ASME-NH) .................................................................32
Figure 20 - Stress Relaxation from Isochronous Stress-Strain Curves (ASME-NH) .........................32
Figure 21 - Stress-Relaxation Limit for Creep Damage (ASME-NH) ..............................................33
Figure 22 - Calculation Procedure of Ke”ε0 (DDS) ........................................................................33
Figure 23 - Calculation Procedure of Initial Stress and Relaxation Process (DDS) .........................34
Figure 24 - Relaxation Behavior and Creep Damage (DDS) ..........................................................34
Figure 25 - Calculation Procedure of Creep Strain Range (RCC-MR) .............................................35

Figure 26 - Calculation Procedure of Σσk (RCC-MR) ......................................................................35
Figure 27 - Creep-Fatigue Damage Envelopes for Mod. 9Cr-1Mo .......................................................36
Figure 28 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at εi = 0.15% ..........................................................36
Figure 29 - Comparison Between Experimental and Calculated Values of Static Relaxation Behavior at εi = 0.2% ..........................................................37
Figure 30 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at εi = 0.3% ..........................................................37
Figure 31 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at εi = 0.1% ..........................................................38
Figure 32 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at εi = 0.2% ..........................................................38
Figure 33 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at εi = 0.3% ..........................................................39
Figure 34 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\varepsilon_t = 0.4535\%$ ................................................................. 39

Figure 35 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta \varepsilon_t = 0.36\%$ ................................................................. 40

Figure 36 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta \varepsilon_t = 0.36\%$ ................................................................. 40

Figure 37 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta \varepsilon_t = 0.494\%$ ................................................................. 41

Figure 38 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta \varepsilon_t = 0.494\%$ ................................................................. 41

Figure 39 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta \varepsilon_t = 1.0\%$ ........................................................................................................ 42

Figure 40 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta \varepsilon_t = 1.0\%$ ........................................................................................................ 42

Figure 41 - Evolution of Creep Damage During Stress Relaxation (DDS)................................................................................................................................. 43

Figure 42 - Creep-Fatigue Damage Calculated by ASME-NH Procedure Using Monotonic Stress-Strain Curves and Strain Amplitude................................................................. 43

Figure 43 - Creep-Fatigue Damage Calculated by ASME-NH Procedure Using Monotonic Stress-Strain Curves and Strain Range................................................................................. 44

Figure 44 - Creep-Fatigue Damage Calculated by DDS Procedure Using Monotonic Stress-Strain Curves............................................................................................................ 44

Figure 45 - Creep-Fatigue Damage Calculated by DDS Procedure Using Cyclic Stress-Strain Curves.................................................................................................................. 45

Figure 46 - Creep-Fatigue Damage Calculated by RCC-MR Procedure Using Cyclic Stress-Strain Curves.............................................................................................................. 45

Figure 47 - Relationship between Observed Life and Predicted Life with ASME-NH Procedure Using Monotonic Stress-Strain Curves and Strain Amplitude......................................................... 46

Figure 48 - Relationship between Observed Life and Predicted Life with ASME-NH Procedure Using Monotonic Stress-Strain Curves and Strain Amplitude......................................................... 46

Figure 49 - Relationship between Observed Life and Predicted Life with ASME-NH Procedure Using Monotonic Stress-Strain Curves with an Interception of (0.3, 0.3) ........................................ 47

Figure 50 - Relationship between Observed Life and Predicted Life with RCC-MR Procedure Using Cyclic Stress-Strain Curves .................................................................................................. 47

Figure 51 - Relationship between Observed Life and Predicted Life with DDS Procedure Using Monotonic Stress-Strain Curves .......................................................................................... 48

Figure 52 - Relationship between Observed Life and Predicted Life with DDS Procedure Using Cyclic Stress-Strain Curves .......................................................................................... 48

Figure 53 - Creep-Fatigue Damage Calculated Using Experimentally Obtained Relaxation Curves ................................................................. 49

Figure 54 - Relationship between Observed Life and Predicted Life with ASME-NH Procedure Using Experimentally Obtained Relaxation Curves .................................................................. 49
Figure 55 - Relationship between Observed Life and Predicted Life with DDS Procedure Using Experimentally Obtained Relaxation Curves .......................................................... 50
Figure 56 - Relationship between Observed Life and Predicted Life with RCC-MR Procedure Using Experimentally Obtained Relaxation Curves .......................................................... 50
Figure 57 - Comparison of Monotonic and Cyclic Stress-Strain Curves .................................................. 51
Figure 58 - Relationship between Observed Life and Predicted Life with ASME-NH Procedure Using Monotonic Stress-Strain Curve ................................................................. 51
Figure 59 - Relationship between Observed Life and Predicted Life with DDS Procedure Using Monotonic Stress-Strain Curves ................................................................. 52
Figure 60 - Relationship between Observed Life and Predicted Life with RCC-MR Procedure Using Cyclic Stress-Strain Curves ................................................................. 52
Figure 61 - Evaluation Flow of Creep-Fatigue Damage by ASME-NH Method ........................................ 53
Figure 62 - Evaluation Flow of Creep-Fatigue Damage by DDS Method ................................................... 54
Figure 63 - Evaluation Flow of Creep-Fatigue Damage by RCC-MR Method ........................................... 55
Figure 64 - Comparison of Creep Damage Evaluation ........................................................................... 56
Figure 65 - Creep-Fatigue Evaluation of Experimental Data by Code Procedure .................................... 56
Figure 66 - Creep-Fatigue Evaluation of Experimental Data by Code Procedure .................................... 57
Figure 67 - Comparison of Creep-Fatigue Life between Tensile Hold Tests and Compressive Hold Tests in Air ................................................................................................................ 57
Figure 68 - Comparison of Creep-Fatigue Life between Tensile Hold Tests and Compressive Hold Tests in Sodium .......................................................................................................... 58
Figure 69 - Comparison of Creep-Fatigue Life between Tensile Hold Tests and Compressive Hold Tests in Vacuum .......................................................................................................... 58
Figure 70 - Comparison of Tensile and Compressive Peak Stresses ............................................................ 59
Figure 71 - Ratio of Creep-Fatigue Life Reduction .................................................................................... 59
Figure 72 - Observed Crack Tip Shape .................................................................................................... 60
Figure 73 - Schematic Illustration of Mechanisms that Affect Crack Propagation .................................... 60
Figure 74 - Comparison of Creep-Fatigue Life between Pre-Aged Material and Unaged Material at 550°C .................................................................................................................. 61
Figure 75 - Comparison of Creep-Fatigue Life between Pre-Aged Material and Unaged Material at 600°C .................................................................................................................. 61
Figure 76 - Comparison of Stress-Strain Response between Pre-Aged Material and Unaged Material at 550°C .................................................................................................................. 62
Figure 77 - Comparison of Stress-Strain Response between Pre-Aged Material and Unaged Material at 600°C .................................................................................................................. 62
Figure 78 - Ratio of Maximum Stress of Mid-Life to First Cycle .............................................................. 63
Figure 79 - Calculation Procedure of Initial Stress Using Monotonic S-S Curve ........................................ 68
Figure 80 - Monotonic and Cyclic Stress-Strain Relation at 550°C .......................................................... 69
Figure 81 - Creep Damage Calculated Based on Various Options ........................................................ 69
Figure 82 - The Effect of the Value of Z on Creep Damage in ASME-NH........................................... 70
Figure 83 - Comparison of Initial Stresses of Stress Relaxation ....................................................... 70
Figure 84 - Monotonic and Cyclic Isochronous Curves at 550°C ...................................................... 71
Figure 85 - Comparison of Relaxation Behavior between Monotonic and Cyclic At 550°C ............. 71
Figure 86 - Creep-Fatigue Damage Calculated Based on Case (a) ..................................................... 72
Figure 87 - Creep-Fatigue Damage Calculated Based on Case (b) ..................................................... 72
Figure 88 - Creep-Fatigue Damage Calculated Based on Case (c) ..................................................... 73
Figure 89 - Creep-Fatigue Damage Calculated Based on Case (d) ..................................................... 73
Figure 90 - Creep-Fatigue Damage Calculated Based on Case (e) ..................................................... 74
Figure 91 - Development of Hastelloy XR .......................................................................................... 80
Figure 92 - Comparison of Environmental Effect in Cr-Depleted Zone Depth between Hastelloy XR and Hastelloy X .......................................................... 80
Figure 93 - Relation between Total Strain Range and Fatigue Life Under Different Strain Rates ..... 83
Figure 94 - Creep Fatigue Test Data on Hastelloy XR ...................................................................... 83
Figure 95 - Creep Rupture Life for Hastelloy XR .............................................................................. 85
Figure 96 - Results of Creep Tests for Hastelloy XR in Air ................................................................. 89
Figure 97 - Results of Creep Tests for Hastelloy XR in Air and in JAERI-Type B Helium Environment .......................................................... 90
Figure 98 - Results of Creep Tests for Hastelloy XR-II in Air ............................................................ 93
Figure 99 - Results of Creep Tests for Hastelloy XR-II in Air and in JAERI-Type B Helium Environment .......................................................... 93
Figure 100 - Comparison of Creep Test Data for Hastelloy XR and Hastelloy XR-II ....................... 94
Figure 101 - Cooling System of the HTTR ..................................................................................... 100
Figure 102 - Tensile Stress-Strain Curves for Hastelloy XR at the Strain Rates of JIS .................... 100
Figure 103 - Stress-Strain Curve for Hastelloy XR (1000°C, Extension Rate = 100%/Min) .......... 101
Figure 104 - Comparison of Creep Rupture Lives for Hastelloy XR in Several Different Helium Environments on the Stability Diagram for Cr (Acr=0.8) At 950°C Under 26MPa .......... 101
Figure 105 - Strain Rate Effect on Creep-Fatigue Interaction for Hastelloy XR .............................. 102
Figure 106 - Hold Time Effect on Creep-Fatigue Interaction for Hastelloy XR .............................. 103
Figure 107 - Creep Rupture Life under Multi-Axial Stress States for Hastelloy XR ..................... 104
Figure 108 - Applicability of Time Functions to Hastelloy XR ....................................................... 105
Figure 109 - Intermediate Heat Exchanger (IHX) for HTTR ......................................................... 114
Figure 110 - Design Fatigue Strain Range for Hastelloy XR ............................................................ 115
Figure 111 - Stress-to-Rupture Curve for Hastelloy XR ................................................................. 115
Figure 112 - Vertical View of the Lower Reducer of the Center Pipe in the IHX ......................... 116
Figure 113 - Relation between Inelastic Strain Range and Fatigue Life at 400°C.................142
Figure 114 - Relation between Inelastic Strain Range and Fatigue Life at 450°C.................142
Figure 115 - Relation between Inelastic Strain Range and Fatigue Life at 500°C.................143
Figure 116 - Relation between Inelastic Strain Range and Fatigue Life at 550°C.................143
Figure 117 - Relation between Inelastic Strain Range and Fatigue Life at 600°C.................144
Figure 118 - Relation between Inelastic Strain Range and Fatigue Life at 650°C.................144
Figure 119 - Relation between Inelastic Strain Range and Creep Fatigue Life at 500°C.........145
Figure 120 - Relation between Inelastic Strain Range and Creep Fatigue Life at 550°C.........145
Figure 121 - Relation between Inelastic Strain Range and Creep Fatigue Life at 600°C.........146
Figure 122 - Comparison of Minimum Rupture Stress between DDS and RCC-MR..............146
Figure 123 - Comparison of Average Rupture Stress between DDS and RCC-MR.................147
FOREWORD

This report describes the results of investigation on Task 5 of DOE/ASME Materials Project based on a contract between ASME Standards Technology, LLC (ASME ST-LLC) and Japan Atomic Energy Agency (JAEA). Task 5 is to collect available creep-fatigue data and study existing creep-fatigue evaluation procedures for Grade 91 steel and Hastelloy XR. Part I of this report is devoted to Grade 91 steel. Part II of this report is devoted to Hastelloy XR.

The American Society of Mechanical Engineers (ASME) is a not-for-profit professional organization 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.

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, expanding upon the former role of ASME’s Codes and Standards Technology Institute (CSTI). The ASME ST-LLC mission includes meeting the needs of industry and government by providing new standards-related products and services, which advance the application of emerging and newly commercialized science and technology and providing the research and technology development needed to establish and maintain the technical relevance of codes and standards. Visit www.stllc.asme.org for more information.
EXECUTIVE SUMMARY

This report describes the results of investigation on Task 5 of DOE/ASME Materials Project based on a contract between ASME Standards Technology, LLC (ASME ST-LLC) and Japan Atomic Energy Agency (JAEA). Task 5 is to collect available creep-fatigue data and study existing creep-fatigue evaluation procedures for Grade 91 steel and Hastelloy XR. Part I of this report is devoted to Grade 91 steel. Existing creep-fatigue data were collected (Appendix A) and analyzed from the viewpoints of establishing a creep-fatigue procedure for VHTR design. A fair amount of creep-fatigue data has been obtained and creep-fatigue phenomena have been clarified to develop design standards mainly for fast breeder reactors. Following this, existing creep-fatigue procedures were studied and it was clarified that the creep-fatigue evaluation procedure of the ASME-NH has a lot of conservatisms and they were analyzed in detail from the viewpoints of the evaluation of creep damage of material. Based on the above studies, suggestions to improve the ASME-NH procedure along with necessary research and development items were presented. Part II of this report is devoted to Hastelloy XR. Existing creep-fatigue data used for development of the high temperature structural design guideline for High Temperature Gas-cooled Reactor (HTGR) were collected. Creep-fatigue evaluation procedure in the design guideline and its application to design of the intermediate heat exchanger (IHX) for High Temperature Engineering Test Reactor (HTTR) was described. Finally, some necessary research and development items in relation to creep-fatigue evaluation for Gen IV and VHTR reactors were presented.
PART I
GRADE 91
1 COLLECTION OF AVAILABLE DATA

1.1 Outline of Collected Data

Data obtained in various organizations such as Japan Atomic Energy Agency (JAEA), Electric Power Research Institute (EPRI), Oak Ridge National Laboratory (ORNL), Central Research Institute of Power Industry in Japan (CRIEPI), National Institute of Material Science in Japan (NIMS) and the University of Tokyo were collected from available sources as listed in Table 1. Data collected include 205 creep data, 281 fatigue data and 78 creep-fatigue data. Product forms include plate, forgings and pipe. Chemical compositions available in the data sources are summarized in Table 2. Most of the data are considered to have been obtained for the application to the development of fast breeder reactors.

1.2 Evaluation of Collected Data

Collected data were evaluated in terms of creep properties, fatigue properties and creep-fatigue properties. Details are described below.

1.2.1 Creep Properties

(a) General trend

Creep rupture life is shown in Figure 1. All the collected data showed a uniform trend and there were no data that showed obvious discrepancy compared to other data.

(b) Environmental effect in sodium

In Figure 1, data in sodium are plotted for comparison at a temperature range from 450 to 600°C. Although creep rupture time was slightly longer in sodium at 600°C, basically it was same both in air and sodium environments, and environmental effects due to sodium were not observed.

1.2.2 Fatigue Properties

(a) General trend

Fatigue life is plotted against total strain range in Figure 2 to Figure 7. All the collected data were obtained under completely reversed strain controlled conditions using uniaxial push-pull specimens. Along with the experimental data, an average trend derived from the DDS procedure (See Reference. Outline of the procedure is shown in Chapter 2 of this report.) by substituting safety margins from design curves are shown in the figures. In general, fatigue life showed clear strain rate dependency. As strain rate becomes slower, fatigue life becomes shorter. EPRI data showed shorter fatigue life at 550°C but the reason is not clear.

(b) Effect of thermal aging

In Figure 5, available data with thermal aging at 550°C are plotted. As far as these data are concerned, no effect of thermal aging on fatigue life was observed.

(c) Effect of environment

From Figure 3 to Figure 6, it is shown that fatigue life in sodium is obviously longer than that in air. This trend is the same for a vacuum environment but the difference is more pronounced in a vacuum than in sodium as shown in Figure 6. The difference of fatigue life in air and vacuum environments is as much as an order of magnitude. This is attributed to the fact that oxidation of test specimens is negligible in vacuum.