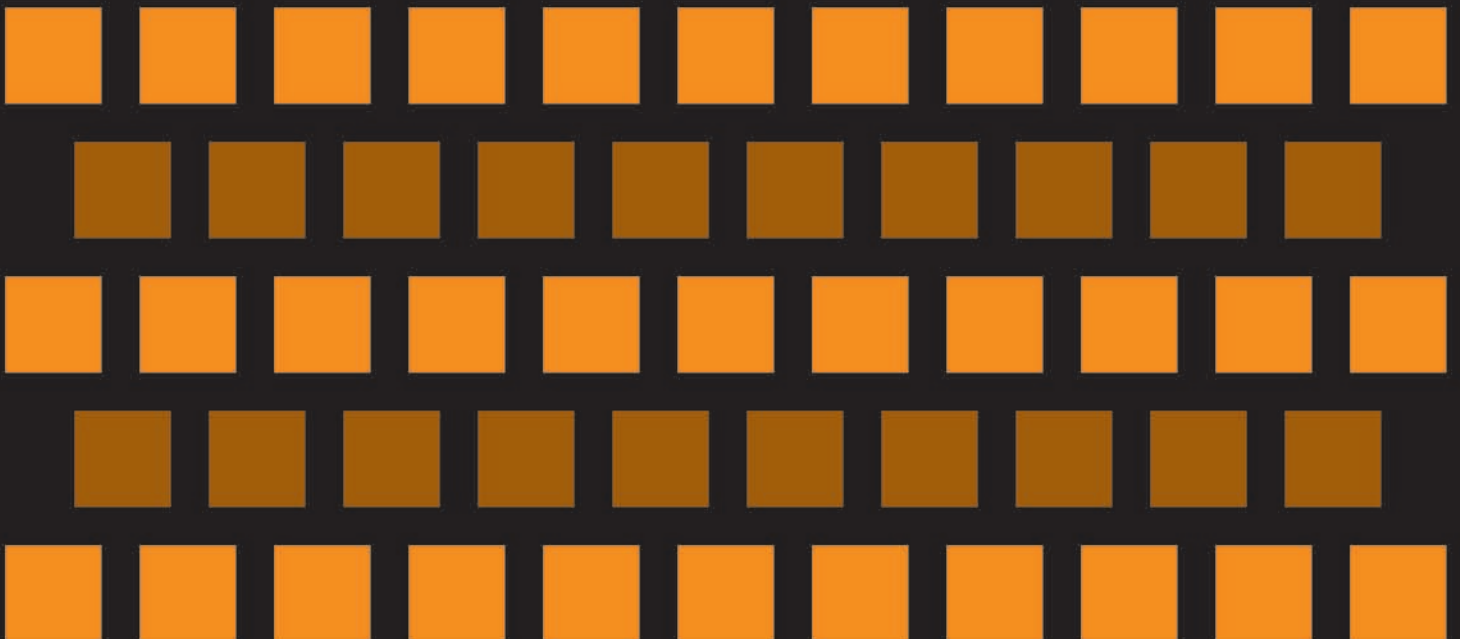


CREEP-FATIGUE DATA AND EXISTING EVALUATION PROCEDURES FOR GRADE 91 AND HASTELLOY XR



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

Prepared by:

Tai Asayama and Yukio Tachibana
Japan Atomic Energy Agency



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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: $\phi 10\text{mm}$).....	90
Table 22 - Results of Creep Tests for Hastelloy XR-II in Air (Plate: $\phi 6\text{mm}$).....	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: $\phi 6\text{mm}$).....	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 $K_{\epsilon}' \epsilon_0$ (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 $\overline{\Delta\sigma_k}$ (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 $\epsilon_t = 0.15\%$	36
Figure 29 - Comparison Between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.2\%$	37
Figure 30 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.3\%$	37
Figure 31 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.1\%$	38
Figure 32 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.2\%$	38
Figure 33 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.3\%$	39

Figure 34 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.4535\%$	39
Figure 35 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 0.36\%$	40
Figure 36 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 0.36\%$	40
Figure 37 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 0.494\%$	41
Figure 38 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 0.494\%$	41
Figure 39 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 1.0\%$	42
Figure 40 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 1.0\%$	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 ($A_{cr}=0.8$) 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.

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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.

(d) Stress-strain relationship

Figure 8 and Figure 12 show stress-strain relationships at mid-life. The slower the strain rate, the smaller the stress ranges. This tendency is more pronounced at higher temperatures. Although from Figure 11, is not clear if additional softening occurs due to aging, this point will be further addressed in Section 2.5 of this report. Effects of environments do not exist for stress-strain response because they are identical irrespective of environments under which they were obtained.

1.2.3 Creep-Fatigue Properties

Available creep-fatigue data are plotted in Figure 13 to Figure 15. Along with the experimental data, average trends derived from DDS procedure by substituting safety margins are shown in the figures. All the collected data were obtained under completely reversed strain controlled conditions using uniaxial push-pull specimens, and strain was held either at a tensile peak, at a compressive peak or at both tensile and compressive peaks.

(a) Reduction of creep-fatigue life due to strain hold

Creep-fatigue life reduction occurs due to introduction of strain hold period. At 500°C, creep-fatigue life is almost identical to fatigue life as long as a hold time is less than 60 minutes. Tests with a compressive hold period showed greater life reduction than those with a tensile hold period.

(b) Effect of strain hold period

Creep-fatigue life is plotted against strain hold time in Figure 16 to Figure 18. Most of the data were obtained with a hold time not larger than 60 minutes and the saturation of creep-fatigue life is not clearly observed.

1.2.4 Points to be Addressed

As described above, a fair amount of creep-fatigue data have been obtained. However, most of the data were originally obtained for the application to fast breeder reactors and the temperature range is limited to 400 to 650 degrees C. Within this temperature range, creep-fatigue data have been accumulated to the extent that they serve to clarify the mechanisms of creep-fatigue life reduction of this steel, if not sufficient in quantity. Tests with a tensile hold time, a compressive hold time and both tensile and compressive hold times have been conducted. Most of the data were obtained in an air environment but data in sodium and vacuum environments are also available, and they give us valuable information. For the effect of aging, available data is not necessarily sufficient to clarify the effects on stress-strain response and creep-fatigue life.

Table 1 - Mod. 9Cr-1Mo Material Data Source List (Temp is 400°C or higher)

Research Laboratories	Creep	Fatigue	Creep Fatigue	Reference
EPRI	3	15	-	(1)
CRIEPI	6	12	9	(1)
ORNL	3	9	17	(2)
Univ. of Connecticut	-	3	-	(3)
Univ. of Tokyo	-	13	3	
JAEA	176	161	27	(4)
NIMS	17	68	22	(5),(6),(7),(8)
Total	205	281	78	

- (1) M. Ruggles and T. Ogata, Creep-Fatigue Criteria and Inelastic Behavior of Modified 9Cr-1Mo Steel at Elevated Temperatures, ORNL/M-3198.
- (2) B. Giseke, C. Brinkman and P.. Maziasz, The Influence of Thermal Aging the Microstructure and Fatigue Properties of Modified 9Cr-1Mo Steel, ORNL, TN 37831-6155, 1993.
- (3) J. McEvily and J. Bunch, Fatigue Behavior of Chromium-Containing Ferritic Steels at Elevated Temperature, IMS, 1985.
- (4) Japan Atomic Energy Agency, Material Test Data of 2.25Cr-1Mo and Mod.9Cr-1Mo Steels, TN9450 2003-004, 2003.
- (5) NRIIM, Fatigue Data Sheet No. 49, 1985.
- (6) NRIIM, Fatigue Data Sheet No. 15, 1979.
- (7) NRIIM, Fatigue Data Sheet No. 78, 1993.
- (8) NRIIM, Fatigue Data Sheet No. 43, 1996.

Table 2 - Chemical Composition of Mod. 9Cr-1Mo

Heat	Research laboratories	C	Si	Mn	P	S	Ni	Cr	Mo	V	Nb	Al	N
F2	IAEA	0.1	0.4	0.43	0.01	0	0.07	8.73	0.96	0.22	0.09	0.01	0.051
F3	IAEA	0.09	0.41	0.42	0.01	0	0.09	8.83	0.98	0.21	0.07	0.02	0.04
F4	IAEA	0.1	0.25	0.37	0.01	0.03	0.08	9.1	0.93	0.22	0.09	0	0.043
F5	IAEA	0.1	0.24	0.38	0.01	0	0.08	8.99	0.95	0.22	0.09	0	0.042
F6	IAEA	0.1	0.39	0.42	0.01	0	0.06	8.75	0.97	0.21	0.089	0.01	0.051
F7	IAEA	0.1	0.39	0.43	0.01	0	0.06	8.69	0.93	0.2	0.09	0.01	0.052
F8	IAEA	0.09	0.23	0.37	0.02	0	0.18	8.82	0.97	0.2	0.066	0	0.048
F9	IAEA	0.1	0.26	0.42	0.01	0	0.1	8.84	0.96	0.22	0.08	0	0.068
F10	IAEA	0.09	0.24	0.44	0	0	0.04	8.76	0.94	0.21	0.08	0.01	0.054
F11	IAEA	0.1	0.25	0.42	0.01	0	0.13	8.67	0.98	0.19	0.09	0.01	0.06
30394	ORNL	0.084	0.4	0.46	0.01	0.003	0.09	8.57	0.198	0.198	0.073	0.014	0.053
ORNL	Univ. of Connecticut	0.09	0.19	0.37		0.02	0.09	8.47	0.88	0.21	0.07	0	0.54
Tokyo	Univ. of Tokyo	0.08	0.26	0.45	0.006	0.001	0.1	8.89	0.95				
NRIM1	NIMS	0.09	0.34	0.46	0.005	0.004	0.09	8.43	0.9	0.2	0.079	0.01	0.062

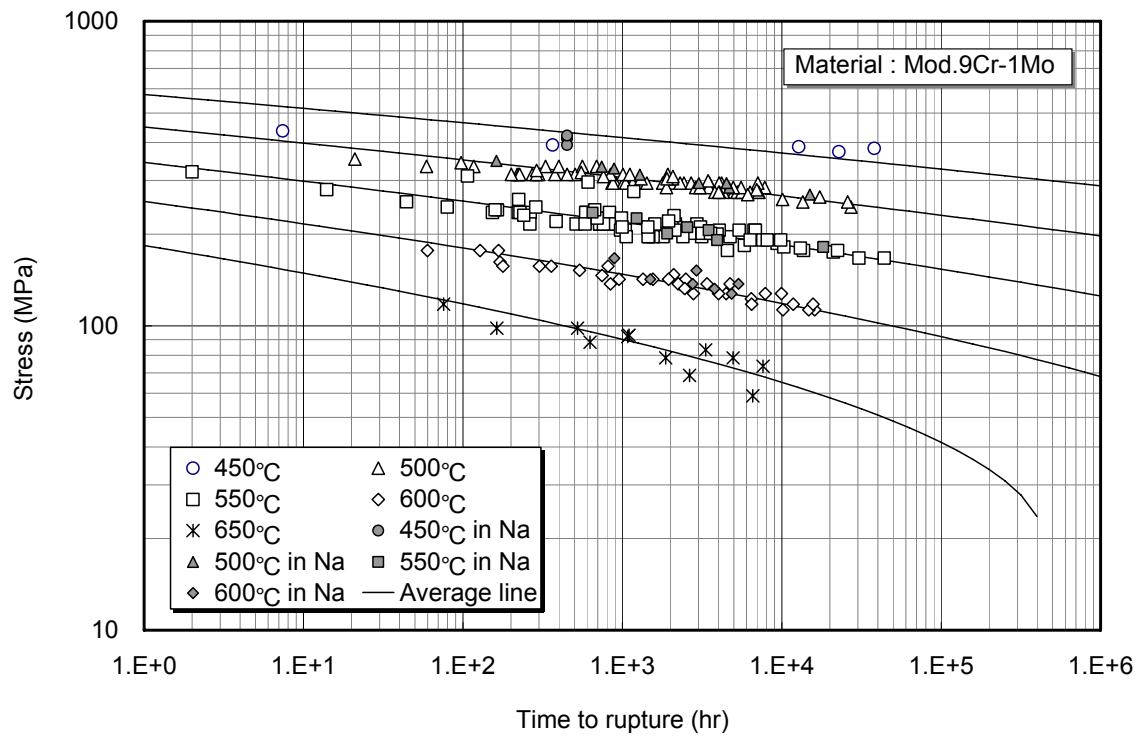


Figure 1 - Creep Rupture: Average Curves and Experimental Values

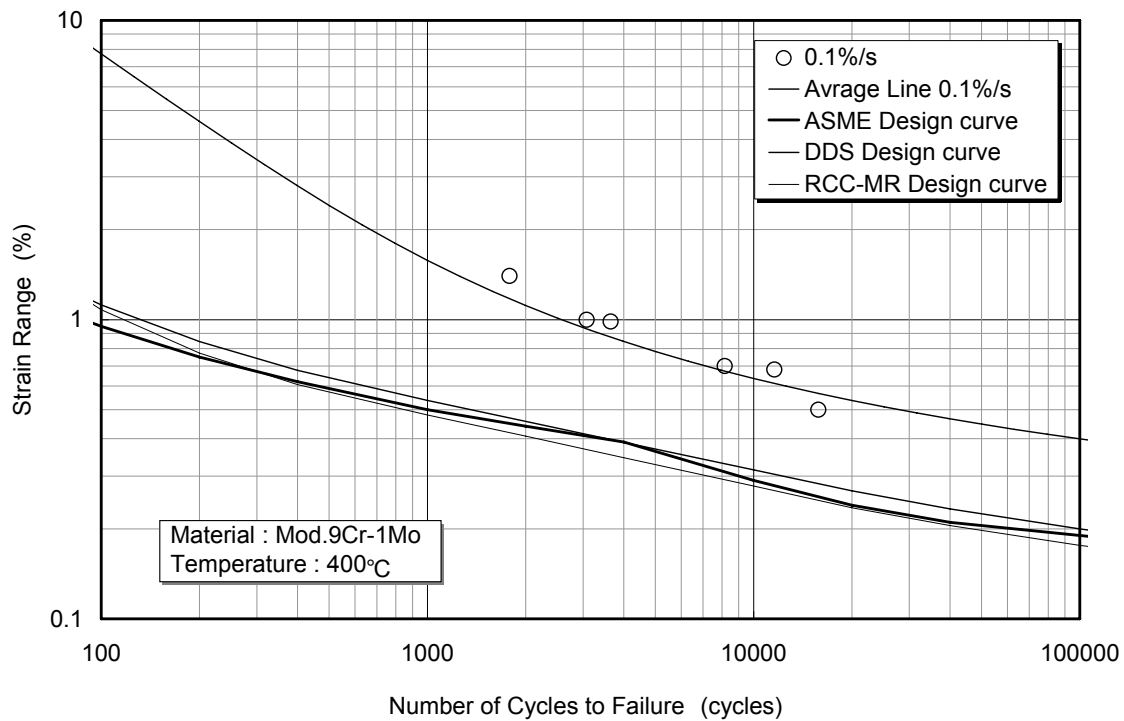


Figure 2 - Fatigue Life: Average Curves and Experimental Values at 400°C

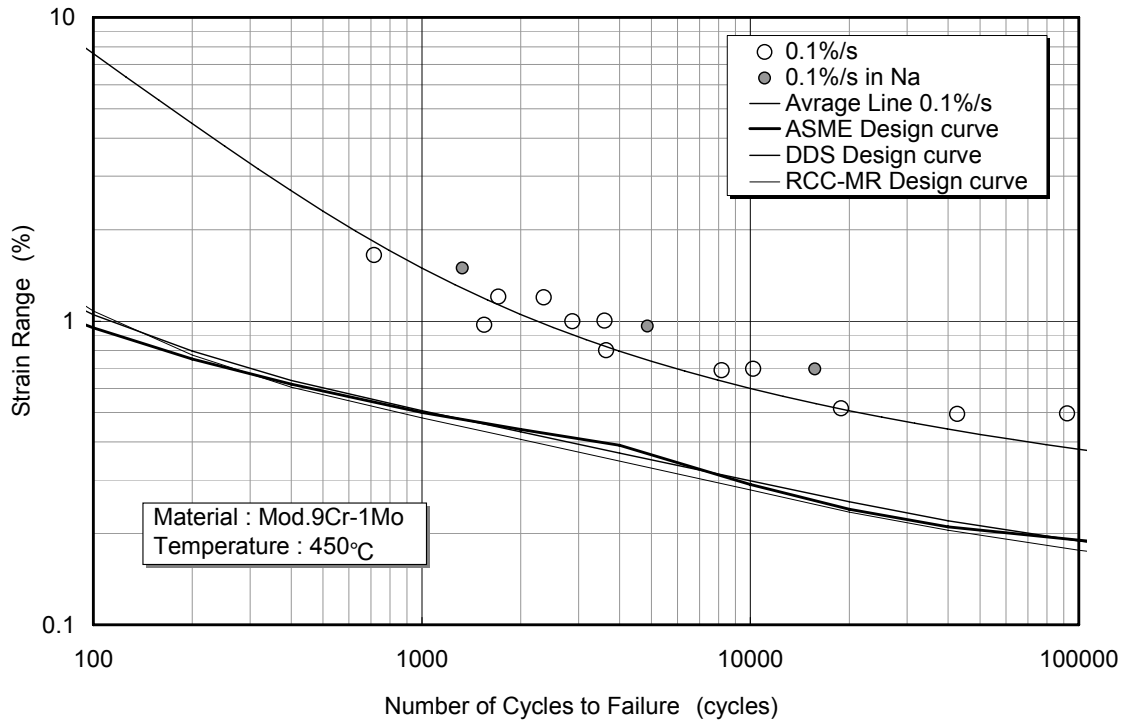


Figure 3 - Fatigue Life: Average Curves and Experimental Values at 450°C

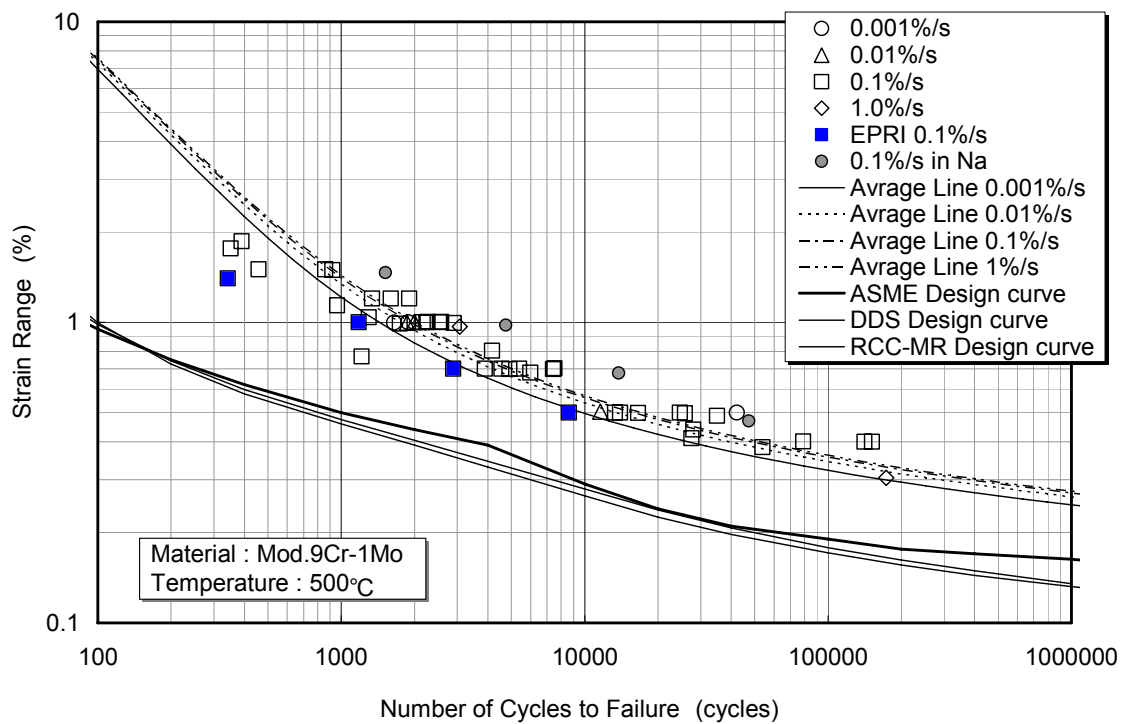


Figure 4 - Fatigue Life: Average Curves and Experimental Values at 500°C

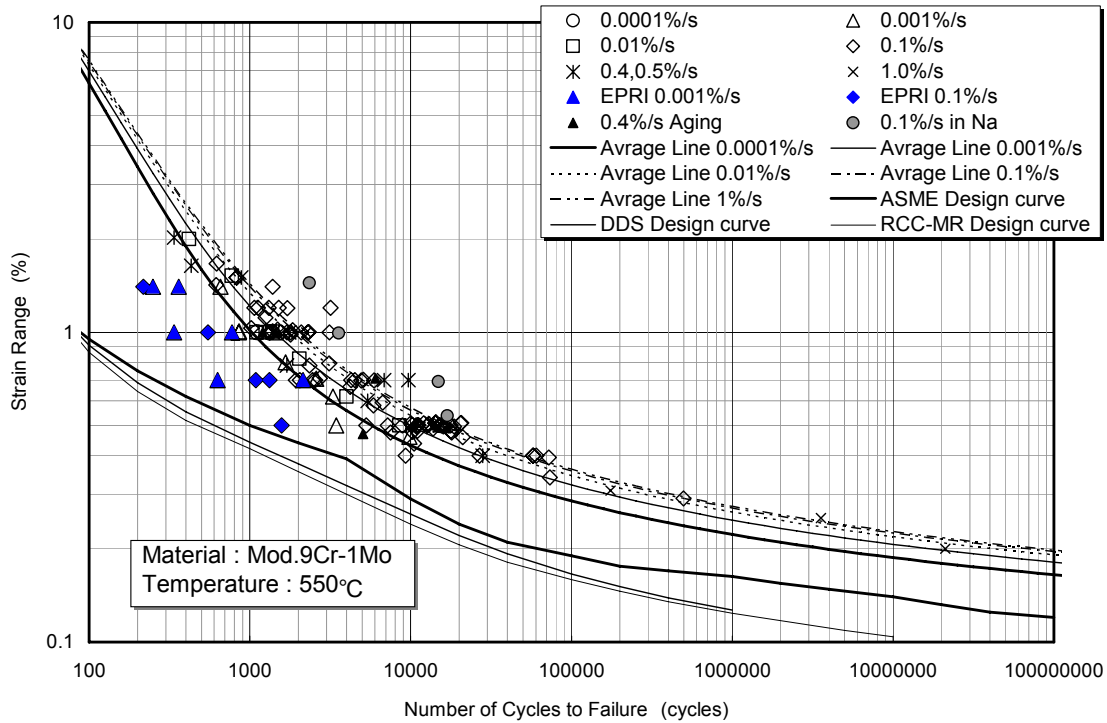


Figure 5 - Fatigue Life: Average Curves and Experimental Values at 550°C

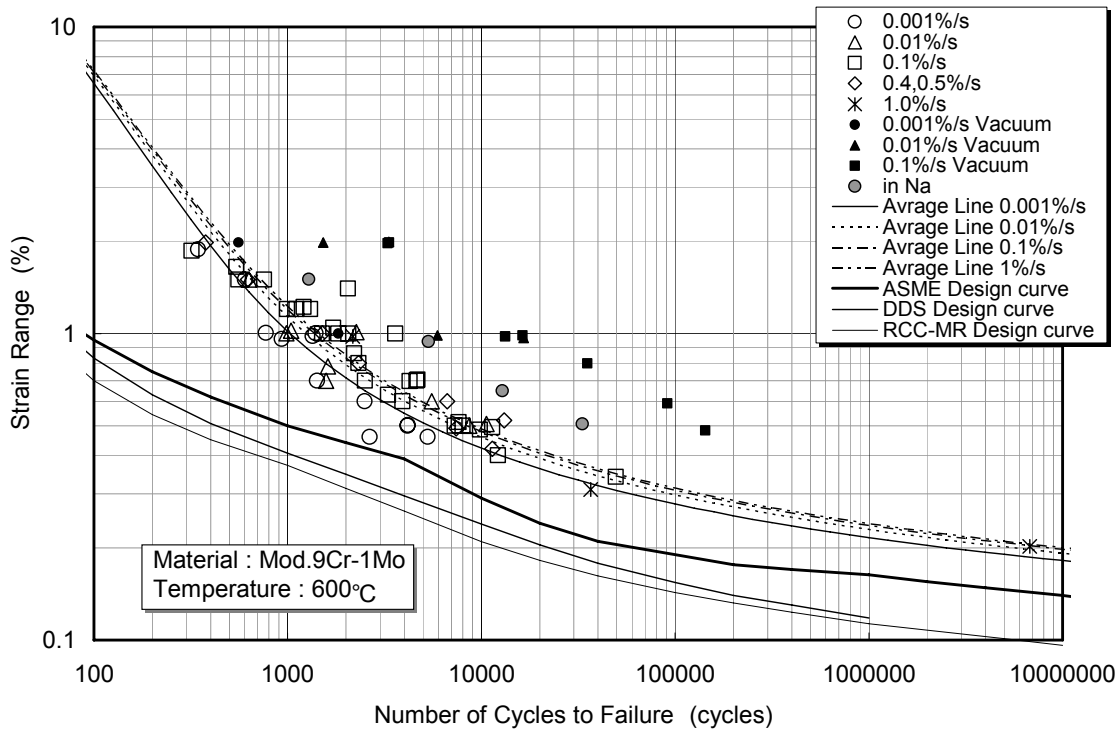


Figure 6 - Fatigue Life: Average Curves and Experimental Values at 600°C

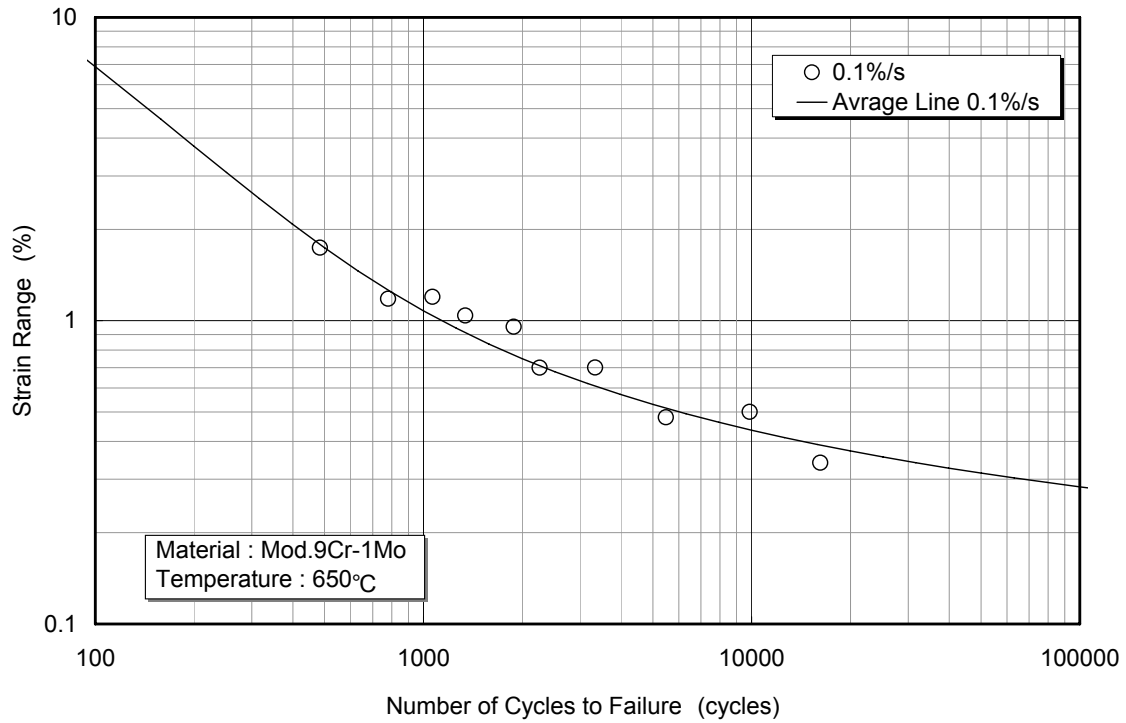


Figure 7 - Fatigue Life: Average Curves and Experimental Values at 650°C

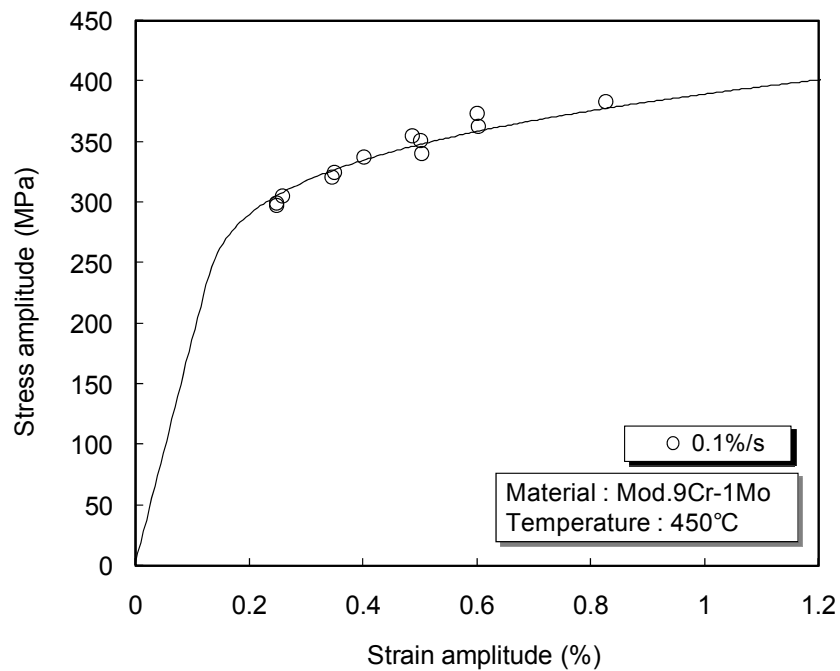


Figure 8 - Cyclic Stress-Strain Curve: Average Curve and Experimental Values at 450°C

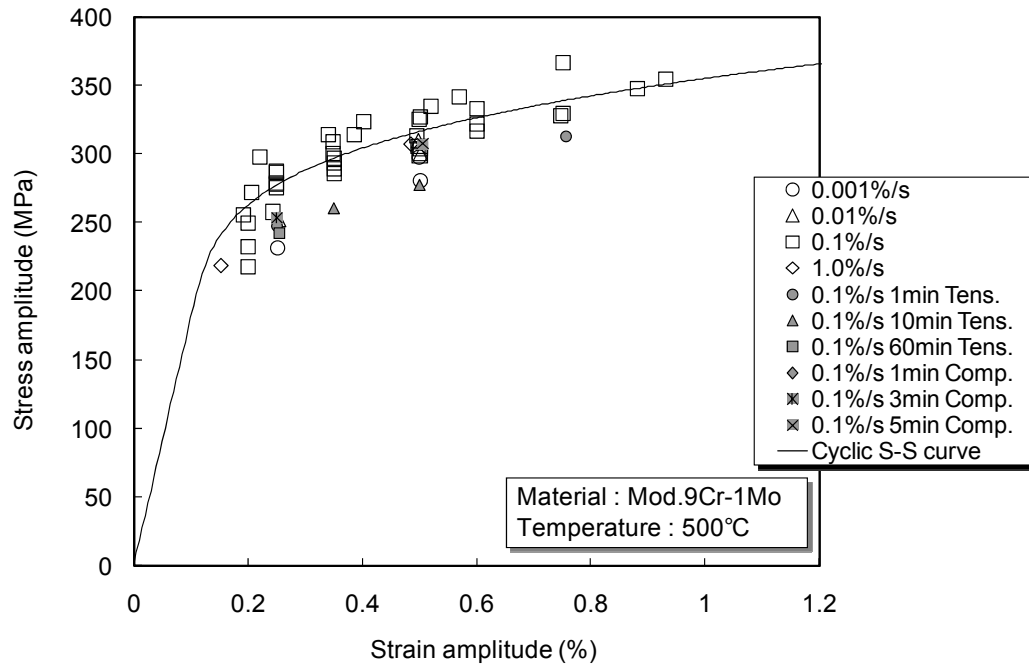


Figure 9 - Cyclic Stress-Strain Curve: Average Curve and Experimental Values at 500°C

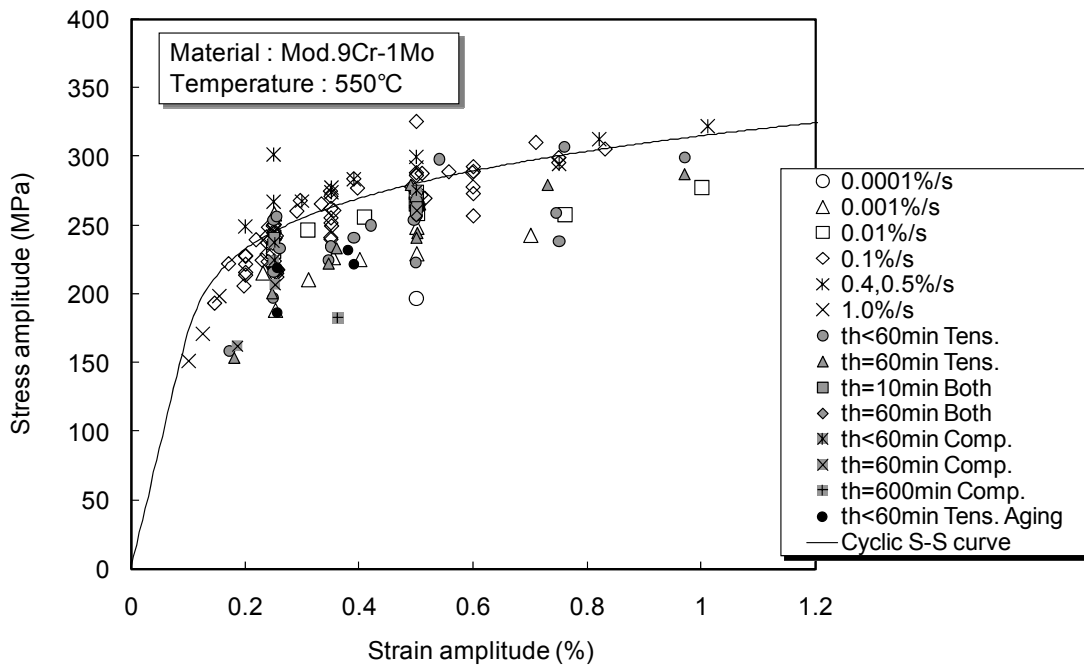


Figure 10 - Cyclic Stress-Strain Curve: Average Curve and Experimental Values at 550°C

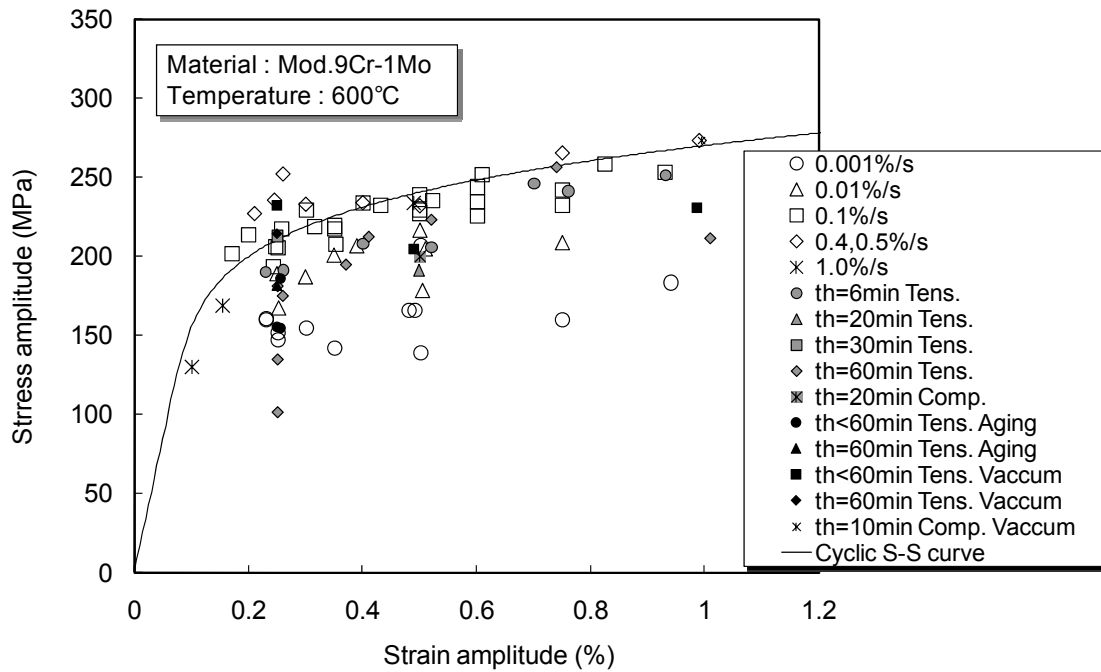


Figure 11 - Cyclic Stress-Strain Curve: Average Curve and Experimental Values at 600°C

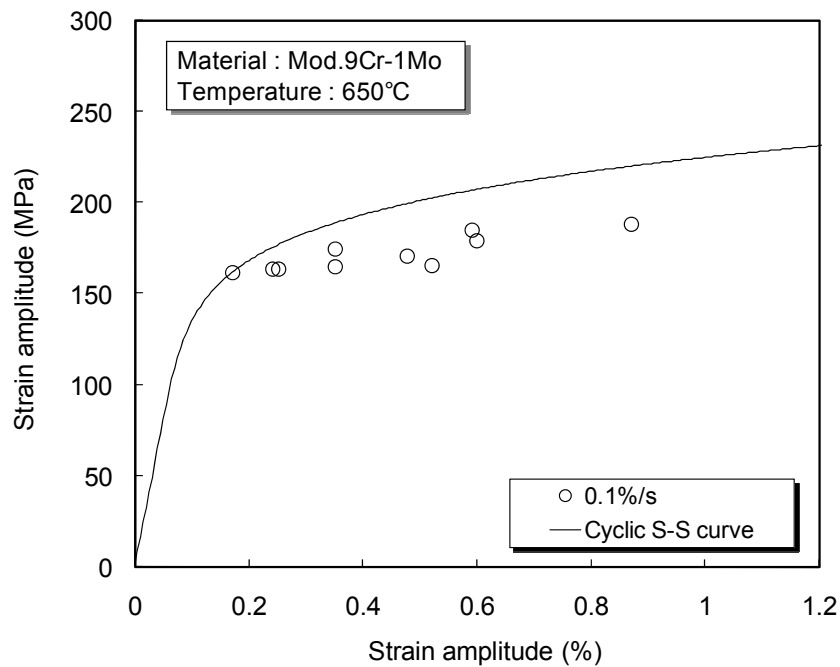


Figure 12 - Cyclic Stress-Strain Curve: Average Curve and Experimental Values at 650°C

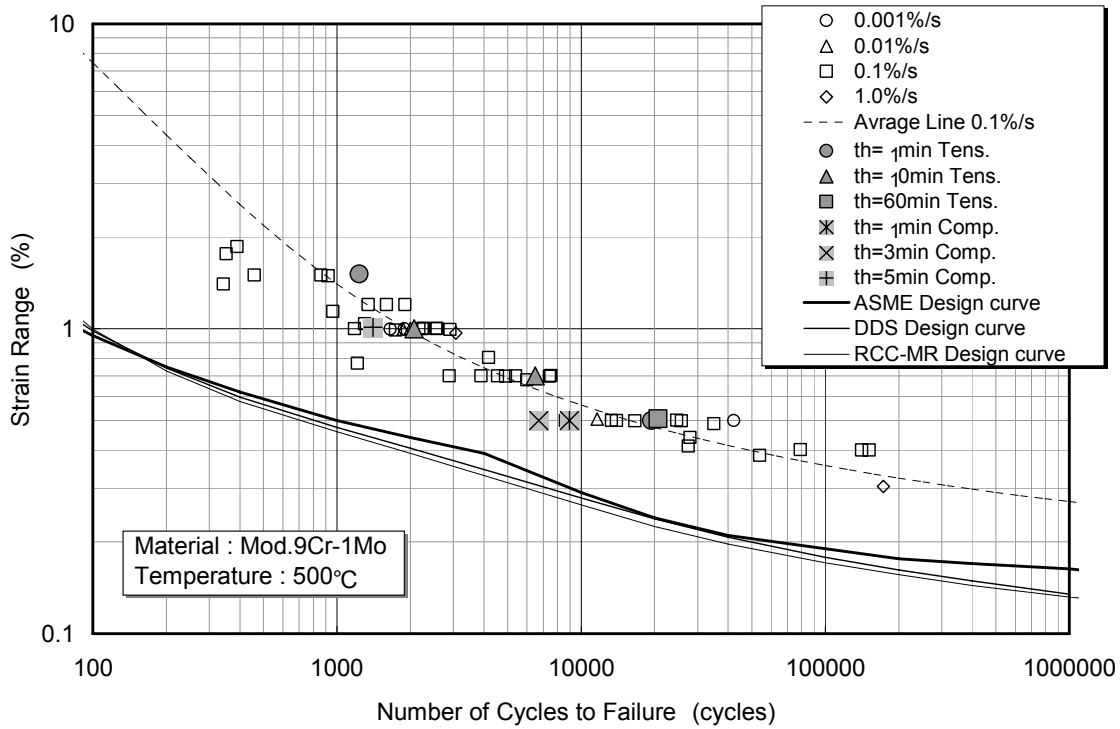


Figure 13 - Creep-Fatigue Life: Average Curves and Experimental Values at 500°C

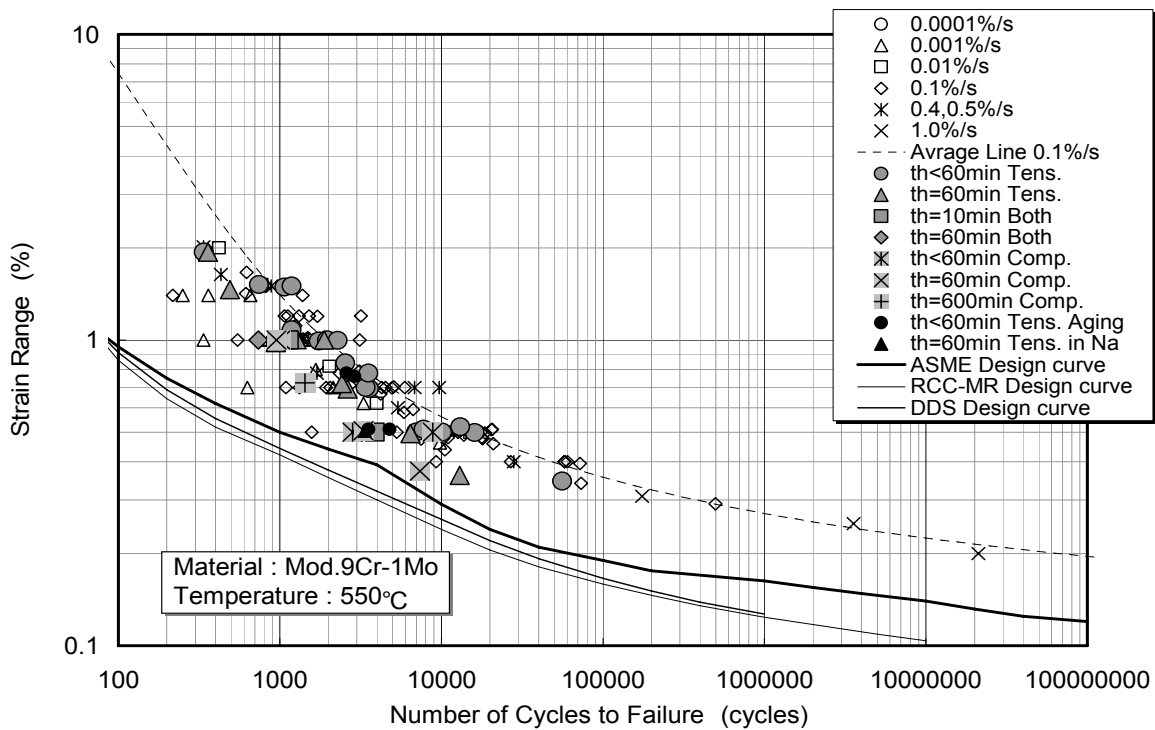


Figure 14 - Creep-Fatigue Life: Average Curves and Experimental Values at 550°C

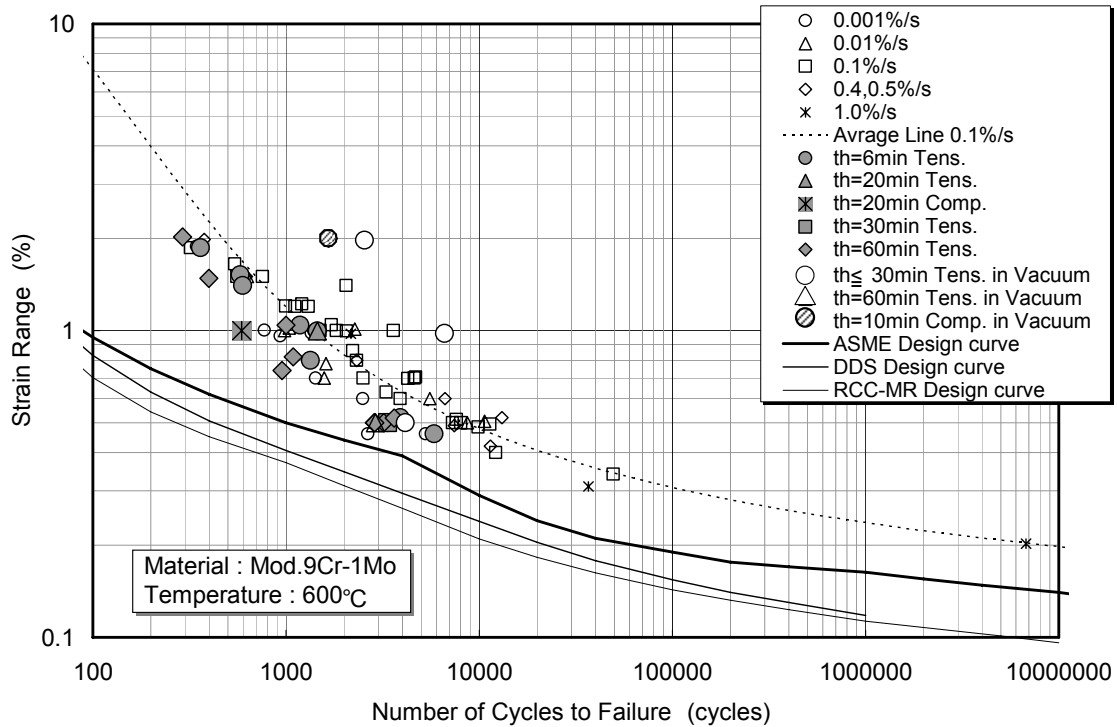


Figure 15 - Creep-Fatigue Life: Average Curves and Experimental Values at 600°C

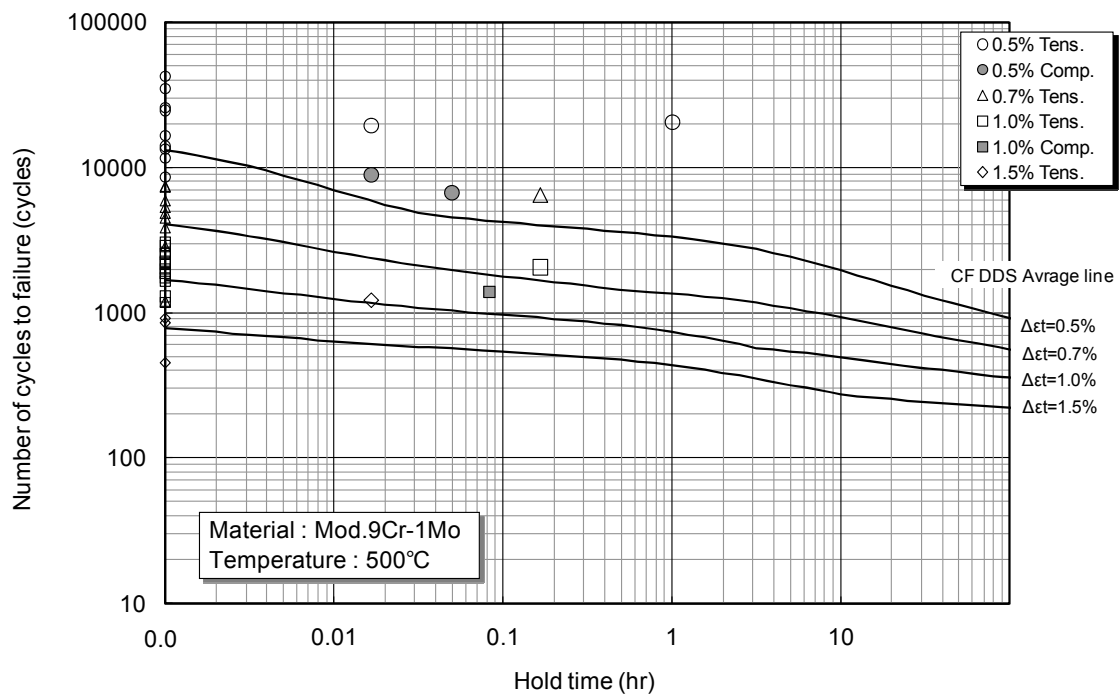


Figure 16 - Creep-Fatigue Life: Average Curves and Experimental Values at 500°C

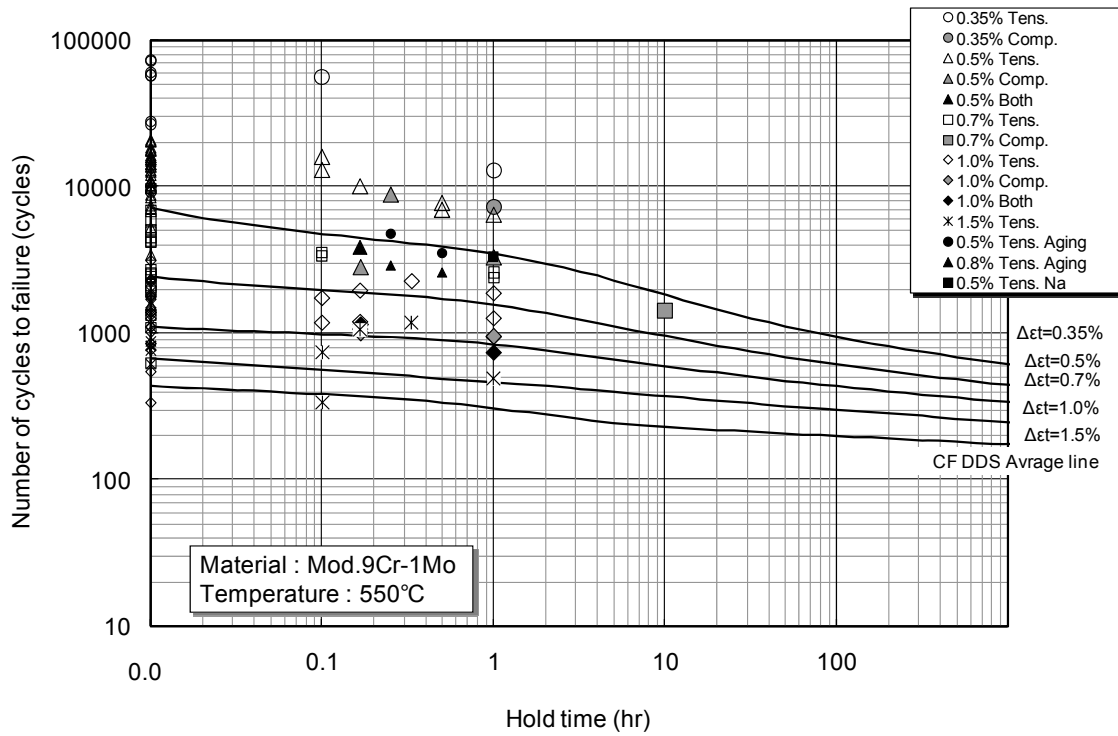


Figure 17 - Creep-Fatigue Life: Average Curves and Experimental Values at 550°C

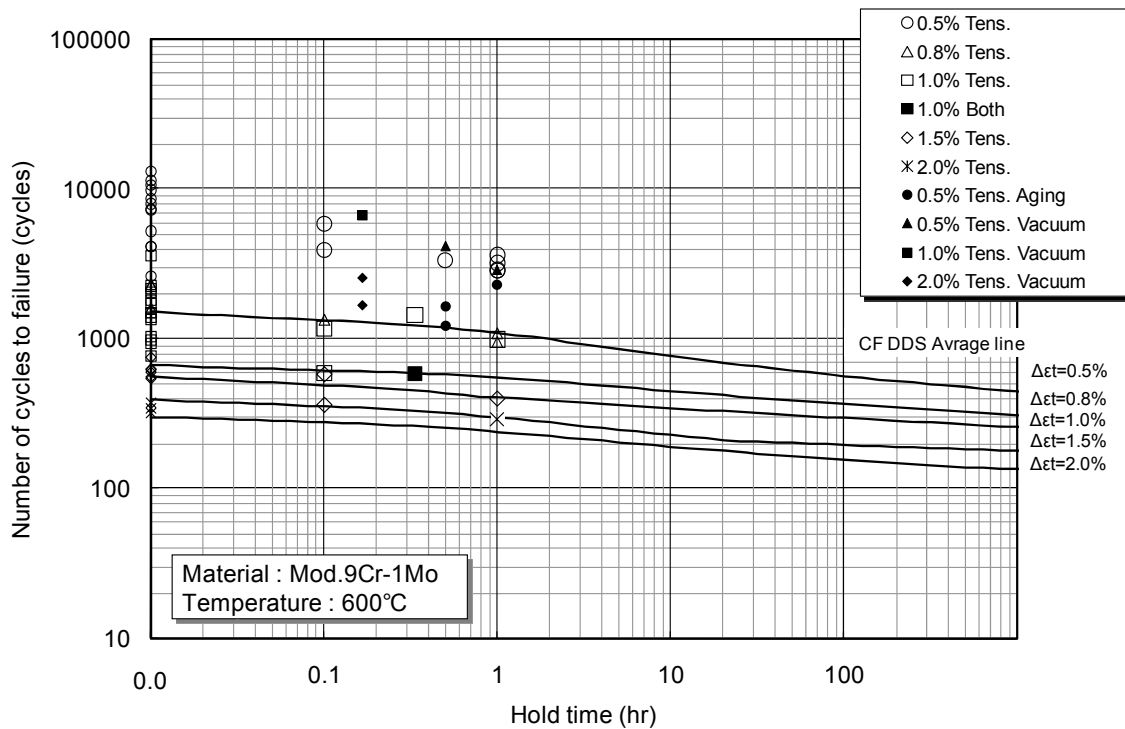


Figure 18 - Creep-Fatigue Life: Average Curves and Experimental Values at 600°C

2 CREEP-FATIGUE EVALUATION METHOD

2.1 Procedures of ASME-NH, DDS and RCC-MR

Procedures for creep-fatigue evaluation methods in ASME-NH, RCC-MR and DDS (See Reference) are summarized. DDS is the draft design standard for Japanese demonstration fast breeder reactor developed by electric utilities. In DDS, a creep-fatigue evaluation procedure for Modified 9Cr-1Mo steel was developed to apply the material to steam generators (Asada et. al., 1991a, Asada et. al., 1991b). The creep-fatigue evaluation procedure in DDS (Asada et. al., 1993, Taguchi et. al., 1993, Taguchi et. al., 1995) is basically the same as that determined in the Elevated Temperature Structural Design Guide for the Prototype Reactor “Monju.”

2.1.1 ASME-NH

2.1.1.1 Fatigue Damage

Creep-fatigue damage evaluation procedure described in Nonmandatory Appendix T is summarized here. Fatigue damage is calculated by equation:

$$D_f = \sum_{j=1}^P \left(\frac{n}{N_d} \right)_j$$

where:

D_f : fatigue damage

$(n)_j$: number of applied repetitions of cycle type, j

$(N_d)_j$: number of design allowable cycles for cycle type, j , determined from one of the design fatigue curves corresponding to the maximum metal temperature occurring during the cycle. The design fatigue curves were determined from completely reversed loading conditions at strain rates greater than, or equal to, those noted on the curves.

Strain range that is used to calculate design fatigue life is obtained by the following equation:

$$\varepsilon_t = K_v \Delta \varepsilon_{\text{mod}} + K \Delta \varepsilon_c$$

K_v : the multiaxial plasticity and Poisson ratio adjustment factor

$\Delta \varepsilon_c$: the creep strain increment

K : local geometric concentration factor

$\Delta \varepsilon_{\text{mod}}$: the modified maximum equivalent strain range

$\Delta \varepsilon_{\text{mod}}$: is calculated using the procedure specified in any one of (a), (b) or (c) described below.

(a) The modified maximum equivalent strain range is calculated as:

$$\Delta \varepsilon_{\text{mod}} = \left(\frac{S^*}{S} \right) K^2 \Delta \varepsilon_{\text{max}}$$

where,

K : either the equivalent stress concentration factor, as determined by test or analysis, or, the maximum value of the theoretical elastic stress concentration factor in any direction for the

local area under consideration. The equivalent stress concentration factor is defined as the effective (von Mises) primary plus secondary plus peak stress. Note that fatigue strength reduction factors developed from low temperature continuous cycling fatigue tests may not be acceptable for defining K when creep effects are not negligible.

S^* : the stress indicator determined by entering the stress-strain curve of Fig. T-1432-1 at a strain range of $\Delta\epsilon_{\max}$

\bar{S} : the stress indicator determined by entering the stress-strain curve of Fig. T-1432-1 at a strain range of $K\Delta\epsilon_{\max}$

$\Delta\epsilon_{\max}$: the maximum equivalent strain range as determined in T-1432 (a).

(b) The modified maximum equivalent strain range is calculated as:

$$\Delta\epsilon_{\text{mod}} = \frac{K^2 S^* \Delta\epsilon_{\max}}{\Delta\sigma_{\text{mod}}}$$

where,

$\Delta\sigma_{\text{mod}}$: the range of effective stress that corresponds to the strain range, $\Delta\epsilon_{\text{mod}}$, in the composite stress-strain curve of Fig. T-1432-1.

(c) The modified maximum equivalent strain range is calculated as:

$$\Delta\epsilon_{\text{mod}} = K_e K \Delta\epsilon_{\max}$$

$$K_e = 1 \text{ if } K \Delta\epsilon_{\max} \leq 3\bar{S}_m / E$$

$$K_e = K \Delta\epsilon_{\max} E / 3\bar{S}_m \text{ for } K \Delta\epsilon_{\max} > 3\bar{S}_m E$$

$$3\bar{S}_m = 1.5S_m + S_{rH}$$

$$\bar{S} = \sigma_S (K \Delta\epsilon_{\max})$$

A schematic illustration of procedures (a) and (b) are shown in Figure 19. Procedure (c) is employed to calculate modified maximum strain range most conservatively.

2.1.1.2 Creep Damage

Creep damage D_c is calculated by the following equation.

$$D_c = \sum_k \left(\frac{\Delta t}{T_d} \right)_k$$

$$\sigma_j = \frac{S_{rj}}{K'}$$

$(T_d)_k$: allowable time duration determined from stress-to-rupture curves for a given stress and the maximum temperature at the point of interest and occurring during the time interval, k . For elastic analysis, the appropriate stress measure is defined in T-1433.

$(\Delta t)_k$: duration of the time interval, k

S_{rj} : the expected minimum stress-to-rupture strength given in Tables I-14.6 during the time interval, j .

K' : the factor determined in Table T-1411-1.

T_d is calculated based on minimum stress-to-rupture curve from applied stress divided by the factor K' . K' is determined as shown in Table 3. The initial stress of relaxation is calculated from ε_t . Stress relaxation behavior is calculated from isochronous stress-strain curves as shown in Figure 20. The initial stress of stress and strain of relaxation are determined by the following equations:

$$S_i = \Delta\sigma_{\text{mod}} - S_{rH}$$

$$\varepsilon_t = \Delta\varepsilon_{\text{mod}} - S_{rH} / E$$

As shown in Figure 21, creep damage per one cycle is calculated as a summation of damage corresponding from peak stress to the relaxation strength associated with the hot extreme S_{LB} , and damage corresponding to the stress level of S_{LB} . S_{LB} is calculated from the following equation, where Z is a factor to take ratcheting into account. In this investigation, Z was set to zero, because all the data collected and used for the evaluation of creep-fatigue evaluation procedure were obtained under strain controlled condition which corresponds to $Z=0$.

$$S_{LB} = 1.25\sigma_c$$

$$\sigma_c = Z \cdot S_y$$

2.1.1.3 Damage Envelope

The intersection of a damage envelope of creep-fatigue criteria for Grade 91 is $(D_f, D_c) = (0.1, 0.01)$ as shown in T-1420-2 (Figure 27). The intersection point is most restrictive compared to other materials such as 304 stainless steel, 316 stainless steel and 2 1/4 Cr-1Mo steel.

2.1.2 DDS

2.1.2.1 Fatigue Damage D_f

Fatigue damage is calculated from the following equation.

$$D_f = \sum_i \frac{n_i}{N_{di}}$$

n_i : number of applied repetition of cycle type, j

N_{di} : number of design allowable cycles for cycle type, j , determined from one of the design fatigue curves corresponding to the maximum metal temperature occurring during the cycle.

Strain range is calculated from the following equation. The first term is calculated as shown in Figure 22.

$$\varepsilon_t = K_{\varepsilon}'' \varepsilon_0 + K_L \varepsilon_c$$

ε_0 : elastically calculated peak strain range including peak strain

ε_c : equivalent creep strain induced in an interested cycle by long term stress controlled loading

K_{ε}'' : elastically calculated stress concentration factor corresponding to peak strain range ε_0

K_L : stress concentration factor corresponding to long term stress controlled loading

Strain range ε_0 can be calculated by the following equation:

$$\varepsilon_0 = S_p E$$

where, S_p is determined based on the stresses at two extreme points 1 and 2. K_ε'' can be calculated by the following equation when a hold time at elevated temperature is introduced in a cycle:

$$K_\varepsilon'' = 1 + (q_p - 1) \left\{ 1 - 3\overline{S_m} / (E\varepsilon_0) \right\}$$

$$3\overline{S_m} = S_{rH} + 1.5S_{mc}$$

$$q_p = K \cdot q_n$$

where,

S_{rH} : stress value determined based on the elevated temperature service time and the history of metal temperature of an interested point

S_{mc} : stress determined for temperature T_c

q_p : elastic follow-up parameter for peak stress

K : stress concentration factor corresponding to primary plus secondary stress

q_n : elastic follow-up parameter for primary plus secondary stress

2.1.2.2 Creep damage D_c

Creep damage is calculated from the following equation:

$$D_C = D_{CR} + D_{CN}$$

$$D_{CR} = D_0^* + \sum n_k D_k^*$$

$$D_k^* = 2 \int_0^{t_k} \frac{dt}{td(T_k, \sigma_k)} - \frac{2t_k}{td(T_k, S_g)}$$

where,

D_{CN} : creep damage factor induced by steady stress

D_0^*, D_k^* : stress relaxation damage factor determined corresponding to strain range that determines strain cycle k , metal temperature history at an interested point, stress level S_g and elastic follow-up parameter q_p .

$td(T_1, \sigma_1)$: allowable hold time determined from creep rupture curve or design stress

$td(T_1, S_g)$: allowable hold time determined from creep rupture curve or design stress S_g

The initial stress of stress relaxation is obtained from the cyclic stress-strain curve in the case of austenitic stainless steels, and from the monotonic stress-strain curve in the case of ferritic steels, in order to account for cyclic hardening and cyclic softening, respectively. Schematic illustration is shown in Figure 23.

(a) Austenitic stainless steels (304, 316 and 316FR)

$$D_0^* : S_i = 1.5S_m$$

$$D^* : \text{Min} \left(S_i = \frac{1}{2} \Delta \sigma_R(\varepsilon_t), E\varepsilon_t - (3\overline{S_m} - S_{rH}) \right)$$

(b) Ferritic steels (2 1/4Cr-1Mo, Mod.9Cr-1Mo)

$$D_0^* : S_i = \langle P_L + P_b + Q \rangle$$

$$D^* : \text{Min}(S_i = S\left(\frac{1}{2}\varepsilon_t\right), E\varepsilon_t - (3\overline{S_m} - S_{rH}))$$

where,

$\Delta\sigma_R(\varepsilon_t)$: stress range determined from the cyclic stress-strain curve

$S_i = S\left(\frac{1}{2}\varepsilon_t\right)$: stress obtained by entering the strain amplitude to elastic-plastic stress-strain curve

Stress relaxation behavior is estimated by creep strain law and the strain hardening rule. A factor that represents the scatter of creep strain curve is taken into account ($\alpha_R = 3$).

$$S(T, t) = \sigma_i + \int_0^t \dot{\sigma}_c dt$$

$$\dot{\sigma}_c = -E\dot{\varepsilon}_c / q_c$$

$$q_c = 3 \cdot K$$

$\dot{\varepsilon}_c$: creep strain rate

E : elastic modulus

q_c : elastic follow-up parameter

K : stress concentration factor

The method of creep damage calculation is schematically illustrated in Figure 24. Creep damage corresponding to a stress level S_g is always accounted for. A safety factor of 20 is incorporated.

$$t_R = 2t^* / D_{CN}$$

t^* : service time at elevated temperature

D_{CN} : creep damage factor due to steadily imposed stress

If long-term stress is low, $D_{CN} = 0.3$

If creep damage is not significant, $D_{CN} = 0.1$

2.1.2.3 Damage Envelope

The intersection of a damage envelope of creep-fatigue criteria for Grade 91 is $(D_f, D_c) = (0.3, 0.3)$ as shown in Figure 27. The intersection point is the same as other materials such as 304 stainless steel, 316 stainless steel, 321 stainless steel and 2 1/4 Cr-1Mo steel.

2.1.3 RCC-MR

2.1.3.1 Fatigue damage

Fatigue damage is calculated by the following equation:

$$D_f = \sum_i \frac{n_i}{N_{di}}$$

Strain range is determined by the following equation, as schematically shown in Figure 25.

$$\overline{\Delta \varepsilon} = \overline{\Delta \varepsilon_{el+pl}} + \overline{\Delta \varepsilon_{cr}}$$

$$\overline{\Delta \varepsilon_{el+pl}} = \overline{\Delta \varepsilon_1} + \overline{\Delta \varepsilon_2} + \overline{\Delta \varepsilon_3} + \overline{\Delta \varepsilon_4}$$

$\overline{\Delta \varepsilon_1}$: strain range obtained from elastic analysis

$\overline{\Delta \varepsilon_2}$: increment of plastic strain corresponding to initial stress range, equals to $\frac{\Delta[P_m + 0.67(P_b + P_L - P_m)]}{\sigma_y}$ see Figure 25

$\overline{\Delta \varepsilon_3}$: see Figure 25

$\overline{\Delta \varepsilon_4}$: plastic strain range to account for multiaxial stress state

$$\overline{\Delta \varepsilon_4} = (K_v - 1) \times \overline{\Delta \varepsilon_1}$$

$\overline{\Delta \varepsilon_{cr}}$: creep strain range

2.1.3.2 Creep Damage

Creep damage is calculated by the following equation. T_d is calculated by entering an equivalent stress divided by 0.9 to the design creep rupture curve.

$$D_C = \sum_k \frac{\Delta t_k}{T_{dk}}$$

$$\sigma_j = \frac{S r_j}{0.9}$$

Stress relaxation behavior is estimated by the creep strain law and the strain hardening rule. The initial stress is calculated as shown in Figure 76. If symmetrization effects are to be taken into account, $\Delta \bar{\sigma}^*$ is replaced by $K_s \Delta \bar{\sigma}^*$.

$$S(T, t) = \bar{\sigma}_k + \int_0^t \dot{\sigma}_c dt$$

$$\bar{\sigma}_k = K_s \Delta \bar{\sigma}^*$$

$$\dot{\sigma}_c = -E \dot{\varepsilon}_c / q_c$$

where,

q_c : elastic follow-up parameter, =3

$\dot{\epsilon}_c$: creep strain rate

E: elastic modulus

Ks: symmetrization effects factor

$\overline{\Delta\epsilon_{cr}}$ can be calculated as follows:

$$\overline{\Delta\epsilon_{cr}} = (\overline{\sigma}_k - S(T, t_H)) / E$$

where t_H is strain hold time.

2.1.3.3 Damage Envelope

The intersection of a damage envelope of creep-fatigue criteria for Grade 91 is $(D_f, D_c) = (0.3, 0.3)$ as shown in Figure 27, which is the same as the other materials in the code.

2.2 Comparison of the Procedures

The differences between ASME-NH, DDS and RCC-MR are described focusing on the method of determination of strain range, initial stress of stress relaxation, stress relaxation behavior and formulation of creep damage.

2.2.1 Determination of Strain Range

ASME-NH determines strain range for fatigue damage calculation by a monotonic stress-strain curve, stress concentration factor, elastically calculated strain range, using the Neuber's rule for both austenitic stainless steels which cyclically harden and ferritic steels which cyclically soften. If elastically calculated stress is the same, the procedure gives a larger strain range for austenitic steels than ferritic steels because monotonic stress-strain curves are softer for austenitic steels. The linear extension of the zero isochronous stress-strain curve by S_{th} as shown in Figure 19 has not been taken into account in Section 2.3 but has been taken into account in Section 2.4.

RCC-MR uses elastically calculated stress range and cyclic stress strain curves based on the Neuber's rule. Since the cyclic stress-strain curve of austenitic steel is harder than that of ferritic steels, a larger strain range is predicted for ferritic steels than for austenitic steels, whose tendency is the opposite of ASME-NH.

DDS determines a strain range applying an elastically calculated stress range that includes peak stress to a perfect elastic-plastic stress strain curve with a yield stress of $3\overline{\sigma}_m$ using an elastic follow-up factor.

2.2.2 Initial Stress of Stress Relaxation

ASME-NH determines the initial stress of relaxation as an intersection of a stress-strain curve and a locus obtained from the Neuber's rule. As a stress-strain curve, an isochronous curve is used and as a strain range is entered into the curve, calculated initial stress becomes large.

RCC-MR is basically the same as ASME-NH, however, as a stress-strain curve, cyclic stress-strain curves that are obtained at the mid-life cycle are used.

DDS uses monotonic stress-strain curves for cyclically softening material such as Grade 91. Elastically calculated stress is entered in to the monotonic stress-strain curve, and the point and perfect elastic-plastic stress-strain curve are connected by a slope corresponding to the elastic follow-up factor.

2.2.3 Estimation of Stress Relaxation Behavior

ASME-NH uses isochronous stress-strain curves to estimate stress relaxation behavior.¹ Although this method does not take elastic follow-up into account, it takes into account multiaxial effects on stress relaxation. The initial stress is multiplied by the K' factor. The value of the factor is 0.67 but revision of the value to 0.9 is in progress.

RCC-MR uses creep strain curves and the strain hardening law. RCC-MR adopts the same kind of factor as K' in ASME-NH, and the value is 0.9.

DDS is the same as RCC-MR. The creep strain curves determined in DDS is derived as a function of creep stress-to-rupture. There is no factor corresponding to the K' factor in ASME-NH.

2.2.4 Formulation of Creep Damage

ASME-NH formulates creep damage as a time fraction of creep rupture time that corresponds to the stress level at a point of interest. Stress relaxation curve is only considered above S_{LB} level.

DDS adopts a similar approach. Creep damage is formulated as a time fraction of creep rupture time that corresponds to the stress level at a point of interest. The stress relaxation curve is only considered above S_g level. Creep damage corresponding to S_g level, which is 0.3 and denoted as D_{c1} , is always taken into account.

The approach in RCC-MR is basically the same.

2.3 Creep-Fatigue Evaluation Without Safety Margins

In evaluating creep-fatigue evaluation procedures, it is very useful to apply them to experimental results. In this case, it is useful to remove safety margins from every step of the procedures. Therefore, the procedures of ASME-NH, RCC-MR and DDS were applied to the collected data described in chapter 1 without safety factors. This evaluation focuses on the following key points.

- (a) Determination of the initial stress of stress relaxation
- (b) Description of stress relaxation behavior during strain hold period
- (c) Creep-fatigue damage diagram

2.3.1 Conditions of Evaluation

In order to capture the characteristics of existing procedures, creep-fatigue evaluation was performed without applying safety margins determined in the procedures. Basic conditions of this evaluation are described below.

The strain ranges in the experiments were used for evaluation. Stress concentration coefficients were not considered because all the tests were performed using smooth bar specimens.

The initial stress of stress relaxation was basically calculated based on the strain range using stress-strain curves that are specified in each procedure. No multiplication factors considered as safety margins such as those determined in ASME-NH (K') were taken into account. As for stress-strain relationship, monotonic stress strain relationship was used for ASME-NH and DDS, while cyclic stress-strain curves were used for RCC-MR, as determined in each procedure. For comparison, the monotonic stress-strain curve was also used with RCC-MR, as the cyclic stress-strain curve was used with DDS.

¹ Although use of the isochronous stress-strain curves to calculate S_{th} is described in ASME-NH, it is also permissible to use a value calculated similarly to the methods employed in the DDS and RCC-MR.

Stress relaxation behavior was estimated using the isochronous stress-strain curves for ASME-NH, and the strain hardening law for RCC-MR and DDS. Elastic follow-up factor during strain hold period was set to 1, because the tests were performed under strain controlled conditions.

Average creep rupture curves and fatigue life curves were used for creep-fatigue damage evaluation. For compressive hold tests, the same procedure for tensile hold tests were applied (Both tensile hold tests and compressive hold tests were evaluated in the same manner).

For fatigue life curves, in addition to the average trend which was obtained by removing safety factors from the design curve, curves with 1/10 of average fatigue life were also used to take into account of crack initiation.

2.3.2 Description of Stress Relaxation Behavior

Description of stress relaxation behavior may affect the estimation of creep damage significantly. Therefore, in this section, monotonic stress relaxation behaviors and stress relaxation behaviors during creep-fatigue tests were examined and compared with predictions by the procedures of ASME-NH, RCC-MR and DDS. For stress relaxation during creep-fatigue tests, relaxation behaviors at the first cycle and the mid-life were examined.

Figure 28 to Figure 34 show monotonic stress relaxation behavior along with the predictions by ASME-NH, RCC-MR and DDS. In the prediction, initial stresses obtained experimentally were used to predict relaxation behaviors. ASME-NH procedure generally predicts higher stress compared to the experimental results. On the other hand, RCC-MR and DDS procedures generally predict stresses closer to experimental results. Overall, all procedures tend to predict higher stresses than experiments during stress relaxation.

Figure 35 to Figure 40 show stress relaxation during creep-fatigue tests along with the predictions by ASME-NH, RCC-MR and DDS. For each creep-fatigue test, relaxation behavior at the first cycle and the mid-life are examined. Generally, ASME-NH gives the highest stress but other two procedures also give higher stress than observed. However, it is to be noted that at lower strain range, i.e., if the initial stress is low, all three procedures tend to give lower stress than actually observed.

Figure 41 shows the evolution of creep damage corresponding to Figure 32. Creep damage was calculated according to the DDS procedure. Vertical axis indicates the ratio of creep damage to creep damage at 2000 hr. at an arbitrary time. It can be seen that more than 70% of the damage has been accumulated in the first 500 hours.

2.3.3 Creep-Fatigue Damage Evaluation and Life Prediction

2.3.3.1 Creep-Fatigue Damage Evaluation

In this section, creep-fatigue damage is evaluated. For strain range, experimental value was used. Fatigue damage per cycle, d_f , is calculated using an average fatigue life curve. Creep damage per cycle, d_c , was calculated according to the method determined in ASME-NH, RCC-MR and DDS. Total fatigue damage, D_f , and creep damage, D_c , were obtained by multiplying d_f and d_c by number of cycles to failure, N_f .

Figure 42 and Figure 43 show creep-fatigue damage calculated according to ASME-NH, using monotonic stress-strain curves. Figure 42 is the result when stress amplitude was used for determining the initial stress. Figure 43 is the result when stress range was used for determining the initial stress. In both cases, creep damage is calculated very conservatively, comparing to the damage envelope of which intersection is (0.1, 0.01). It is understood that this conservatism is caused by the description of stress relaxation by isochronous stress-strain curves, in that the same initial stress as used in Figure 44 and Figure 45, which will be described later, was used.

Figure 44 and Figure 45 show creep-fatigue damage calculated according to DDS, using monotonic stress-strain curves and cyclic stress-strain curves. When monotonic stress-strain curves were used, creep damage is calculated somewhat conservatively, comparing to damage envelope of which intersection is (0.3, 0.3). When cyclic stress-strain curves were used, calculated creep damage is plotted approximately on the damage envelope.

Figure 46 shows creep-fatigue damage calculated according to RCC-MR, using cyclic stress strain curves. Creep damage is plotted approximately on the damage envelope of which intersection is (0.3, 0.3). The difference of calculated creep damage between Figure 45 and Figure 46 (DDS and RCC-MR) is caused by the difference of creep rupture curves determined in each procedure.

2.3.3.2 Life Prediction

Creep-fatigue life prediction was performed based on the creep-fatigue damage evaluation described above. The trends in creep-fatigue life prediction coincide with these in creep-fatigue damage evaluation. ASME-NH procedure gives the most conservative results as shown in Figure 47 to Figure 48. The degree of conservatism is up to 100 times in life when stress range is used for the estimation of initial stress, and 50 times when stress amplitude is used. Figure 49 shows the result when damage envelope was replaced by the one used in DDS and RCC-MR of which intersection point is (0.3, 0.3). Somewhat less conservative results were obtained but the difference is not significant.

Figure 50 shows creep-fatigue life predicted by RCC-MR. Predicted life scatters around the observed life without any significant conservatism.

Figure 51 and Figure 52 show creep-fatigue life predicted by DDS. When monotonic stress-strain curves were used, somewhat conservative result was obtained. The conservatism tended to be larger in long term region. When cyclic stress-strain curves were used, the degree of conservatism reduced, yet maintaining the tendency that the conservatism becomes larger in long term region.

2.3.3.3 Applicability of Linear Damage Summation Rule

(a) Creep-Fatigue Damage Evaluation

In the above evaluation, stress relaxation behavior during strain hold was estimated either by isochronous stress-strain curves (ASME-NH) or creep strain equation and strain hardening law (RCC-MR and DDS). Here, experimentally obtained stress relaxation curves were used for creep-fatigue damage calculation and creep-fatigue life prediction. This is to examine the applicability of linear damage summation rule that are commonly employed in the three procedures to the evaluation of creep-fatigue damage.

Figure 53 shows the results using experimentally obtained stress relaxation curves at the first cycle and the mid-life cycle of creep-fatigue loading.² When the stress relaxation curve at the first cycle was used, results became very conservative. If the stress relaxation curves at the mid-life were used, creep-fatigue damage was plotted approximately on the damage envelope of which intersection of (0.3, 0.3). This shows the applicability of the linear damage summation rule to the creep-fatigue damage evaluation of Grade 91 steels. However, if the same data and calculation results are plotted in a normal scale, the figure looks very different and one will have an impression that creep-fatigue damage is evaluated too much unconservatively. Which type of the figures is to be used depends on how it is used. When it is used for creep-fatigue life prediction, observed life and predicted life are normally plotted in logarithmic scale. Therefore,

² An “experimentally obtained stress relaxation curve” means a curve corresponding to a specific test piece obtained by a creep-fatigue experiment.

adequacy of damage envelope should also be discussed based on figures drawn using logarithmic scale.

(b) Creep-Fatigue Life Prediction

Creep-fatigue life was predicted using the experimentally obtained stress relaxation curves at the first cycle and at the mid-life cycle with damage envelopes with intersection point of (0.1, 0.01) and (0.3, 0.3), as shown in Figure 54. When the stress relaxation curve of the first cycle was used with a damage envelope of which intersection is (0.1, 0.01), very conservative results were obtained, in which predicted life was about an order of magnitude shorter than actual life. When the stress relaxation curves at the mid-life cycle were used, predicted life becomes closer to actual life with conservatism retained somewhat.

When a damage envelope of which intersection point of (0.3, 0.3) is used, the degree of conservatism becomes smaller to some extent. The results corresponding to the first cycle stress relaxation curves are not much different from those obtained with a damage envelope of which intersection is (0.1, 0.01), while obvious improvement is observed when the results obtained from the mid-life cycle with the envelope with (0.3, 0.3). In this case, experimentally obtained creep-fatigue life was predicted fairly well, as shown in Figure 55.

In the calculation of creep-fatigue life prediction in Figure 54 and Figure 55, creep rupture curves determined in the DDS were used. Because creep rupture curves are different in RCC-MR, the same calculation as Figure 55 was performed using the curves determined in RCC-MR. The result is shown in Figure 56, which is almost identical to Figure 55 (See Appendix B for comparison of creep rupture curves between DDS and RCC-MR).

2.3.4 Discussions

2.3.4.1 Estimation of Initial Stress of Relaxation

(a) Stress-strain curve for estimation of initial stress of relaxation

In ASME-NH and DDS, monotonic stress-strain curves are used for the estimation of the initial stress of stress relaxation. This is to reserve margins in the estimation of initial stress, because Grade 91 steel cyclically softens. However, RCC-MR uses cyclic stress-strain curves. Even if we use cyclic stress-strain curves, if they are obtained from fatigue tests of which strain rate is 0.01%/s for example, possibly there still remains conservatism. It is because the steel not only cyclically softens but also softens further due to the introduction of strain hold time and aging, as shown in Figure 57. In the practical application, strain hold time is long and corresponding softening is considered to occur. Therefore, if sufficient cyclic loading is expected in the application, from the viewpoint of creep-fatigue evaluation, there is a possibility to adopt cyclic stress-strain curves for the estimation of initial stress without losing conservatism necessary in creep-fatigue life evaluation. For the effect of aging on stress-strain relationship, also see Figure 76 and Figure 77.

(b) Description of stress relaxation behavior

ASME-NH uses isochronous stress-strain curves for description of stress relaxation behavior while RCC-MR and DDS use creep strain curves and strain hardening law. Generally, both methods predicted higher stresses than actually observed, except for stress relaxation in a low strain range creep-fatigue tests. Of the two methods, ASME-NH procedure predicted even higher stresses. For the purpose of reproducing stress relaxation curves, adopting the method used in RCC-MR and DDS can be an option.

(c) Creep damage estimation

All the procedures investigated in this study use creep rupture curve obtained by creep tests with as-received material. There may be a possibility that the creep strength of cyclically softened material is degraded by softening. If so, this should be taken into account. However, one can also consider that this effect, if it exists, is already taken into account in a creep-fatigue damage envelope, which normally takes into account creep-fatigue interaction by setting intersection point to (0.3, 0.3) or (0.1, 0.01), which can be (0.5, 0.5) if no interaction is assumed.

(d) Creep-fatigue damage envelope

ASME-NH uses (0.1, 0.01) as an intersection point while RCC-MR and DDS uses (0.3, 0.3). Creep-fatigue damage evaluation based on experimentally obtained stress relaxation curves revealed that the ASME-NH envelope is conservative, as shown in Figure 53 (Because plots in Figure 53 were obtained using average properties, plots should be expected to scatter around the envelope, not totally outside of the envelope). On the other hand, an intersection point of (0.3, 0.3) seems to be reasonable as shown in the same figure.

Another point to be noted regarding damage envelopes is that the difference of envelope is most pronounced when fatigue damage and creep damage occur at a comparable magnitude. If creep damage is far dominant, which is expected in certain applications, evaluation points are plotted on the upper left part of the envelope where creep damage is close to 1 and fatigue damage is not much larger than zero. In this region, the effect of intersection point is small. In the discussion of an intersection point, the ratio of fatigue damage and creep damage of interest should be made clear.

(e) Safety margins

Safety margins in creep-fatigue evaluation can be maintained in the steps of evaluation investigated above. ASME-NH procedure seems to have margins at every step of evaluation, i.e., strain range, initial stress of relaxation, description of stress relaxation curve during strain hold and damage envelope for creep-fatigue interaction. This is made clear based on the evaluation of creep-fatigue tests using average trends, and the margins can be considered as of unintended nature. In the application of the procedure, in addition to those intended safety margins unintended margins are incorporated and the degree of conservatism can be even larger. This point is discussed in the next chapter.

(f) Miscellaneous: Fatigue damage corresponding to crack initiation

Fatigue damage is calculated based on experimentally obtained fatigue curves. The definition of fatigue life is a cycle that corresponds to 25% drop of peak tensile stress during fatigue tests. This is considered to correspond to a situation where a visible crack has been initiated and propagated to cover approximately 25% of the cross section of the specimen. However, some consider that fatigue life used in creep-fatigue damage evaluation should be defined based on the initiation of a crack whose size is something equivalent to grain size. Therefore, in this study, creep-fatigue damage evaluation and life prediction was also performed assuming “fatigue life corresponding to crack initiation” is 1/10 of normally used fatigue life. The results are shown in Figure 58 to Figure 60. As a result, fatigue damage becomes 10 times larger than “normal fatigue damage.” Correspondence between observed and predicted creep-fatigue life was improved, but the difference is not significant.

2.4 Creep-Fatigue Evaluation According to Code Procedures

2.4.1 Purpose

In the previous chapter, to capture the characteristics of ASME-NH, RCC-MR and DDS, creep-fatigue evaluation without safety or design factors that are particular to each procedure was performed and conservatism adherent to each procedure was clarified. In this chapter, based on the knowledge thus obtained, creep-fatigue evaluation according to each procedure, including factors of various kinds, was performed.

2.4.2 Conditions for Evaluation

Considering creep-fatigue loadings in power plants, strain range is low and hold period is long, and creep damage is dominant. Therefore, in this section, creep damage was calculated according to the three procedures and compared. The conditions for evaluation are shown in Table 5.

Creep damage was calculated for various elastically calculated stress ranges. Parameters used in the calculation are summarized in Table 6. Since misprints were found with S_r values of ASME-NH, S_r values of DDS were used for the evaluation of ASME-NH. If necessary material properties were not determined explicitly in a procedure, those described in DDS were used.

Moreover, the creep fatigue damage evaluation with the design base was performed based on the strain range and the failure life obtained by experiments. In this case, strain range was assumed to be already known, an initial stress was calculated from the stress-strain relation, and damage was calculated assuming all creep damage. The stress concentration coefficient provided in ASME-NH was assumed to be one. The procedures in the three codes are schematically shown in Figure 61 to Figure 63.

2.4.3 Discussions

Figure 64 shows creep damage evaluated according to the three procedures. Generally, ASME-NH gives the highest value, and DDS and RCC-MR follow. In the region corresponding to the stress level of around 400MPa, ASME gives a prediction 10 times more conservative than that of DDS. For components in which stress concentration is significant, the difference may enlarge because ASME-NH uses Neuber's rule. Figure 65 shows the result of creep-fatigue damage evaluated based on the procedures determined in ASME-NH, RCC-MR and DDS. In the evaluation of Figure 65, safety factors/margins were included. Creep damage calculated according to ASME-NH, RCC-MR and DDS procedures scatter around 10^4 , 10 and 10^2 , respectively. The strain ranges of creep-fatigue tests correspond to 400 to 600 MPa, where the differences among the three procedures are pronounced. RCC-MR gives smallest values because it adopts cyclic stress-strain curves for the estimation of the initial stress of relaxation and it estimates stress relaxation behavior less conservatively compared to other two methods. In Figure 66, the margin compared to the creep fatigue damage envelope is shown. The margins calculated this way are approximately 10 to 10^2 for RCC-MR, 10^2 to 10^3 for DDS and 10^3 to 10^4 for NH.

Although the difference between the three methods is pronounced in the region where experimental results are available, it is understood from Figure 64 that the difference may not be so large in the region where actual design is performed. It is to be noted that the observations obtained in a relatively high stress region where experimental results are available are not necessarily applicable to a low stress region where most of the actual components are operated.

2.5 Other Factors to be Considered

2.5.1 Environmental Effects on Tensile and Compressive Hold Tests

Figure 67 compares the creep-fatigue life under tensile hold conditions and compressive hold conditions in an air environment. In a temperature range of 500 to 600°C and a hold time range of 1 to 60 minutes, compressive hold tests showed shorter creep-fatigue life than tensile hold tests under all conditions. In a sodium environment, a test has been performed at 550°C with a strain range of 0.5% and a hold time of 60 minutes as shown in Figure 68. In this case, a compressive hold test showed a longer life. In a vacuum environment, a test has been performed at 600°C with a strain range of 2% and a hold time of 10 minutes as shown in Figure 63. In this case, a tensile hold test showed a longer life.

For the life reduction under compressive hold tests of Grade 91 steel, principally two mechanisms have been suggested, one is the effect of oxidation and the other is tensile mean stress developed during cyclic creep-fatigue loading. Figure 70 shows tensile peak stress and compressive peak stress at the mid-life cycle for tensile hold tests, compressive hold tests and tests with both tensile and compressive hold period. It is obviously observed that compressive mean stress develops in tensile hold tests and that tensile mean stress develops in compressive hold tests.

The creep-fatigue test results in air, sodium and vacuum environments can be interpreted as follows. When there is virtually no effect of oxidation, which is the case with sodium and vacuum environments, creep damage and tensile mean stress effect are to be considered. As indicated in Figure 71, when strain range is high and hold time is short, the effect of tensile mean stress is more harmful than creep damage, and a creep-fatigue life of compressive hold tests becomes shorter than that of tensile hold tests. This is basically the same in a sodium environment. However, when a strain range becomes lower and hold time becomes longer, the effect of creep damage can suppress that of a tensile mean stress. Therefore, tensile hold tests can show shorter creep-fatigue life. In an air environment, in addition to the effects of creep damage and tensile mean stress, the effect of oxidation has to be considered (Aoto et. al., 1994). The effect of oxidation can be interpreted as shown in Figure 72 and Figure 73. Oxide layer is formed and develops during a hold time. When the layer is formed during a compressive hold time, it can break during a subsequent tensile deformation. This can accelerate the initiation of cracks, and also the propagation of cracks, once they have been initiated. The oxide layers formed during a tensile hold time will experience compressive loading in the subsequent loading, and no harmful effects such as the one formed in a compressive hold period is expected. The creep-fatigue life in an air environment may be determined by a complicated combination of effects of creep damage, tensile mean stress effect and oxidation. In a short term region, compressive hold tests show shorter creep rupture time due to the effects of tensile mean stress and oxidation which are basically time-independent. On the contrary, in a long term region, creep damage, which is time-dependent, is considered to become dominant.

2.5.2 Effect of Thermal Aging

Figure 74 and Figure 75 show creep-fatigue life of aged material. Aged material shows shorter creep-fatigue compared to as-received material and this tendency is more obvious at lower strain ranges (The reason why the tests with 30 minutes hold time showed shorter creep-fatigue life than a test with 60 minutes hold time in Figure 75 is not clear). Figure 76 and Figure 77 show cyclic stress-strain response of aged material. There is possibility that additional softening due to aging exists but a quantitative relationship between aging and additional softening to creep-fatigue is not clear.

Figure 78 shows the tendency of cyclic softening behavior in terms of a ratio of tensile peak stress at mid-life to that of the first cycle. The magnitude of softening becomes larger when strain range becomes larger. It is again observed that the introduction of hold time enhances cyclic softening.

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

All three creep-fatigue evaluation procedures evaluated so far employ time fraction approach for creep damage evaluation. It would be worthwhile to consider the relationship between time fraction rule and the ductility exhaustion method. Although there are a variety of methods to calculate creep damage according to a “ductility exhaustion” method, what is considered as the simplest formation is examined in this investigation.

Creep damage according to ductility exhaustion method is described as follows (Aoto et. al., 1994):

$$d_c = \int \frac{d\varepsilon_h}{\varepsilon_F} = \frac{\varepsilon_h}{\varepsilon_F}$$

Where,

d_c : creep damage per cycle

ε_h : accumulated creep strain during a hold period

ε_F : fracture elongation

If we focus on the secondary creep, generally, Monkman-Grant equation holds.

$$\varepsilon_F = \dot{\varepsilon}_m t_R$$

Where,

$\dot{\varepsilon}_m$: Steady state creep rate

t_R : Creep rupture time

From the above equations, we can derive the following:

$$d_c = \int \frac{d\varepsilon_h}{\varepsilon_F} = \int \frac{\dot{\varepsilon}_m dt}{\dot{\varepsilon}_m t_R} = \int \frac{dt}{t_R}$$

This means that when only secondary creep is considered to be responsible for creep damage, time fraction rule and ductility exhaustion method are equivalent.

In order to confirm this assumption, very detailed observation of microstructure focusing on deformation in grain and on grain boundaries will be necessary. From the viewpoint of design standard, the adequacy of the method of creep damage evaluation is only judged in combination with a creep-fatigue interaction damage envelope, in terms of accuracy of life prediction. In that light, making an assumption that steady state creep is solely responsible for creep damage, in other words the use of time fraction rule, can be justified as far as the rule is used with a creep-fatigue interaction envelope whose intersection point is (0.3, 0.3), because Figure 55 gives fairly good prediction of creep-fatigue life.

Table 3 - Factor K' (TABLE T-1411.1)

Material	Elastic analysis ³	Inelastic analysis
Austenitic Stainless Steel	0.9	0.67
Ni-Fe-Cr(Alloy 800H)	0.9	0.67
2 1/4Cr-1Mo	0.9	0.67
9Cr-1Mo-V	0.9	0.67

Table 4 - Average Material Properties

Parameter	ASME-NH	DDS	RCC-MR
Stress-Strain Curves	DDS (Monotonic)	DDS (Monotonic, Cyclic)	RCC-MR (Cyclic)
Creep strain curves	DDS	DDS	RCC-MR
Fatigue curves	DDS	DDS	DDS
Creep rupture curves	DDS	DDS	RCC-MR
Estimation of stress relaxation	Isochronous stress-strain curves	Strain hardening rule	Strain hardening rule
Stress factor on the initial stress of relaxation	1	1	1
Elastic Following-up Coefficient	-	1	1

³ Currently, 0.67 for all materials. Revision to 0.9 is underway in the Code Committee.

Table 5 - Creep Fatigue Evaluation Conditions on Elastic Design Base

Item	Contents
Temperature	550 C
Stress concentration factor K	1
$\Delta\sigma$	100~500 MPa
Hold time	1000 hr
Number of cycles	263 cycles (for 30years)
Ratcheting creep effects	No effects
Symmetrization effects	No effects

Table 6 - Material Properties and Design Values

Parameter	ASME-NH	DDS	RCC-MR
Stress-Strain Curves	DDS (monotonic)	DDS (monotonic)	RCC-MR (cyclic)
Creep	DDS	DDS	RCC-MR
The minimum value of creep rupture S_r	DDS	DDS	RCC-MR
The allowable strain range	ASME-NH	DDS	RCC-MR
Estimation of stress relaxation	Isochronous stress- strain curves	Strain hardening rule	Strain hardening rule
Stress factor on creep behavior (relaxation)	0.9	1	0.9
Elastic Following-up Coefficient	-	3	3
S_{rH}	DDS	DDS	-

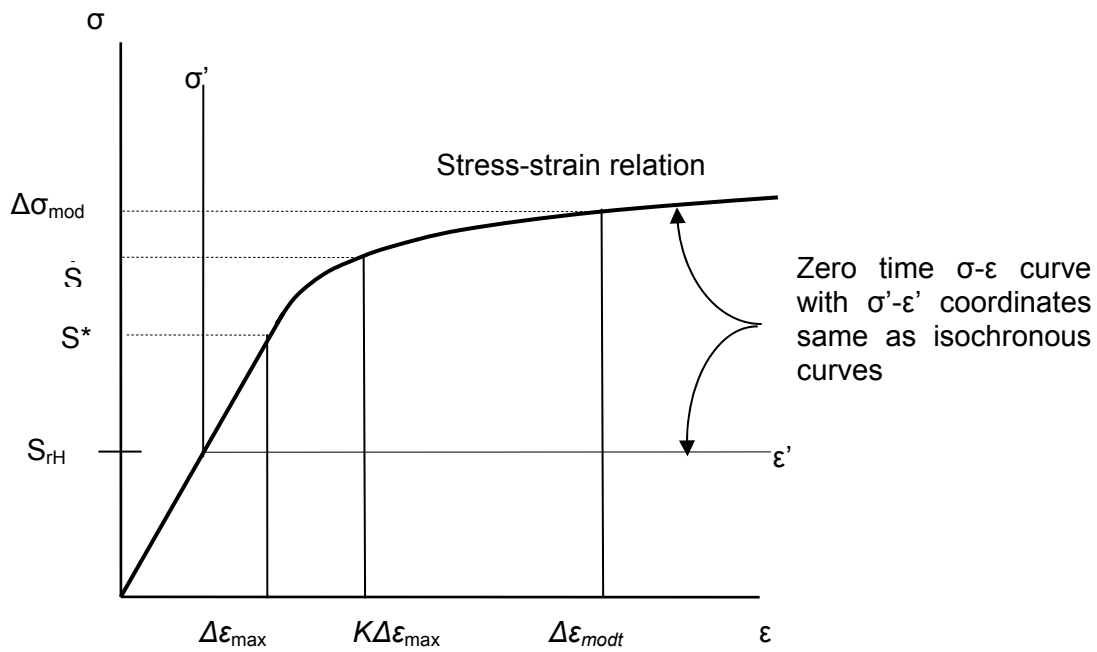


Figure 19 - Stress-Strain Relationship (ASME-NH)

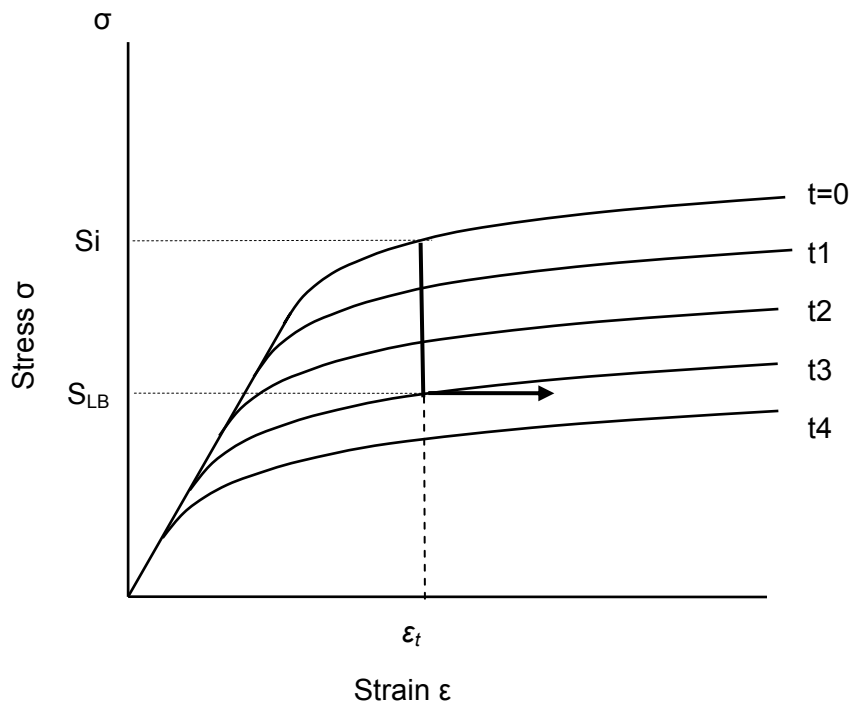


Figure 20 - Stress Relaxation from Isochronous Stress-Strain Curves (ASME-NH)

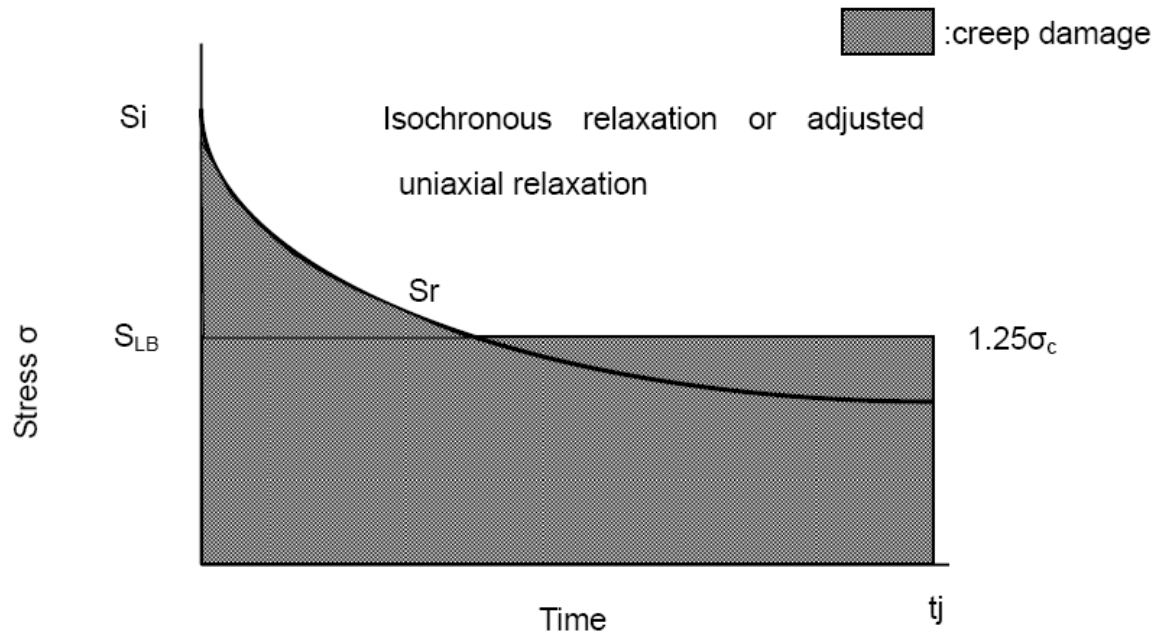
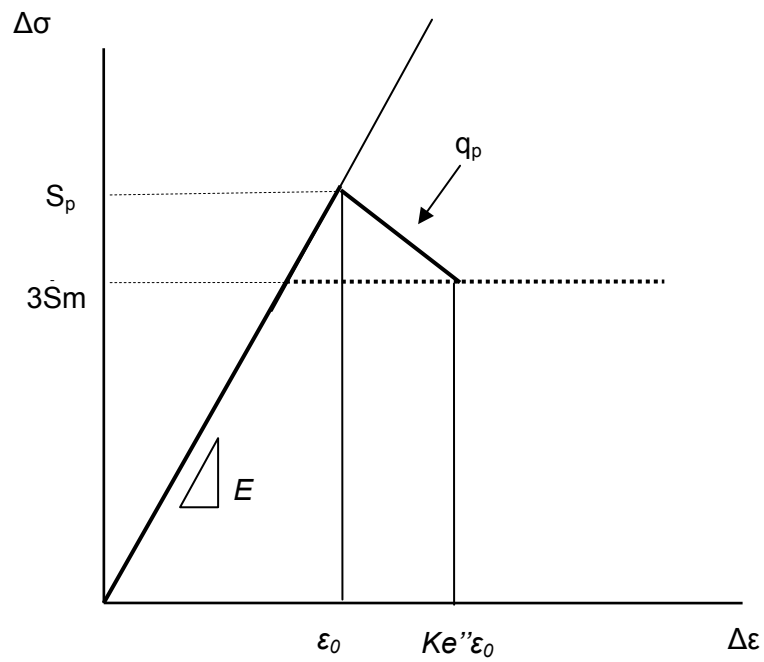


Figure 21 - Stress-Relaxation Limit for Creep Damage (ASME-NH)

Figure 22 - Calculation Procedure of $Ke''\epsilon_0$ (DDS)

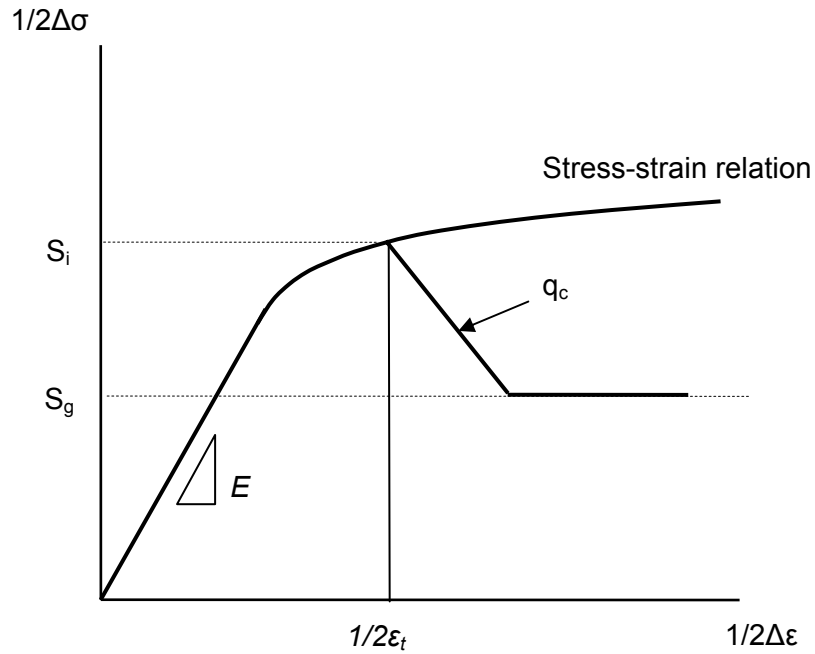


Figure 23 - Calculation Procedure of Initial Stress and Relaxation Process (DDS)

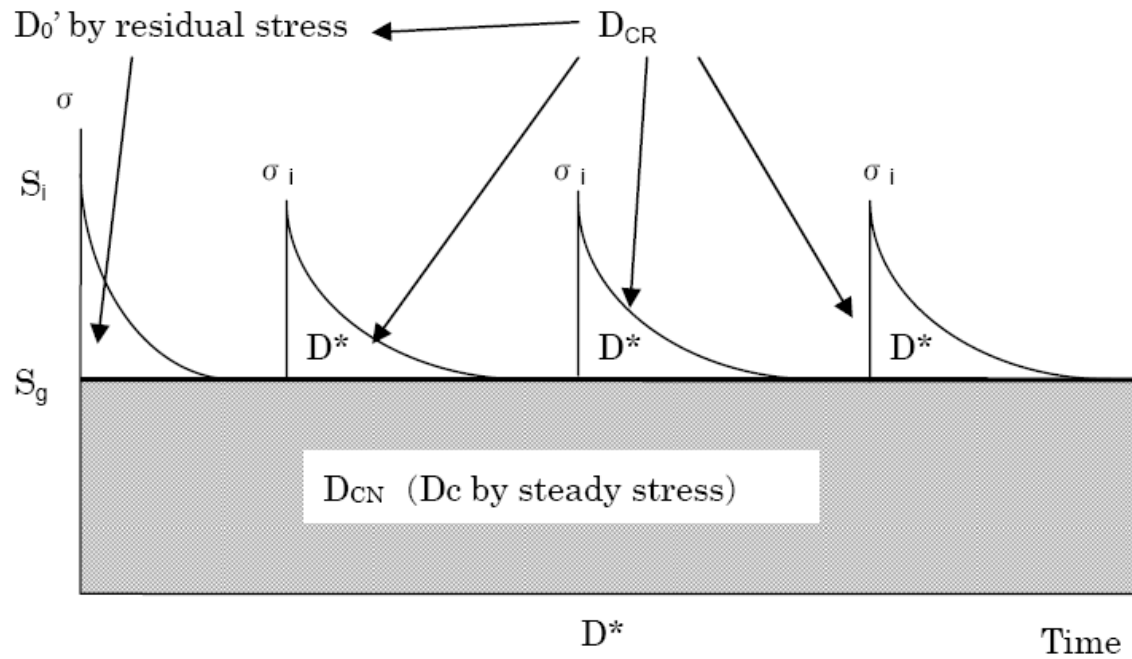


Figure 24 - Relaxation Behavior and Creep Damage (DDS)

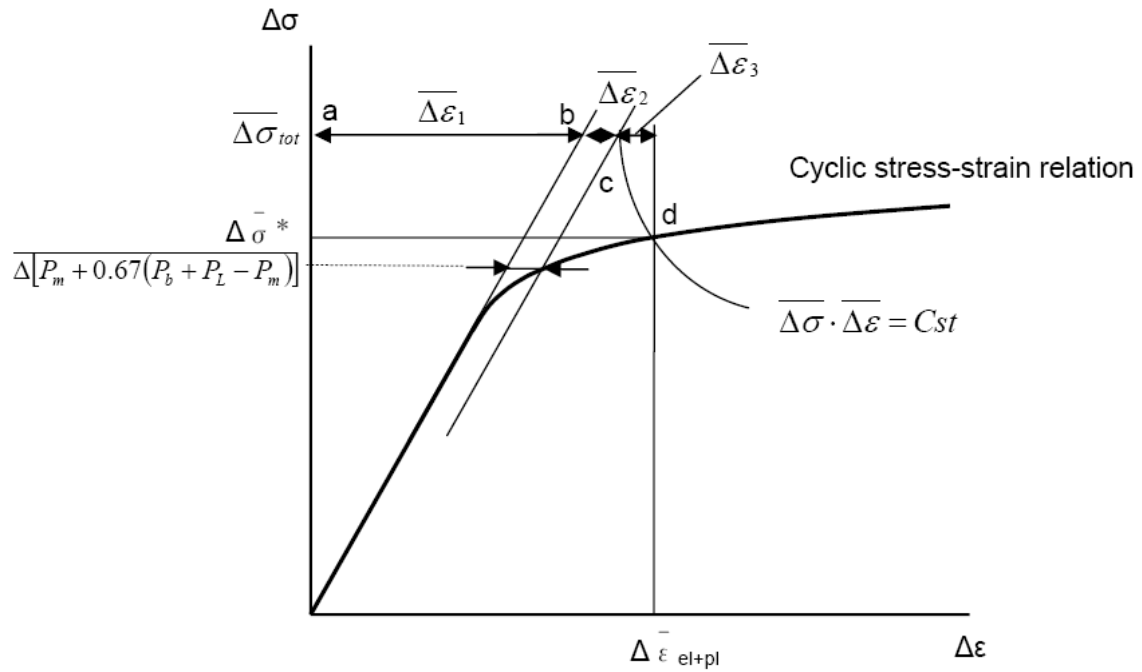
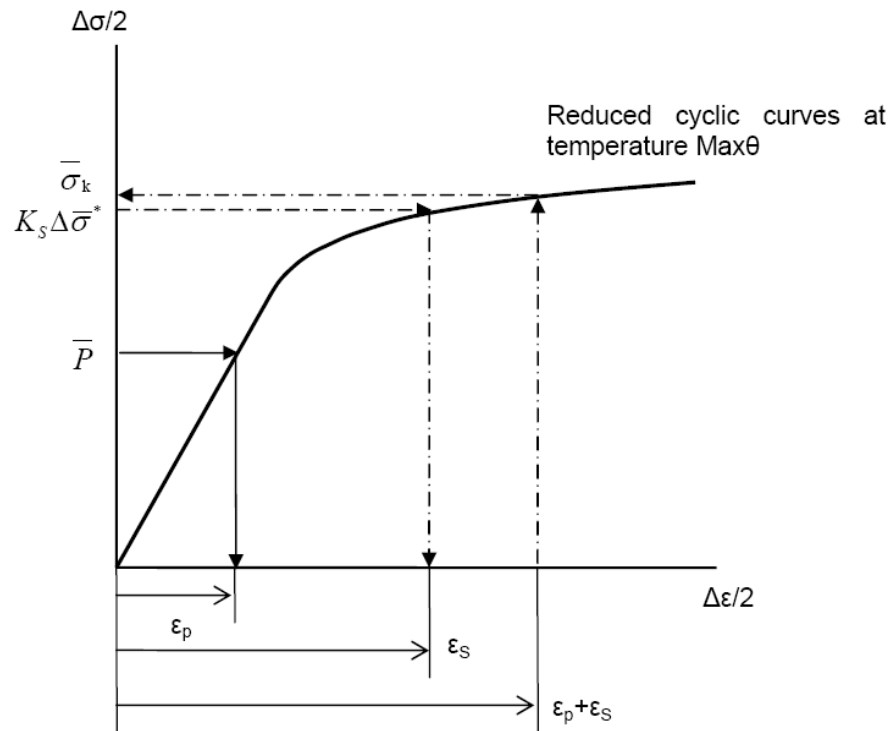


Figure 25 - Calculation Procedure of Creep Strain Range (RCC-MR)

Figure 26 - Calculation Procedure of $\Delta\sigma_k$ (RCC-MR)

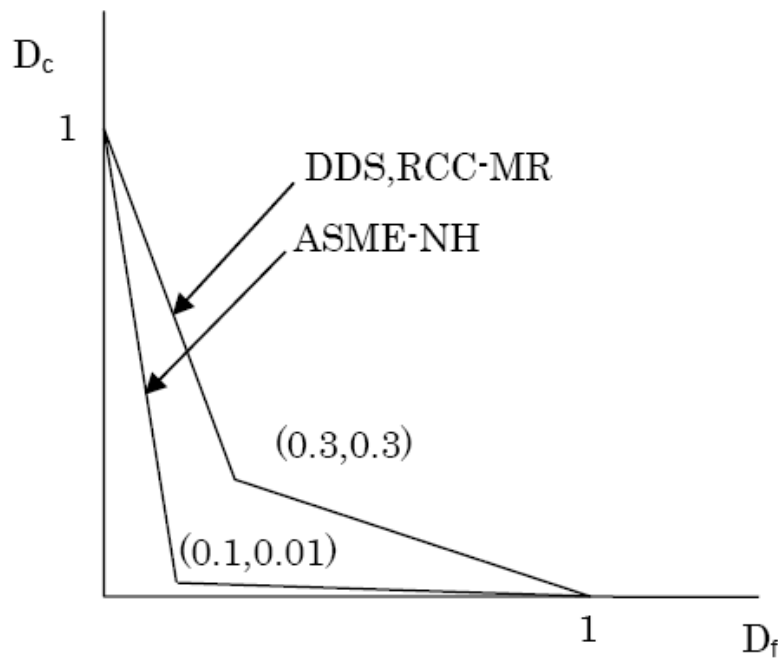


Figure 27 - Creep-Fatigue Damage Envelopes for Mod. 9Cr-1Mo

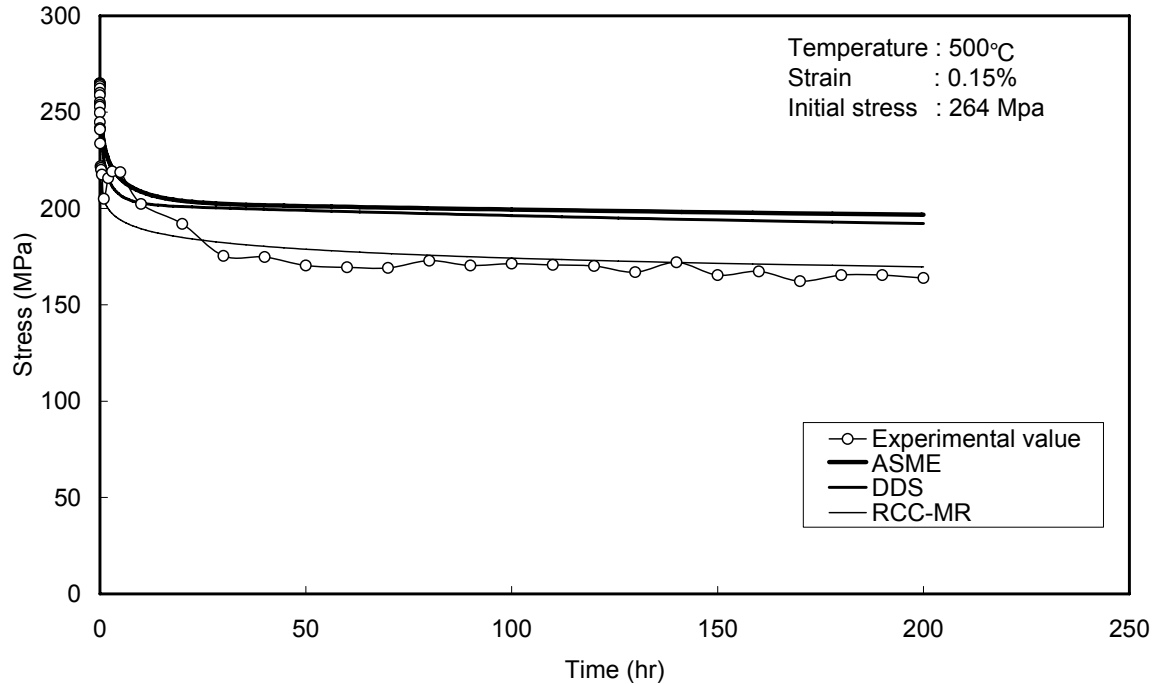


Figure 28 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.15\%$

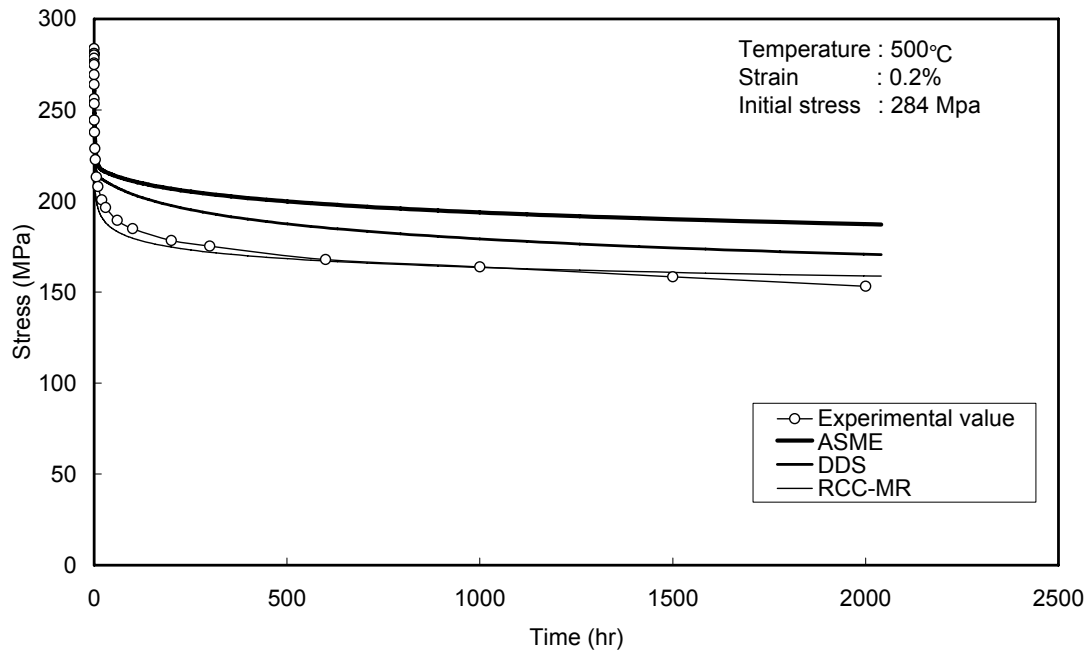


Figure 29 - Comparison Between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.2\%$

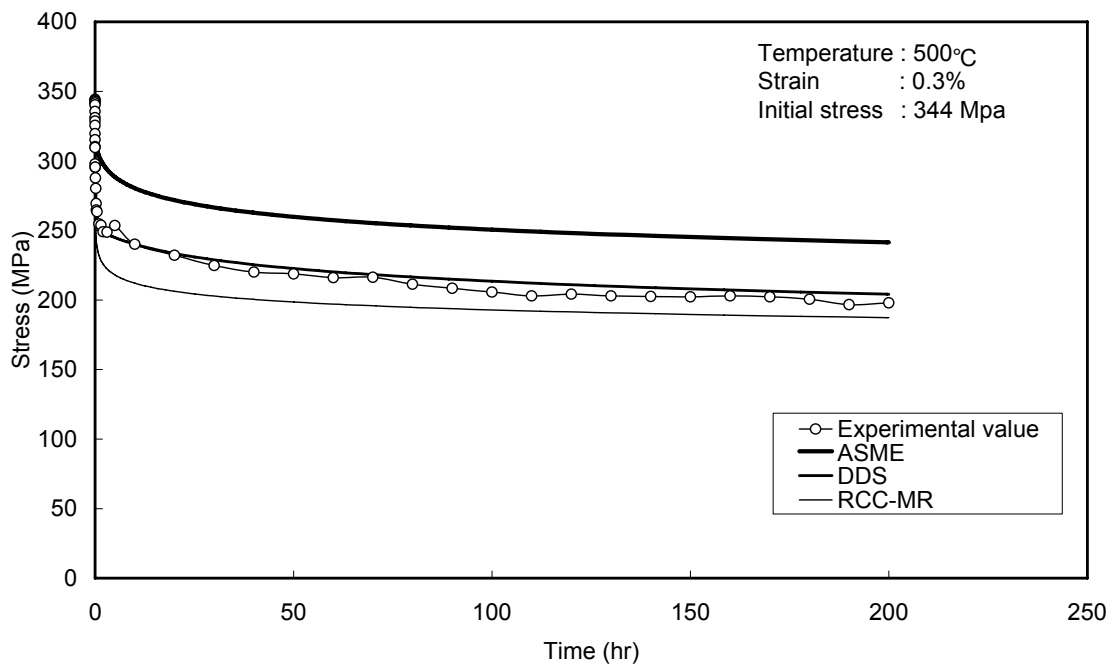


Figure 30 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.3\%$

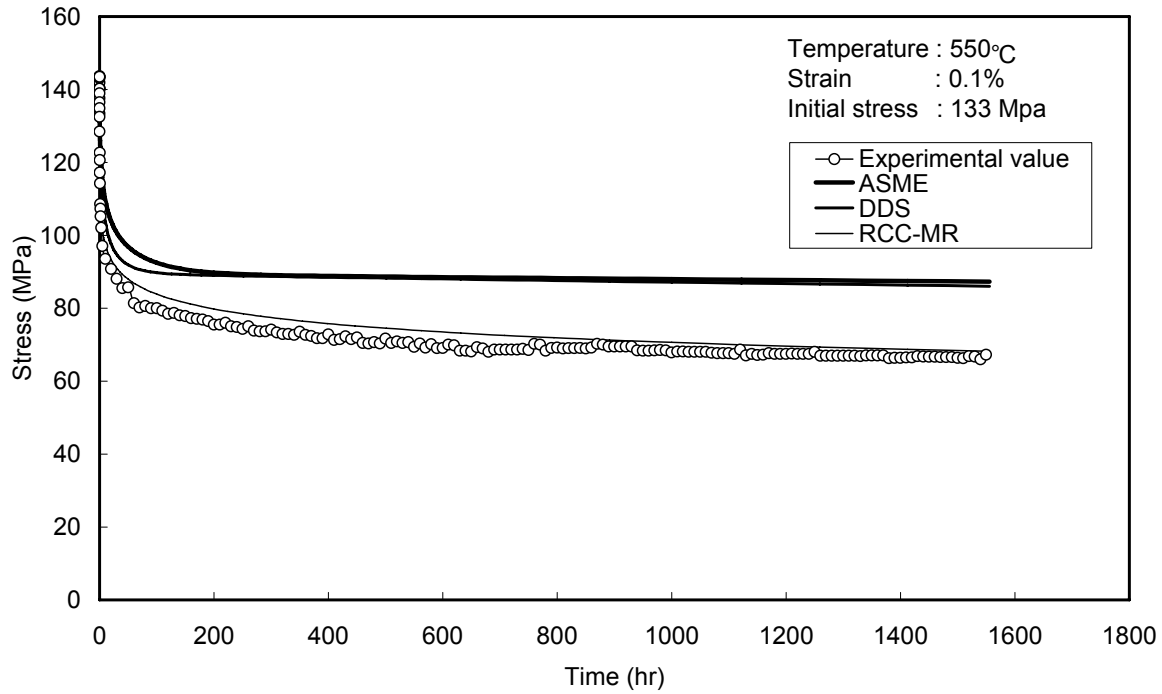


Figure 31 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.1\%$

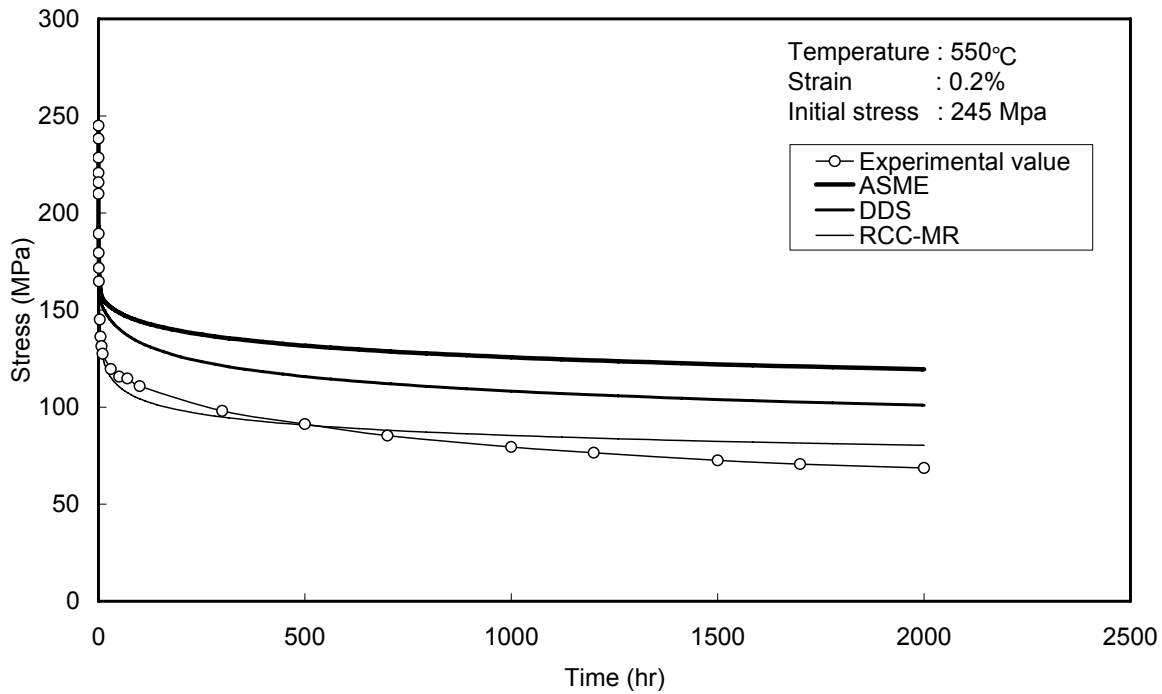


Figure 32 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.2\%$

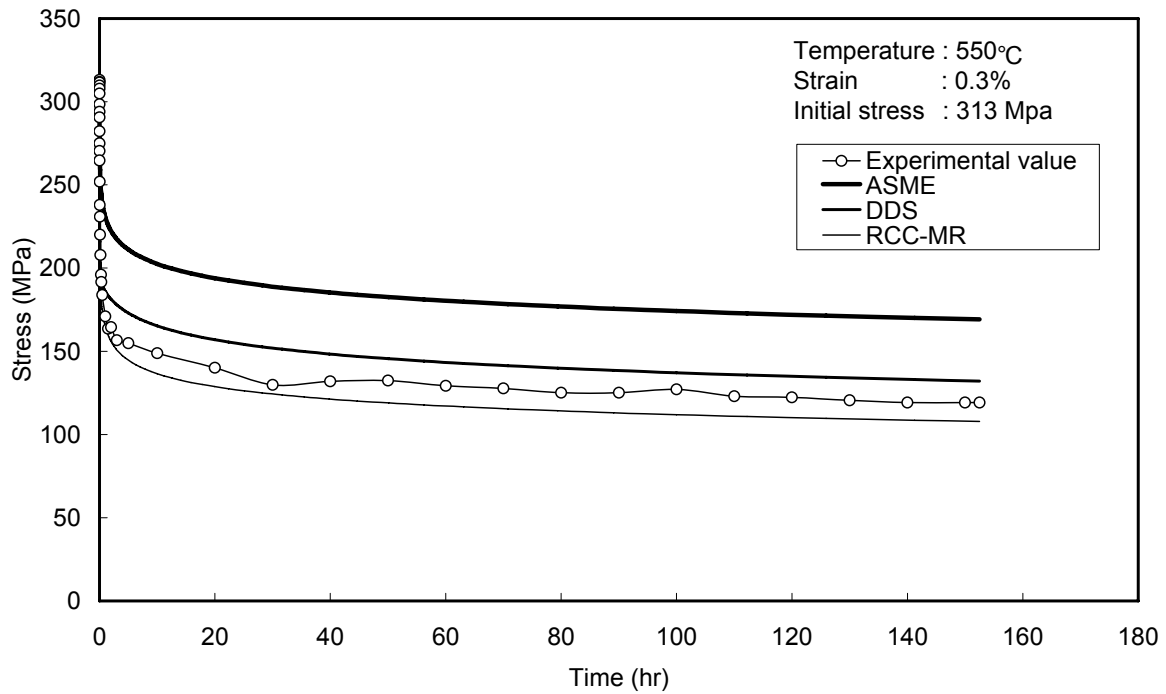


Figure 33 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.3\%$

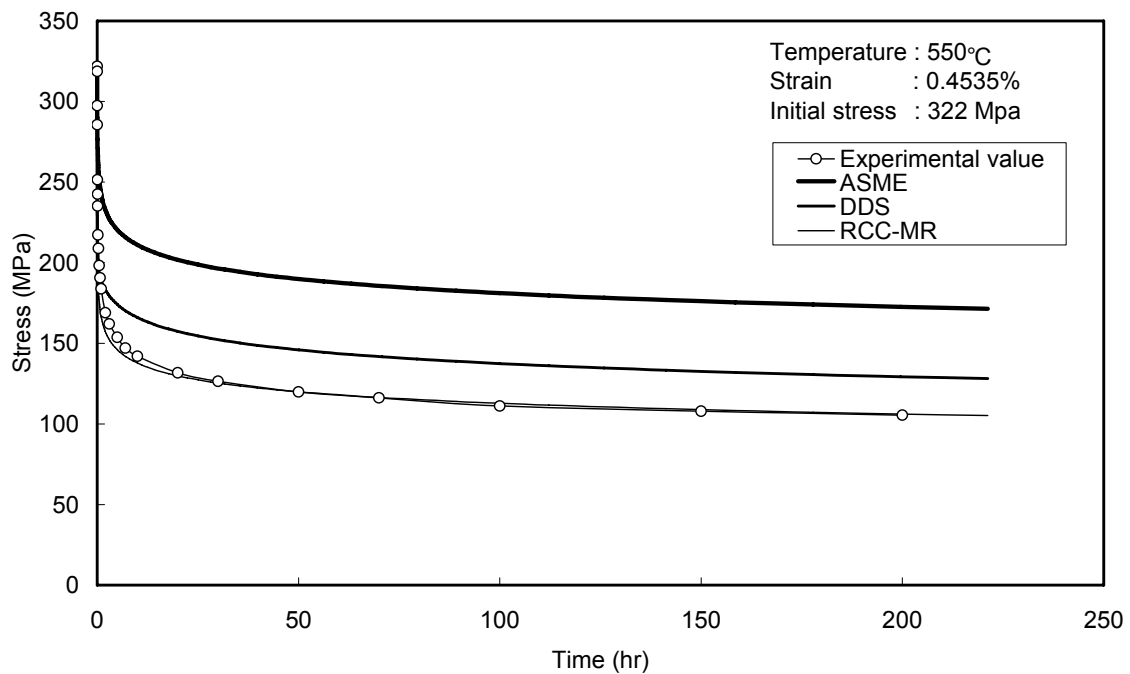


Figure 34 - Comparison between Experimental and Calculated Values of Static Relaxation Behavior at $\epsilon_t = 0.4535\%$

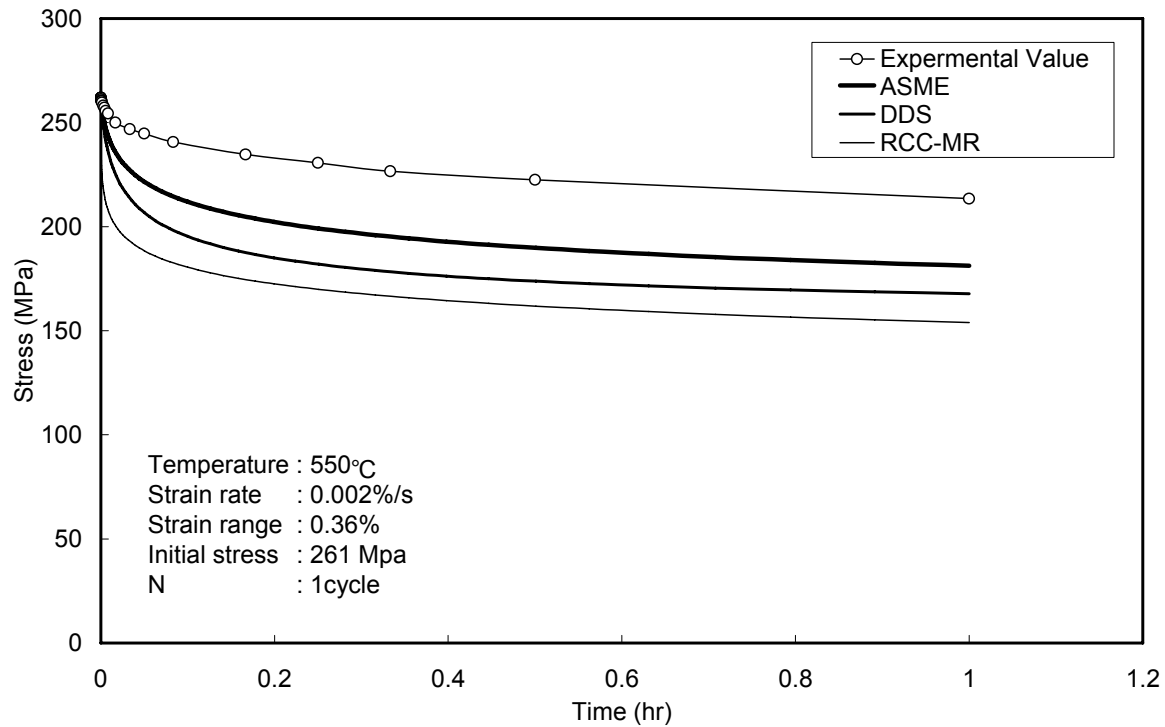


Figure 35 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 0.36\%$

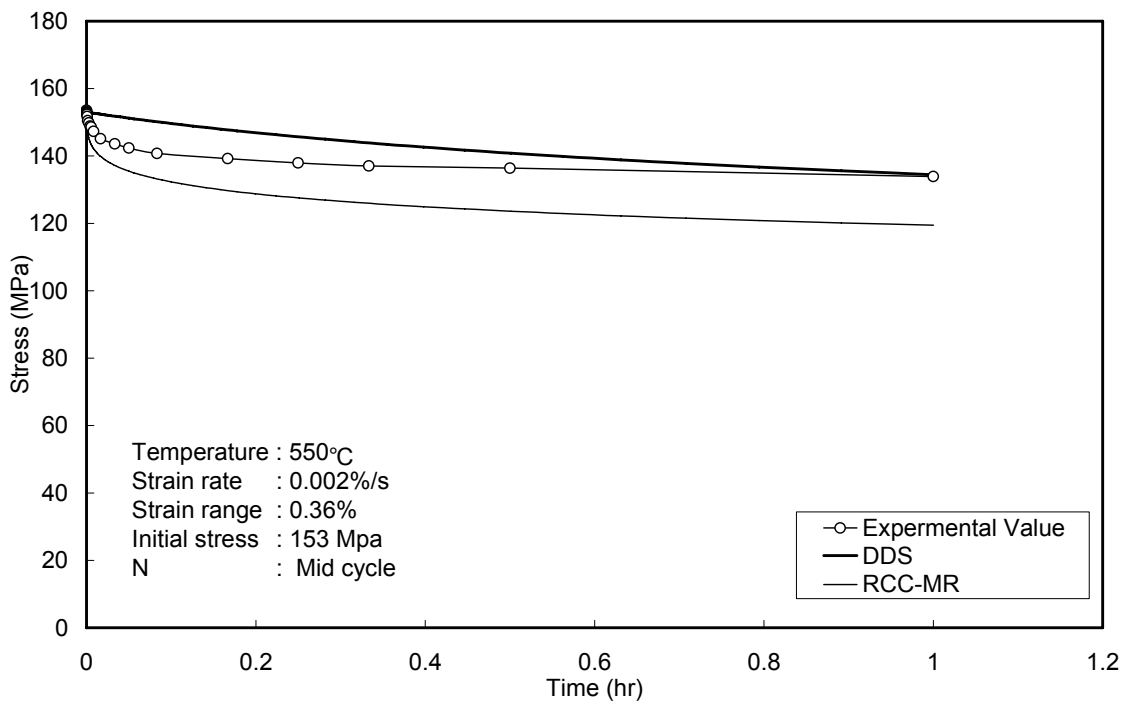


Figure 36 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 0.36\%$

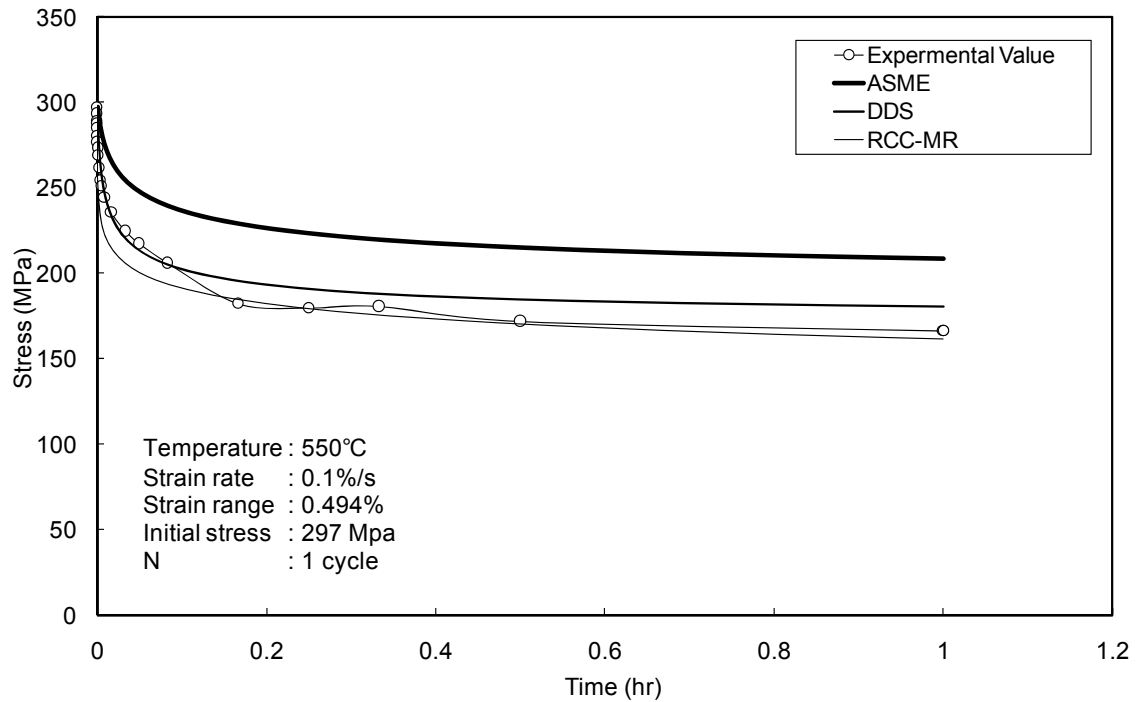


Figure 37 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 0.494\%$

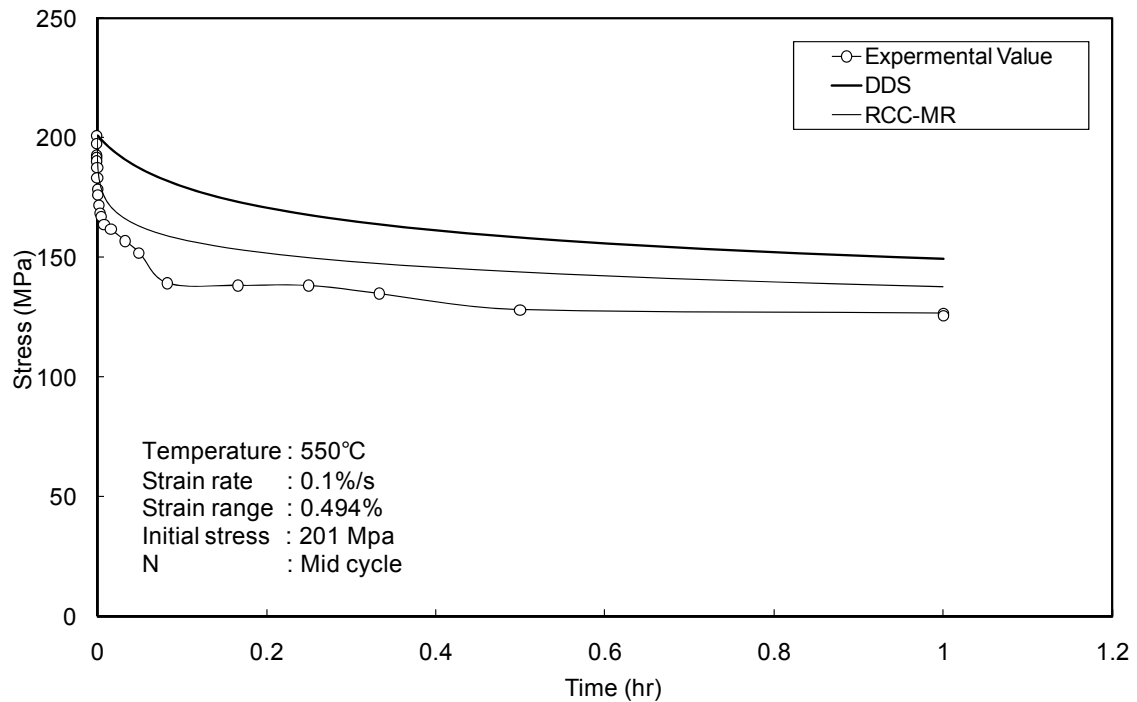


Figure 38 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 0.494\%$

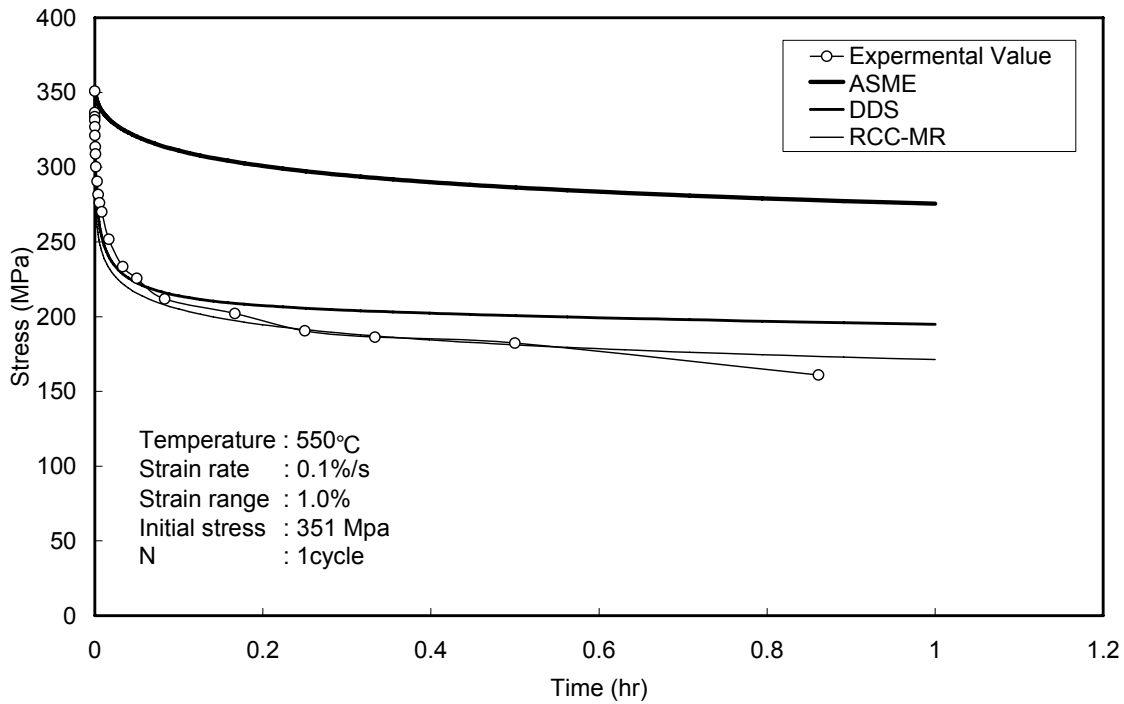


Figure 39 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 1.0\%$

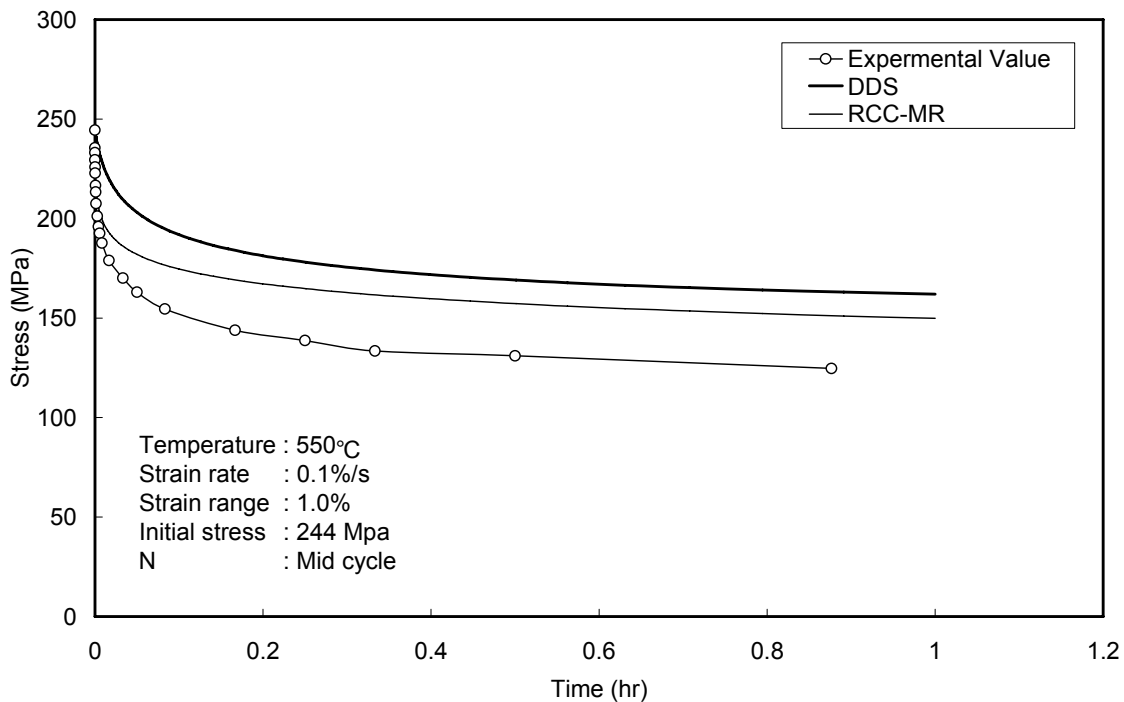


Figure 40 - Comparison between Experimental and Calculated Values of Cyclic Relaxation Behavior at $\Delta\epsilon_t = 1.0\%$

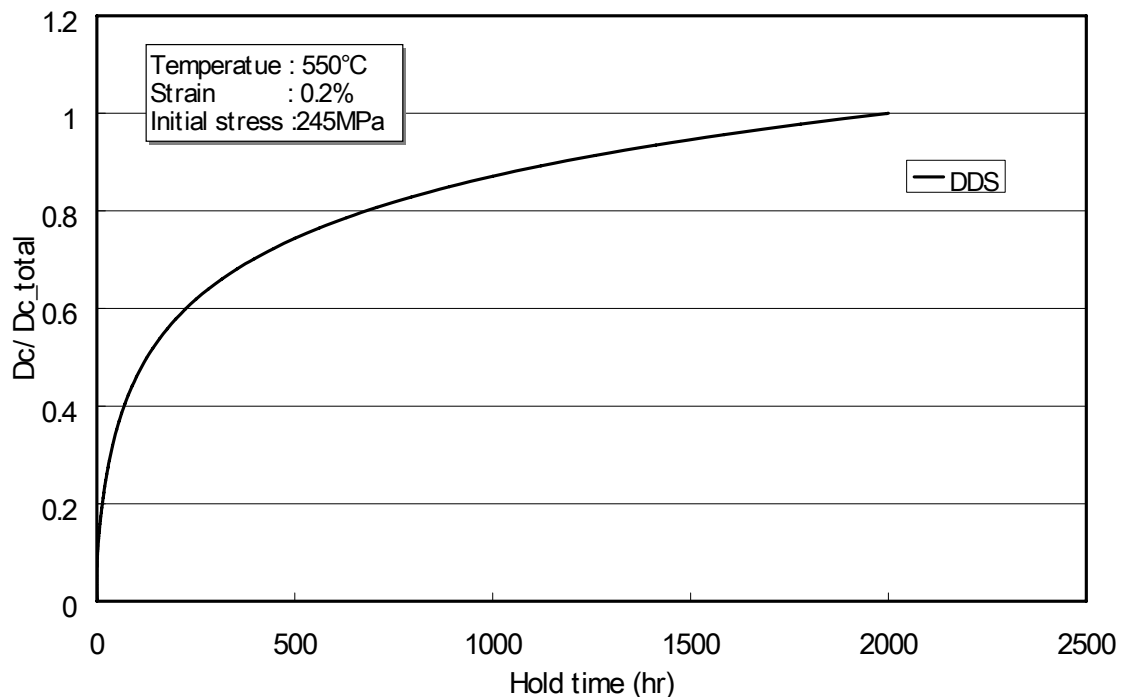


Figure 41 - Evolution of Creep Damage During Stress Relaxation (DDS)

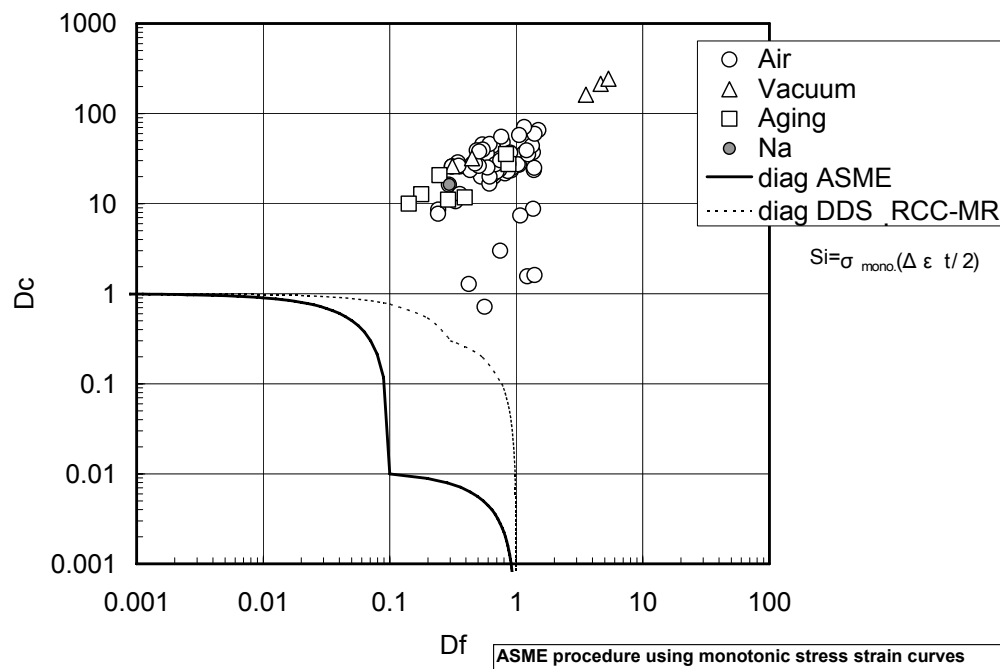


Figure 42 - Creep-Fatigue Damage Calculated by ASME-NH Procedure Using Monotonic Stress-Strain Curves and Strain Amplitude

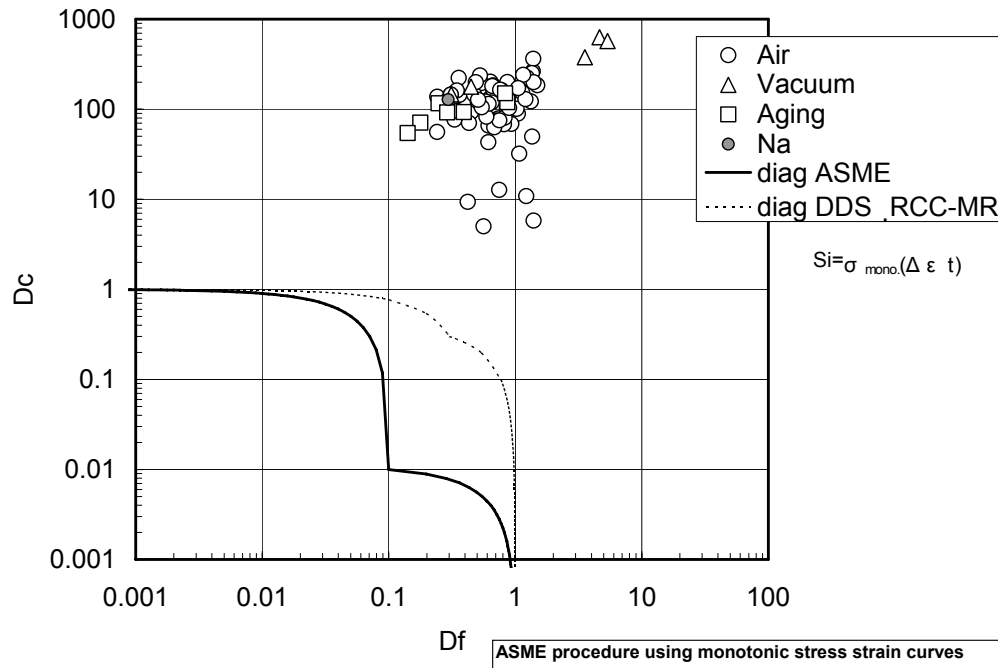


Figure 43 - Creep-Fatigue Damage Calculated by ASME-NH Procedure Using Monotonic Stress-Strain Curves and Strain Range

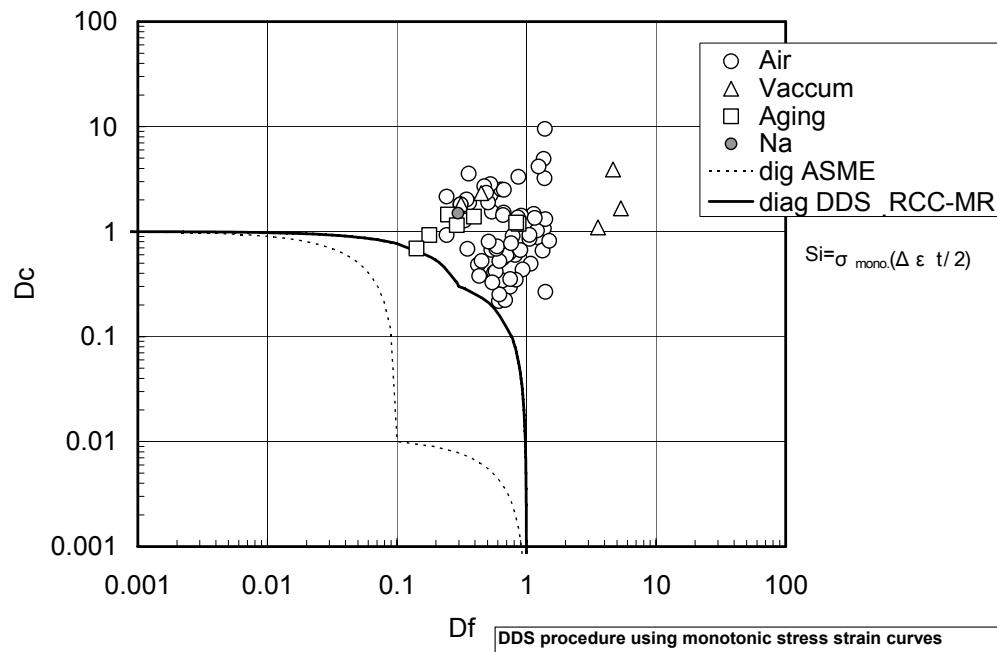


Figure 44 - Creep-Fatigue Damage Calculated by DDS Procedure Using Monotonic Stress-Strain Curves

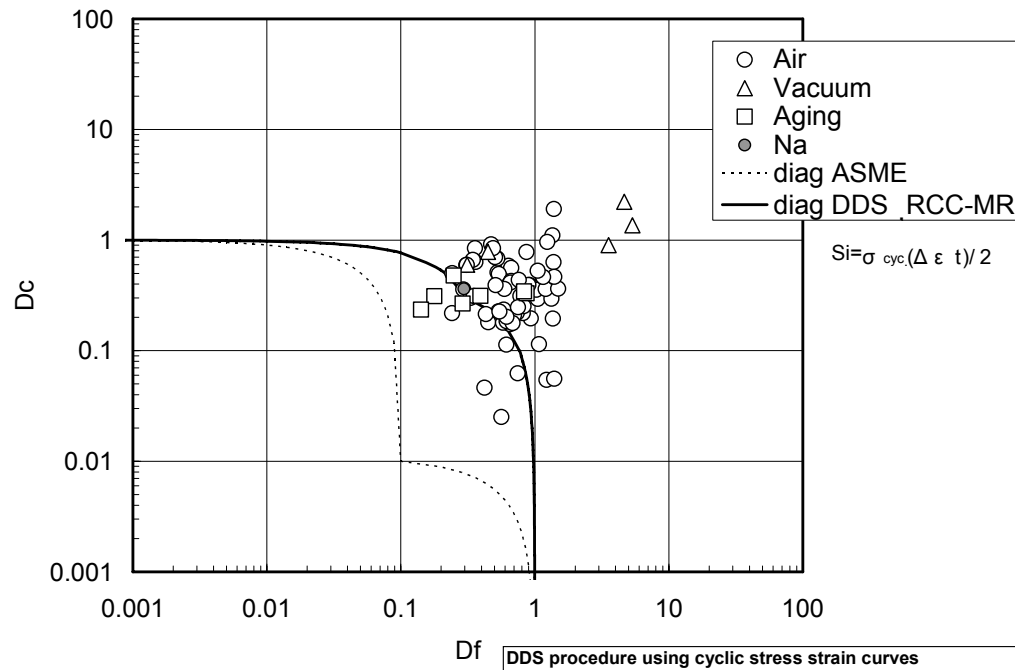


Figure 45 - Creep-Fatigue Damage Calculated by DDS Procedure Using Cyclic Stress-Strain Curves

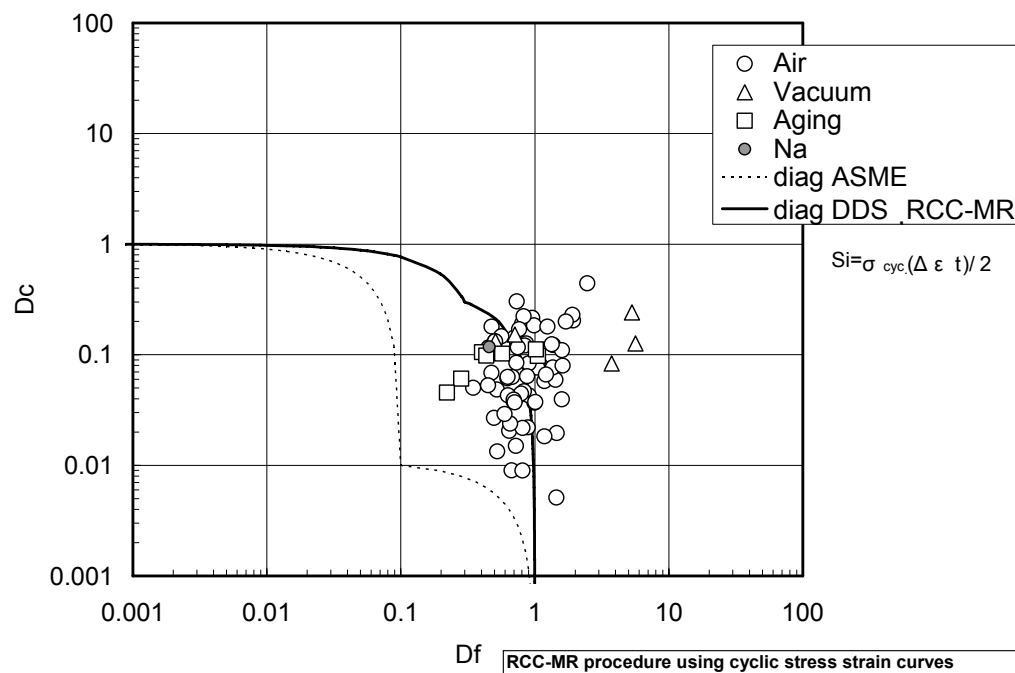


Figure 46 - Creep-Fatigue Damage Calculated by RCC-MR Procedure Using Cyclic Stress-Strain Curves

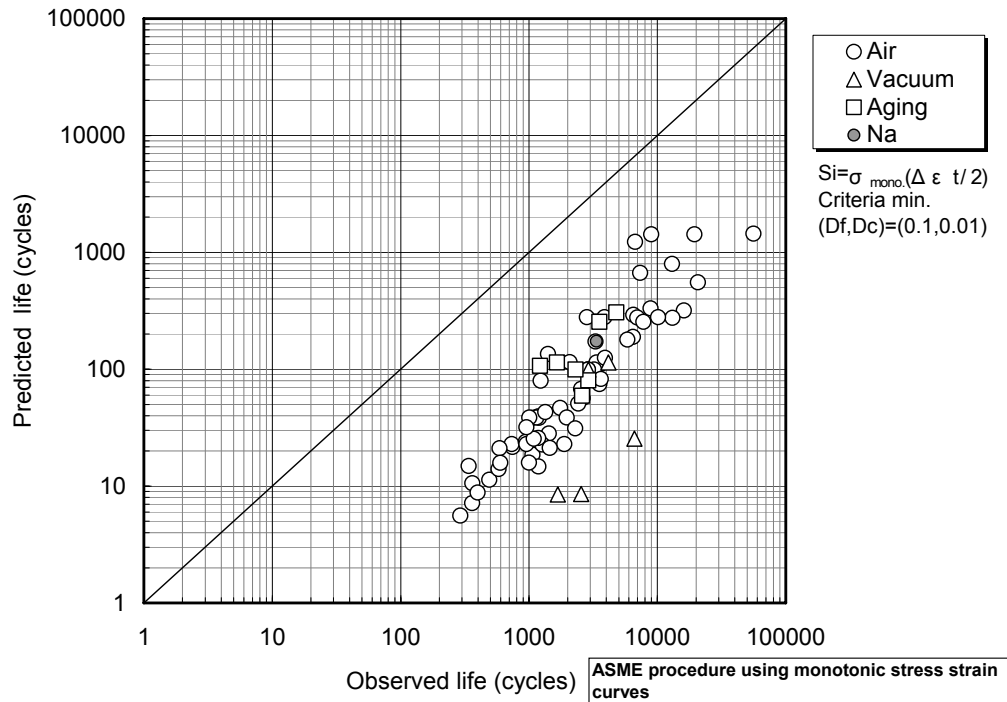


Figure 47 - Relationship between Observed Life and Predicted Life with ASME-NH Procedure Using Monotonic Stress-Strain Curves and Strain Amplitude

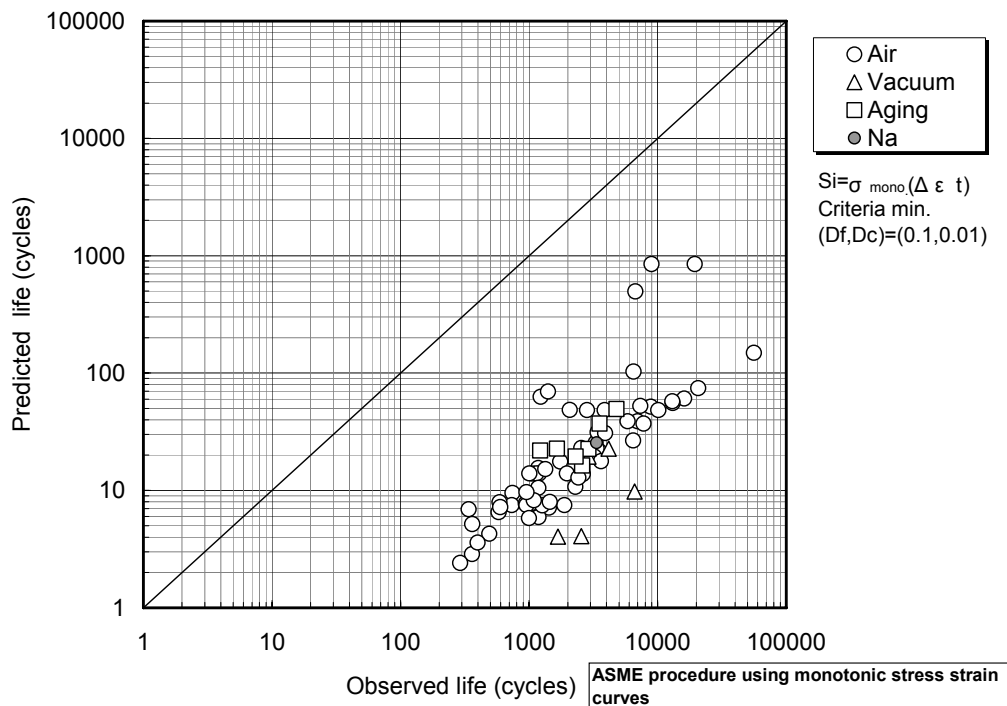


Figure 48 - Relationship between Observed Life and Predicted Life with ASME-NH Procedure Using Monotonic Stress-Strain Curves and Strain Amplitude

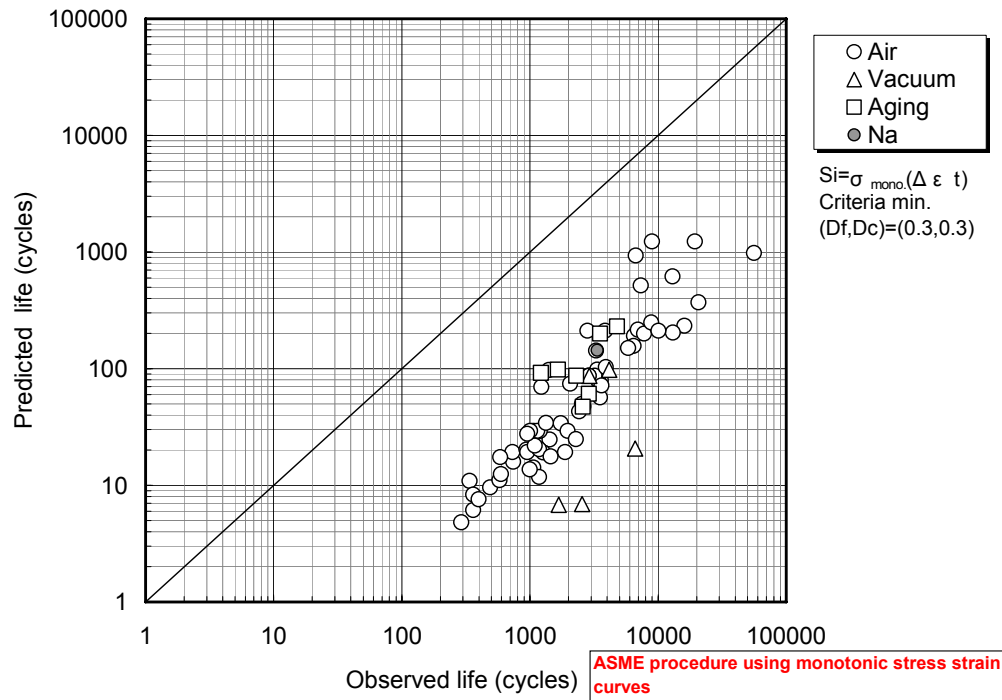


Figure 49 - Relationship between Observed Life and Predicted Life with ASME-NH Procedure Using Monotonic Stress-Strain Curves with an Interception of (0.3, 0.3)

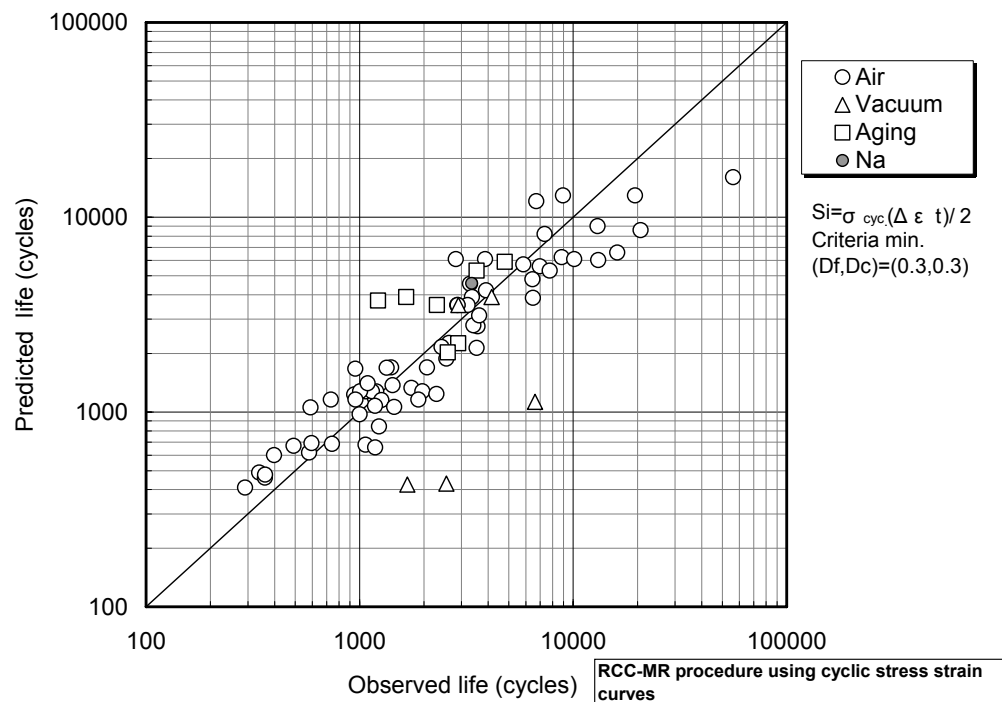


Figure 50 - Relationship between Observed Life and Predicted Life with RCC-MR Procedure Using Cyclic Stress-Strain Curves

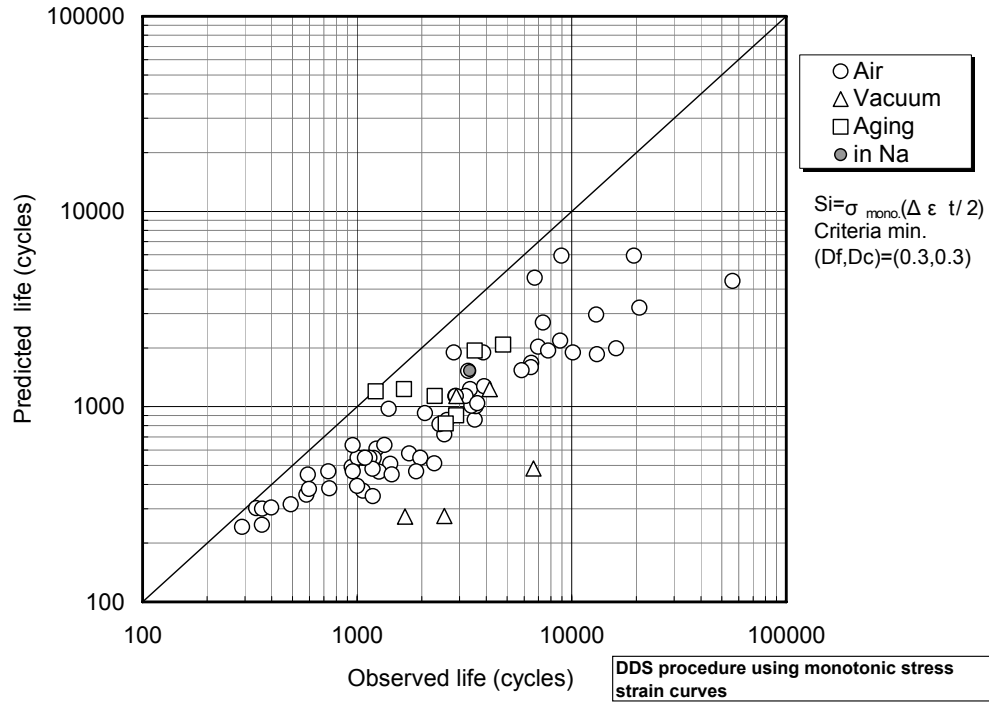


Figure 51 - Relationship between Observed Life and Predicted Life with DDS Procedure Using Monotonic Stress-Strain Curves

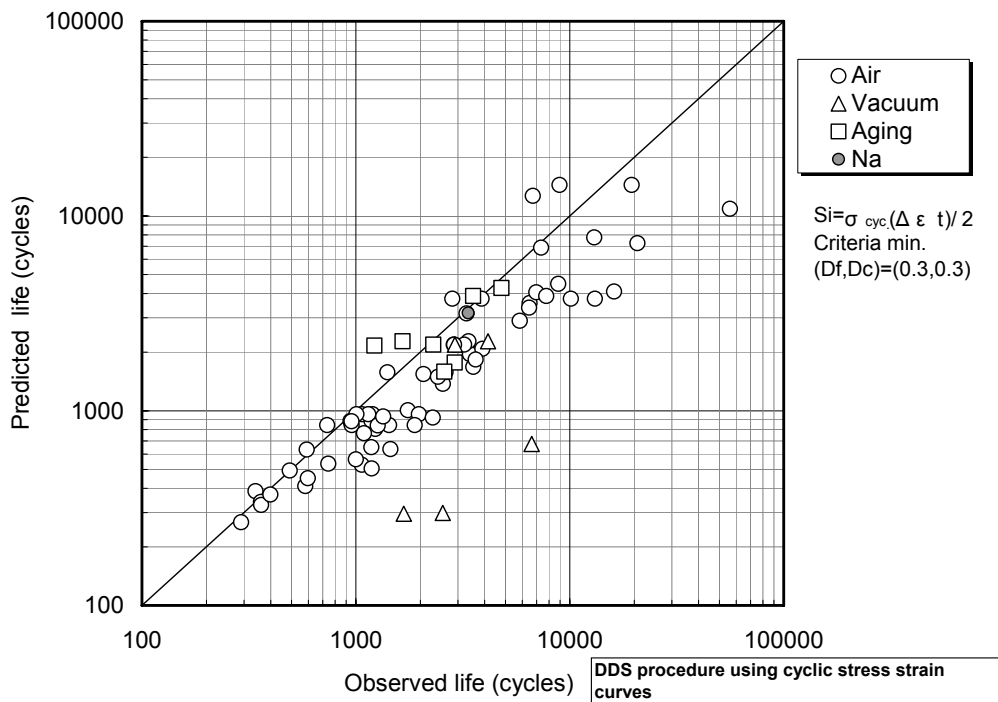


Figure 52 - Relationship between Observed Life and Predicted Life with DDS Procedure Using Cyclic Stress-Strain Curves

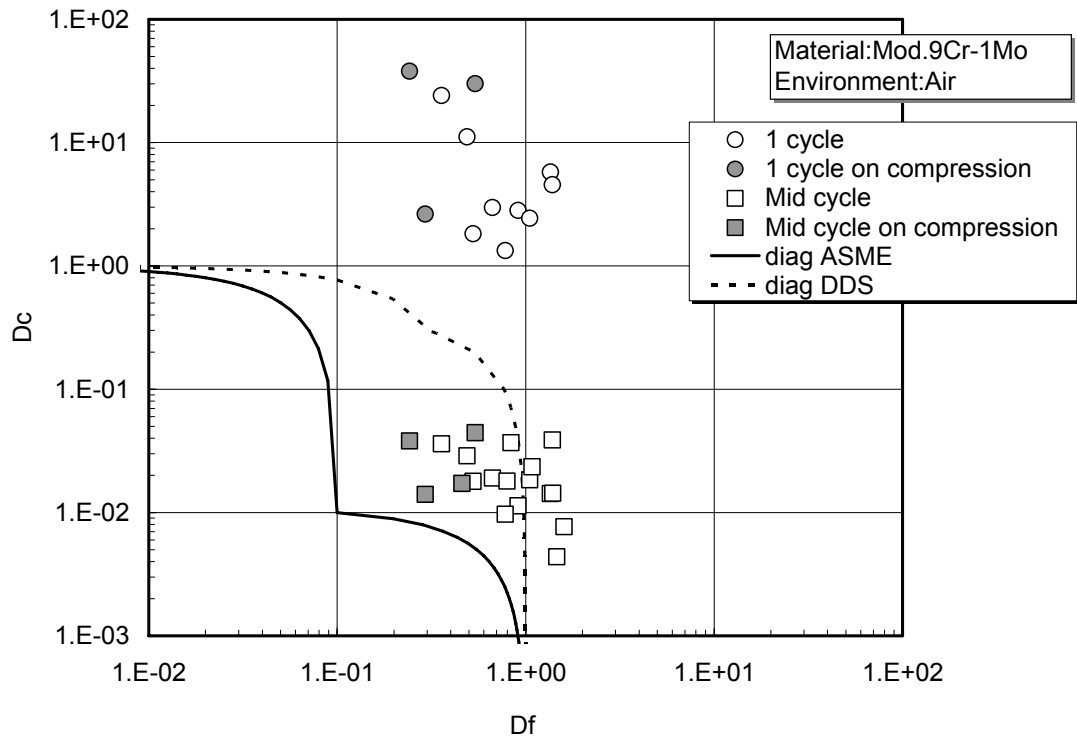


Figure 53 - Creep-Fatigue Damage Calculated Using Experimentally Obtained Relaxation Curves

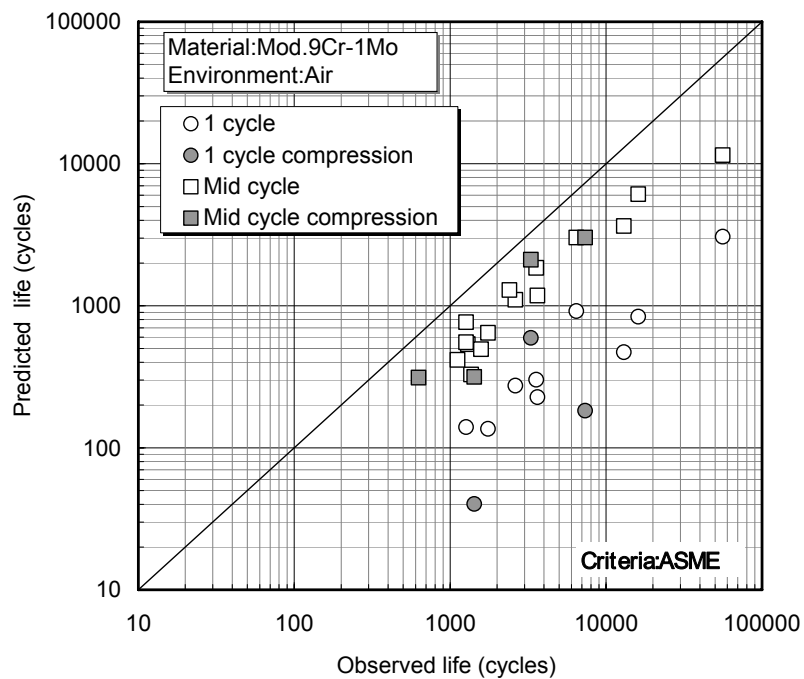


Figure 54 - Relationship between Observed Life and Predicted Life with ASME-NH Procedure Using Experimentally Obtained Relaxation Curves

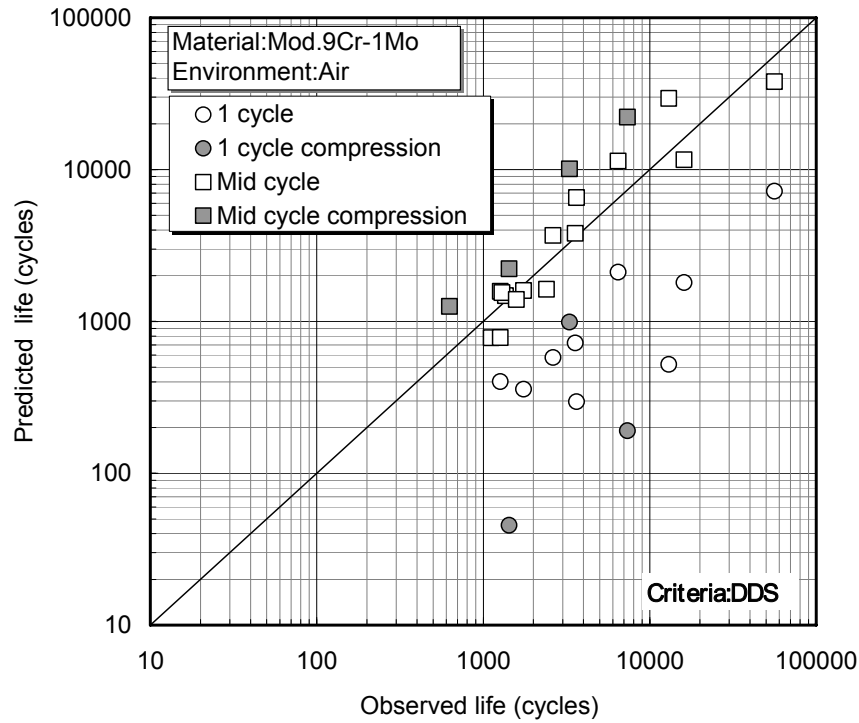


Figure 55 - Relationship between Observed Life and Predicted Life with DDS Procedure Using Experimentally Obtained Relaxation Curves

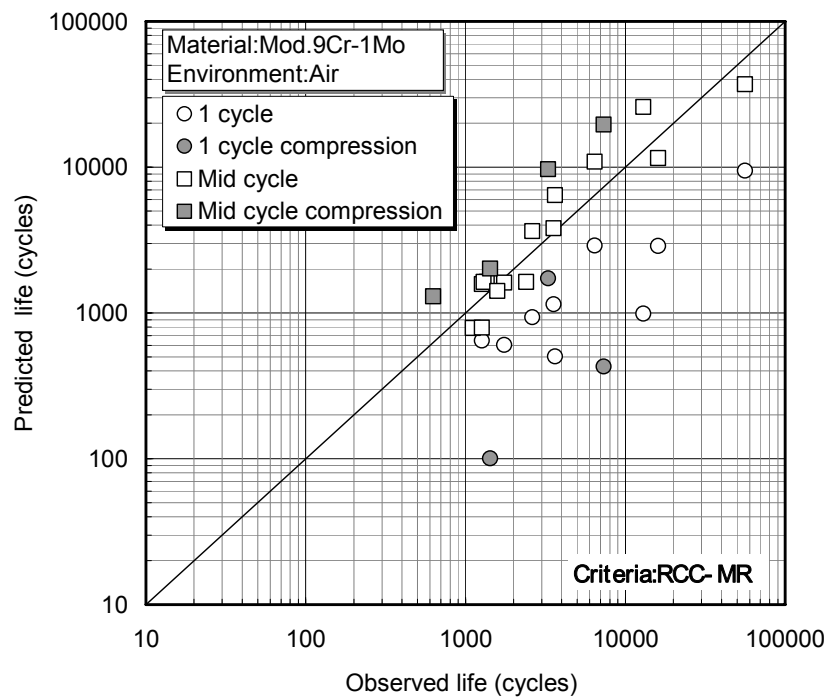


Figure 56 - Relationship between Observed Life and Predicted Life with RCC-MR Procedure Using Experimentally Obtained Relaxation Curves

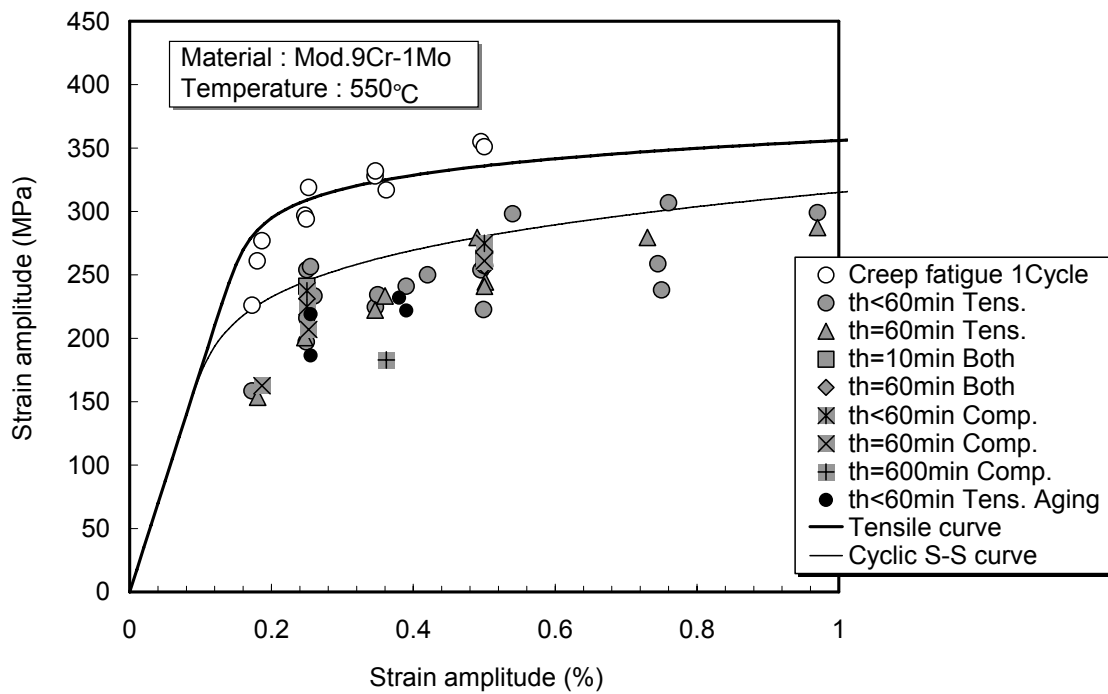


Figure 57 - Comparison of Monotonic and Cyclic Stress-Strain Curves

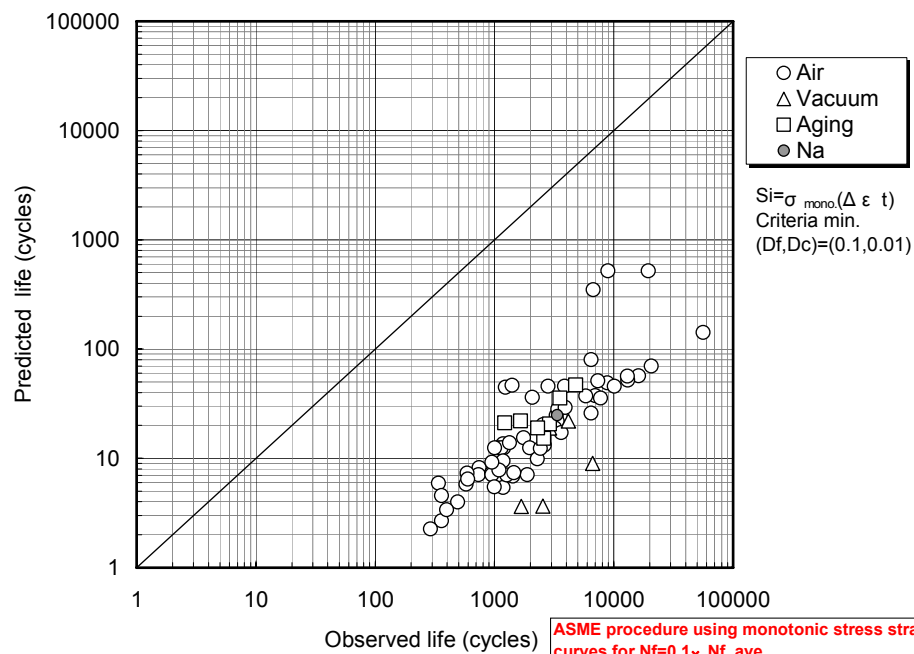
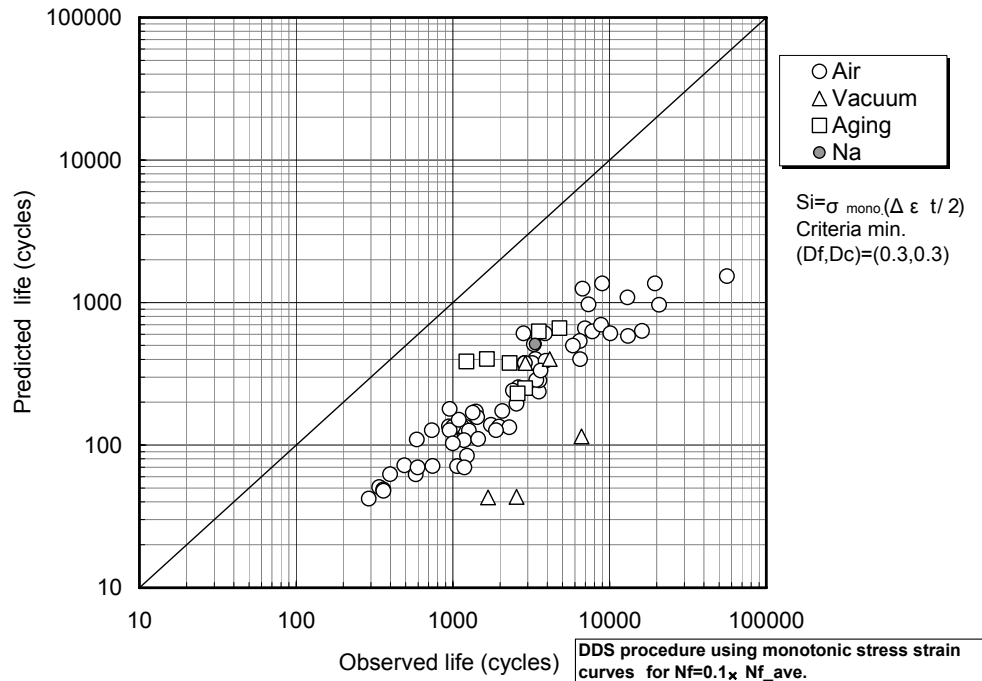
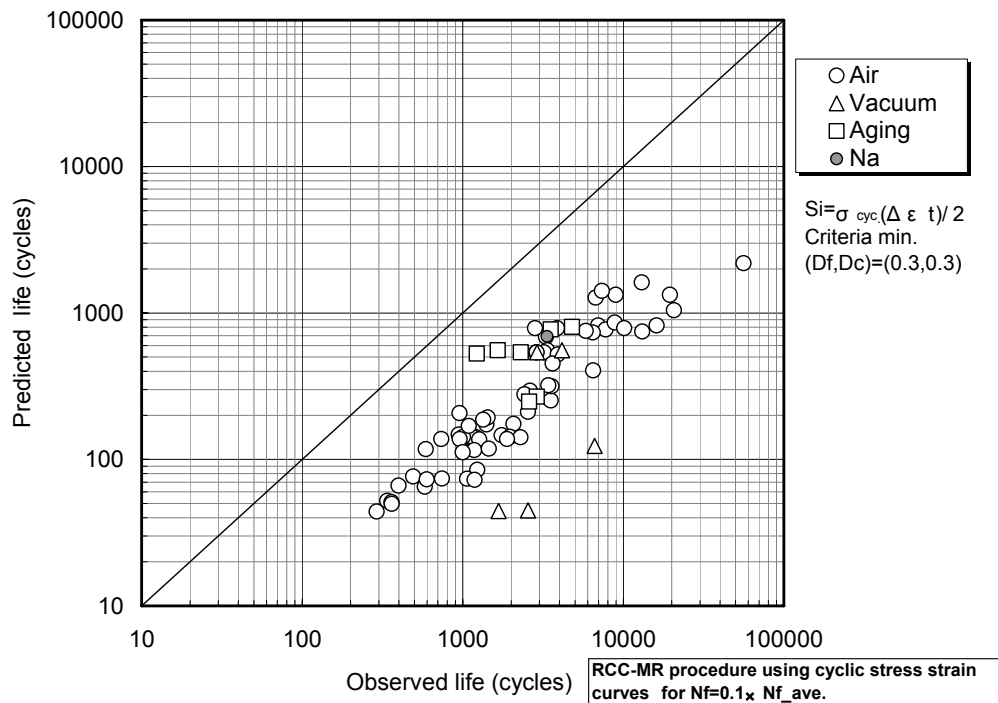


Figure 58 - Relationship between Observed Life and Predicted Life with ASME-NH Procedure Using Monotonic Stress-Strain Curve (Presumed Fatigue Crack Initiation Life = $0.1 \times N_f$)



**Figure 59 - Relationship between Observed Life and Predicted Life with DDS Procedure Using Monotonic Stress-Strain Curves
(Presumed Fatigue Crack Initiation Life = $0.1 \times N_f$)**



**Figure 60 - Relationship between Observed Life and Predicted Life with RCC-MR Procedure Using Cyclic Stress-Strain Curves
(Presumed Fatigue Crack Initiation Life = $0.1 \times N_f$)**

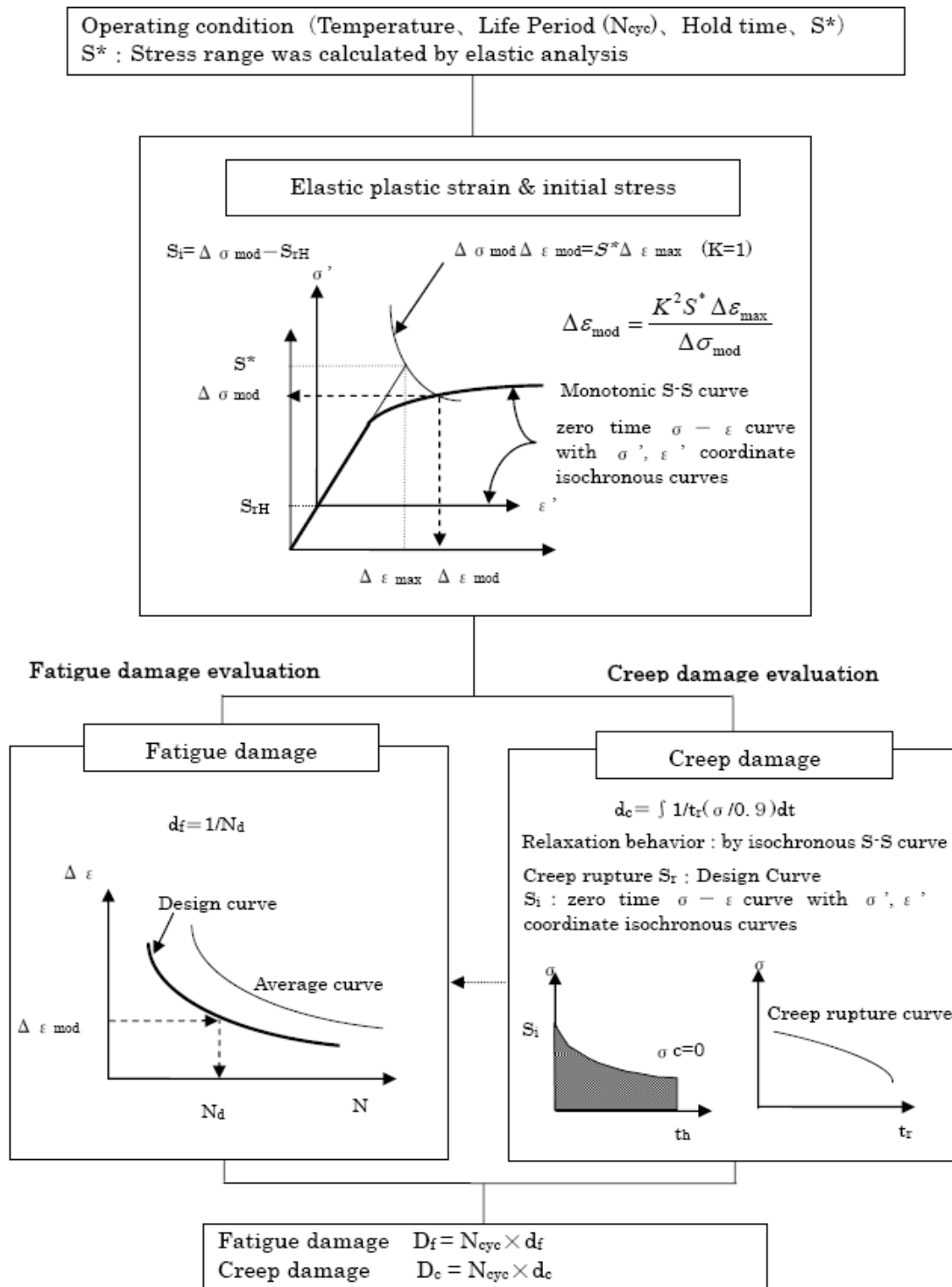


Figure 61 - Evaluation Flow of Creep-Fatigue Damage by ASME-NH Method

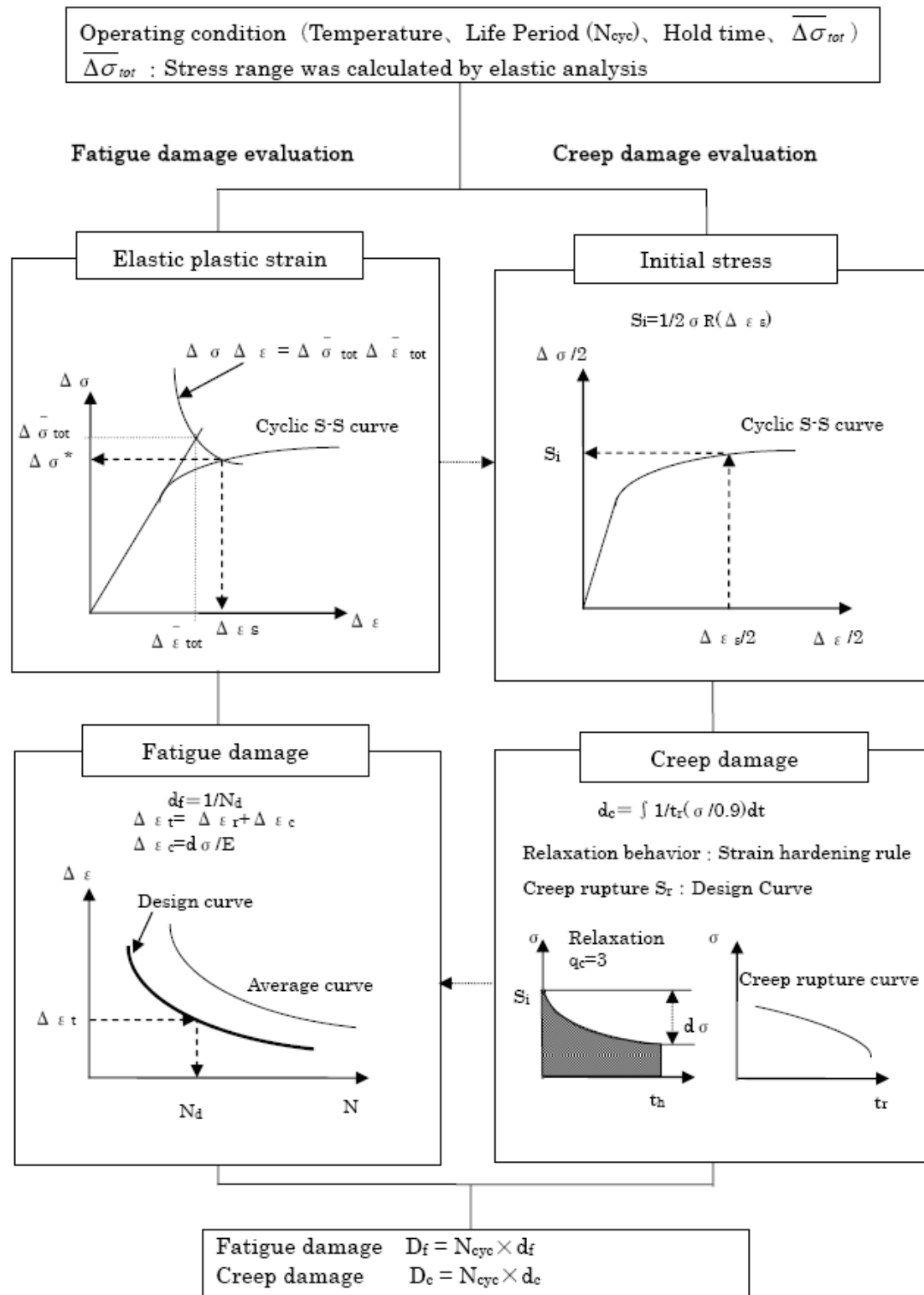


Figure 62 - Evaluation Flow of Creep-Fatigue Damage by DDS Method

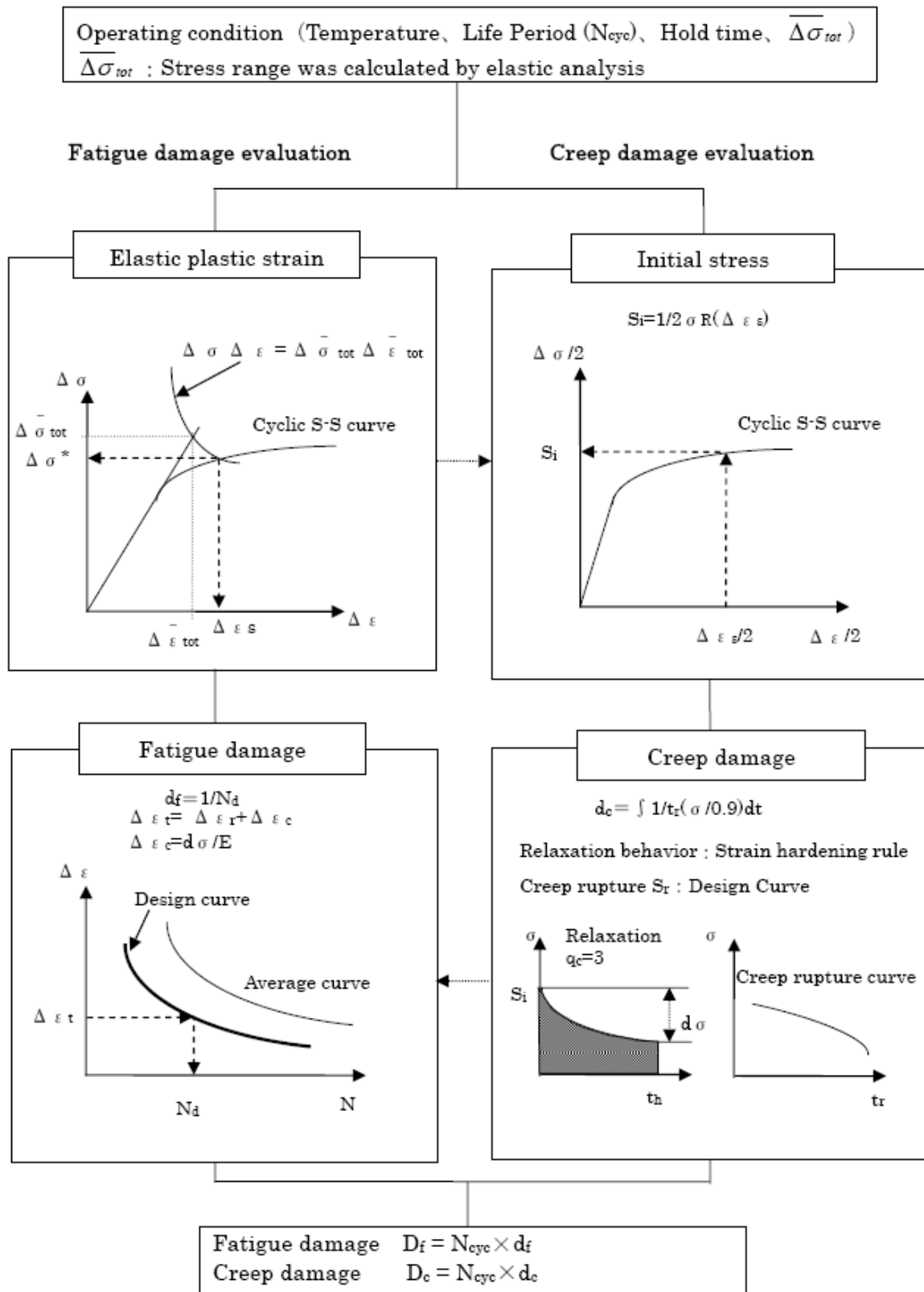


Figure 63 - Evaluation Flow of Creep-Fatigue Damage by RCC-MR Method

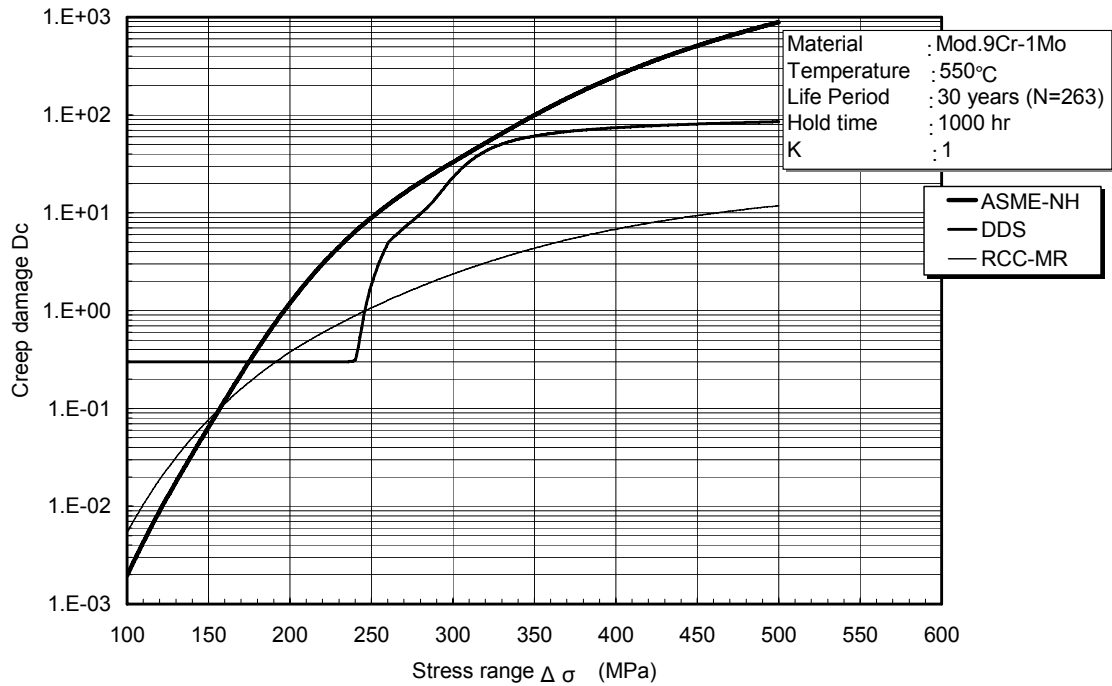


Figure 64 - Comparison of Creep Damage Evaluation

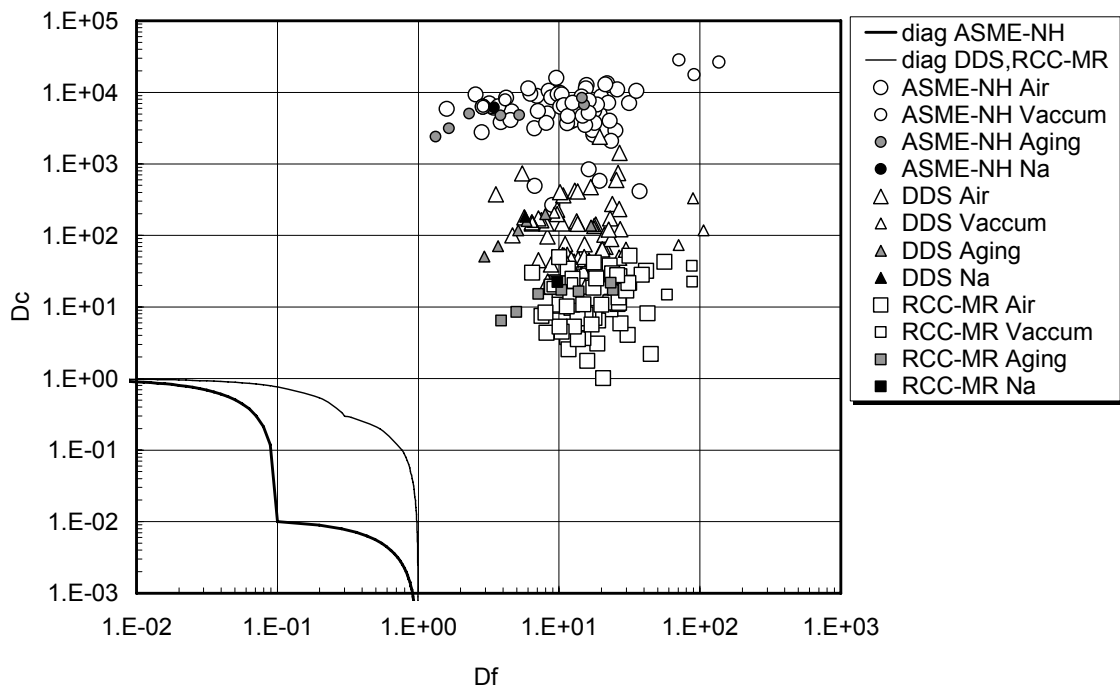


Figure 65 - Creep-Fatigue Evaluation of Experimental Data by Code Procedure

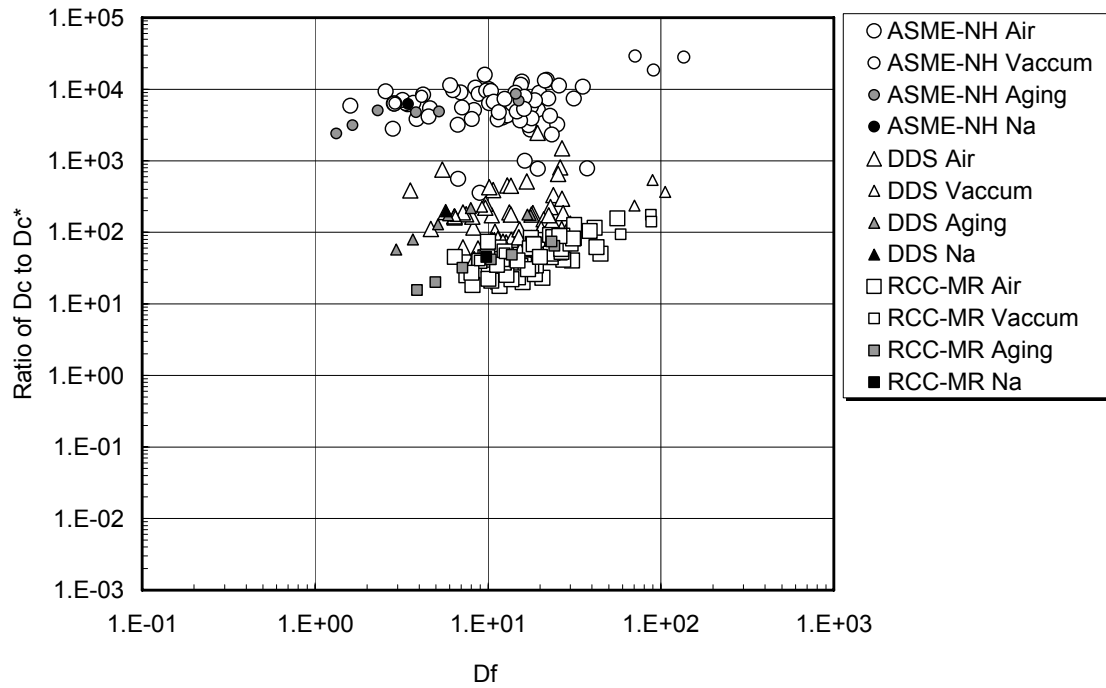


Figure 66 - Creep-Fatigue Evaluation of Experimental Data by Code Procedure

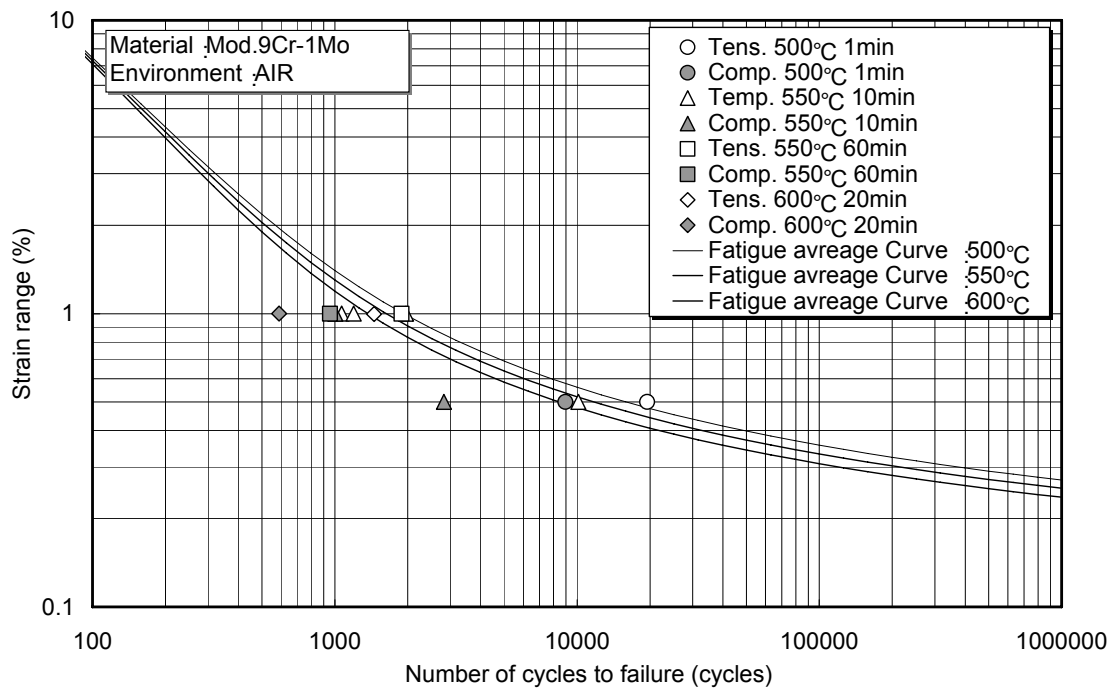


Figure 67 - Comparison of Creep-Fatigue Life between Tensile Hold Tests and Compressive Hold Tests in Air

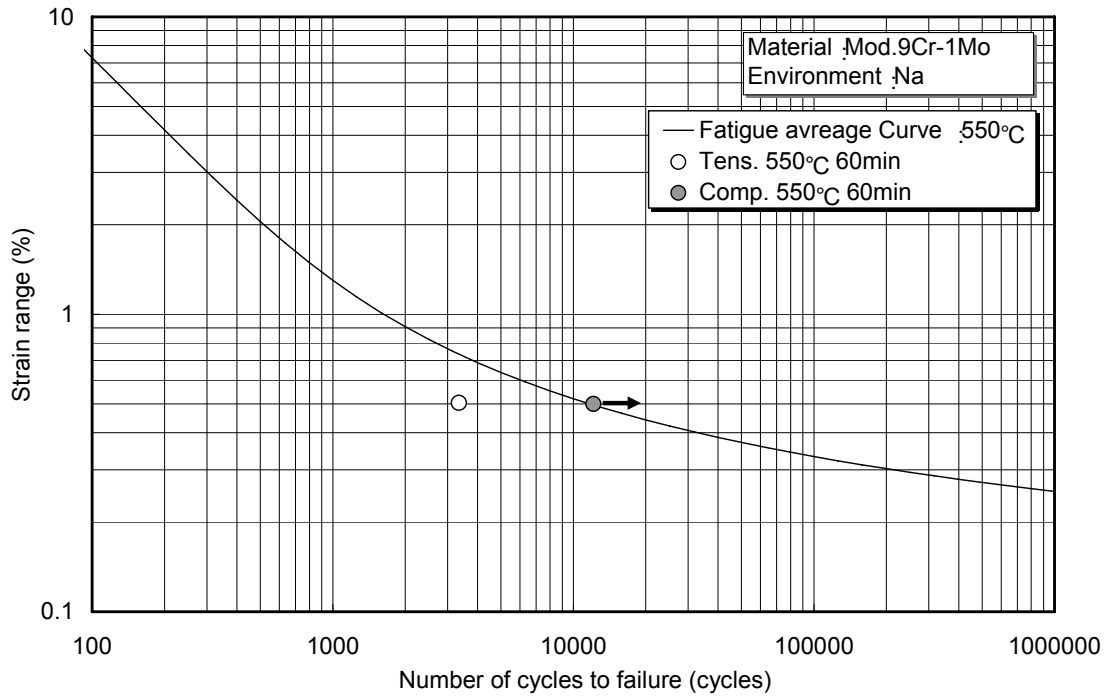


Figure 68 - Comparison of Creep-Fatigue Life between Tensile Hold Tests and Compressive Hold Tests in Sodium

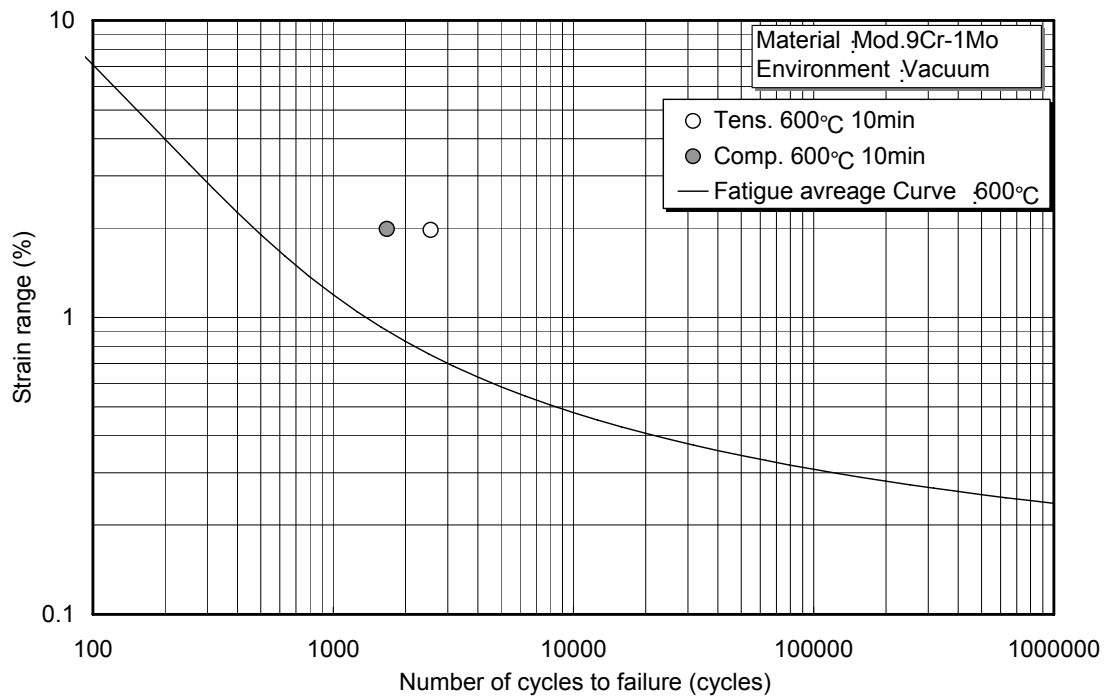


Figure 69 - Comparison of Creep-Fatigue Life between Tensile Hold Tests and Compressive Hold Tests in Vacuum

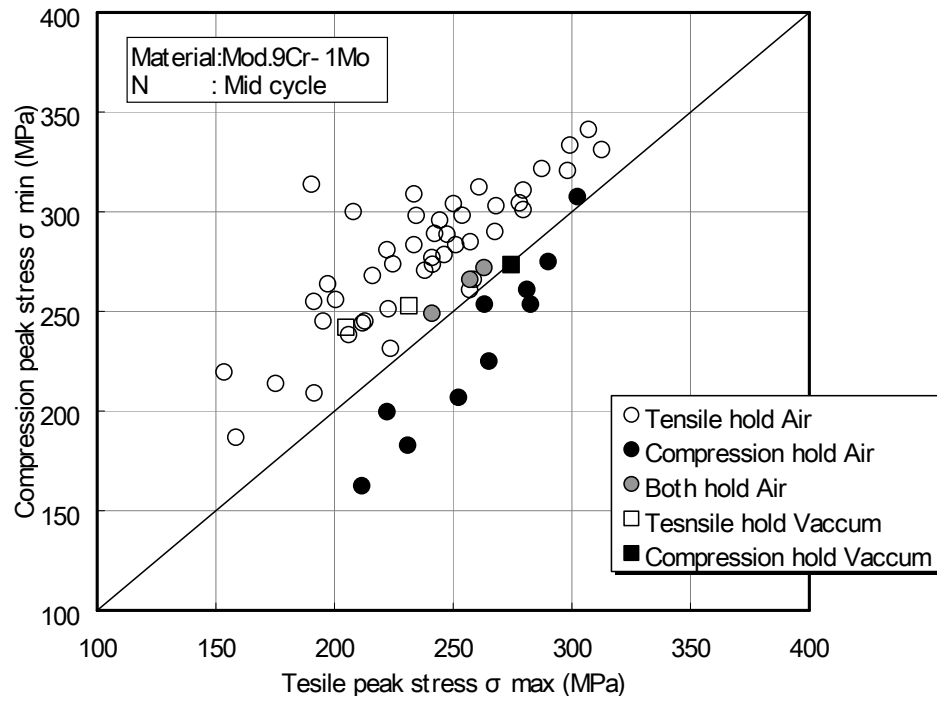


Figure 70 - Comparison of Tensile and Compressive Peak Stresses

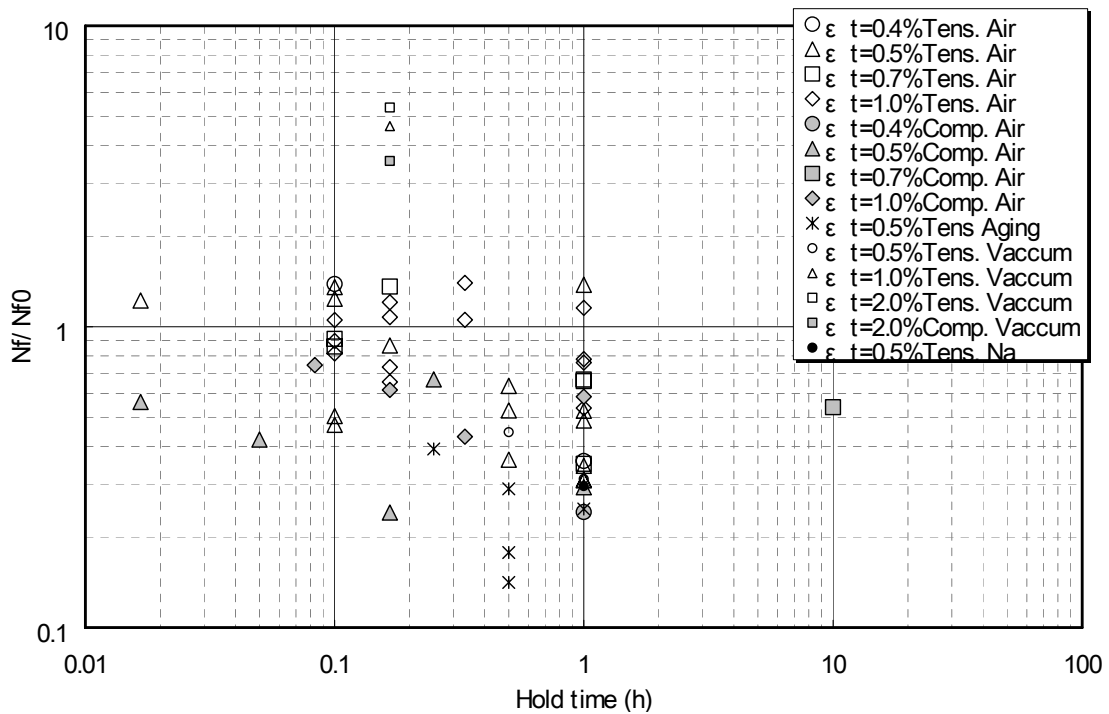


Figure 71 - Ratio of Creep-Fatigue Life Reduction

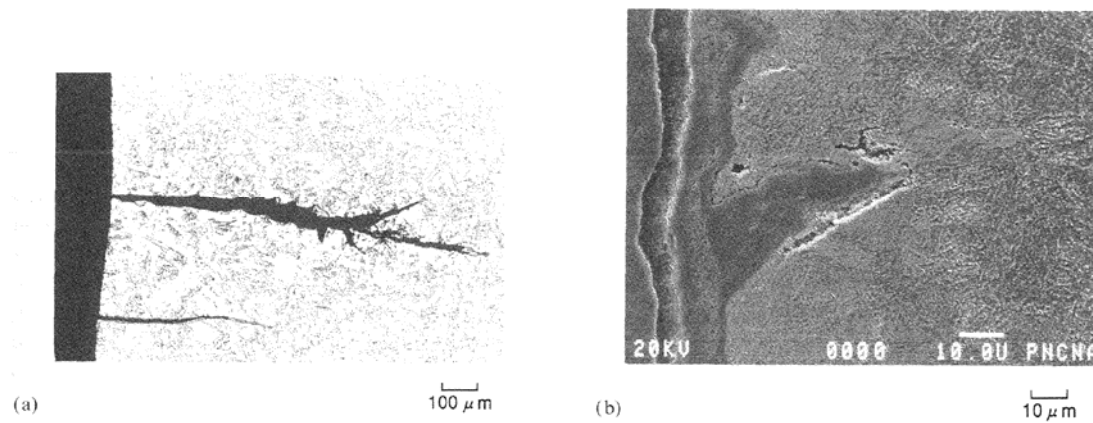


Figure 72 - Observed Crack Tip Shape

(a) Crack Tip Shape Observed in a Compressive Hold Specimen

(b) Crack Tip Shape Observed in a Tensile Hold Specimen

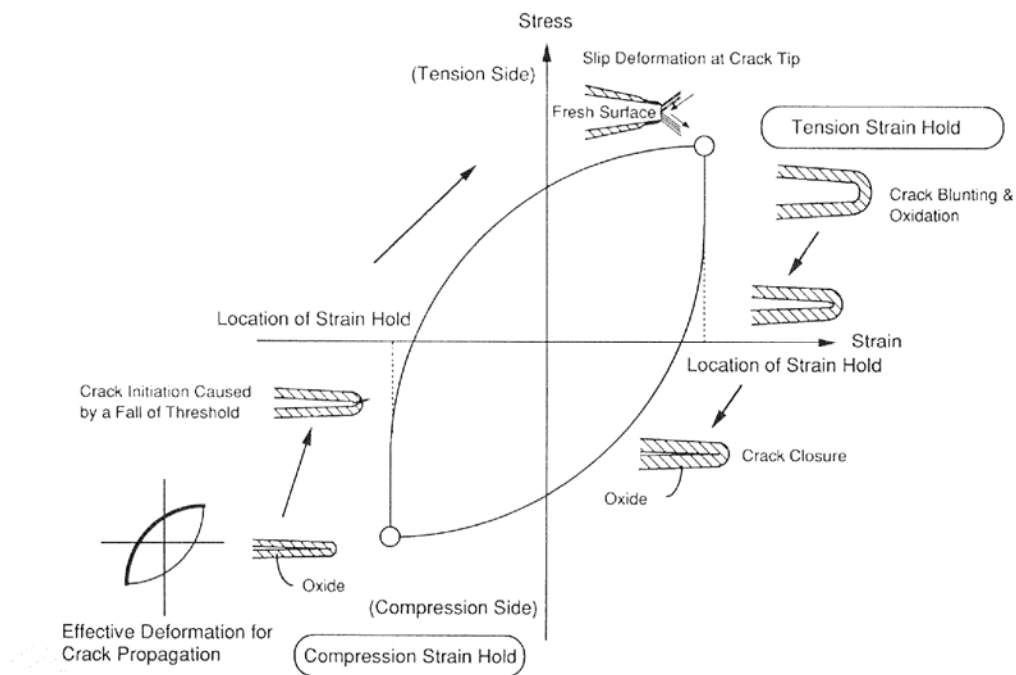


Figure 73 - Schematic Illustration of Mechanisms that Affect Crack Propagation

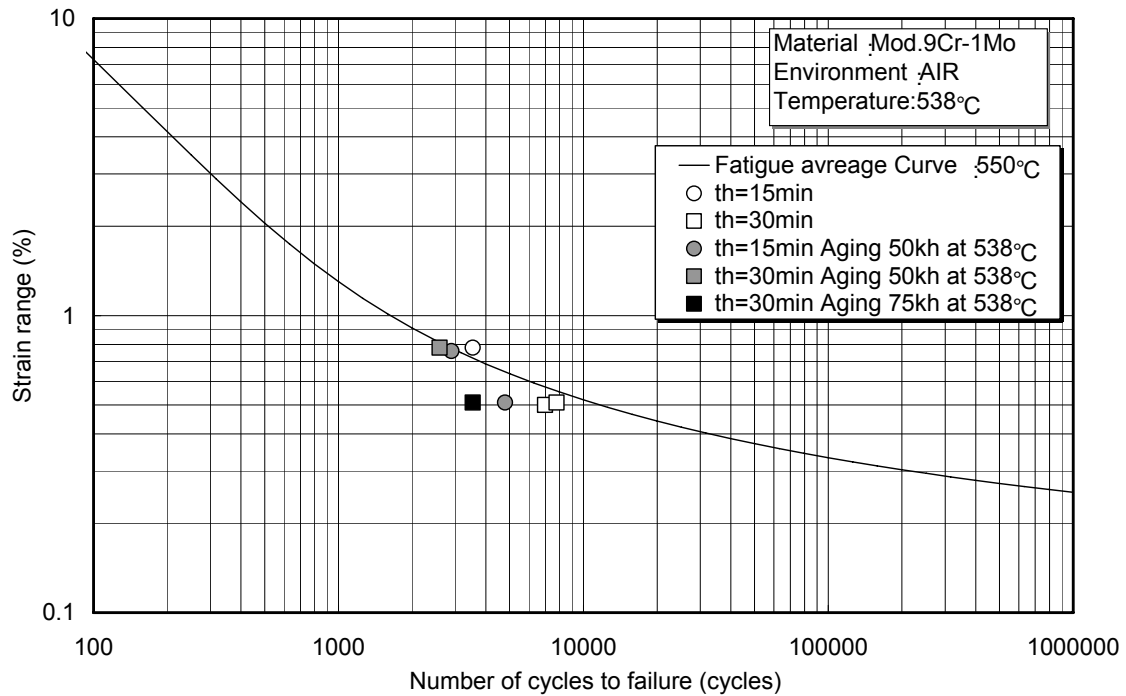


Figure 74 - Comparison of Creep-Fatigue Life between Pre-Aged Material and Unaged Material at 550°C

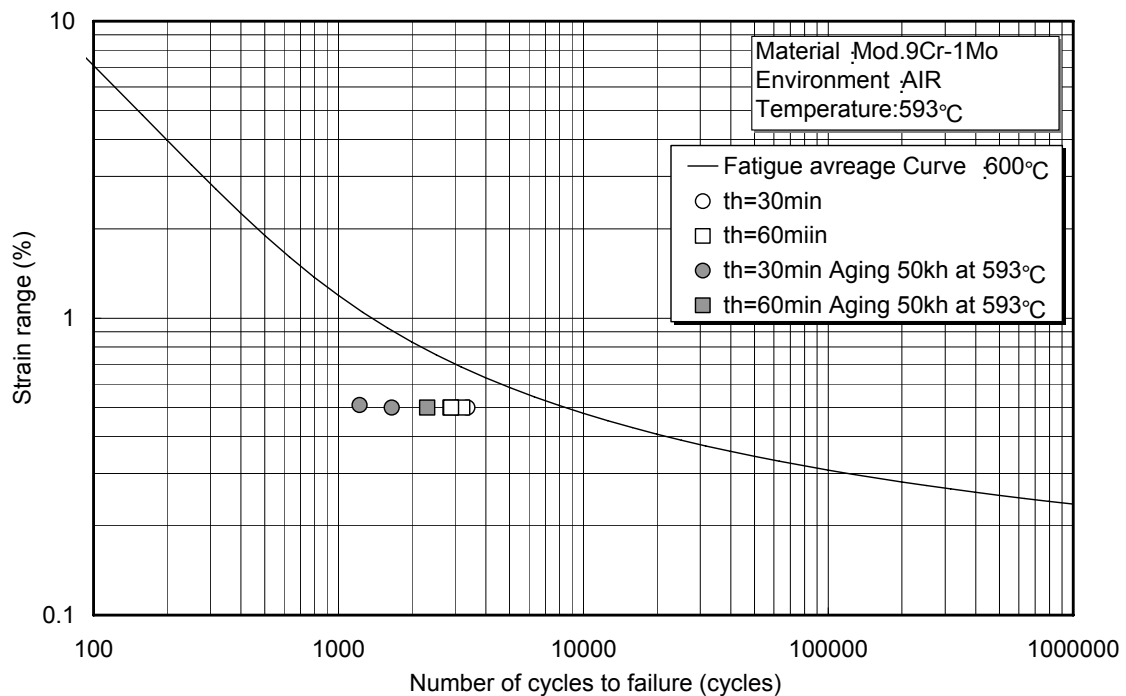


Figure 75 - Comparison of Creep-Fatigue Life between Pre-Aged Material and Unaged Material at 600°C

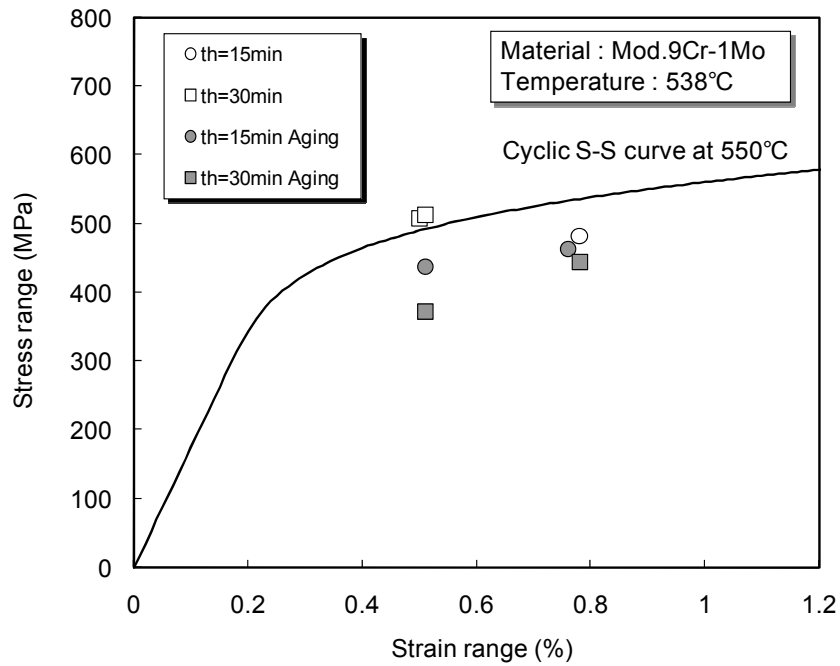


Figure 76 - Comparison of Stress-Strain Response between Pre-Aged Material and Unaged Material at 550°C

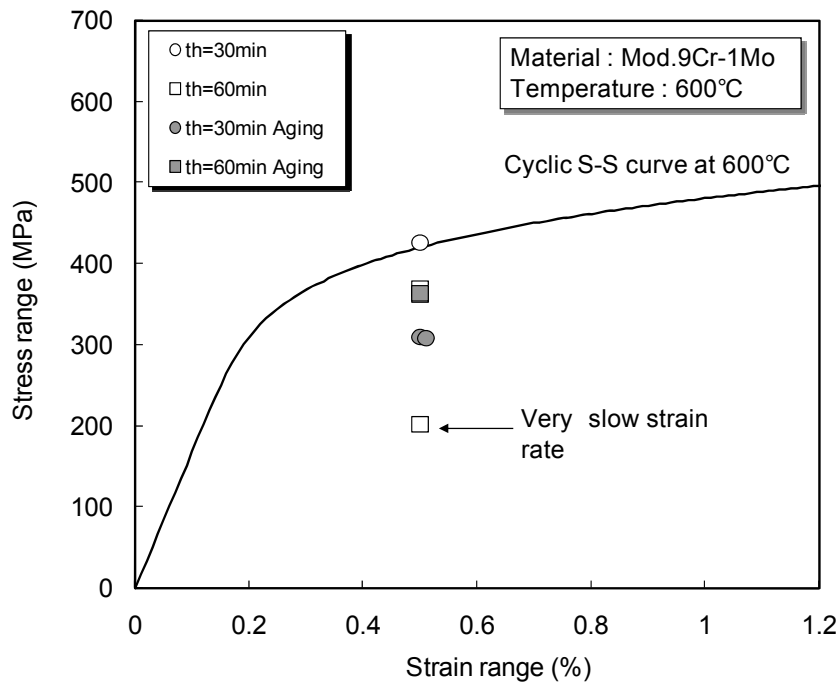
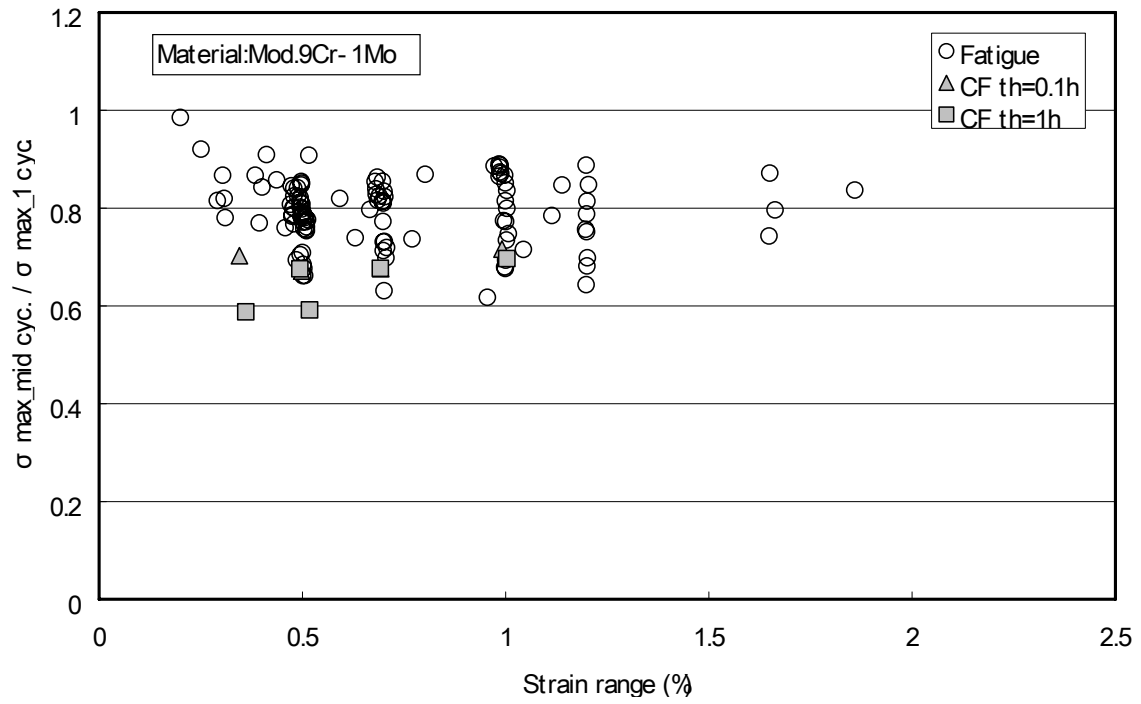


Figure 77 - Comparison of Stress-Strain Response between Pre-Aged Material and Unaged Material at 600°C

**Figure 78 - Ratio of Maximum Stress of Mid-Life to First Cycle**

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

As pointed out in the previous sections, ASME-NH gives relatively conservative estimation of creep damage compared to other procedures. In this chapter, suggestions to improve the ASME-NH procedure are summarized and necessary research and development items are accordingly proposed.

3.1 Suggestions to Improve ASME-NH Procedure

In this section, suggestions to improve ASME-NH procedure are presented in two categories, i.e., items concerning the evaluation of creep damage and the evaluation of creep-fatigue life.

3.1.1 Evaluation of Creep Damage

In the previous section, reasons for the relatively large conservatism involved in the ASME-NH procedure were clarified. In this section, options to improve the procedure are suggested corresponding to the identified reasons of conservatism.

The suggested options for improvement of ASME-NH are summarized in Table 7. Their impacts on the evaluation of creep damage were investigated by calculating creep damage by five different methods corresponding to one of the options or a combination of options. The reference case corresponds to the current procedure and is the same as the calculation in Chapter 2.

In case (a), a modified strain amplitude, the modified strain range divided by two, is used instead of the modified strain range for the estimation of the initial stress of relaxation. In case (b), cyclic stress-strain curve is used instead of monotonic stress-strain curve. In case (c), a creep strain law and the strain hardening rule are used instead of the isochronous stress-strain curve for the estimation of stress relaxation behavior. Case (d) is the combination of cases (b) and (c). In case (e), the K' factor for this steel was changed from 0.67 to 0.9. The schematic illustration of calculation procedure is shown in Figure 79. The monotonic and cyclic stress-strain curves at 550°C are shown in Figure 80 for information. Other conditions for calculation are the same as those used for the calculation of Figure 64.

The results of the evaluation are shown in Figure 81. In ASME-NH, lower bound stress is given by the core stress which is zero for $Z=0$. Therefore, to check the sensitivity of calculated creep damage to the lower bound stress, creep damage was calculated fictionally setting Z to 0, 0.3, 0.4, 0.5, as shown in Figure 82. It is understood from this figure that the effect of the value of Z on creep damage is small when elastically calculated stress is below 300 MPa approximately. Figure 83 shows the initial stresses estimated by various options. Case (a) shows a very large reduction in estimated creep damage due to the decrease of the initial stress of relaxation, particularly in lower stress ranges. This is because reduction of strain range is directly reflected to the reduction of the initial stress at regions close to an elastic region. Case (b) does not reduce the conservatism as far as isochronous curves are used, because although the initial stress is reduced by substituting monotonic stress-strain curves by cyclic stress-strain curves, the amount of stress relaxation estimated by the isochronous curves is reduced, due to the increased strain range, as shown in Figure 84 and Figure 85. The other three cases show some reduction in estimated creep damage, maintaining approximately the same degree of conservatism as RCC-MR or DDS. Corresponding results of creep-fatigue damage calculation of the experimental results are shown in Figure 86 to Figure 90.

From the above results, use of cyclic stress-strain curve, use of creep-strain law in conjunction with the strain hardening law, or the combination of both is recommended options for the improvement of the ASME-NH procedure. Which combination to choose depends on the conservatism necessary in the design of VHTR. If the material is to be applied to conditions under which sufficient data are not available, fairly large conservatism should be maintained.

3.1.2 Evaluation of Creep-Fatigue Life Based on Creep-Damage

As described in the previous chapter, the creep-fatigue damage envelope adopted in the ASME-NH procedure has a lot of conservatism. A damage envelope with an intersection point of (0.3, 0.3) can be adopted instead of (0.1, 0.01), as far as the experimental results analyzed in this investigation are concerned. It is to be kept in mind that the value of intersection point can only be determined by engineering judgment and theoretical derivation is most difficult. In other words, for employing different intersections for different materials, mechanistic explanation that only emerges from capturing the nature of each material is necessary, but it is normally difficult to prepare such basis.

3.2 Necessary R&D Items

In this section, R&D items that are necessary to improve the ASME-NH procedure to apply to VHTR conditions are summarized. They are categorized into short-term items and long-term items.

3.2.1 Short-Term Items

3.2.1.1 Acquisition of Material Data

Creep-fatigue data of Grade 91 have been accumulated to the extent that design procedures for fast breeder reactors can be established. However, to apply this material to VHTR, more data at the temperature range expected in VHTR will be necessary. At temperatures higher than those encountered in fast breeder reactors, creep-fatigue life should naturally decrease. Therefore, the behavior of material should be captured more precisely to make the degree of conservatism optimum to ensure flexibility in design components and systems.

As described in the previous chapters, there are many factors that can affect the creep-fatigue life of Mod.9Cr-1Mo steel. Creep damage, tensile mean stress, oxidation, aging and loading sequence effects (creep rupture strength after cyclic softening) are among these factors. The effects of oxidation, aging and cyclic softening are not problematic in the case of austenitic steels but must be carefully addressed in the case of ferritic steels such as Grade 91.

It is not very practical to take every factor that can affect creep-fatigue life explicitly in a code procedure. Therefore, material tests should be performed systematically to identify relative importance of those factors. Very long term tests will not be necessary, tests to identify the limit where the effects of each factor saturates will be enough (For example, perform tensile hold tests and compressive hold tests until creep-fatigue life of tensile hold tests becomes shorter than that of compressive hold tests).

3.2.1.2 Identification of Issues to be Addressed

Based on the material tests described above, decisions should be made as to how these effects, if they exist, should be incorporated into the creep-fatigue evaluation procedures. It would not be practical to introduce new factors into the code procedure. If additional phenomena that can reduce creep-fatigue life were identified, these should be accounted for in the conservatism in estimating either the initial stress or stress relaxation. It would be helpful to make a list of the phenomena of concern and the corresponding way to ensure conservatism (creep-fatigue life reduction due to aging is covered by which factor in the procedure, for example). In this case, attention should be paid to the possibility that relative importance may change in short-term region and long-term region in which we are interested.

3.2.2 Long-Term Items

3.2.2.1 Long-Term Material Tests

In this perspective, more creep-fatigue data with longer hold times (10 hours, for example) either with a tensile hold time or a compressive hold time are desirable at strain ranges not larger than 0.5% to confirm the results obtained so far about the mechanisms of life reduction of creep-fatigue life reduction, i.e., the effects of creep, tensile mean stress and oxidation.

Recommended test conditions for VHTR design are shown in Table 8 and Table 9. The conditions in these tables are limited up to 600°C because the design conditions of VHTR are not clear.

3.2.2.2 Evaluation Method of Welded Joints

Another point which is very important in applying Grade 91 steel to VHTR is the treatment of welded joint. For fast breeder reactors, a mechanistic model has been developed and incorporated in the DDS procedure (Asada et. al., 1992, Asayama et. al., 1993, Taguchi et. al., 1996). The procedure in DDS accounts for the fatigue strength of weld metal, the increase of initial stress of relaxation due to harder stress-strain response of weld metal, and the increase of elastic follow-up as well.

At temperatures above 600°C, Type IV cracking has been reported to occur. Tests should be performed at and above temperatures to which components of VHTR will be subjected. Therefore, a creep-fatigue evaluation method that can take into account Type IV cracking is also necessary.

3.2.2.3 Extrapolating Experimental Data to the Design Regime

In design, extrapolating high stress/strain and relatively short hold time experimental data to the significantly lower stress and longer hold time design regime is inevitable primarily because of limitation of time, and this can be a problem particularly in evaluating margins we have in our design codes and procedures. Much research has been performed on this subject but no satisfactory definitive methods that can be applied to design evaluation have been proposed. A simple question whether or not saturation of creep-fatigue life reduction due to hold time occurs has yet to be answered. Therefore, full resolution of this problem would hardly be envisioned in the short or long terms.

However, there has been progress and important findings are beginning to be reported from recent researches in terms of mechanisms of deformation and failure of which understanding is a key to solve the issue. One approach is to use these results. For example, Kimura et. al. reported that “region splitting method” can be applied to predict long-term creep rupture strength of Grade 91. This method divides stress range by one half of yield strength at corresponding temperature and it correlates stress and rupture time in each region, with better accuracy compared to the case where one curve is applied to the whole region. This method is simple enough to be used in establishing material strength standards.

Another approach is to focus our attention precisely to the design regime. Grade 91 steels have relatively high yield strength and the magnitude of work hardening and ductility are less than austenitic stainless steels. Therefore it is anticipated that the materials will be used within the elastic region. This implies that cyclic softening may be small and we would be able to concentrate on softening that comes from hold time (and aging). This may lead to a finding that the possibility of degradation of creep properties due to cyclic softening can be ignored (no evidence at this point). From this viewpoint, tests focusing on material behavior rather than material strength could be prioritized because this type of tests can save significant time. The results of these tests would produce valuable information to determine the conditions of material strength tests that give maximum output with minimum resources.

3.2.2.4 Structural Tests for Validation

In establishing design code based on the information obtained from material tests, structural tests are indispensable for validation. The first step of structural tests will be a simple pipe subjected to cyclic thermal loading, for example. The next step will be tests with structural models that have more complex configurations that reproduce the essential features of VHTR components. If the components in VHTR may be thick, structural tests with thick structural test pieces are desirable, considering the possibility of Type IV cracking.

Table 7 - Suggested Options for the Improvement of Creep-Fatigue Evaluation Procedure in ASME-NH

Case	Contents	S-S curve	Strain type	Description of relaxation	Note
Reference	Current procedure with $k=1$, $K_s=1$ Ratchet is not considered.	Monotonic	$\Delta\epsilon_{\text{mod}}$	Isochronous	
(a)	Initial stress is calculated based on half of the modified strain range	Monotonic	$\Delta\epsilon_{\text{mod}}/2$	Isochronous	
(b)	Cyclic stress-strain curve is used.	Cyclic	$\Delta\epsilon_{\text{mod}}$	Isochronous	
(c)	Strain hardening rule is used.	Monotonic	$\Delta\epsilon_{\text{mod}}$	Strain hardening rule	$q_c=1$
(d)	Cyclic stress-strain curve is used. Strain hardening rule is used.	Cyclic	$\Delta\epsilon_{\text{mod}}$	Strain hardening rule	$q_c=1$
(e)	Stress factor on relaxation changed from 0.9 to 1.0.	Monotonic	$\Delta\epsilon_{\text{mod}}$	Isochronous	

q_c : Elastic follow-up coefficient on relaxation behavior

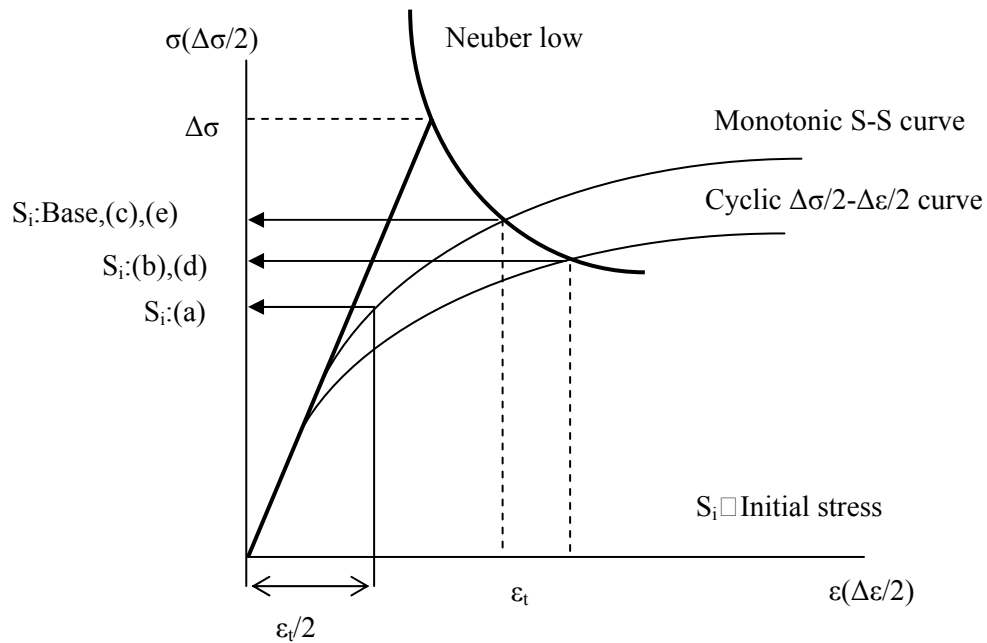
Table 8 - Recommended Creep Test Conditions

Temperature (°C)	Stress (MPa)	Estimated time
550	150	100,000 h
600	100	50,000 h

Table 9 - Recommended Creep-Fatigue Test Conditions

$\Delta\epsilon_t$ (%)	500°C		550°C		600°C	
	Hold time (h)		Hold time (h)		Hold time (h)	
	1	10	1	10	1	10
under 0.5	○	○	●	☆ (18,000 at $\Delta\epsilon=0.35\%$)	☆ (1,700 at $\Delta\epsilon=0.35\%$)	☆ (11,000 at $\Delta\epsilon=0.35\%$)
0.5 ~ 1.0	●	○	●	● (compression) ☆ (6,000 at $\Delta\epsilon=0.7\%$)	●	☆ (5,000 at $\Delta\epsilon=0.7\%$)
1.0 over	●	○	●	○	●	○

- Completion
- Incompleteness
- ☆ Recommended test condition
- () Estimated time by DDS average

**Figure 79 - Calculation Procedure of Initial Stress Using Monotonic S-S Curve**

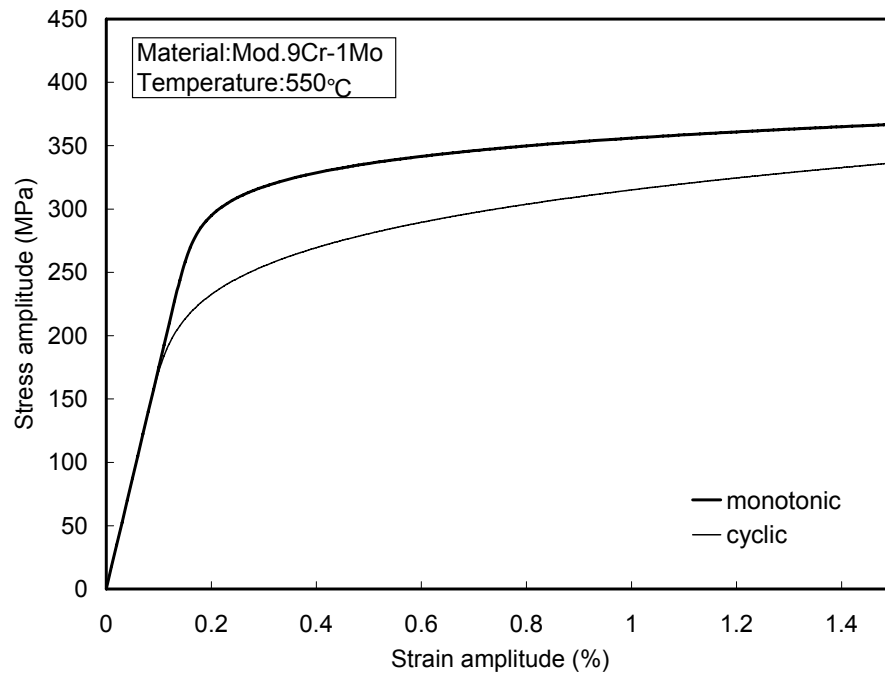


Figure 80 - Monotonic and Cyclic Stress-Strain Relation at 550°C

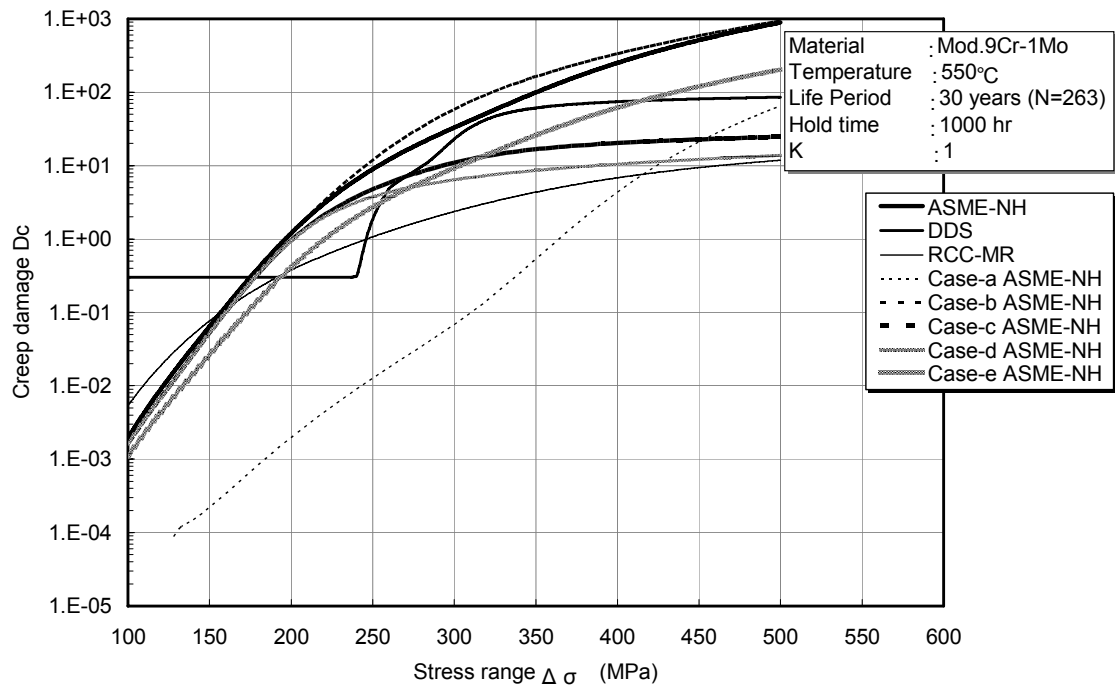


Figure 81 - Creep Damage Calculated Based on Various Options

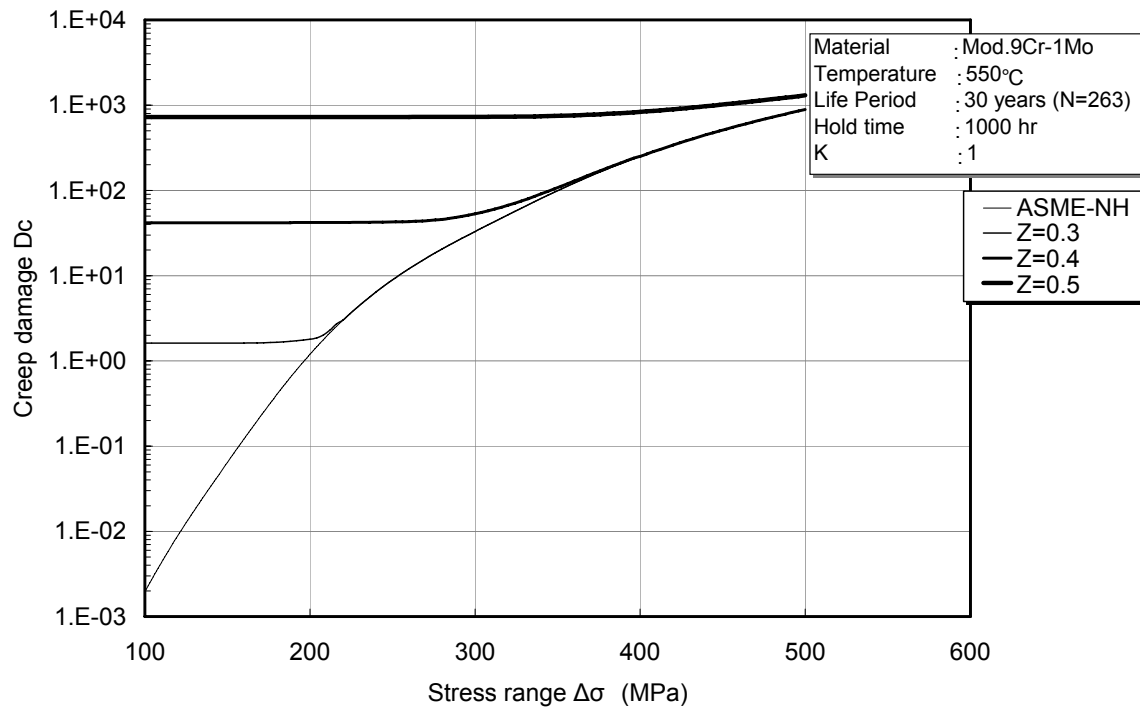


Figure 82 - The Effect of the Value of Z on Creep Damage in ASME-NH

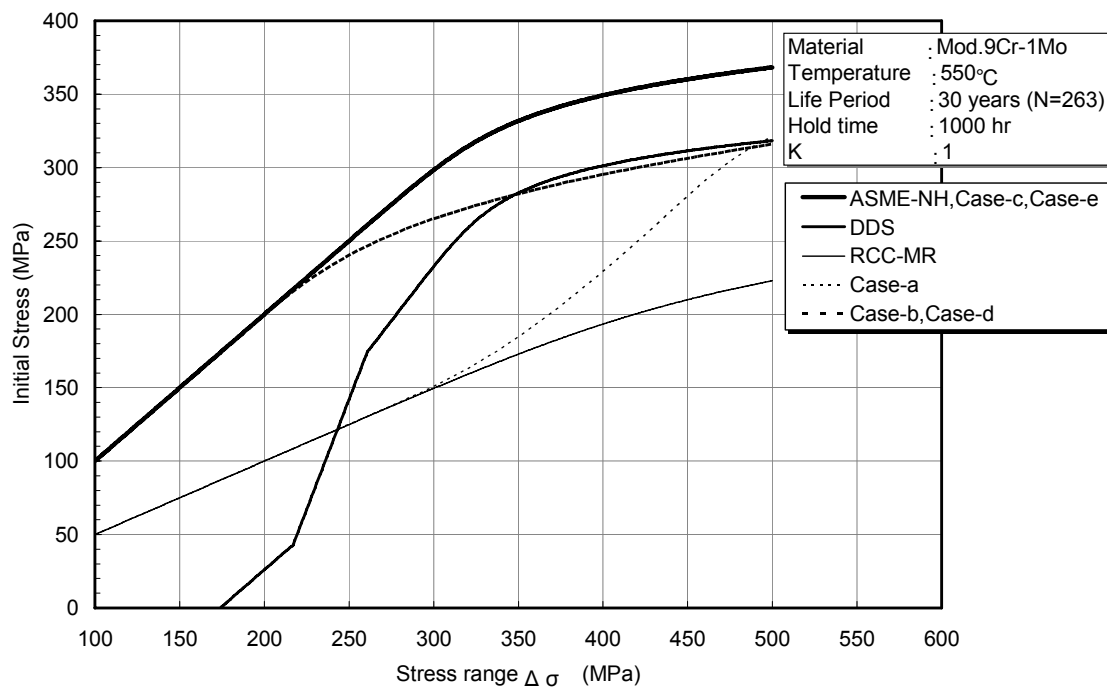


Figure 83 - Comparison of Initial Stresses of Stress Relaxation

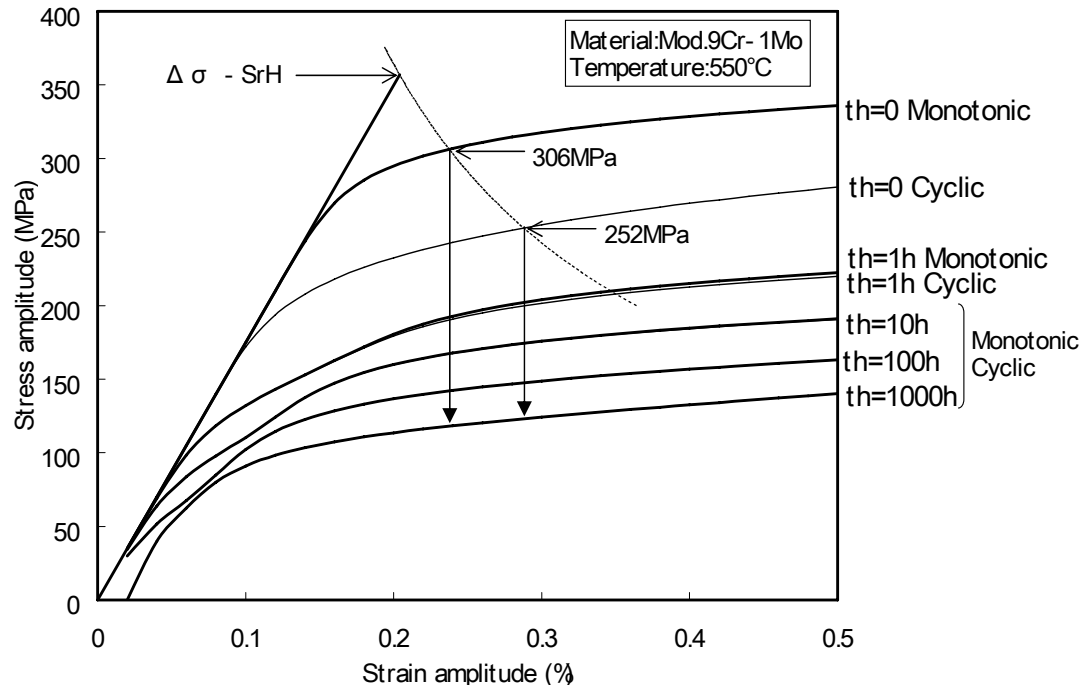


Figure 84 - Monotonic and Cyclic Isochronous Curves at 550°C

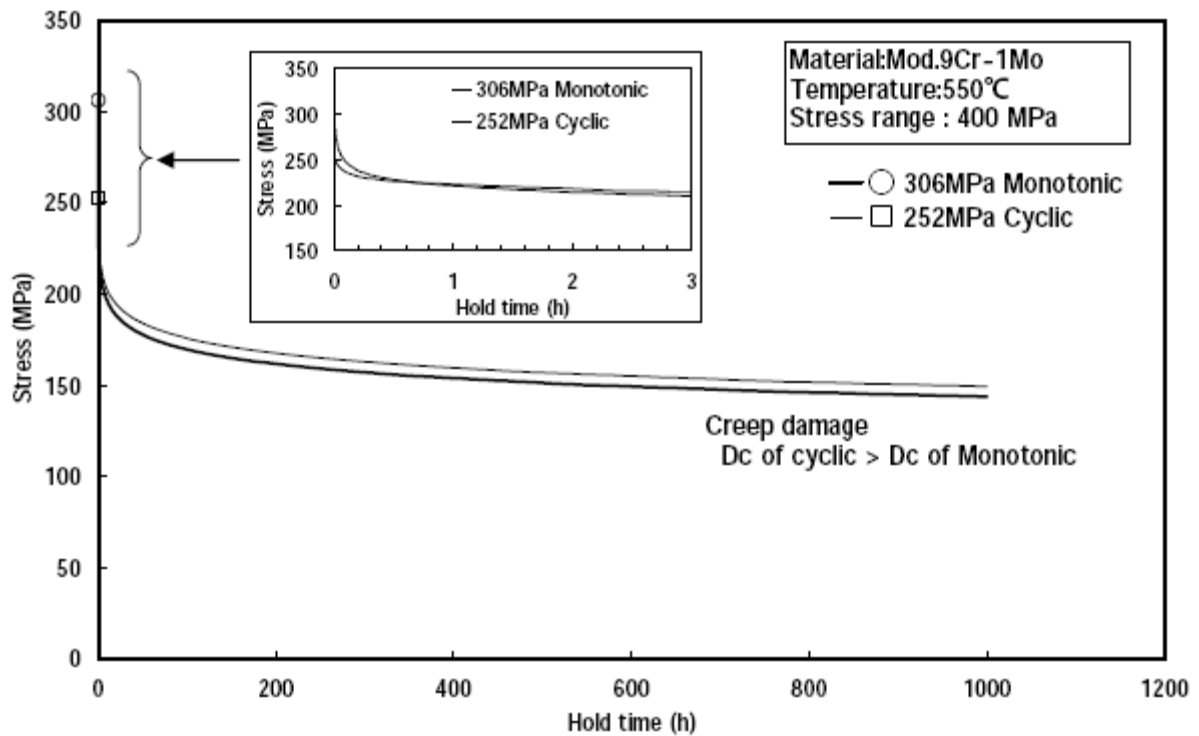


Figure 85 - Comparison of Relaxation Behavior between Monotonic and Cyclic At 550°C

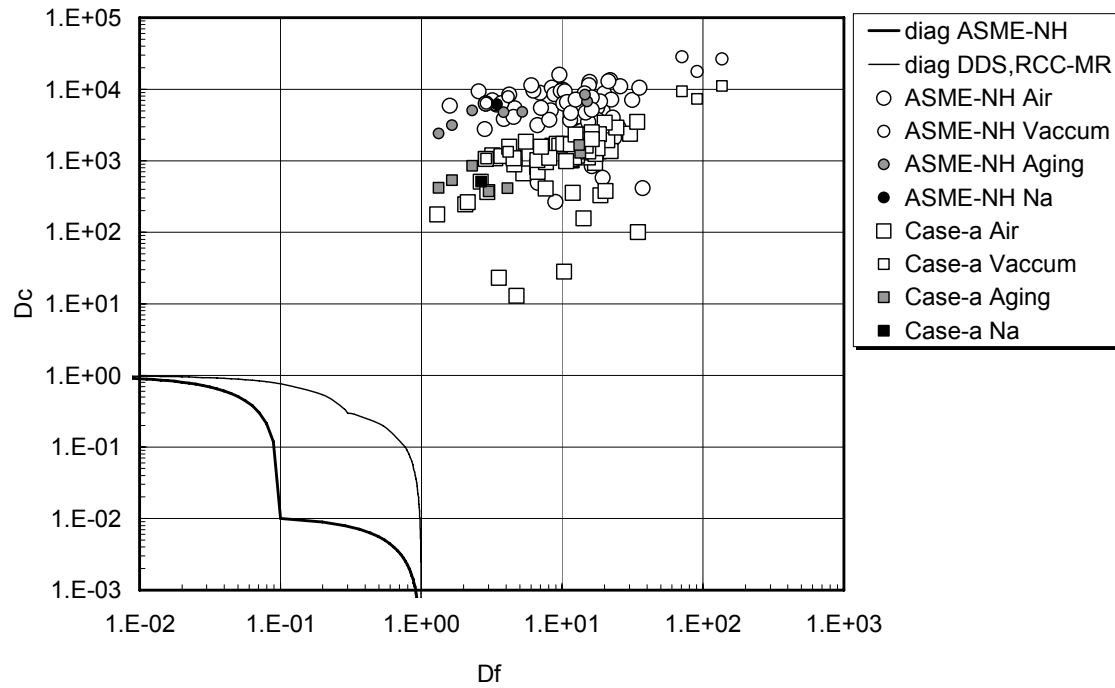


Figure 86 - Creep-Fatigue Damage Calculated Based on Case (a)

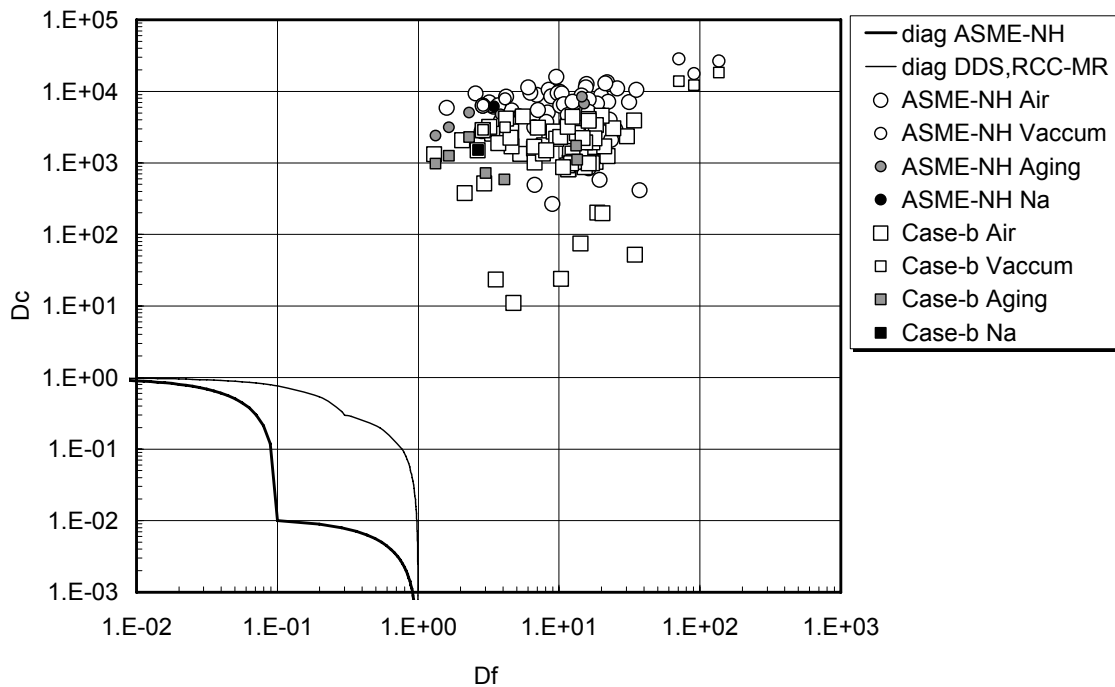


Figure 87 - Creep-Fatigue Damage Calculated Based on Case (b)

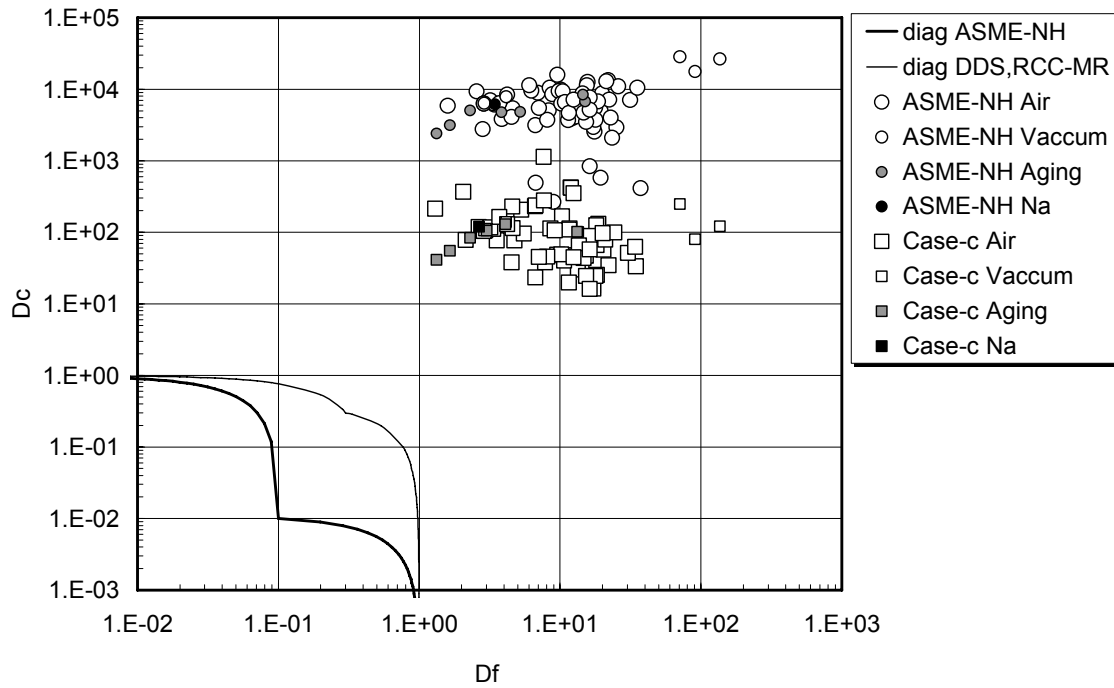


Figure 88 - Creep-Fatigue Damage Calculated Based on Case (c)

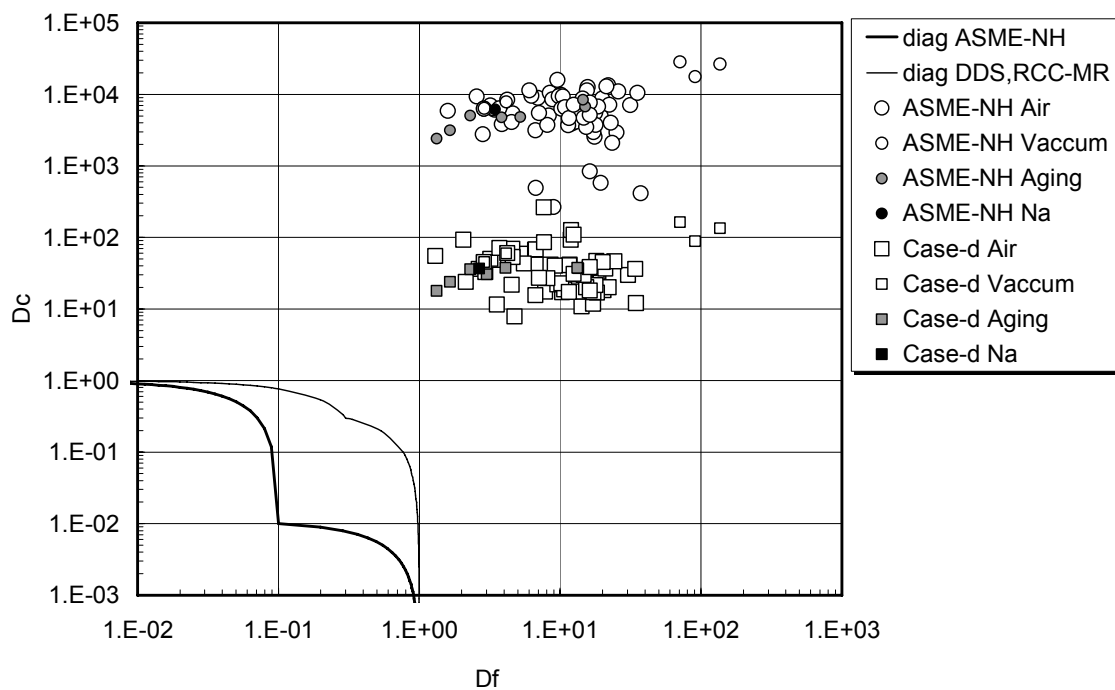


Figure 89 - Creep-Fatigue Damage Calculated Based on Case (d)

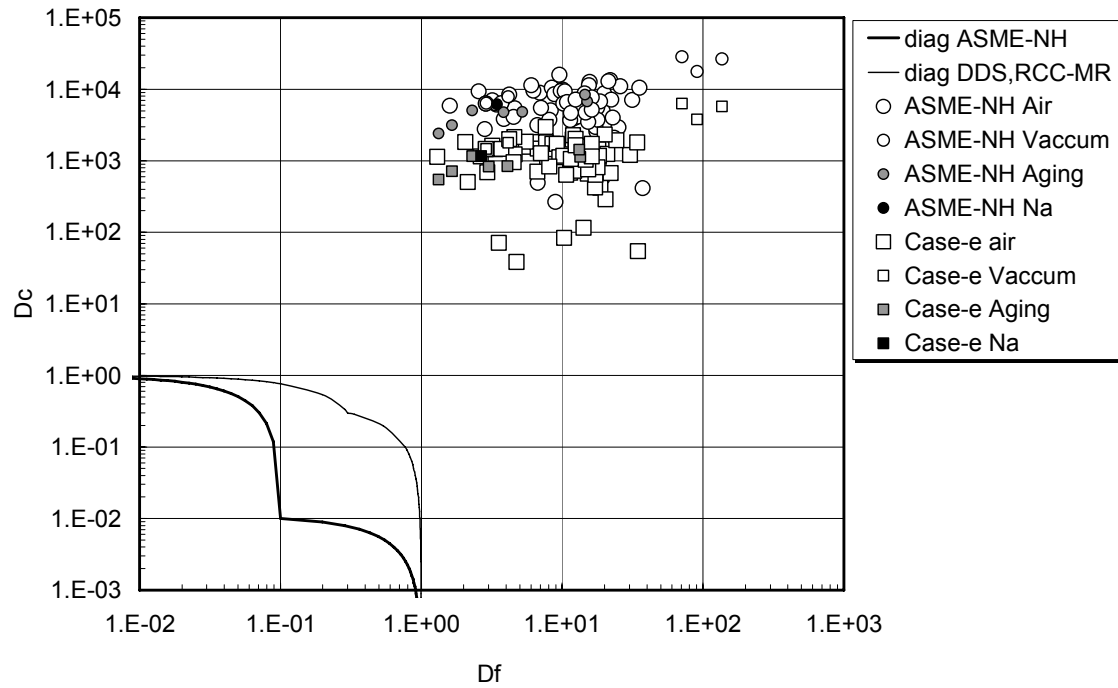


Figure 90 - Creep-Fatigue Damage Calculated Based on Case (e)

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PART II

HASTELLOY XR

1 DATA COLLECTION ON HASTELLOY XR

1.1 Development of Hastelloy XR

In 1970s, material selection tests of heat-resistant alloys for the High-Temperature Gas-cooled Reactor (HTGR) were performed as shown in Figure 59 mainly on long-term corrosion resistance in impure HTGR helium environment. Taking into account also service conditions of the intermediate heat exchanger (IHX) of the HTGR, a nickel-base Cr-Mo-Fe superalloy Hastelloy X, which has excellent accumulated experiences in jet engines was selected for the heat transfer tubes and the hot header in the IHX. Since Hastelloy X does not have sufficient compatibility with the primary helium coolant at very high temperatures, Hastelloy XR was developed from Hastelloy X to improve the compatibility.

It was found that for Hastelloy X, tightening the contents of some elements even within the specification of the chemical compositions results in remarkable improvements in the compatibility. The following modification items (a) and (b) were made on Hastelloy X to improve the compatibility and further modification items (c) and (d) were given to improve applicability to the HTGR.

(a) Optimizing manganese and silicon contents

Formation of stable and adherent oxidation films of MnCr_2O_4 spinel and SiO_2 is essential for the very high temperature components. Such an oxidation film is formed on the base metal through optimizing the Mn and Si contents for Hastelloy X (Shindo, 1982).

(b) Lowering aluminum and titanium contents

Internal oxidation and intergranular attack are suppressed through lowering the Al and Ti contents (Shindo, 1982).

(c) Lowering cobalt content

Radioactive contamination in the primary cooling system by Co-containing corrosion products decreases to negligible levels through lowering the Co content (Shindo, 1982).

(d) Optimizing boron content

Addition of boron improves the creep strength for Hastelloy XR (Kurata, 1986), but causes contamination of the core and degradation in weldability. Optimization of the B content, therefore, is needed for a specific purpose. To a Tungsten-arc Inert-gas (TIG) welding wire, the addition of boron within 40-60 ppm was made to improve the creep strength of the welded joints.

JAEA in cooperation with Mitsubishi Materials Group developed Hastelloy XR with the modifications (a) to (c) above by 1976. Then, various tests were conducted on Hastelloy XR to construct an engineering database for design of the HTGR. In addition, quality of Hastelloy XR including creep strength was improved with the modification (d) above by 1984. Based on the engineering database of Hastelloy XR, JAEA developed high temperature structural design guidelines including design allowable limits on Hastelloy XR by 1990.

The specification of the improved version of Hastelloy X, which is called the nuclear grade alloy Hastelloy XR, is shown in Table 8, with a comparison to that of Hastelloy X. Hastelloy XR with optimization of boron content is called Hastelloy XR-II, when it is necessary to distinguish Hastelloy XR-II from Hastelloy XR. Heat transfer tubes, hot header, etc. of the intermediate heat exchanger of the High Temperature Engineering Test Reactor (HTTR) is made of Hastelloy XR-II.

Figure 92 shows results of long-term corrosion tests under severe thermal cycles, wherein superiority of Hastelloy XR to Hastelloy X is demonstrated as expected from the protective oxide film formed on Hastelloy XR.

Table 10 - Specifications for Chemical Composition of Hastelloy XR and X

Material	Chemical Compositions (wt%)															
	Range	Elements														
		C	Mn	Si	P	S	Cr	Co	Mo	W	Fe	Ni	B	Al	Ti	Cu
Hastelloy XR	max	0.15	1.00	0.50	0.040	0.030	23.00	2.50	10.00	1.00	20.00	Remainder	0.010	0.05	0.03	0.50
	min	0.05	0.75	0.25	-	-	20.50	-	8.00	0.20	17.00	Remainder	-	-	-	-
Hastelloy X	max	0.15	1.00	1.00	0.040	0.030	23.00	2.50	10.00	1.00	20.00	Remainder	0.010	0.50	0.15	0.50
	min	0.05	-	-	-	-	20.50	0.50	8.00	0.20	17.00	Remainder	-	-	-	-

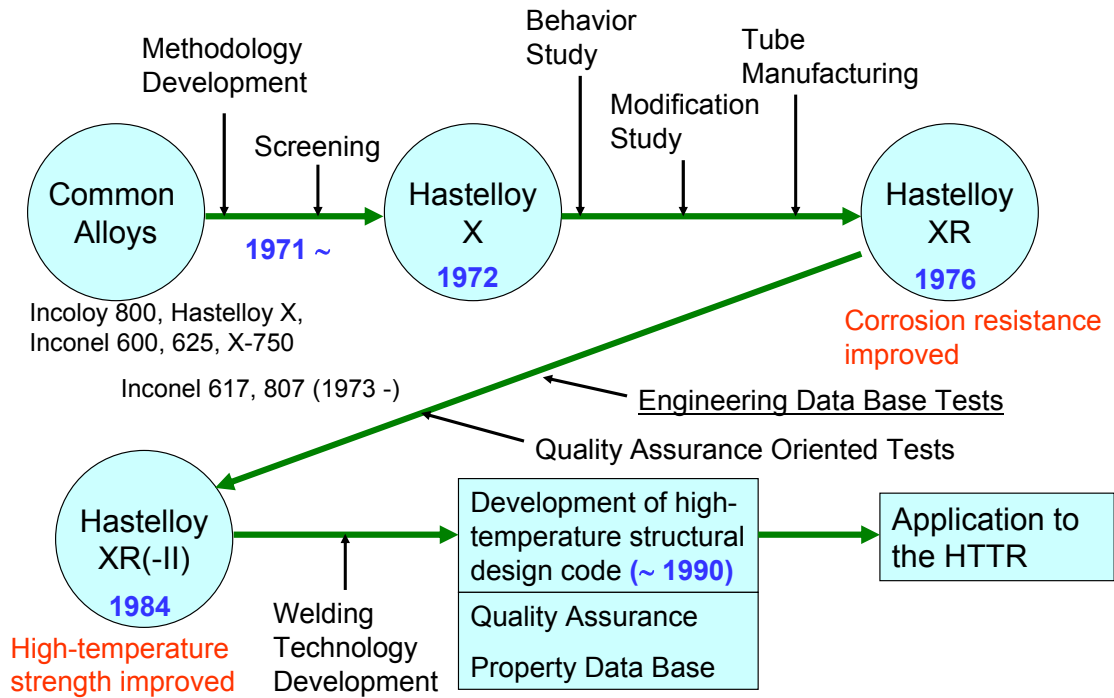


Figure 91 - Development of Hastelloy XR

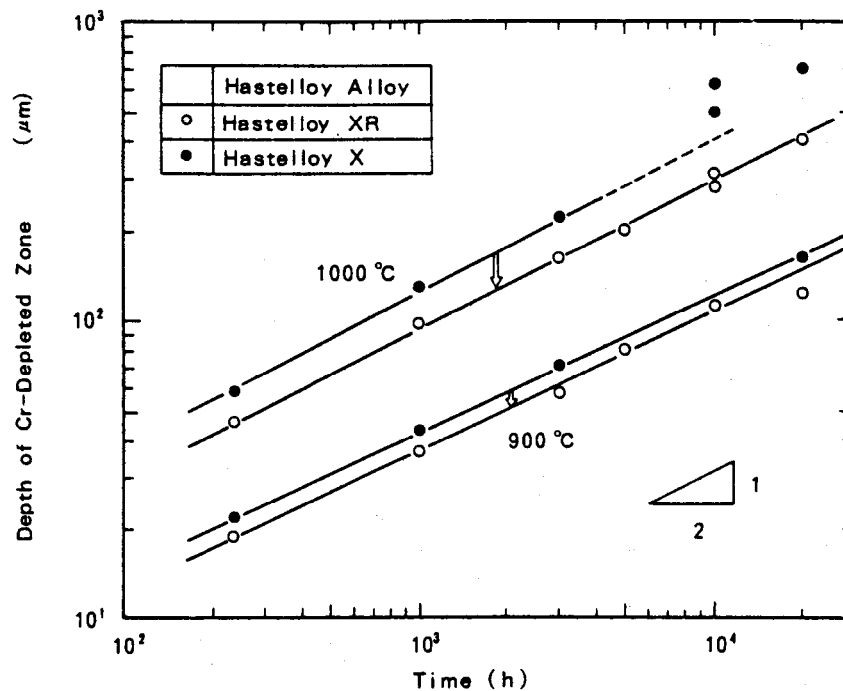


Figure 92 - Comparison of Environmental Effect in Cr-Depleted Zone Depth between Hastelloy XR and Hastelloy X

1.2 Data of Hastelloy XR

1.2.1 Creep fatigue

Creep fatigue test data of Hastelloy XR is shown in Table 11 and Table 12 and Figure 92 and Figure 94.

Table 11 shows results of low cycle fatigue tests with symmetric triangular strain waveform on Hastelloy X and Hastelloy XR at 900°C in simulated HTGR helium called JAERI-type B helium environment with impurity contents indicated in Table 13. Chemical composition of these materials is shown in Table 14.

Table 12 shows results of low cycle fatigue tests with trapezoidal strain waveform on Hastelloy XR at 900°C in JAERI-type B helium environment.

Figure 94 shows relation between total strain range and fatigue life under different strain rates arranging the data in Table 11. No significant difference in fatigue strength was observed between Hastelloy X and Hastelloy XR under the given conditions.

Figure 94 shows low cycle fatigue and creep fatigue data on Hastelloy XR at 900°C in JAERI-type B helium environment, which was used for development of high temperature structural design guidelines. Among the three different types of loadings with trapezoidal strain waveform, the creep fatigue life was reduced most effectively in tensile hold-time tests. Similar tendency is reported by Meurer et. al. (1984) on Incoloy 800H at 850°C and Inconel 617 at 950°C.

1.2.2 Creep

Creep rupture test data of Hastelloy XR from 800°C to 1050°C in air and in simulated HTGR helium, which was used for determination of design allowable limits in high temperature structural design guideline, is shown in Figure 95. Trends in stress dependence and data scattering of the creep rupture strength are judged to be quite similar at 1000°C to those at lower temperatures. Therefore, it was concluded that Hastelloy XR is stable at 1000°C or below.

Most of the data in Figure 63 was obtained in cooperative research of JAEA and National Institute for Materials Science (NIMS). Creep rupture test data of the cooperative research in air and in simulated HTGR helium (JAERI-type B helium) is shown in Table 15–Table 18 and Table 19, respectively. Figure 96 shows the creep rupture test data in air in Table 15–Table 18. Figure 97 shows comparison of the creep test data in air and JAERI-type B helium. No environmental effect can be observed by Figure 97. Chemical composition of Hastelloy XR used for the tests is shown in Table 18.

Creep rupture test data of Hastelloy XR-II from 700°C to 1000°C in air and in JAERI-type B helium is shown in Table 21–Table 23 and Table 24, respectively. The data was obtained in cooperative research of JAEA and NIMS. Figure 98 shows the creep rupture test data in air in Table 21–Table 23. Figure 99 shows comparison of the creep test data in air and JAERI-type B helium. Again, no environmental effect can be observed by Figure 67. Chemical composition of Hastelloy XR-II used for the tests is shown in Table 23.

Comparison of creep rupture test data on Hastelloy XR and Hastelloy XR-II is shown in Figure 100. Creep rupture time of Hastelloy XR-II is much larger than that of Hastelloy XR under the same condition.

1.2.3 Fatigue

In addition to the low cycle fatigue tests with symmetric triangular strain waveform in simulated HTGR helium described above, similar low cycle fatigue tests in air at various temperatures from

room temperature to 1000°C were conducted on Hastelloy XR so as to determine design allowable limits (Design fatigue strain range) in high temperature structural design guidelines.

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

Material	$\dot{\epsilon}t$ (1/s)	$\Delta\epsilon t$ %	$\Delta\epsilon_{in}$ (at 1/2 N_f) %	N_f
Hastelloy X	1×10^{-3}	0.28	0.07	56701
		0.40	0.17	5590
		0.80	0.58	1899
		1.20	0.97	512
	1×10^{-4}	0.28	0.12	11535
		0.40	0.23	4535
		0.80	0.60	1351
	2×10^{-5}	0.40	0.28	2974
		0.80	0.68	530
Hastelloy XR	1×10^{-3}	0.28	0.08	32238
		0.40	0.18	9978
		0.80	0.62	1326
		0.80	0.57	1664
		1.20	0.98	511
	1×10^{-4}	0.28	0.11	18160
		0.40	0.23	5856
		0.80	0.64	1103
	2×10^{-5}	0.40	0.28	1918
		0.40	0.28	2326
		0.80	0.67	551

Table 12 - Results of Low Cycle Fatigue Tests with Trapezoidal Strain Waveform on Hastelloy XR at 900°C in JAERI-Type B Helium Environment

Holdtime		$\Delta\epsilon t$ %	$\Delta\epsilon_{in}$ (at 1/2 N_f) %	N_f
Tension Side	Compression Side			
1 min	0	0.8	0.64	641
10 min	0	0.8	0.67	451
10 min	0	0.8	0.67	365
0	1 min	0.8	0.65	1427
0	10 min	0.8	0.66	1349
1 min	1 min	0.8	0.74	837
10 min	10 min	0.81	0.76	786

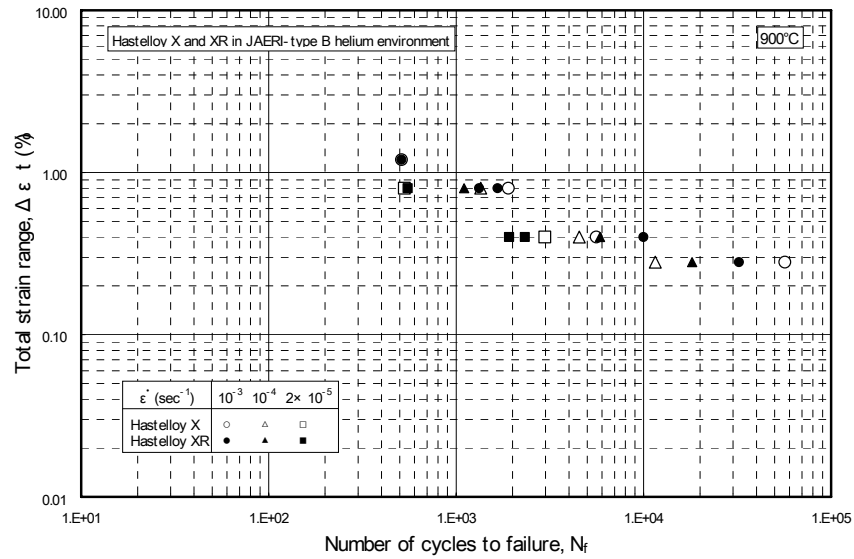


Figure 93 - Relation between Total Strain Range and Fatigue Life Under Different Strain Rates

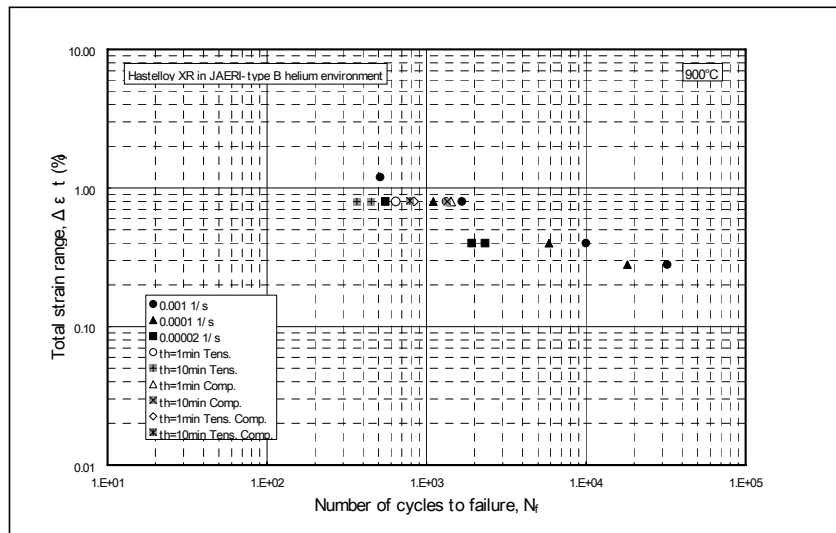


Figure 94 - Creep Fatigue Test Data on Hastelloy XR

Table 13 - Impurity Levels of Simulated HTGR Helium Called JAERI-Type B Helium

Impurity Levels (Pa)				
H2	H2O	CO	CO2	CH4
20 to 21	0.08 to 0.12	10 to 11	0.2 to 0.3	0.5 to 0.6

Table 14 - Chemical Composition of the Materials Hastelloy X and Hastelloy XR

Material	Chemical Compositions (wt%)													
	C	Mn	Si	P	S	Cr	Co	Mo	W	Fe	Ni	B	Al	Ti
Hastelloy X	0.07	0.61	0.39	0.012	<0.001	21.26	1.71	8.89	0.57	18.98	Bal.	0.00085	0.25	<0.01
Hastelloy XR	0.07	0.83	0.32	<0.005	0.006	21.84	0.19	9.06	0.53	18.26	Bal.	0.0001	0.02	<0.01

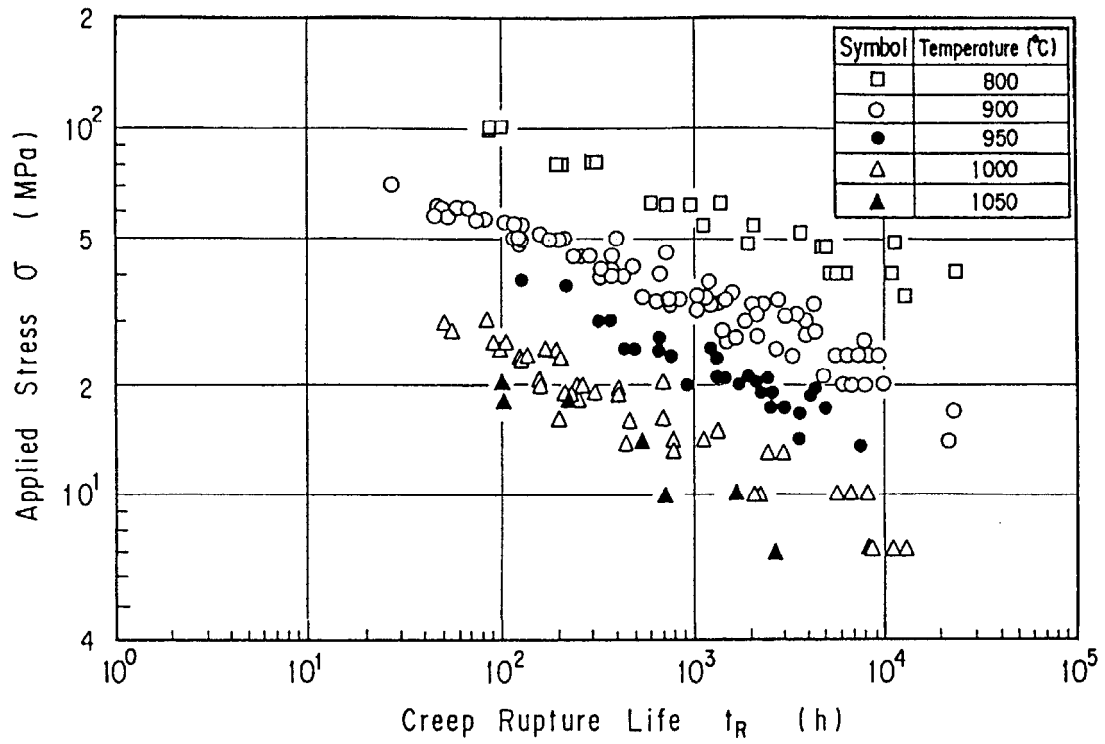
**Figure 95 - Creep Rupture Life for Hastelloy XR**

Table 15 - Results of Creep Tests for Hastelloy XR in Air (Tube)

Specimen No.	Temp (°C)	Stress (MPa)	t_r (h)	El (%)	RA (%)	e_0 (%)	\dot{e}_m (%/h)	$t_{1\%}$ (h)	t_3 (h)	e_3 (%)
XRT14	800	98.1	88.9	23.9	28.6	0.070	9.38E-02	9.8	29.2	3.020
XRT18		60.8	608.6	38.5	15.1	0.043	3.08E-03	187.0	173.8	0.885
XRT28		53.0	1119.2	15.5	13.4	0.038	1.95E-03	317.2	290.8	0.858
XRT20		47.1	1952.0	11.4	12.3	0.035	4.53E-04	782.0	475.0	0.430
XRT26		39.2	5624.6	8.7	11.7	0.028	4.67E-04	1901.0	3828.0	2.100
XRT16		39.2	6455.4	7.7	12.7	0.028	4.46E-04	1973.0	4384.8	2.270
XRT10		33.3	12884.8	5.2	9.1	0.023	1.27E-04	5794.0	10526.0	1.800
XRT21	850	39.2	1569.3	10.2	13.7	0.028	8.23E-04	530.4	331.6	0.525
XRT11	900	49.0	123.0	17.4	17.6	0.035	6.38E-02	14.6	40.3	2.840
XRT03		39.2	412.9	11	18.6	0.030	6.40E-03	95.3	77.8	0.776
XRT23		33.3	764.8	10.2	11.6	0.026	4.57E-03	201.8	341.0	1.815
XRT07		26.5	1675.6	9.1	11.6	0.020	1.53E-03	614.0	990.0	1.780
XRT27		23.5	3345.3	10.8	10.6	0.018	6.86E-04	1056.0	1720.0	1.640
XRT08		19.6	6434.7	8.1	9.5	0.015	2.02E-04	3475.0	3460.0	0.990
XRT06		13.7	21396.0	6.7	5.3	0.012	9.53E-05	6210.0	12480.0	1.800
XRT29	950	19.6	928.9	10.3	13.7	0.016	3.27E-03	222.0	210.6	0.906
XRT19	1000	18.6	316.9	15.1	12.3	0.018	5.74E-03	78.8	60.8	0.579
XRT09		13.7	795.7	12	13	0.013	3.71E-03	213.1	222.0	1.060
XRT17		9.8	2124.8	18.4	8.4	0.010	6.55E-04	849.0	739.0	0.792
XRT02		6.9	10920.6	27.3	11.6	0.007	4.67E-04	480.0	3726.0	3.068
XRT12	1050	17.7	105.0	18.8	17.6	0.020	1.65E-02	18.3	10.5	0.420
XRT15		9.8	718.5	10.2	10.6	0.012	1.55E-03	371.0	363.0	0.963
XRT04		6.9	2641.6	38.2	2.1	0.008	1.75E-03	437.0	922.0	2.050

Table 16 - Results of Creep Tests for Hastelloy XR in Air (Plate)

Specimen No.	Temp (°C)	Stress (MPa)	t_R (h)	El (%)	RA (%)	e_0 (%)	$\dot{\epsilon}_m$ (%/h)	$t_{1\%}$ (h)	t_3 (h)	e_3 (%)
XRS07	800	78.5	314.6	19.6	22.8	0.057	8.35E-03	82	81	0.97
XRS02		60.8	1409.9	10.1	14.4	0.042	8.28E-04	550	448	0.67
XRS15		53	2105.1	8.9	10.6	0.038	6.70E-04	786	636	0.72
XRS12		47.1	4981.4	7.7	9.9	0.033	2.29E-04	2292	1464	0.56
XRS09		39.2	23593.6	8.9	14	0.028	6.37E-05	9620	17126	1.70
XRS05	900	49	177.7	18.4	23.5	0.038	3.23E-02	22	24	1.08
XRS03		33.3	1479.2	9.4	11.9	0.027	2.36E-03	388	582	1.60
XRS16		26.5	4019.8	7.1	5.2	0.022	4.69E-04	1685	3000	1.70
XRS20		23.5	9487.7	5.7	10.9	0.018	1.18E-04	6110	6254	1.05
XRS01		19.6	9909	5.2	8.4	0.015	1.40E-04	4618	6322	1.43
XRS13		16.7	23521.6	6.8	7.7	0.013	5.94E-05	12720	14208	1.20
XRS08	1000	23.5	208.3	17	20.2	0.022	4.00E-03	60	38	0.40
XRS18		18.6	435.4	13	26.4	0.018	5.71E-03	103	91	0.78
XRS19		13.7	1124.7	11	9.1	0.013	1.97E-03	341	384	1.22
XRS11		9.8	5849.5	15	14	0.010	4.77E-04	751	2760	2.24
XRS17	1050	17.7	225.1	14.9	18.6	0.020	5.50E-03	69	54	0.53
XRS04		13.7	550.7	15.5	15.7	0.015	8.99E-03	66	151	1.99
XRS06		9.8	1696.4	9.8	9.5	0.012	2.02E-03	313	894	2.38
XRS14		6.9	8608.1	15.6	19.3	0.008	1.93E-04	361	4416	2.94

Table 17 - Results of Creep Tests for Hastelloy XR in Air (Bar)

Specimen No.	Temp (°C)	Stress (MPa)	t_R (h)	El (%)	RA (%)	e_0 (%)	$\dot{\epsilon}_m$ (%/h)	$t_{1\%}$ (h)	t_3 (h)	e_3 (%)
XRB09	800	78.5	307.9	25.6	24.7	0.057	1.78E-02	48	79	1.75
XRB04		47.1	5063.0	14.1	16.5	0.033	7.08E-04	1038	1145	1.11
XRB06	900	49.0	203.0	46.1	46.9	0.038	3.17E-02	20	17	0.80
XRB10		23.5	5611.9	25.8	32.0	0.018	2.09E-03	382	1314	3.16
XRB11	1000	18.6	263.5	38.5	45.9	0.018	4.55E-02	16	36	2.45
XRB07		9.8	5928.1	37.1	34.1	0.010	2.61E-03	242	1327	4.01

Table 18 - Results of Creep Tests for Hastelloy XR in Air (Subsize Specimen Machined from Tube)

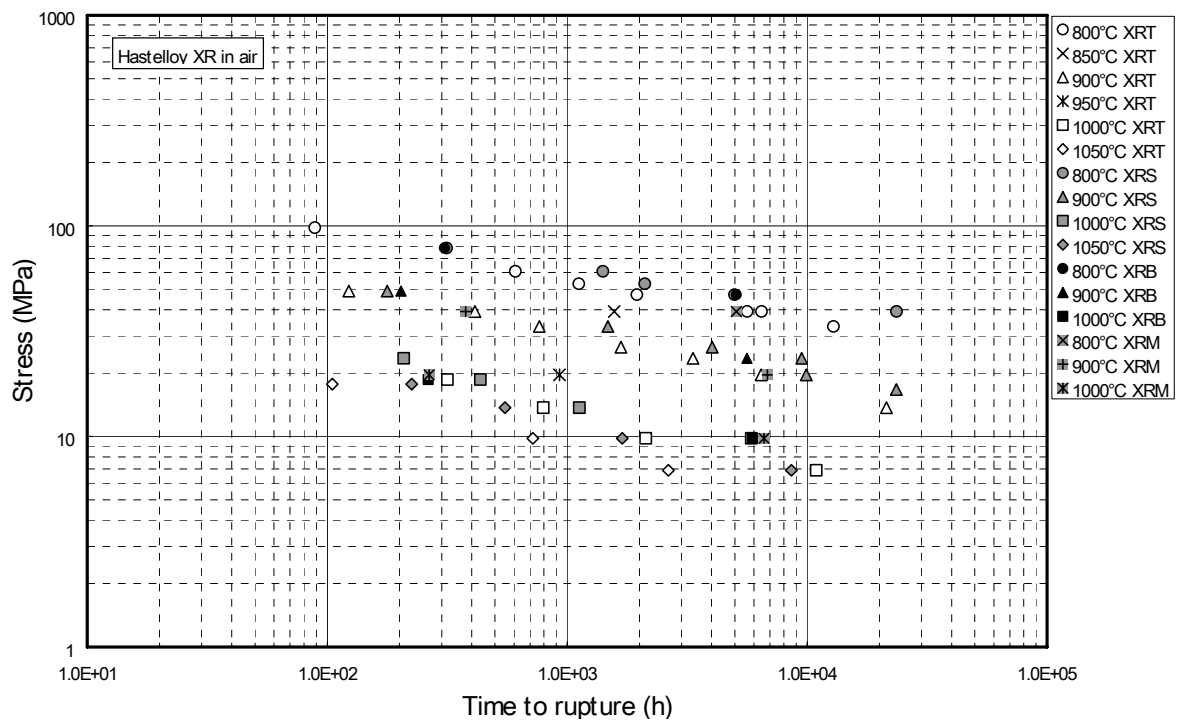
Specimen No.	Temp (°C)	Stress (MPa)	t _R (h)	EI (%)	RA (%)
XRM2	800	39.2	5070.1	4.8	9.8
XRM7	900	39.2	377.4	7.3	14.3
XRM3		19.6	6821.1	7.0	13.9
XRM4	1000	19.6	265.8	11.4	17.7
XRM5		9.8	6610.7	37.0	23.5

Table 19 - Results of Creep Tests for Hastelloy XR in JAERI-Type B Helium Environment

Temp (°C)	Stress (MPa)	t _R (h)	EI (%)	RA (%)	t _{1%} (h)	t ₃ (h)	e ₃ (%)
800	98.1	104.4	41.3	36.1	8	35	4.3
	78.5	298.5	31.2	23.7	41	105	3
	60.8	980.7	18	16	135	580	6.8
	51	3706.8	16	13.6	360	2180	5
	47.1	11485.8	26	24.2	360	6500	8.5
	39.2	10944.1	32	36	360	4050	6.2
900	58.8	62	47.3	55.3	4	30	9.1
	51	160.7	55.3	44.2	10	69	8.6
	49	217.8	43.3	41.2	18	110	12
	44.1	283.7	50	37.1	20	140	11
	39.2	694.7	41.7	36	48	360	12.6
	34.3	1579.6	35.8	30.6	130	860	9
	29.4	3839.7	24.6	21.3	210	2000	7.7
	26.5	3999.7	22	17.8	660	2400	7.6
	23.5	7447.1	26	30	720	4130	9
	19.6	7936.6	34	30	720	3300	7
1000	24.5	196.2	55	43.2	22	112	16.3
	19.6	410.6	42.3	33.4	36	212	12.5
	15.7	699.2	41	32.2	43	350	10.8
	12.7	2498.3	35.3	24.6	250	1380	12
	9.8	2247.3	45.3	35.5	500	1100	7.1
	9.8	8111.1	34	22	1160	2650	4.1

Table 20 - Chemical Composition of Hastelloy XR for Creep Tests

Material	Chemical Compositions (wt%)													
	C	Mn	Si	P	S	Cr	Co	Mo	W	Fe	Ni	B	Al	Ti
Hastelloy XR	0.07	0.88	0.27	<0.005	<0.005	21.9	Tr	9.1	0.47	18.2	Bal.	0.00028	0.03	0.02

**Figure 96 - Results of Creep Tests for Hastelloy XR in Air**

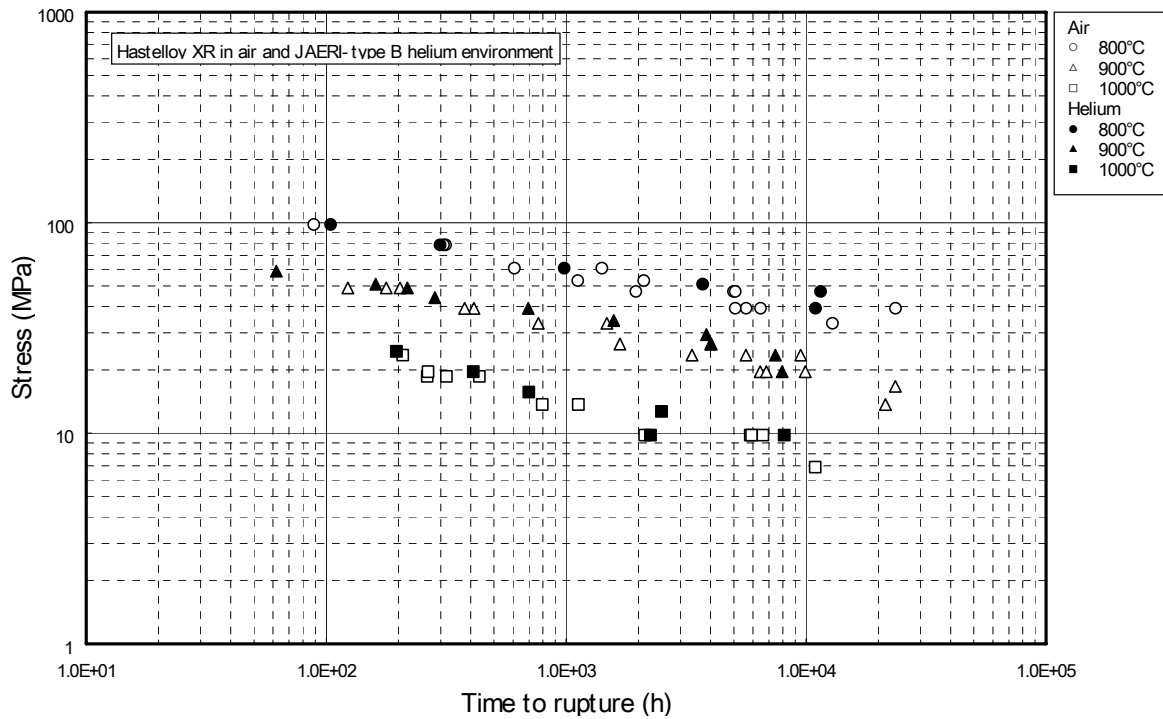


Figure 97 - Results of Creep Tests for Hastelloy XR in Air and in JAERI-Type B Helium Environment

Table 21 - Results of Creep Tests for Hastelloy XR-II in Air (Plate: $\phi 10\text{mm}$)

Specimen No.	Temp (°C)	Stress (MPa)	t_r (h)	El (%)	RA (%)	e_0 (%)	$\dot{\epsilon}_m$ (%/h)	$t_{1\%}$ (h)	t_3 (h)
XR2P10	700	225.6	129.0	97.1	76.8	0.412	1.65E-01	4.7	41.5
XR2P11		196.1	329.6	111.5	81.5	0.171	8.52E-02	10.8	98.0
XR2P12		176.5	796.8	86.1	85.3	0.132	3.32E-02	20.2	354.0
XR2P13		147.1	3016.4	103.3	87.2	0.109	8.75E-03	49.5	1404.0
XR2P14		117.7	26733.4	69.4	86.4	0.077	3.09E-04	207.0	9984.0
XR2P16	800	117.7	164.5	75.3	92.3	0.091	1.51E-01	4.2	67.0
XR2P01		98.1	651.6	62.7	88.0	0.069	2.77E-02	21.5	292.0
XR2P02		85.3	1418.2	83.2	87.9	0.066	1.18E-02	35.0	566.4
XR2P03		75.5	4341.1	35.1	67.3	0.048	2.30E-03	222.0	1680.0
XR2P15		68.6	7148.2	67.7	77.8	0.049	1.53E-03	327.0	1896.0
XR2P17	900	68.6	70.8	66.2	91.8	0.057	2.33E-01	4.0	13.8
XR2P18		58.8	197.7	109.1	82.9	0.043	9.08E-02	8.0	27.5
XR2P04		44.1	917.1	80.3	83.4	0.031	1.62E-02	54.5	68.0
XR2P05		39.2	2486.4	45.3	71.7	0.023	1.99E-03	286.0	193.5
XR2P06		31.4	8218.5	39.4	57.1	0.024	7.63E-04	1223.0	1872.0
XR2P20	1000	29.4	112.0	80.1	89.3	0.022	3.55E-02	19.0	16.0
XR2P07		22.6	623.8	55.9	50.9	0.018	2.56E-03	127.0	88.0
XR2P08		16.7	1462.5	66.2	55.8	0.014	1.11E-03	266.0	214.5
XR2P09		11.8	4437.8	53.8	34.6	0.006	1.45E-04	824.0	573.0
XR2P19		7.8	16194.7	34.0	36.8	0.004	9.41E-06	4423.0	3408.0

Table 22 - Results of Creep Tests for Hastelloy XR-II in Air (Plate: $\phi 6\text{mm}$)

Specimen No.	Temp ($^{\circ}\text{C}$)	Stress (MPa)	t_R (h)	El (%)	RA (%)	e_o (%)	\dot{e}_m (%/h)	$t_{1\%}$ (h)	t_3 (h)
XR2S3	700	117.7	24651.5	41.3	85.1	0.077	2.58E-04	168.0	9408.0
XR2S5	800	75.5	4116.6	60.6	74.5	0.065	2.88E-03	162.5	1656.0
XR2S6		68.6	8459.0	76.8	73.4	0.053	1.29E-03	354.5	2376.0
XR2S8	900	39.2	2895.7	56.8	65.7	0.027	1.16E-03	345.5	215.8
XR2S9		31.4	8590.2	40.9	48.4	0.023	7.62E-04	1167.0	1560.0
XR2S10	950	29.4	829.5	71.9	77.7	0.050	2.98E-03	140.0	111.0
XR2S10		22.6	2647.6	62.9	56.1	0.032	1.38E-03	335.5	280.0

Table 23 - Results of Creep Tests for Hastelloy XR-II in Air (Tube)

Specimen No.	Temp ($^{\circ}\text{C}$)	Stress (MPa)	t_R (h)	El (%)	RA (%)	e_o (%)	\dot{e}_m (%/h)	$t_{1\%}$ (h)	t_3 (h)
XR2T1	700	225.6	135.7	109.9	75.0	0.668	1.94E-01	2.7	44.0
XR2T11		196.1	355.8	106.3	78.8	0.183	7.18E-02	12.1	88.0
XR2T12		176.5	622.1	66.0	84.5	0.127	3.81E-02	24.7	202.0
XR2T13		147.1	3237.4	59.7	84.1	0.101	6.14E-03	78.5	1200.0
XR2T15	800	117.7	178.3	87.6	91.8	0.091	1.27E-01	6.6	62.5
XR2T16		98.1	604.2	70.8	86.0	0.071	3.44E-02	21.8	247.0
XR2T01		85.3	1387.4	71.2	79.5	0.060	1.36E-02	45.0	556.8
XR2T02		75.5	3446.1	57.4	71.1	0.052	4.81E-03	142.5	1152.0
XR2T03		68.6	6196.2	41.4	61.6	0.049	2.01E-03	445.5	1536.0
XR2T17	900	68.6	101.4	67.7	86.5	0.052	1.02E-01	8.5	13.0
XR2T18		58.8	201.6	51.7	77.7	0.046	4.96E-02	16.5	19.5
XR2T04		44.1	1231.7	42.4	61.9	0.037	2.57E-03	164.0	127.2
XR2T05		39.2	2285.1	34.8	60.4	0.027	1.51E-03	279.0	1207.2
XR2T06		31.4	7830.8	33.5	54.5	0.022	6.92E-04	692.0	3120.0
XR2T19	1000	29.4	215.0	50.5	64.6	0.027	6.00E-03	42.0	24.2
XR2T20		22.6	737.5	46.3	56.1	0.021	2.28E-03	199.0	178.5
XR2T07		16.7	2021.6	47.3	45.2	0.013	6.85E-04	415.0	1156.8
XR2T08		11.8	6308.3	34.3	28.6	0.019	2.48E-04	941.5	3312.0

Table 24 - Results of Creep Tests for Hastelloy XR-II In JAERI-Type B Helium Environment (Plate: $\phi 6\text{mm}$)

Specimen No.	Temp ($^{\circ}\text{C}$)	Stress (MPa)	t_R (h)	El (%)	RA (%)	e_0 (%)	\dot{e}_m (%/h)	$t_{1\%}$ (h)	t_3 (h)
60P21	700	225.6	117.5	70.0	66.8	0.540	1.77E-01	3.4	54.0
60PH12		196.1	301.7	69.2	79.9	0.177	7.35E-02	17.5	128.5
60P10A		176.5	784.8	64.7	71.1	0.125	2.94E-02	24.0	433.0
60P12		147.1	3167.0	56.1	71.5	0.105	5.32E-03	50.0	2140.0
60P07	800	117.7	123.0	80.8	75.2	0.085	1.00E-02	5.0	22.0
60P09		98.1	443.1	64.7	69.1	0.071	3.30E-02	18.5	89.5
60P10		85.3	1287.4	55.9	63.7	0.062	9.45E-03	43.0	272.0
60P11		75.5	4851.6	43.9	56.4	0.056	1.40E-03	208.0	1520.0
60P19W		68.6	10175.8	24.8	29.3	0.051	4.87E-04	490.0	3520.0
60P22	900	68.6	75.2	88.3	74.5	0.051	2.61E-01	3.4	16.7
60P06		58.8	191.2	72.3	60.6	0.044	1.01E-01	6.8	56.0
60P25W		44.1	1787.3	62.4	60.4	0.034	2.84E-03	138.0	117.0
60P13		39.2	2683.0	31.1	44.4	0.031	9.19E-04	230.0	655.0
60P14		31.4	10056.3	24.5	20.5	0.025	1.36E-04	3500.0	3660.0
60P24	1000	29.4	183.5	49.1	53.7	0.024	1.35E-02	35.5	33.7
60P23		22.6	504.4	39.7	32.6	0.016	2.84E-03	100.0	37.0
60P16		16.7	1754.3	38.3	28.2	0.015	1.22E-03	347.0	274.0

Table 25 - Chemical Composition of Hastelloy XR-II for Creep Tests

Material	Chemical Compositions (wt%)													
	C	Mn	Si	P	S	Cr	Co	Mo	W	Fe	Ni	B	Al	Ti
Hastelloy XR-II (tube)	0.07	0.86	0.32	<0.01	<0.01	21.98	0.05	8.83	0.51	17.70	Bal.	0.005	0.02	0.01
Hastelloy XR-II (plate)	0.07	0.88	0.33	<0.001	0.001	21.99	0.06	8.73	0.63	17.80	Bal.	0.006	0.03	0.01

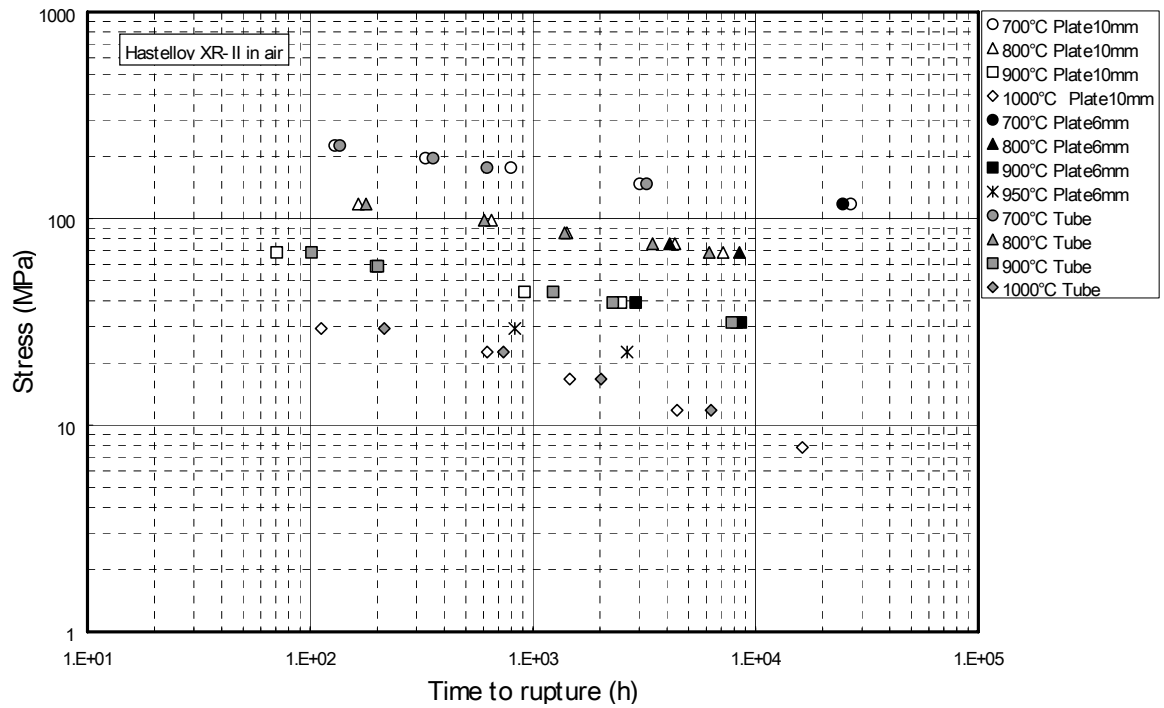


Figure 98 - Results of Creep Tests for Hastelloy XR-II in Air

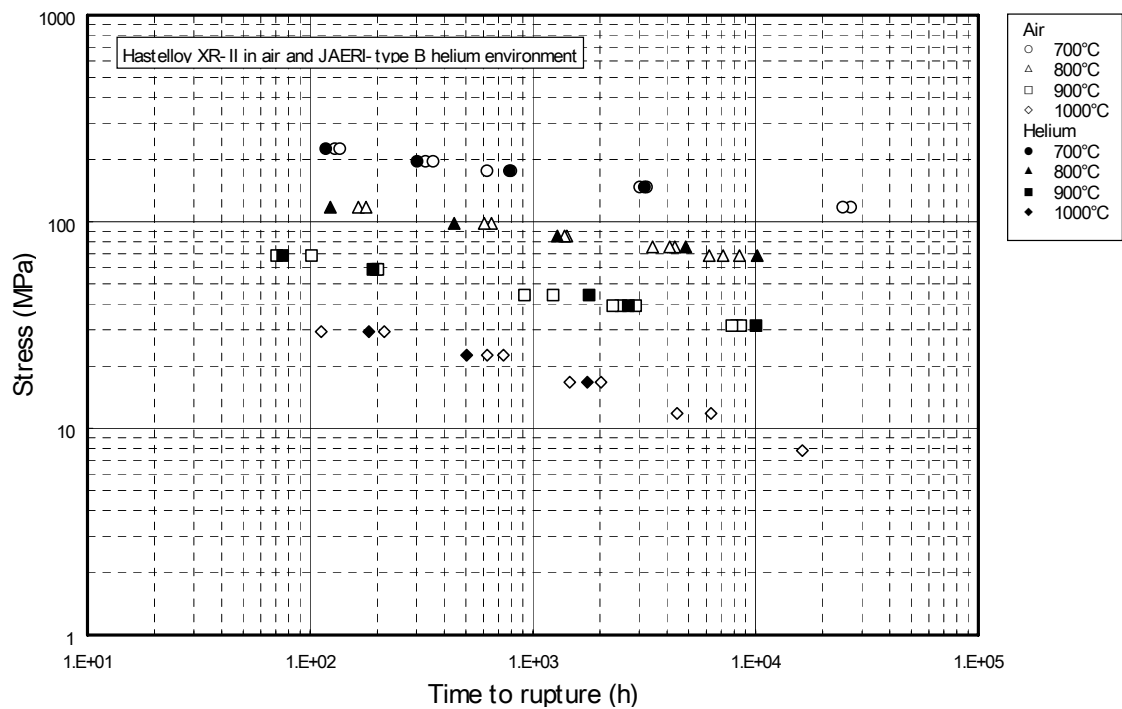


Figure 99 - Results of Creep Tests for Hastelloy XR-II in Air and in JAERI-Type B Helium Environment

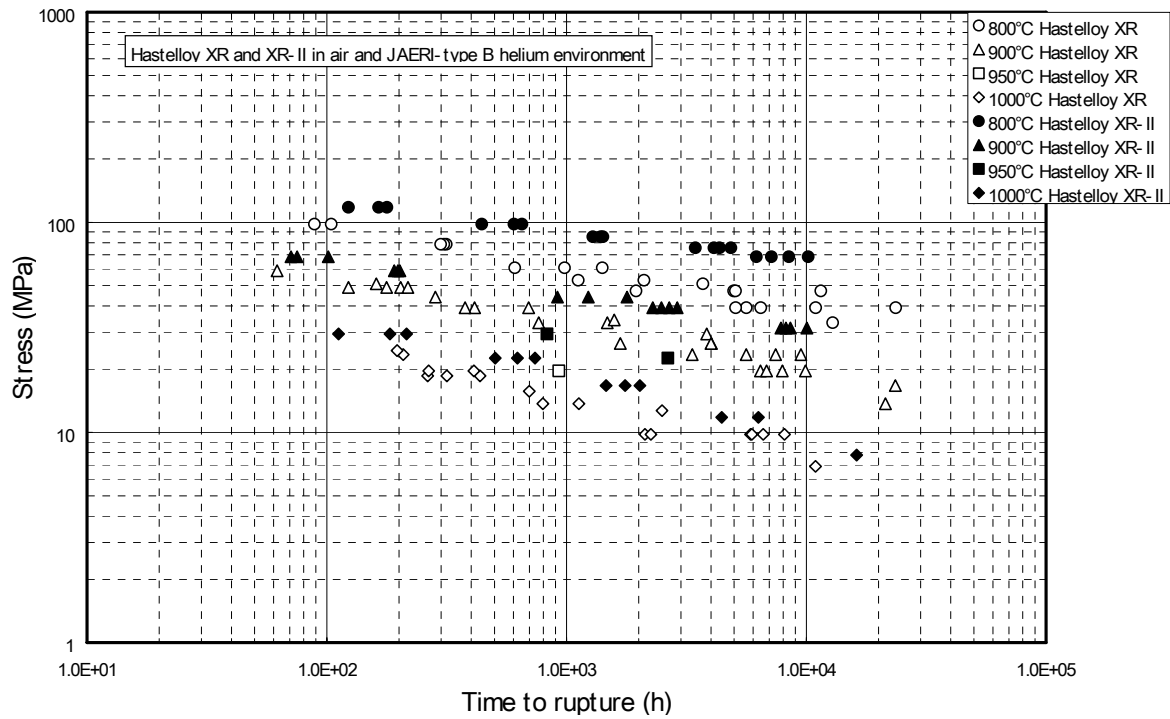


Figure 100 - Comparison of Creep Test Data for Hastelloy XR and Hastelloy XR-II

2 CREEP-FATIGUE CRITERIA ON HASTELLOY XR

2.1 High Temperature Structural Design Guideline for HTGR

2.1.1 Introduction

The primary cooling system components and related components that serve as the reactor coolant pressure boundaries of the HTTR are used at high temperatures in creep regime. Figure 101 shows cooling system of the HTTR. In particular, the heat transfer tubes and hot header of the intermediate heat exchanger (IHX) are subjected to temperatures above 900°C. The reactor pressure vessel as well as the metallic core support structures are exposed to the reactor coolant at temperatures of around 400°C under an irradiation condition. High temperature structural materials are chosen for the high temperature components of the HTTR, taking into careful considerations the service conditions and safety functions of the components. The material used are as follows.

- A nickel-base corrosion and heat resistant superalloy Hastelloy XR
- A normalized and tempered (NT) 2 1/4Cr-1Mo steel
- Two types of austenitic stainless steel, SUS321TB and SUS316
- 1Cr-0.5Mo-V steel, an alloy steel bolting material for high temperature service.

Some of the high temperature materials and their service temperatures are beyond the well-established high temperature structural design codes such as the Elevated Temperature Structural Design Guide for the Prototype Fast Breeder Reactor “Monju” (abbreviated as FBR Code) and the ASME Boiler and Pressure Vessel Code Case N-47 (ASME, 1986). Accordingly, development of a new high temperature structural design guideline was necessary for these materials at their service temperatures. Moreover, at the very high temperatures, where creep deformation is significant, component design based on elastic analysis is not possible.

Thus, extensive R&D was carried out not only in JAEA but also in national and private research organizations in Japan to establish a reliable high temperature structural design guideline.

2.1.2 Identification of Failure Modes

A high temperature structural design guideline provides design limits and rules for guarding high temperature components against failure modes. Development of a new high temperature structural design guideline, therefore, requires

- (a) Identification of failure modes under exposure to service environments within the guideline application temperature range for each material, and
- (b) Development of design limits and rules for guarding against each failure mode with appropriate safety margins.

From reviewing material test results and information on failures at commercial plants and experimental facilities, the following failure modes were identified.

- (a) Ductile rupture by short-term loading
- (b) Creep rupture by long-term loading
- (c) Buckling by short-term loading
- (d) Creep buckling by long-term loading
- (e) Creep fatigue failure

(f) Gross distortion by incremental collapse and ratcheting

(g) Loss of function by excessive deformation.

These failure modes are the same as those considered in well-established high temperature structural design codes. It should be noted here that the long-term loading means loading at high temperatures that develops significant creep effect over a long period.

2.1.3 Developments of Design Limits and Rules

The fact that the failure modes for the new materials are the same as for those of the well-established codes suggests the possibility that fundamental philosophies on design limits and rules of the well-established codes can be applicable to the new material, Hastelloy XR. Among the well-established high temperature structural design codes, the FBR Code was the only one that had been authorized by the Japanese government, and so it was the most appropriate for discussion on applicability to the new material. We came to the conclusion that design limits and rules for the above-mentioned seven failure modes can be developed on the basis of the fundamental philosophies of the FBR Code as shown in Table 26.

On this conclusion, the detailed design limits and rules were developed based on experimental data on material properties and structural mechanics behavior under multi-axial stress states, referring to those of the FBR Code, as described below.

2.1.4 Material Characterization on Hastelloy XR

The maximum metal temperature of Hastelloy XR in the HTTR reaches about 900°C even during the normal operation and is likely to exceed 950°C but less than 1000°C in events such as a loss of secondary cooling.

Taking into account the service temperature conditions, material tests and structural mechanics tests for both base metals and TIG-weld joints were conducted at temperatures ranging from room temperature to 1050°C, mainly in JAEA but also in the National Institute for Materials Science (NIMS) and research laboratories of private nuclear power companies. Test conditions of major material property tests for the base metals are briefly listed in Table 27. Test specimens were taken from product forms of tubes, plates, forging cylinders and bars simulating application to the HTTR high temperature components.

By carefully reviewing the experimental data, the following results were derived.

(a) Tensile property

At low or intermediate temperatures up to 800°C, Hastelloy XR is work-hardening under monotonic loadings at the strain rate of 0.3%/min which is specified for tensile tests by the Japan Industrial Standards (JIS), and has hardening ratios of two or above, similarly to austenitic stainless steels (the hardening ratio is defined as a ratio of ultimate tensile strength to yield strength). On the other hand, at high temperatures above 850°C, an abrupt decrease in load or a wavy stress-strain curve under straining at this strain rate is observed due to dynamic recrystallization, as shown in Figure 102.

Taking into consideration that dynamic recrystallization is not observed at higher strain rates of about 100%/min as shown in Figure 103, the strain rate for the tensile tests was changed for Hastelloy XR from 0.3%/min to 100%/min at high temperatures over 800°C. Time-independent allowable limits were generated from the tensile test data at this higher strain rate.

(b) Creep property

Since many commercial superalloys are known to lose their stability of mechanical strength at very high temperatures above 1000°C, the maximum temperature by which high temperature strengths, in particular creep rupture strength, are stable for Hastelloy XR is required to be identified. Figure 103 shows that trends in stress dependence and data scattering of the creep rupture strength are quite similar at 1000°C to those at lower temperatures. Therefore, it was concluded that Hastelloy XR is stable up to 1000°C.

Concerning the helium environmental effect on creep rupture strength, Figure 104 shows creep rupture lives under a specific stress in various helium environments. Hastelloy XR suffers no degradation in creep rupture strength except in a decarburizing environment. In this figure, a helium environment is characterized fairly well in the stability diagram for Cr ($a_{Cr}=0.8$) which is expressed by a carbon activity a_C and oxygen partial pressure PO_2 . Atmospheres denoted as the areas I and II lead to rapid decarburization with or without oxidation, while in the areas IV and V rapid carburization occurs. In area III, mild carburization occurs. In Figure 104, a creep rupture life at a specified helium environment is scaled to lengths of the bar located on the stability diagram. A detailed description of this diagram is given in Kurata, Y. et. al., (1989). The primary coolant of the HTTR shall be in the area III where any significant degradation in creep rupture life is not observed for Hastelloy XR. Then, it is not necessary to consider helium environment effects on design allowable limits for Hastelloy XR.

(c) Creep-fatigue interaction

Creep-fatigue interaction for Hastelloy XR is quite similar to those for austenitic stainless steels such as SUS304 and 316. Degradations in lifetime are more pronounced due to holds in tension than those in compression. Figure 105 and Figure 106 show the applicability of the well-known cycle and time fraction rule proposed by Robinson (1952) and Taira (1962), which is adopted in the FBR Code. The accumulated fatigue and creep damage fractions in the figures were calculated with design parameters. It can be concluded from these figures that the linear summation rule of cycle and time fractions is applicable to Hastelloy XR with a great deal of safety margins even at very high temperatures.

(d) Applicability of the Fast Breeder Reactor Code

As discussed above, the material properties for Hastelloy XR were observed to be basically similar to those for austenitic stainless steels. These observations lead to the conclusion that the FBR Code is, in principle, applicable to Hastelloy XR at the temperatures ranging to 1000°C, with a modification to the tensile test procedure.

(e) Structural mechanics behavior

The high temperature structural design guideline for class 1 components of the HTTR was established on the basis of component-wise structural mechanics behavior data as well as material property data referring to the FBR Code. The emphasis of the structural mechanics research works was placed on the applicability of the FBR Code to Hastelloy XR under the service conditions of the very high temperature components. Research works for Hastelloy XR include experiments on multiaxiality of creep rupture strength and creep-fatigue interaction, and on creep buckling. Further research works were carried out for establishment of creep analysis methods for Hastelloy XR.

(1) Multiaxiality of creep rupture strength and creep fatigue damage

Since the very high temperature components are exposed to multiaxial loading conditions, multiaxial formulations are required for high temperature strengths of Hastelloy XR. In the FBR Code, the stress intensity criterion, i.e., the maximum shear stress criterion, is adopted

as the multiaxial formulation for primary stresses, while Von Mises' stresses is that for primary + secondary stresses in evaluating a creep damage. Figure 107 shows the applicability of Von Mises' criterion to that of creep rupture strength. The experiments were carried out in such a manner that a tubular test specimen was subjected to a combination of axial and torsional loads. From this figure, it was concluded that the Von Mises' criterion predict the creep rupture life on the safe side. Consequently, the multiaxial formulations, which were given in the FBR Code, were demonstrated to be applicable to Hastelloy XR

(2) Creep buckling

Heat transfer tubes of the IHX shall not fail by a creep buckling at a piping rupture accident in the secondary cooling system. Component-wise experiments, therefore, were conducted at the Helium Engineering Demonstration Loop (HENDEL) at JAERI so as to demonstrate the structural integrity of the tubes against the creep buckling and the applicability of a design rule given in the design code. The creep buckling data demonstrated the structural integrity with a great safety margin. A finite element calculation predicted the creep buckling time in good agreement with the experimental data, i.e., within an accuracy of 50%.

(3) Creep analysis method

Key items for establishing an appropriate creep analysis method are as follows:

- Generation of an appropriate creep constitutive equation,
- Definition of correct safety margins for uncertainties in predicting creep behavior, and
- A procedure to define loading sequences or combinations

For item one several research experiments were carried out to clarify a hardening rule and a flow rule under multiaxial stress states and also statistical analyses were made to formulate a creep equation, i.e., a correlation of creep data from constant uniaxial load tests under isothermal conditions. The experimental data showed the applicability of strain hardening rule and Von Mises' flow rule to Hastelloy XR. The statistical analyses revealed that the time function proposed by Garofalo, et al (1963) correlates the creep curve data in the superior agreement to the rational time function (Booker, 1977). Figure 108 shows the superiority of Garofalo's expression.

For item two, principles to define the safety margins for variations in creep behavior of a high temperature structure were established through sensitivity analysis of a creep constitutive equation. The analytical results clarified that the variations might be covered with those in fundamental creep property such as creep strain curves.

For item three, creep analyses of the very high temperature components were conducted, taking into account a unique feature of thermal transient behavior of the components.

Finally, the design limits and rules for Hastelloy XR in the HTTR high temperature structural design guideline were developed referring to those of the FBR Code, with exceptions.

Table 26 - HTGR High Temperature Structural Design Guideline Features

Materials	Code features
Hastelloy XR	Referred to the FBR Code (Elevated Temperature Structural Design Guide for Class 1 Components of Prototype Fast Breeder Reactor “Monju”), design and limits are established from material properties and component test data.
2 1/4Cr-1Mo steel and Austenitic stainless steels (SUS321 and SUS316)	Design rules and limits are the same as those of the FBR Code. Helium environment and neutron irradiation effects are newly added to the design limits.
1Cr-0.5Mo-V steel	Design rules and limits are established from material properties data, taken into account the semi-creep service conditions in the HTTR

Table 27 - Mechanical Properties Data on Hastelloy XR Obtained for High Temperature Structural Design Guideline

Test item	Test conditions
Tensile tests	Temperatures : RT to 1000 °C, every 25 °C Strain rates : 0.3 %/min to 100 %/min
Creep tests	Temperatures : 500 to 1050 °C, every 50 °C Maximum test time : about 38,000 hours Total number of tests : about 300
Fatigue and creep-fatigue interaction tests	Temperatures : RT to 1000 °C, every 50 °C at high temperatures Strain rates : 2×10^{-5} to 1×10^{-3} /s Hold times : 0 to 1 hour Materials : as-received and thermally aged
Fracture toughness tests	Thermal aging conditions Temperatures : 800 to 1000 °C Maximum aging time : 2,000 hours Test items : V-notch charpy, fracture toughness and fatigue crack propagation rate
Corrosion tests	Environment : HTTR coolant gas-simulated helium Temperatures : 900 to 1000 °C Maximum test time : 30,000 hours
Others	Poisson’s ratio, thermal expansion and so on

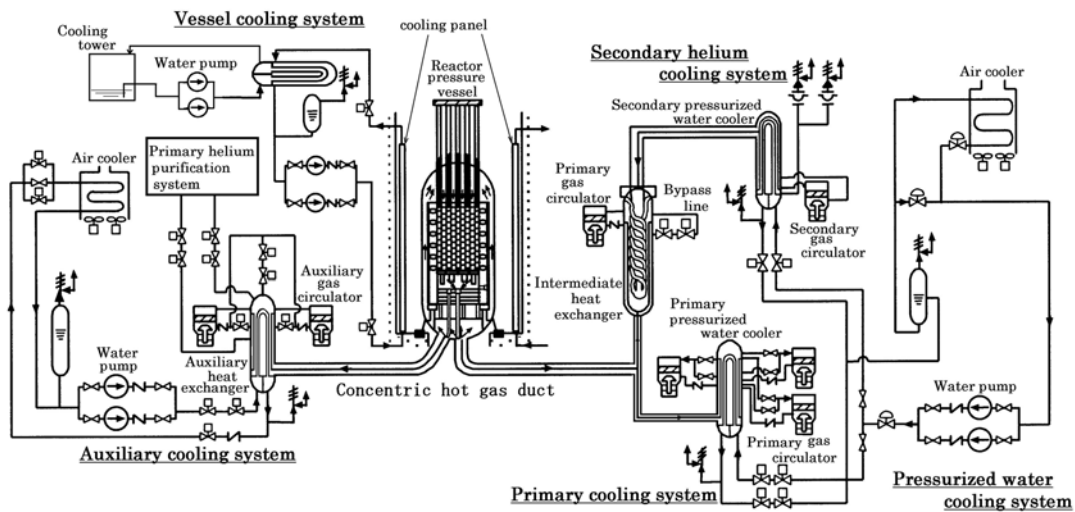


Figure 101 - Cooling System of the HTTR

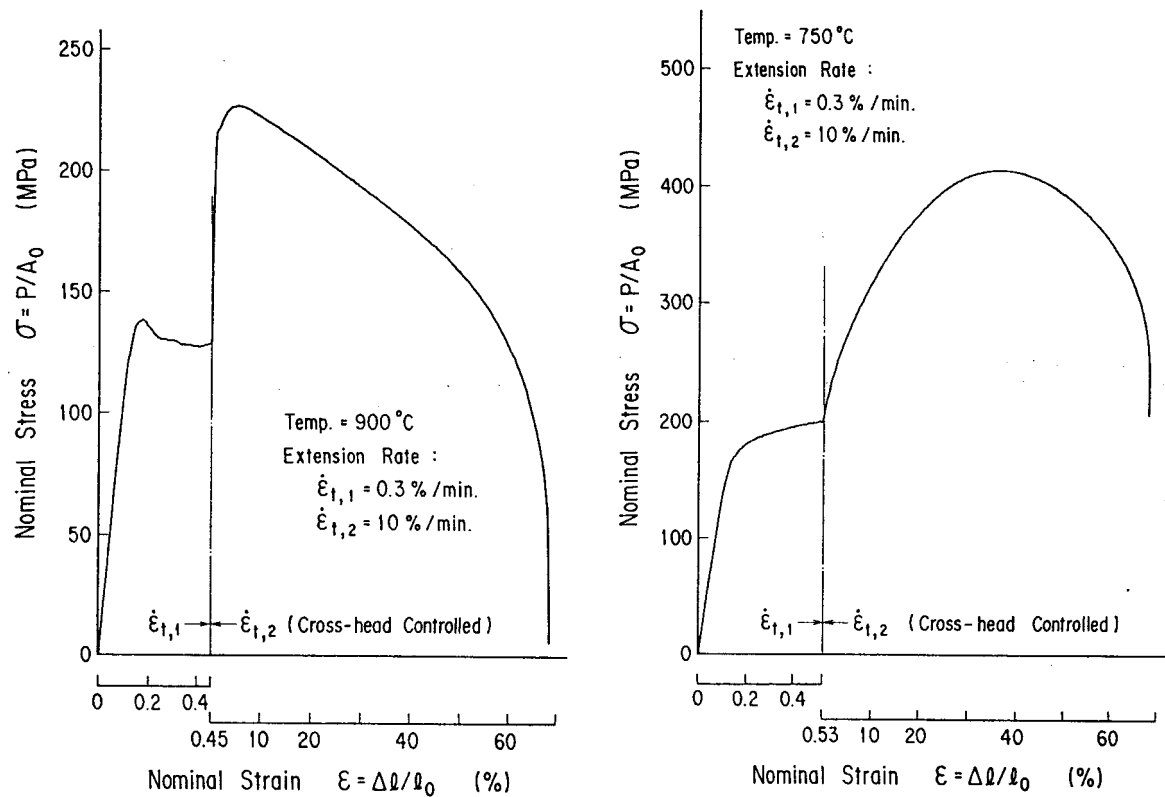


Figure 102 - Tensile Stress-Strain Curves for Hastelloy XR at the Strain Rates of JIS

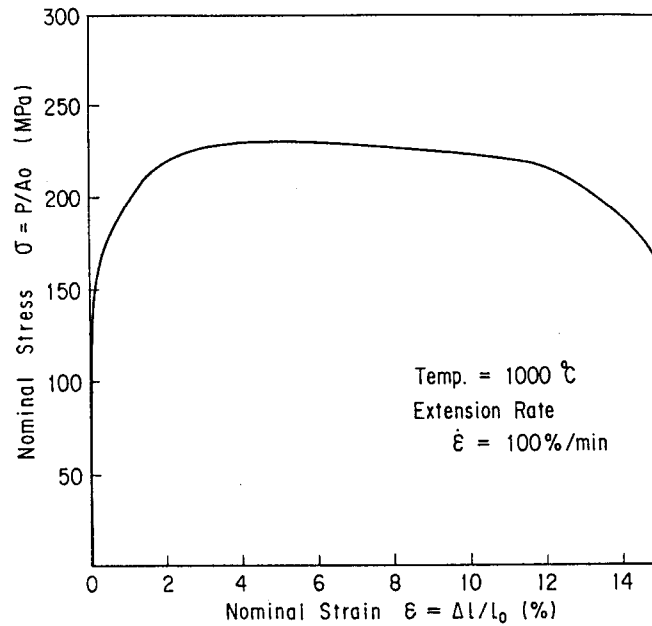


Figure 103 - Stress-Strain Curve for Hastelloy XR (1000°C, Extension Rate = 100%/Min)

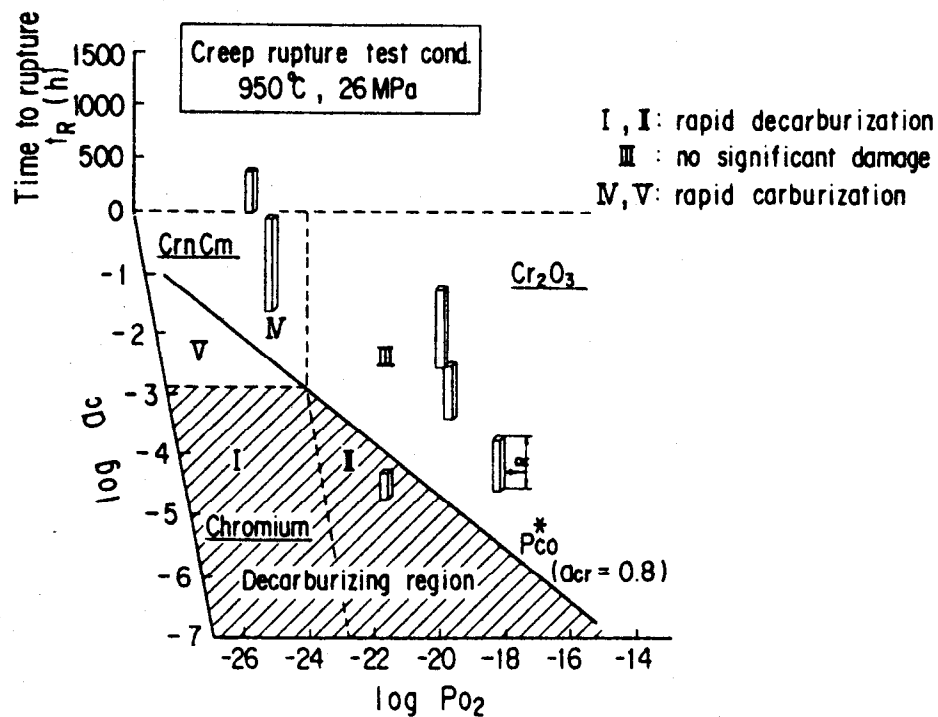


Figure 104 - Comparison of Creep Rupture Lives for Hastelloy XR in Several Different Helium Environments on the Stability Diagram for Cr ($A_{cr}=0.8$) At 950°C Under 26MPa

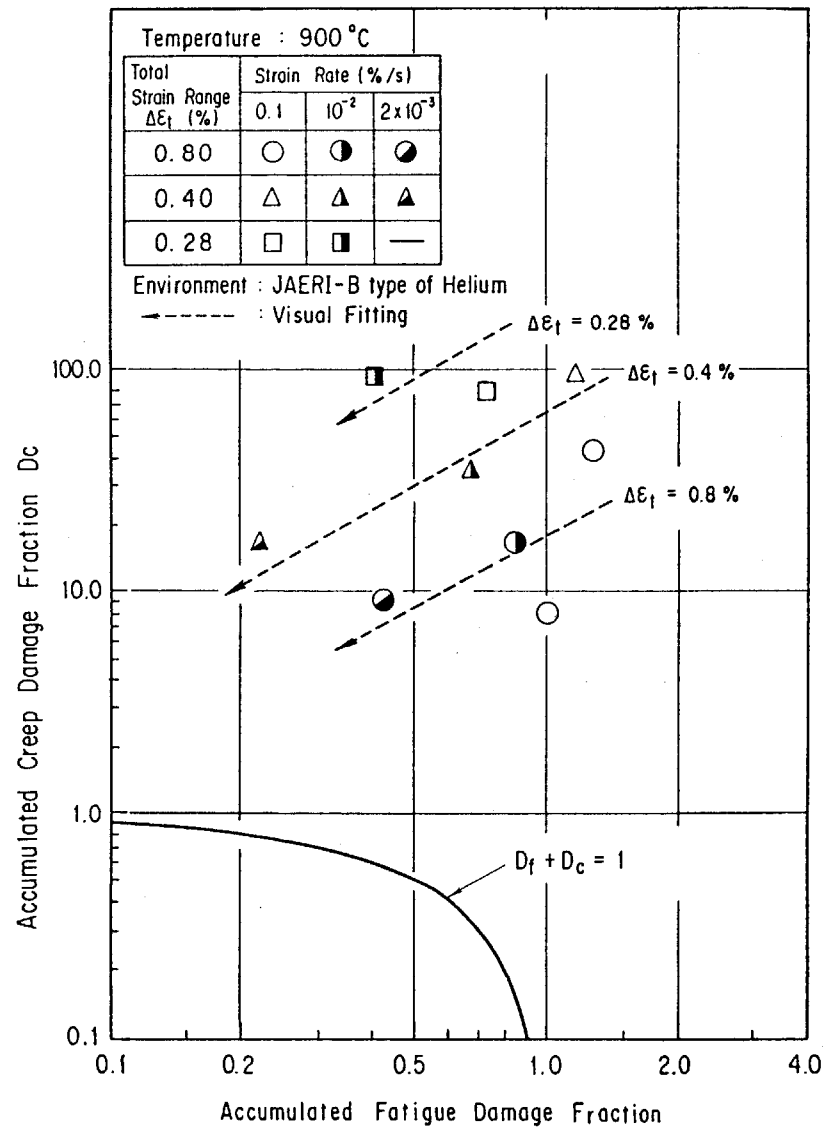


Figure 105 - Strain Rate Effect on Creep-Fatigue Interaction for Hastelloy XR

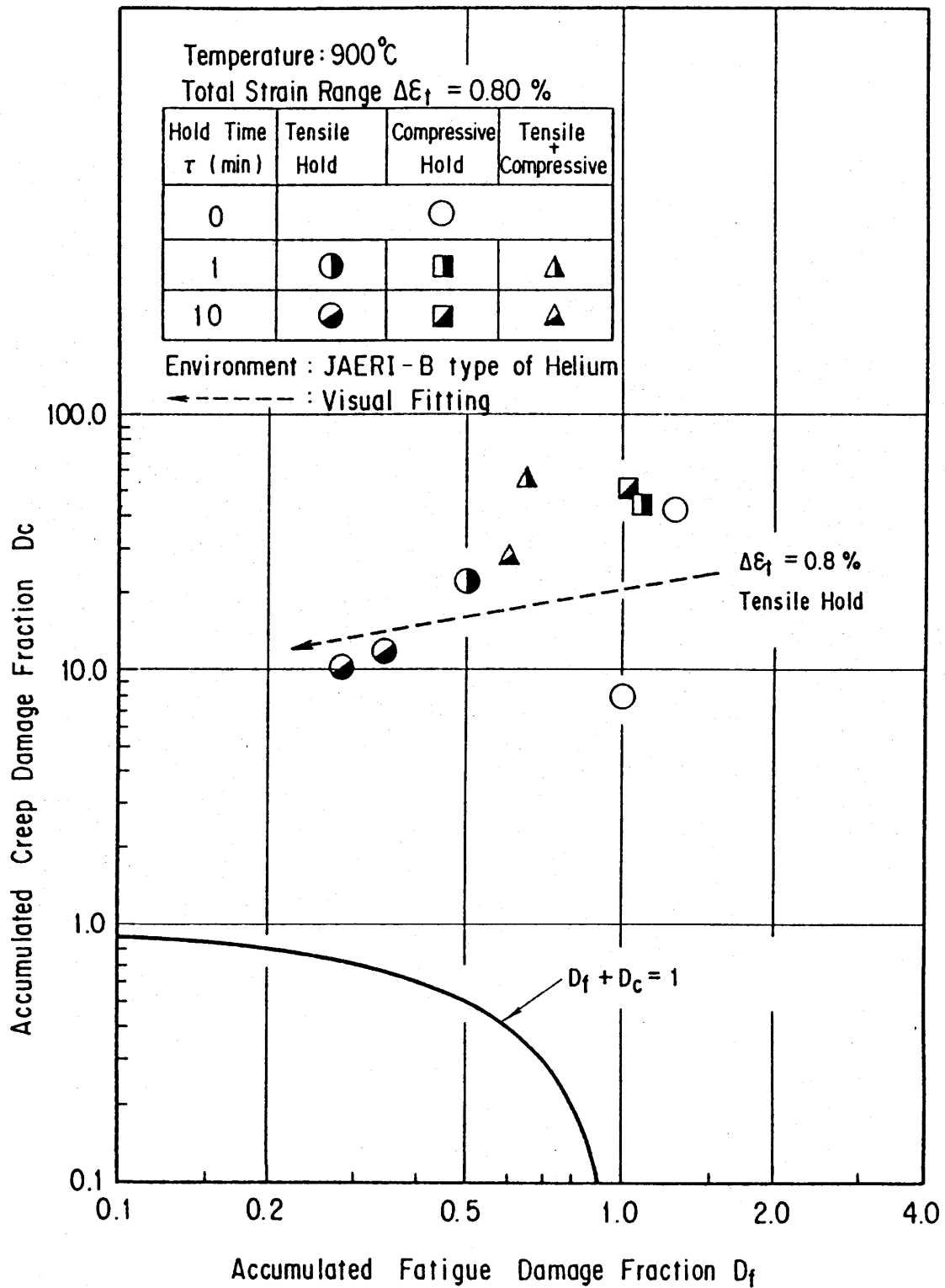


Figure 106 - Hold Time Effect on Creep-Fatigue Interaction for Hastelloy XR

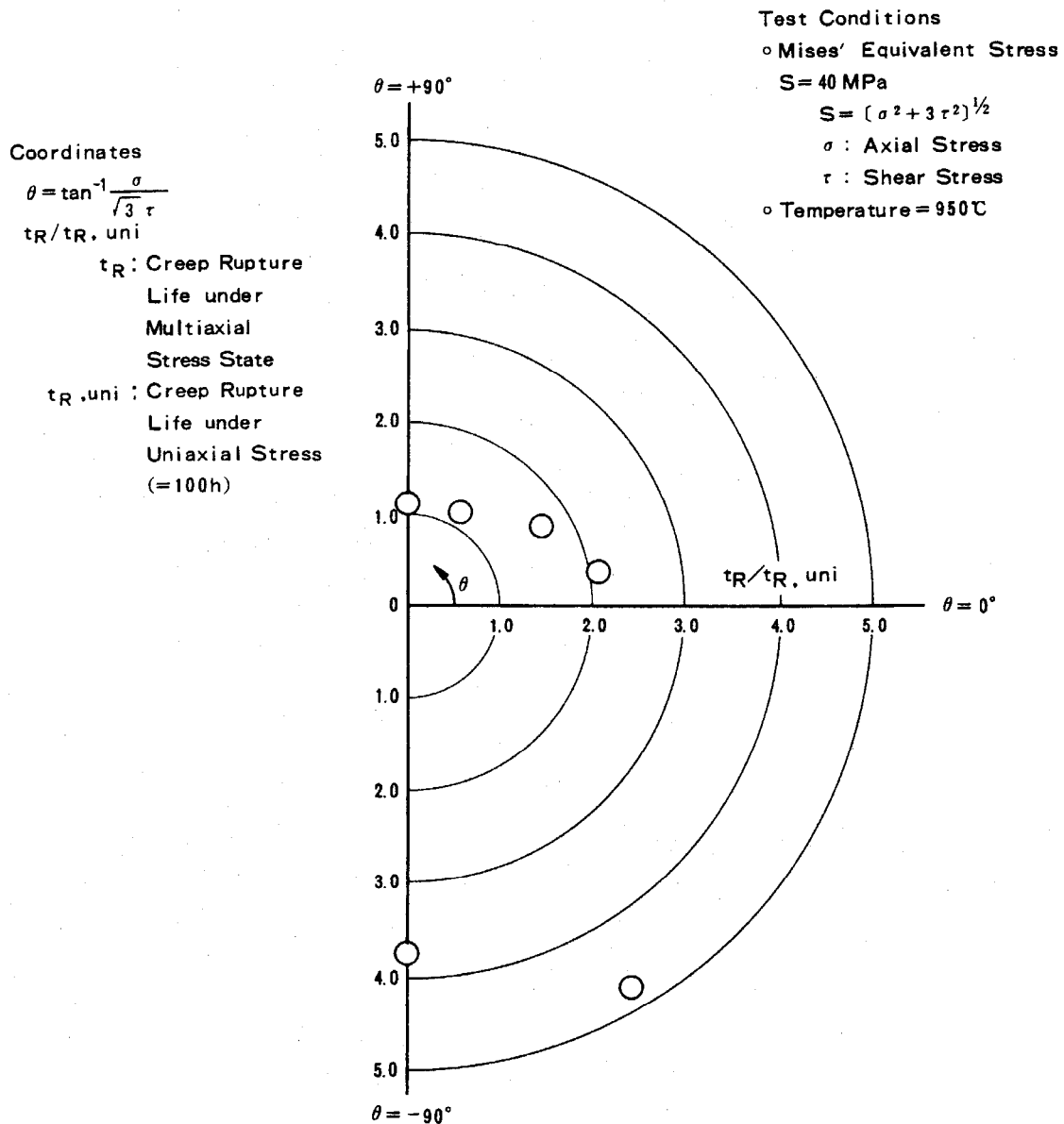


Figure 107 - Creep Rupture Life under Multi-Axial Stress States for Hastelloy XR

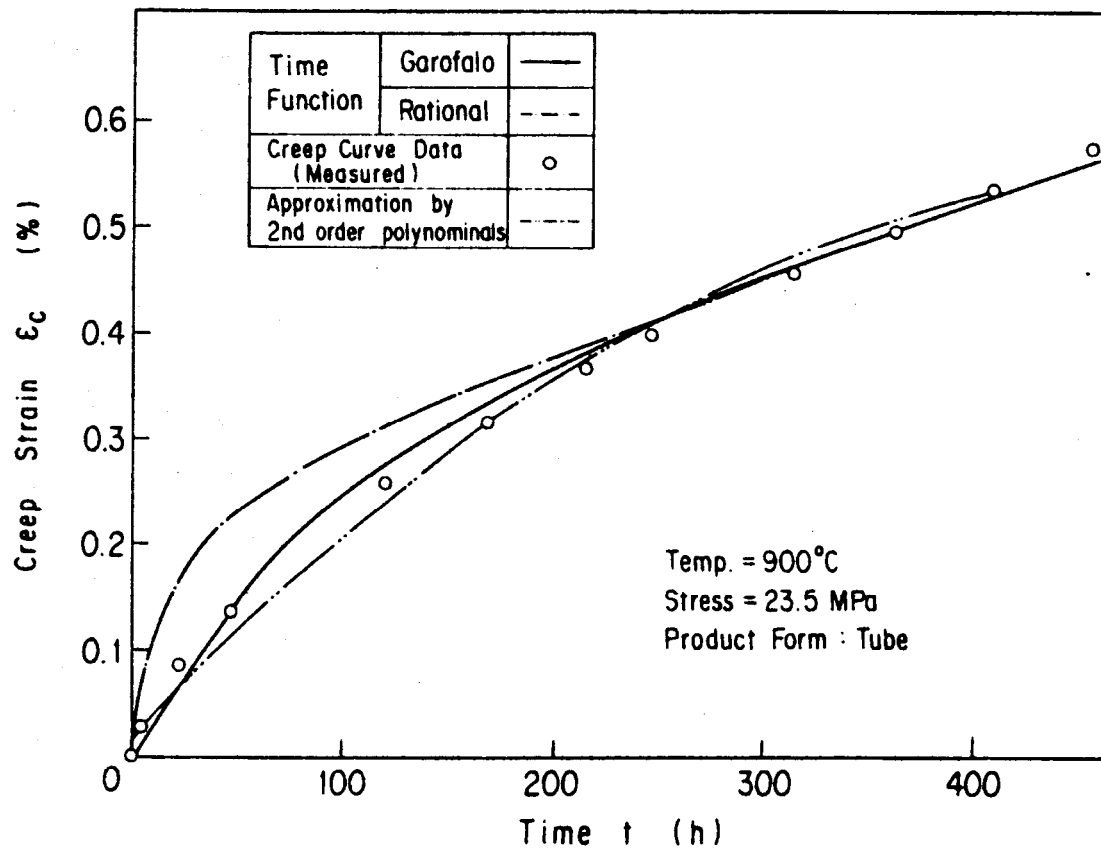


Figure 108 - Applicability of Time Functions to Hastelloy XR

2.2 Inelastic Analysis of the Intermediate Heat Exchanger (IHX) for HTTR

2.2.1 Intermediate Heat Exchanger (IHX) for the HTTR

The IHX is a vertical helically-coiled counter flow type heat exchanger in which primary helium gas flows on the shell side and secondary helium gas in the tube side as shown in Figure 109. Table 28 shows the major specifications of the IHX.

Primary helium gas enters the IHX through the inner pipe of the primary concentric hot gas duct. It is deflected under a hot header and discharged around the heat transfer tubes to transfer the heat to the secondary helium cooling system. It flows to the primary gas circulator via the upper outlet nozzle and flows back to the annular space between the inner and outer shells.

Secondary helium gas flows downwards in the heat transfer tubes and upwards in the central hot gas duct through the hot header. The inner insulation is installed inside the inner shell to maintain its temperature below 440°C. The insulation outside and inside the central hot gas duct restrain the heat transfer so that high efficiency can be obtained. In addition, it also keeps the temperature of the central duct below 940°C.

Primary helium gas is contained only in the primary cooling system because the pressure in the secondary helium cooling system is adjusted somewhat higher than that in the primary cooling system.

The tube support assemblies hold the heat transfer tubes. Both the central hot gas duct and the heat transfer tube support assemblies are hung from the vessel top so that the thermal expansion is not constrained.

The material of the heat transfer tubes and the hot header is Hastelloy XR and the inner and outer shells are made of 2 1/4Cr–1Mo steel.

The IHX has a bypass line, which prevents natural circulation from the reactor core to the IHX during the single loaded operation. The forced circulation from the Primary Pressurized Water Cooler (PPWC) through the bypass line occurs and keeps the temperature of the outer shell below 430°C. Primary helium gas flows from the PPWC and enters into annulus space between the inner and outer shells and then flows inside the inner shell through the bypass line. It returns to the PPWC through the IHX and the primary concentric hot gas duct. The shutoff valve stops this forced circulation during the parallel loaded operation and in case of a scram when the auxiliary cooling system is activated.

The inner structures such as the heat transfer tubes, the central hot gas duct and the hot header are operated beyond 900°C. A design method based on the elastic analysis cannot meet the criteria of the high temperature structural design guideline for the HTGR class 1 components. Therefore, the design method based on a creep analysis is used for evaluation of their structural integrity. The creep fatigue damage was properly evaluated and is capable of meeting the criteria.

2.2.2 Structural Integrity Evaluation of the HTTR IHX

Hastelloy XR is used for the heat transfer tubes, the center pipe and the hot header of the IHX. The heat transfer tubes, the center pipe and the hot header form the boundary of primary helium and secondary helium. The material creep becomes remarkably large at operation temperatures higher than 900°C. Therefore, creep strain and creep damage was evaluated by inelastic analysis, i.e., elastic creep analysis in the structural integrity evaluation. The elastic creep analysis was employed, because at the high temperature around 900°C where creep deformation is dominant, it is meaningless and impossible to separate creep and plastic deformation. Thus, only creep strain is treated as inelastic strain.

2.2.2.1 Creep analysis method

As a uni-axial creep constitutive equation, the following Garofalo's expression is used as described above:

$$\varepsilon_c = \varepsilon_t (1 - e^{-rt}) + \dot{\varepsilon}_{\min} \cdot t$$

where:

- ε_c : creep strain
- ε_t : maximum primary creep strain
- r : inverse number of time constant for primary creep
- t : time
- $\dot{\varepsilon}_{\min}$: minimum creep strain rate

The material constants of Hastelloy XR are shown in Table 29.

For the flow rule, the following flow rule of Mises is used:

$$\dot{\varepsilon}_{cij} = \lambda \cdot s_{ij} = \frac{3\dot{\varepsilon}_{ceq}}{2\sigma_{eq}} s_{ij}$$

where:

$\dot{\varepsilon}_{cij}$: creep strain rate tensor

$\dot{\varepsilon}_{ceq}$: equivalent creep strain rate

σ_{eq} : equivalent stress

s_{ij} : stress deviator tensor

For the hardening rule, strain hardening rules was adopted and ORNL rule was used when stress reversal occurs.

2.2.2.2 Evaluation of cumulative inelastic strain

In the high temperature structural design guideline for HTGR, it is required to limit cumulative principal inelastic strain (membrane) lower than 0.01 and cumulative principal inelastic strain (membrane + bending) lower than 0.02.

In the first step, some events with severer thermal transients were selected, their order and duration time was considered, and loading hysteresis was determined. Then, elastic creep analysis of selected parts of the IHX was performed according to the loading hysteresis, and creep strain was derived.

In order to obtain cumulative inelastic strain at the end of lifetime of the IHX, creep strain at certain evaluation points in the first several (at least three) cycles of the loading hysteresis were calculated, and then extrapolated using the following equation:

$$\varepsilon_{ji}(eoh) = \varepsilon_{ji}(last) + \{\varepsilon_{ji}(last) - \varepsilon_{ji}(last - 1)\} \times (N - last)$$

where

ε_{ji} : cumulative creep strain in the loading hysteresis j ($i = 1$ to 6)

eoh : end of the loading hysteresis j

$last$: the last cycle number (three or larger) analyzed in the loading hysteresis j

N : number of cycles in the loading hysteresis j

The equation above is applicable when:

$$\{\varepsilon_{ji}(last) - \varepsilon_{ji}(last - 1)\} \leq \{\varepsilon_{ji}(last - 1) - \varepsilon_{ji}(last - 2)\}$$

Finally, the cumulative creep strain was derived using the following equation:

$$\varepsilon_i(eoh) = \sum_j \varepsilon_{ji}(eoh)$$

2.2.2.3 Evaluation of cumulative creep fatigue damage factor

In the high temperature structural design guideline for HTGR, it is required to limit cumulative creep fatigue damage factor as follows:

$$D_f + D_c \leq D$$

where

D_f : cumulative fatigue damage factor

D_c : cumulative creep damage factor

D : 1 (Allowable limit)

and

$$D_c = 2 \int_0^{t^*} \frac{dt}{T_d} D_f = \sum_i \frac{n_i}{N_{di}}$$

where:

N_{di} : number of design allowable cycles (Figure 110)

T_d : allowable time duration derived from stress-to-rupture curve (Figure 111)

Similarly to the process of evaluation of cumulative creep strain, in the first step of evaluating creep damage, some events with severer thermal transient were selected, their order and duration time was considered, and loading hysteresis was determined. Then, elastic creep analysis of selected parts of the IHX was performed according to the loading hysteresis, and Mises equivalent stress at certain evaluation points in the first several (at least three) cycles of the loading hysteresis was calculated using the following equation:

$$(D_c)_{cycle} = 2 \sum \left(\frac{\Delta t_i}{T_{di}^*} \right)$$

where:

$(D_c)_{cycle}$ = creep damage factor of a certain cycle number

T_{di}^* : $T_d(T, \sigma_{eq}^*)$; allowable time duration for temperature T and Mises eq stress σ_{eq}^*

σ_{eq}^* : $\max(\sigma_{eq,i}, \sigma_{eq,i+1})$

$\sigma_{eq,i}$: Mises equivalent stress at time point i

$\sigma_{eq,i+1}$: Mises equivalent stress at time point $i+1$

Δt_i : time increment from time point i to time point $i+1$

Then, the creep damage factor was extrapolated to the end of lifetime using the following equation:

$$(D_c)_{eoh,j} = \sum_1^{last} (D_c)_{cycle,j} + (D_c)_{last,j} \times (N - last)$$

where:

$(D_c)_j$: creep damage factor of the loading hysteresis j

$(D_c)_{cycle,j}$: creep damage factor of a certain cycle number in the loading hysteresis j

eoh : end of the loading hysteresis j

$last$: the last cycle number (three or larger) analyzed in the loading hysteresis j

N : number of cycles in the loading hysteresis j

The equation above is applicable when:

$$(D_c)_{last,j} \leq (D_c)_{cycle,j}$$

Finally, the cumulative creep damage factor was derived using the following equation:

$$(D_c)_{eoh} = \sum_j (D_c)_{eoh,j}$$

On the other hand, cumulative fatigue damage factor was derived by elastic analysis procedure in the high temperature structural design guideline for HTGR and added to the cumulative creep damage factor.

The thermal stress in the first layer of heat transfer tube is evaluated since it becomes possibly the maximum value. This originates due to the short horizontal distance to the first bend from the hot header and due to the temperature gradient between the center pipe and the heat transfer tube. Table 30 shows evaluation results of the heat transfer tube. The cumulative principal creep strain is calculated to be 0.0013 for membrane and 0.0021 for the sum of membrane and bending, respectively. The cumulative creep and fatigue factors reach 0.26. These results satisfy the allowable limits, which were established in the high temperature structural design code for the HTGR class 1 components.

Figure 112 shows a vertical view of a lower reducer of the center pipe in the intermediate heat exchanger. Table 31 shows evaluation results for the lower reducer of the center pipe. The maximum cumulative principal creep strain is calculated to 0.0011 for membrane and 0.0032 for the sum of membrane and bending, respectively. The cumulative creep and fatigue factors reach 0.28. These results also satisfy the allowable limits in the same structural design code.

Table 28 - Major Specifications of the Intermediate Heat Exchanger for HTTR

Type	Vertical helically-coiled counter flow	
Design pressure		
Outer shell	4.7 MPa	
Heat transfer tube	0.29 MPa (differential pressure)	
Design temperature		
Outer shell	430 °C	
Heat transfer tube	955 °C	
Operating condition	Rated operation	High temperature test operation
Flow rate of primary helium gas (maximum)	15 t/h	12 t/h
Inlet temperature of primary helium gas	850 °C	950 °C
Outlet temperature of primary helium gas	390 °C	390 °C
Flow rate of secondary helium gas	14 t/h	12 t/h
Inlet temperature of secondary helium gas	300 °C	300 °C
Outlet temperature of secondary helium gas	775 °C	860 °C
Heat capacity	10 MW	
Heat transfer tube		
Number	96	
Outer diameter	31.8 mm	
Thickness	3.5 mm	
Length	30 m	
Outer diameter of shell	2.0 m	
Total height	11.0 m	
Material		
Outer and inner shell	2 1/4Cr-1Mo steel	
Heat transfer tube	Hastelloy XR	
Hot header and center pipe	Hastelloy XR	

Table 29 - Material Constants of the Creep Constitutive Equation for Hastelloy XR

$\varepsilon_c = \varepsilon_t (1 - e^{-rt}) + \dot{\varepsilon}_{\min} \cdot t$	
<p>where</p> <p>ε_c = creep strain (mm/mm)</p> <p>ε_t = maximum primary creep strain (mm/mm)</p> <p>r = inverse number of time constant for primary creep (1/h)</p> <p>t = time (h)</p> <p>$\dot{\varepsilon}_{\min}$ = minimum creep strain rate (mm/mm/h)</p> <p>and</p> <p>σ = stress (kg/mm²)</p> <p>T = temperature (°C)</p>	
ε_t	<p>4.0 < σ : $\varepsilon_t = 0.056 \times 10^{-2}$</p> <p>2.0 < $\sigma \leq 4.0$: $\varepsilon_t = (-0.0578 + 0.454 / \sigma) \times 10^{-2}$</p> <p>0.5 < $\sigma \leq 2.0$: $\varepsilon_t = 0.169 \times 10^{-2}$</p> <p>$\sigma \leq 0.5$: $\varepsilon_t = \{0.169 \cdot (\sigma / 0.5)\} \times 10^{-2}$</p>
r	<p>0.5 ≤ σ : $r = 10^{p(\sigma, T)}$</p> <p>$\sigma < 0.5$: $r = 10^{p(\sigma = 0.5, T)} \cdot (\sigma / 0.5)$</p> <p>where</p> <p>$p(\sigma, T) = f_1(T) + f_2(T) \cdot \sigma$</p> <p>$f_1(T) = 4.854 - 2.415 \times 10^{-2} \cdot T + 1.674 \times 10^{-5} \cdot T^2$</p> <p>$f_2(T) = 3.399 - 9.898 \times 10^{-3} \cdot T + 7.693 \times 10^{-6} \cdot T^2$</p>
$\dot{\varepsilon}_{\min}$	<p>0.5 ≤ σ : $\dot{\varepsilon}_{\min} = 10^{fa(\sigma, T)} \times 10^{-2}$</p> <p>0.1 ≤ $\sigma < 0.5$: $\dot{\varepsilon}_{\min} = 10^{fb(\sigma, T)} \times 10^{-2}$</p> <p>$\sigma < 0.1$: $\dot{\varepsilon}_{\min} = 10^{fb(\sigma = 0.1, T)} \cdot (\sigma / 0.1) \times 10^{-2}$</p> <p>where</p> <p>$fa(\sigma, T) = 14.326 + 3.222 (\log_{10} \sigma) + 2.400 (\log_{10} \sigma)^2 - 2.246 \times 10^4 / (T + 273.15)$</p> <p>$fb(\sigma, T) = 1.777 (\log_{10} \sigma + 0.30103) + 13.574 - 2.246 \times 10^4 / (T + 273.15)$</p>

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

Evaluation items		Evaluation result	Allowable limit
ϵ_c	Membrane	0.0013	0.01
	Membrane+Bending (inner surface)	0.0021	0.02
	Membrane+Bending (outer surface)	0.0005	0.02
D_c	Inner surface	0.187	-
	Outer surface	0.106	-
D_f	Inner surface	0.072	-
	Outer surface	0.066	-
D_c+D_f	Inner surface	0.26	1.0
	Outer surface	0.18	1.0

Note:

ϵ_c : cumulative principal creep strain.
 D_c : cumulative creep damage factor.
 D_f : cumulative fatigue damage factor.

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

EC	Evaluation items		Evaluation result	Allowable limit
1	ϵ_c	Membrane	0.0008	0.01
		Membrane+Bending (inner surface)	0.0004	0.02
		Membrane+Bending (outer surface)	0.0009	0.02
	D_c	Inner surface	0.076	-
		Outer surface	0.111	-
	D_f	Inner surface	0.001	-
		Outer surface	0.001	-
	D_c+D_f	Inner surface	0.08	1.0
		Outer surface	0.12	1.0
2	ϵ_c	Membrane	0.0007	0.01
		Membrane+Bending (inner surface)	0.0006	0.02
		Membrane+Bending (outer surface)	0.0008	0.02
	D_c	Inner surface	0.078	-
		Outer surface	0.107	-
	D_f	Inner surface	0.001	-
		Outer surface	0.001	-
	D_c+D_f	Inner surface	0.08	1.0
		Outer surface	0.11	1.0
3	ϵ_c	Membrane	0.0011	0.01
		Membrane+Bending (inner surface)	0.0006	0.02
		Membrane+Bending (outer surface)	0.0012	0.02
	D_c	Inner surface	0.076	-
		Outer surface	0.110	-
	D_f	Inner surface	0.001	-
		Outer surface	0.001	-
	D_c+D_f	Inner surface	0.08	1.0
		Outer surface	0.12	1.0

Note: EC: Evaluation cross section. ϵ_c : cumulative principal creep strain.
 D_c : cumulative creep damage factor. D_f : cumulative fatigue damage factor.

EC	Evaluation items		Evaluation result	Allowable limit
4	ε_c	Membrane	0.0009	0.01
		Membrane+Bending (inner surface)	0.0027	0.02
		Membrane+Bending (outer surface)	0.0013	0.02
	D_c	Inner surface	0.077	-
		Outer surface	0.081	-
	D_f	Inner surface	0.001	-
		Outer surface	0.001	-
	D_c+D_f	Inner surface	0.08	1.0
		Outer surface	0.09	1.0
5	ε_c	Membrane	0.0006	0.01
		Membrane+Bending (inner surface)	0.0032	0.02
		Membrane+Bending (outer surface)	0.0023	0.02
	D_c	Inner surface	0.259	-
		Outer surface	0.080	-
	D_f	Inner surface	0.002	-
		Outer surface	0.001	-
	D_c+D_f	Inner surface	0.27	1.0
		Outer surface	0.09	1.0
6	ε_c	Membrane	0.0010	0.01
		Membrane+Bending (inner surface)	0.0014	0.02
		Membrane+Bending (outer surface)	0.0007	0.02
	D_c	Inner surface	0.270	-
		Outer surface	0.096	-
	D_f	Inner surface	0.001	-
		Outer surface	0.001	-
	D_c+D_f	Inner surface	0.28	1.0
		Outer surface	0.10	1.0

Note: EC: Evaluation cross section. ε_c : cumulative principal creep strain.
 D_c : cumulative creep damage factor. D_f : cumulative fatigue damage factor.

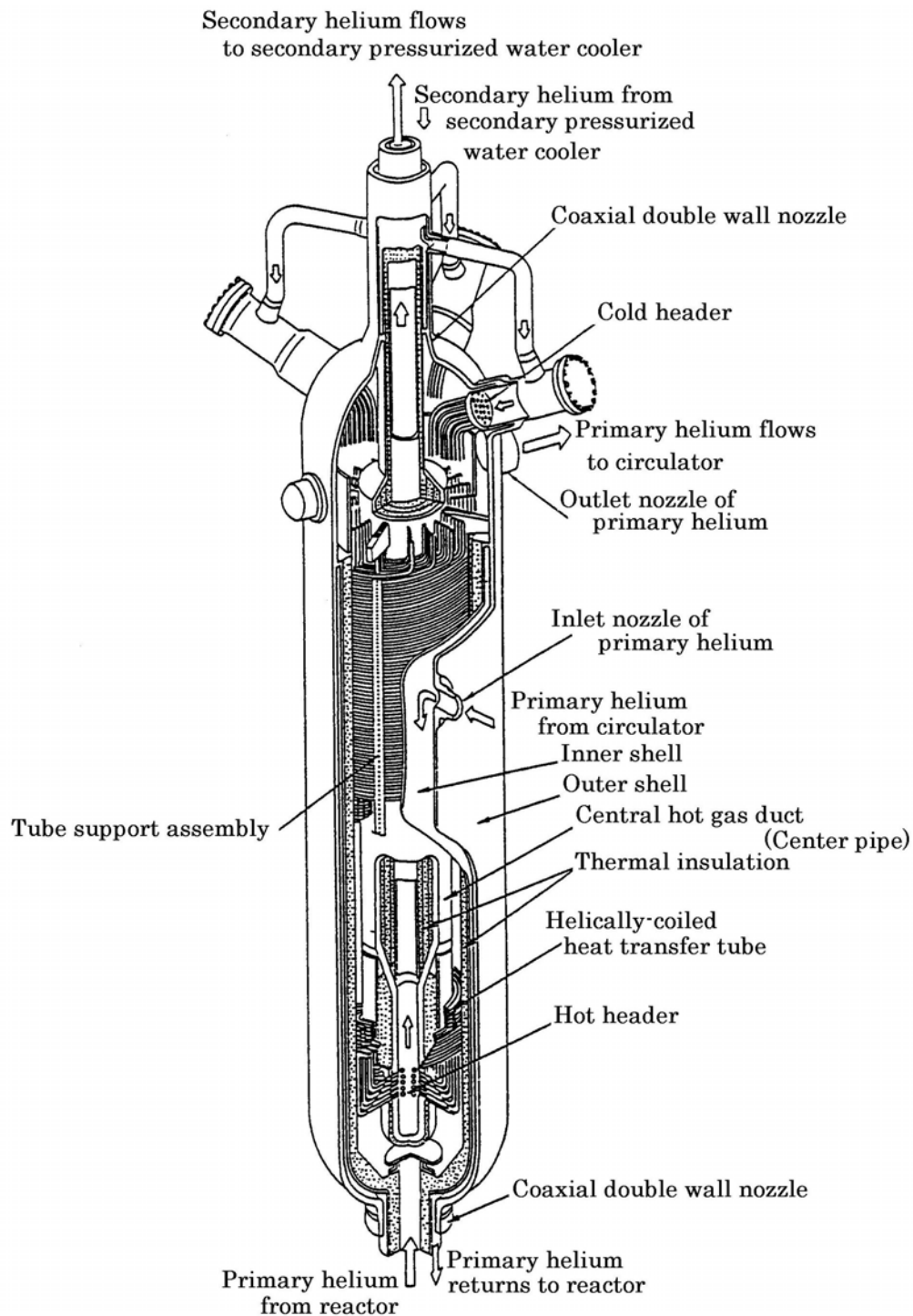


Figure 109 - Intermediate Heat Exchanger (IHX) for HTTR

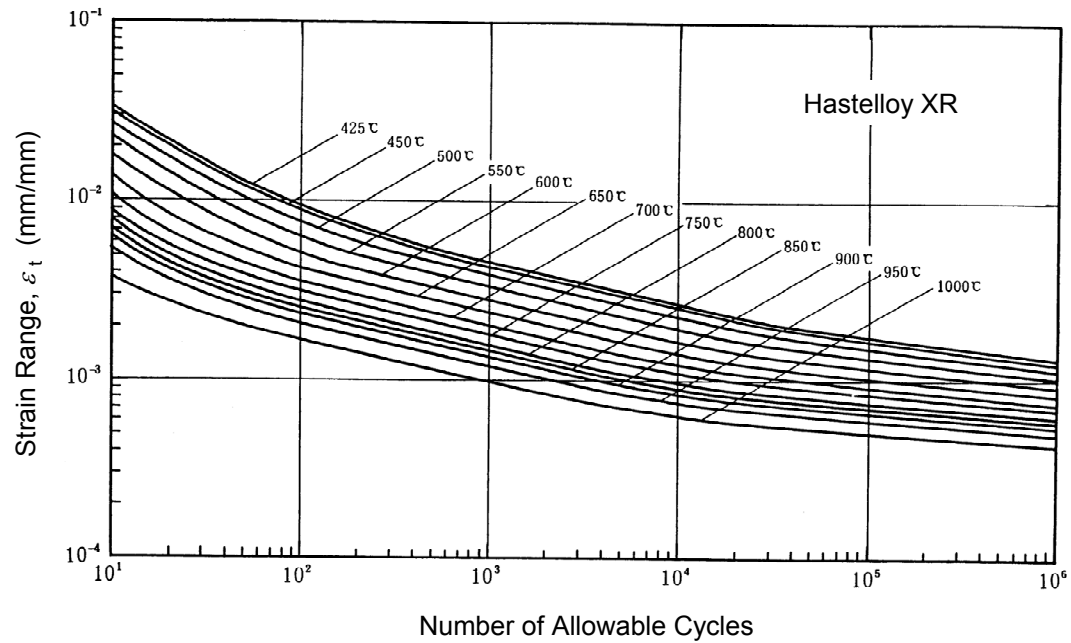


Figure 110 - Design Fatigue Strain Range for Hastelloy XR

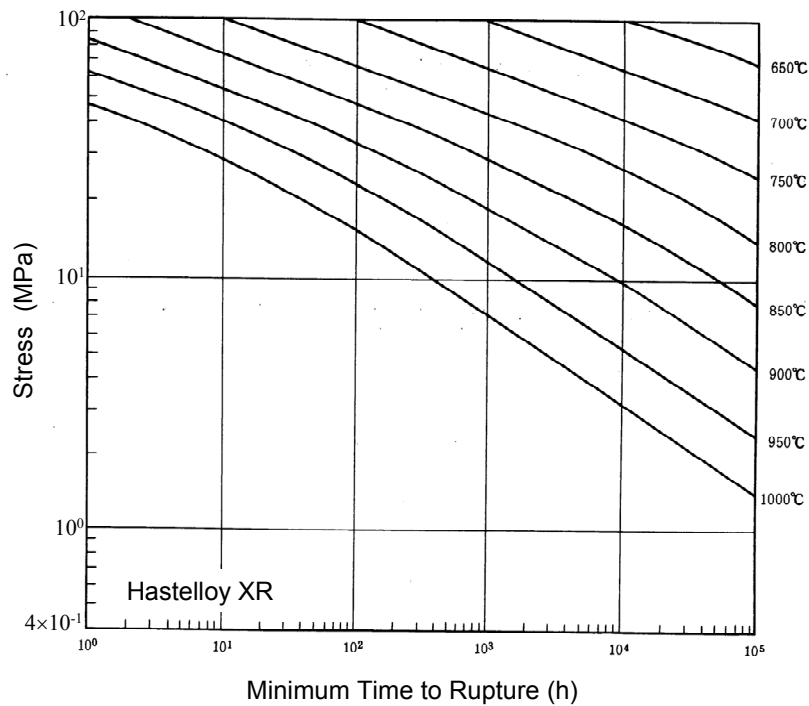


Figure 111 - Stress-to-Rupture Curve for Hastelloy XR

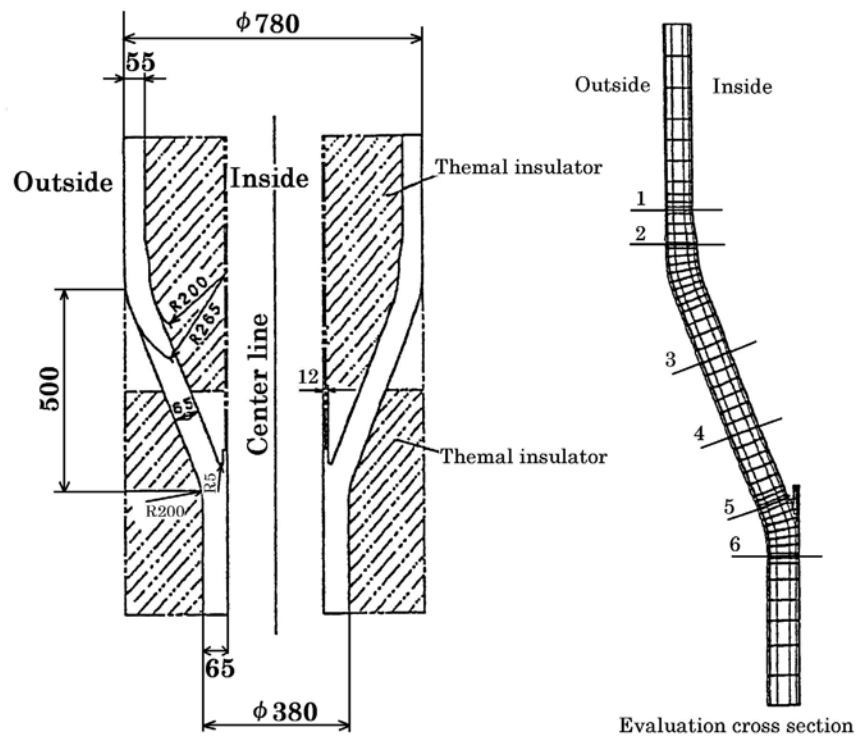


Figure 112 - Vertical View of the Lower Reducer of the Center Pipe in the IHX

2.3 Summary of Creep-Fatigue Criteria on Hastelloy XR

From a screening of commercial and experimental superalloys available in the 1970s, Hastelloy X was selected for the very high temperature structures such as the heat transfer tubes of the IHX. Since Hastelloy X does not have sufficient compatibility with the primary helium coolant, the improved version of Hastelloy X, which is called Hastelloy XR, was developed through optimizing or lowering contents of several elements.

Since some of the high temperature materials and their service temperatures were out of scope of the existing FBR Code, many research works on material characterizations and structural mechanics behavior were made in order to establish a high temperature structural design code for both materials.

Material characterizations for Hastelloy XR suggested that special considerations should be taken into account for dynamic recrystallization at high temperatures. A new tensile test procedure with a change in strain rate to 100%/min at temperatures over 800°C was proposed to obtain the time-independent elastic-plastic property for Hastelloy XR. The further material characterization and component-wise structural mechanics research works revealed that design rules for austenitic stainless steels can be applied to Hastelloy XR, and, therefore, the high temperature structural design guideline was established, referring to the FBR Code. A creep analysis method was established for Hastelloy XR through several research works. In the creep analysis method, the creep equation was generated from Garofalo's type of the time function, and it was also demonstrated that the strain hardening rule and Von Mises' flow rule is applicable to Hastelloy XR.

In the design of the intermediate heat exchanger (IHX) for HTTR, inelastic analysis was conducted to evaluate cumulative creep strain and cumulative creep and fatigue damage factors based on the high temperature structural design guideline.

3 NECESSARY RESEARCH AND DEVELOPMENT ITEMS IN RELATION TO CREEP-FATIGUE EVALUATION FOR GEN IV AND VHTR REACTORS

3.1 Linear Summation Rule of Cycle and Time Fractions

As described in section 1.1 and 2.1, creep fatigue tests on Hastelloy XR by JAEA were performed in order to confirm conservativeness of conventional linear summation rule of cycle and time fractions (fatigue and creep damage factors) with the allowable limit D of 1. It was concluded in section 2.1 that the linear summation rule is applicable to Hastelloy XR with a great deal of safety margins even at very high temperatures.

It is envisaged that the linear summation rule is similarly applicable to other Ni-base superalloys like Inconel 617 and Haynes 230. However, creep fatigue tests on Inconel 617 and Haynes 230 will be needed to confirm conservativeness of conventional linear summation rule or to develop new methods.

3.2 Inelastic Constitutive Equations

In the design of the intermediate heat exchanger (IHX) for HTTR, inelastic analysis was necessary to evaluate creep strain and creep damage at very high temperatures. Similarly, in the design of high temperature components such as IHX made of Inconel 617 and Haynes 230, inelastic analysis will be inevitable. In the design of HTTR IHX, conventional Garofalo's expression was used as a creep constitutive equation because the high temperature structural design guideline was developed in 1980s. Recently, a lot of constitutive equations using so called unified theory have been developed by Chaboche, Krempl, etc. In the future design of high temperature components, applicability of unified inelastic constitutive equations should be investigated.

3.3 Helium Environmental Effect

Impurities in the primary coolant of the HTTR must be controlled so that primary coolant shall be in area III of Figure 104, where mild carburization occurs. For this purpose, research and developments are underway in the HTTR to develop methods to control helium purification system.

Similarly, research and developments will be needed for future HTGRs on Inconel 617 and Haynes 230 to determine optimum level of impurities in the primary coolant as well as to develop methods of controlling helium purification system to keep the optimum level.

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APPENDIX A

Table 32 - Mod. 9Cr-1Mo Creep Data (Temperature is 400°C or more)

Research Laboratories	Test piece name	Product	Heat name	Test condition	Aging Process	Temperature (°C)	Stress (MPa)	Time to rupture (h)	Elongation after rupture (%)	Reduction of area (%)	Steady state creep rate (%/h)
JAEA	FTF6C0	Plate	F6	Air		450	436	7.4	25.7	76.4	8.08E-01
JAEA	FTF6D9	Plate	F6	Air		450	392	364.7	26.4	80.6	1.41E-02
JAEA	FTF6E4	Plate	F6	Air		450	387	12785	18.8	81.4	7.55E-05
JAEA	FTF6E5	Plate	F6	Air		450	382	37992.7	19.5	79.1	1.45E-05
JAEA	FTF6B9	Plate	F6	Air		450	373	22824.5	21.3	80.3	2.17E-05
JAEA	FTF6B4	Plate	F6	Air		500	353	21	26.1	82.1	2.26E-01
JAEA	FTF6B2	Plate	F6	Air		500	333	116.9	34.3	83.7	4.04E-02
JAEA	FTF6A4	Plate	F6	Air		500	314	505.4	28.1	84	5.64E-03
JAEA	9CR-4	Plate	F6	Air		500	294	2435.7	18	82.9	8.10E-04
JAEA	FTF6A2	Plate	F6	Air		500	294	3514.3	21.6	84.5	5.47E-04
JAEA	9CR-3	Plate	F6	Air		500	284	7812.4	17.4	83.3	2.67E-04
JAEA	FTF6B7	Plate	F6	Air		500	275	4997	30.1	85.6	4.51E-04
JAEA	FTF6B8	Plate	F6	Air		500	255	13553.4	24.2	85.5	2.02E-04
JAEA	FTF6A7	Plate	F6	Air		500	245	27147.7	25.3	84.9	1.09E-04
JAEA	FTF6B5	Plate	F6	Air		550	255	44.3	30.9	87	1.12E-01
JAEA	FTF6B6	Plate	F6	Air		550	235	153.1	35.6	87.7	3.19E-02
JAEA	FTF6A5	Plate	F6	Air		550	216	884.2	33.7	89.8	4.90E-03
JAEA	FTF6A3	Plate	F6	Air		550	206	2282.1	29.3	89.5	2.14E-03
JAEA	FTF6B0	Plate	F6	Air		550	196	3148.1	25	89.1	1.23E-03
JAEA	FTF6B1	Plate	F6	Air		550	186	9348.6	39.1	89.4	4.01E-04
JAEA	FTF6A8	Plate	F6	Air		550	177	13688.4	30.5	87.7	2.11E-04
JAEA	FTF6A1	Plate	F6	Air		550	167	43918.4	24.3	80.2	5.30E-05
JAEA	FTF6C2	Plate	F6	Air		600	177	59.9	40.3	91.5	9.45E-02
JAEA	FTF6C1	Plate	F6	Air		600	157	301.7	33.4	91.8	1.63E-02
JAEA	FTF6C9	Plate	F6	Air		600	137	2311.8	27.8	90.3	1.46E-03
JAEA	FTF6E3	Plate	F6	Air		600	127	4477.7	29.3	89.3	7.32E-04

Research Laboratories	Test piece name	Product	Heat name	Test condition	Aging Process	Temperature (°C)	Stress (MPa)	Time to rupture (h)	Elongation after rupture (%)	Reduction of area (%)	Steady state creep rate (%/h)
JAEA	FTF6C5	Plate	F6	Air		600	118	11769.9	21.8	84.3	2.04E-04
JAEA	FTF6E0	Plate	F6	Air		600	113	16109.7	19.3	79.1	1.83E-04
JAEA	FTF6C4	Plate	F6	Air		650	118	75.6	37.1	92.7	9.68E-02
JAEA	FTF6C3	Plate	F6	Air		650	98	523.8	33.2	95.1	6.79E-03
JAEA	FTF6E2	Plate	F6	Air		650	93	1102.3	29.6	90.6	3.10E-03
JAEA	FTF6C8	Plate	F6	Air		650	83	3328.4	25.6	86.1	9.54E-04
JAEA	FTF6C6	Plate	F6	Air		650	78	4945.6	27.9	87	5.95E-04
JAEA	FTF6E1	Plate	F6	Air		650	74	7614.2	23.5	83.7	1.60E-04
JAEA	C9B-1	Plate	F7	Air		500	333	329.7	23.9	84	8.45E-03
JAEA	GAC1	Plate	F7	Air		500	333	687.8	23.3	85.6	4.11E-03
JAEA	TBC-1	Plate	F7	Air		500	333	560.6	21.5	83.7	3.44E-03
JAEA	C9B-2	Plate	F7	Air		500	294	4184.3	23.3	86	7.18E-04
JAEA	GAC2	Plate	F7	Air		500	294	7074.1	23.3	85.5	3.70E-04
JAEA	TBC-2	Plate	F7	Air		500	294	4040.7	14.4	86	4.25E-04
JAEA	C9B-3	Plate	F7	Air		550	235	264.3	28.9	89	1.65E-02
JAEA	GAC3	Plate	F7	Air		550	235	596.6	26.2	93.5	8.15E-03
JAEA	TBC-3	Plate	F7	Air		550	235	588.9	21.7	84.2	5.22E-03
JAEA	C9B-4	Plate	F7	Air		550	206	2343	26	88	1.47E-03
JAEA	TBC-5	Plate	F7	Air		550	206	6700.1	22.7	86.8	5.89E-04
JAEA	MC9C-1	Plate	F9	Air		500	314	219.2	21.5	85.8	1.86E-02
JAEA	MC9C-3	Plate	F9	Air		500	284	3485.6	31.8	29.3	8.80E-04
JAEA	MB9	Plate	F9	Air		550	235	830.1	29	87.9	-
JAEA	MB2	Plate	F9	Air		550	216	2933.8	27.7	88.5	1.49E-03
JAEA	MB6	Plate	F9	Air		550	206	6831	23	87.4	5.86E-04
JAEA	MC9C-2	Plate	F9	Air		550	206	1541.5	26.9	41.3	1.00E-03
JAEA	MC9C-4	Plate	F9	Air		550	196	4744.1	25.5	66	6.20E-04
JAEA	MC9C-6	Plate	F9	Air		550	183	5819.9	24	43	5.80E-04
JAEA	MC9C-8	Plate	F9	Air		550	175	21042.1	26.4	86.9	2.03E-04
JAEA	MB7	Plate	F9	Air		600	177	167	30.6	90.8	-
JAEA	MB8	Plate	F9	Air		600	157	812.3	34.2	90.7	-

Research Laboratories	Test piece name	Product	Heat name	Test condition	Aging Process	Temperature (°C)	Stress (MPa)	Time to rupture (h)	Elongation after rupture (%)	Reduction of area (%)	Steady state creep rate (%/h)
JAEA	MB5	Plate	F9	Air		600	147	2097.3	26.7	89.9	1.93E-03
JAEA	MB4	Plate	F9	Air		600	137	4736.1	24.6	88.5	5.45E-04
JAEA	MB3	Plate	F9	Air		600	127	9941	28.7	84.9	2.50E-04
JAEA	PNC833	Plate	F9	Air		550	216	2150	26.7	87.7	2.06E-03
JAEA	AC3	Plate	F9	Air		550	211	3093.5	28.6	89.6	1.31E-03
JAEA	BC3	Plate	F9	Air		550	211	2163.4	26.1	89.1	2.03E-03
JAEA	CC3	Plate	F9	Air		550	211	2045.6	31.1	89.8	2.02E-03
JAEA	DC3	Plate	F9	Air		550	211	1469.9	25.6	89.4	2.23E-03
JAEA	PNC834	Plate	F9	Air		550	206	4049.8	23.6	88	9.32E-04
JAEA	AC7	Plate	F9	Air		600	142	1348.6	29	92.3	3.56E-03
JAEA	BC7	Plate	F9	Air		600	142	1949	31	92	2.20E-03
JAEA	CC7	Plate	F9	Air		600	142	2496.7	33.6	93.4	1.50E-03
JAEA	DC7	Plate	F9	Air		600	142	1555.7	27.9	91.3	2.57E-03
JAEA	FMF6C5	Forging	F4	Air		500	333	59.1	25.9	81.6	8.20E-02
JAEA	FMF6A4	Forging	F4	Air		500	314	272.7	28.8	83.9	1.67E-02
JAEA	FMF6B6	Forging	F4	Air		500	314	223.7	23.5	82.5	1.64E-02
JAEA	FMF6D4	Forging	F4	Air		500	314	226.8	30.9	82.8	2.20E-02
JAEA	FMF6F1	Forging	F4	Air		500	314	201.3	24.2	82.7	2.00E-02
JAEA	FMF6G6	Forging	F4	Air		500	314	298.5	39	83.6	1.58E-02
JAEA	FMF6A5	Forging	F4	Air		500	294	1157	30.7	84.7	3.21E-03
JAEA	FMF6B0	Forging	F4	Air		500	294	906.7	29.3	85	4.17E-03
JAEA	FMF6B7	Forging	F4	Air		500	294	1129.2	28.2	84.2	2.77E-03
JAEA	FMF6C6	Forging	F4	Air		500	294	1010.8	26.8	83.4	3.55E-03
JAEA	FMF6D6	Forging	F4	Air		500	294	860.7	26.8	82.6	4.09E-03
JAEA	FMF6E5	Forging	F4	Air		500	294	1160.8	25.3	83.7	2.80E-03
JAEA	FMF6F2	Forging	F4	Air		500	294	1280.9	34.1	85	2.91E-03
JAEA	FMF6F7	Forging	F4	Air		500	294	871.2	29.5	84.3	4.52E-03
JAEA	FMF6G0	Forging	F4	Air		500	294	1047.7	25.3	86.3	3.19E-03
JAEA	FMF6A6	Forging	F4	Air		500	275	4288.8	23.6	87.4	5.64E-04
JAEA	FMF6B8	Forging	F4	Air		500	275	7156.8	23.4	83.4	4.83E-04

Research Laboratories	Test piece name	Product	Heat name	Test condition	Aging Process	Temperature (°C)	Stress (MPa)	Time to rupture (h)	Elongation after rupture (%)	Reduction of area (%)	Steady state creep rate (%/h)
JAEA	FMF6C7	Forging	F4	Air		500	275	4068.6	25.7	83.3	7.56E-04
JAEA	FMF6D8	Forging	F4	Air		500	275	3803.4	26.6	85.2	7.72E-04
JAEA	FMF6F3	Forging	F4	Air		500	275	4020.2	28.1	85.5	8.28E-04
JAEA	FMF6E0	Forging	F4	Air		550	235	222.4	33.4	87.3	2.03E-02
JAEA	FMF6G7	Forging	F4	Air		550	235	228.1	28.7	86.4	2.30E-02
JAEA	FMF6B1	Forging	F4	Air		550	216	839.7	35.8	88.7	5.62E-03
JAEA	FMF6D7	Forging	F4	Air		550	216	907.2	31.4	87.6	4.70E-03
JAEA	FMF6E6	Forging	F4	Air		550	216	721.6	26.1	88.6	5.92E-03
JAEA	FMF6F8	Forging	F4	Air		550	216	720.1	31	87.8	6.66E-03
JAEA	FMF6G1	Forging	F4	Air		550	216	835.4	30.9	88.6	5.41E-03
JAEA	FMF6D9	Forging	F4	Air		550	201	2649.9	28.4	87.3	1.55E-03
JAEA	FMF6C8	Forging	F4	Air		600	146	746.2	30.6	91	6.52E-03
JAEA	FMF6C9	Forging	F4	Air		650	92	1080.2	29.6	96.7	3.01E-03
JAEA	FMF9A4	Forging	F5	Air		550	196	1803.4	26.2	88.3	1.97E-03
JAEA	FMF9A8	Forging	F5	Air		550	196	1563.4	32.7	89.1	2.74E-03
JAEA	FMF9B6	Forging	F5	Air		550	196	1463.9	27.2	88.1	2.48E-03
JAEA	FYF6C6	Forging	F8	Air		500	314	376.9	28.1	79.3	9.83E-03
JAEA	FYF6D5	Forging	F8	Air		500	314	289.3	32.4	80.4	1.68E-02
JAEA	FYF6F2	Forging	F8	Air		500	314	841.1	26.8	82.6	2.39E-03
JAEA	FYF6G1	Forging	F8	Air		500	314	449.8	25.2	82.9	6.42E-03
JAEA	FYF6C5	Forging	F8	Air		500	294	2011.7	24.6	81.4	7.20E-04
JAEA	FYF6D4	Forging	F8	Air		500	294	1790.5	22.4	80.6	7.14E-04
JAEA	FYF6F1	Forging	F8	Air		500	294	2705.8	28.3	84.1	5.84E-04
JAEA	FYF6G0	Forging	F8	Air		500	294	2300.6	23.7	83.8	5.86E-04
JAEA	FYF6C7	Forging	F8	Air		500	275	5340	18.8	83.4	1.22E-04
JAEA	FYF6D6	Forging	F8	Air		500	275	5243	21.7	82.1	1.93E-04
JAEA	FYF6F3	Forging	F8	Air		500	275	6322.6	26.4	84.8	1.70E-04
JAEA	FYF6G2	Forging	F8	Air		500	275	5609.9	30	84.9	2.24E-04
JAEA	FYF6D7	Forging	F8	Air		550	216	262.9	28.9	86.1	1.60E-02
JAEA	L-1	Forging	F8	Air		550	216	513	32.3	84	7.29E-03

Research Laboratories	Test piece name	Product	Heat name	Test condition	Aging Process	Temperature (°C)	Stress (MPa)	Time to rupture (h)	Elongation after rupture (%)	Reduction of area (%)	Steady state creep rate (%/h)
JAEA	M-1	Forging	F8	Air		550	216	584.6	31	84	7.07E-03
JAEA	L-2	Forging	F8	Air		550	206	1044.7	34	84	3.57E-03
JAEA	M-2	Forging	F8	Air		550	206	976.4	29.7	87.7	4.27E-03
JAEA	FVF6D8	Forging	F8	Air		550	196	1059.2	25.4	87.3	3.15E-03
JAEA	L-3	Forging	F8	Air		550	196	1454.7	25	85	2.07E-03
JAEA	M-3	Forging	F8	Air		550	196	2402.1	27.3	84	1.23E-03
JAEA	FVF6D9	Forging	F8	Air		550	177	4567.3	29.8	88.1	7.69E-04
JAEA	FVF0A1	Forging	F11	Air		550	167	30507.8	20.6	82.4	7.23E-05
JAEA	FVF0A0	Forging	F11	Air		600	127	4011.9	25.3	90.3	8.82E-04
JAEA	FXZ7A-0	Tube	F3	Air		500	343	97.3	23.6	73.3	-
JAEA	FXZ7A0	Tube	F3	Air		500	324	290.1	26	74	-
JAEA	FXZ7A-3	Tube	F3	Air		500	314	1006.8	19.9	71.8	-
JAEA	M9TT-18	Tube	F3	Air		500	314	1114.8	17	77.8	1.78E-03
JAEA	FXZ7A1	Tube	F3	Air		500	309	760.1	27	81	-
JAEA	M9TC-2	Tube	F3	Air		500	304	2063.5	15.4	77.8	1.18E-03
JAEA	FXZ7A2	Tube	F3	Air		500	294	1423	22	78	-
JAEA	FXZ7A-6	Tube	F3	Air		500	284	1890.9	21.4	70.3	-
JAEA	FXZ7A9	Tube	F3	Air		500	284	2881.9	21	80	-
JAEA	M9TC-9	Tube	F3	Air		500	284	3068.1	17.8	76.8	8.56E-04
JAEA	FXZ7B-0	Tube	F3	Air		500	260	10109.1	31.1	74.8	-
JAEA	FXZ7A-1	Tube	F3	Air		550	245	79.8	30	78.8	-
JAEA	FXZ7A3	Tube	F3	Air		550	230	240.5	24	85	-
JAEA	M9TC-4	Tube	F3	Air		550	226	987.4	19.2	80.4	4.96E-03
JAEA	FXZ7A-4	Tube	F3	Air		550	216	762.1	26.8	75.4	-
JAEA	FXZ7A4	Tube	F3	Air		550	211	997.5	33	83	-
JAEA	M9TC-8	Tube	F3	Air		550	206	5398.2	20.7	74.8	7.44E-04
JAEA	FYZ7A3	Tube	F3	Air		550	191	7600	-	-	-
JAEA	M9TC-10	Tube	F3	Air		550	191	6327.8	15.8	70.9	3.53E-04
JAEA	FXZ7A-7	Tube	F3	Air		550	181	10306.1	23.8	58.4	-
JAEA	FXZ7A-2	Tube	F3	Air		600	162	170.7	31.2	77.7	-

Research Laboratories	Test piece name	Product	Heat name	Test condition	Aging Process	Temperature (°C)	Stress (MPa)	Time to rupture (h)	Elongation after rupture (%)	Reduction of area (%)	Steady state creep rate (%/h)
JAEA	FXZ7A6	Tube	F3	Air		600	152	538.5	32	87	-
JAEA	FXZ7A-5	Tube	F3	Air		600	142	952.3	24.9	73.3	-
JAEA	FXZ7A7	Tube	F3	Air		600	137	2237.3	24	79	-
JAEA	FXZ7A8	Tube	F3	Air		600	132	2457.4	25	79	-
JAEA	FXZ7A-8	Tube	F3	Air		600	123	6434.7	18.6	35.4	-
JAEA	FXZ7A-9	Tube	F3	Air		600	113	14774.2	9.6	9.8	-
JAEA	FUF6B1	Plate	F2	Air		500	333	399.5	26.6	82.4	7.09E-03
JAEA	FUF6B5	Plate	F2	Air		500	314	1926.7	33.4	84.4	1.09E-03
JAEA	FUF6A0	Plate	F2	Air		500	304	1903.9	28.4	84.3	9.72E-04
JAEA	FUN7A0	Plate	F2	Air		500	304	1309.2	30.6	85.3	2.06E-03
JAEA	FUF6A3	Plate	F2	Air		500	284	5554	33.2	84.8	4.00E-04
JAEA	FUN7A2	Plate	F2	Air		500	284	4953.6	28.6	92	2.13E-04
JAEA	FUN7A5	Plate	F2	Air		500	275	7167.9	25.9	86.5	3.89E-04
JAEA	FUF6A6	Plate	F2	Air		500	265	17283.7	22.1	85.5	1.36E-04
JAEA	FUF6A9	Plate	F2	Air		500	255	25855.4	24.5	85.9	1.32E-04
JAEA	FUF6B3	Plate	F2	Air		550	245	286.4	34	87.3	1.51E-02
JAEA	FUF6A1	Plate	F2	Air		550	226	696.4	25.6	87.6	5.95E-03
JAEA	FUF6B6	Plate	F2	Air		550	216	1598.4	29.2	87.5	2.66E-03
JAEA	FUN7A1	Plate	F2	Air		550	211	1445.4	27.8	89.9	3.47E-03
JAEA	FUF6A4	Plate	F2	Air		550	206	2141	22.7	87.8	1.88E-03
JAEA	FUN7A3	Plate	F2	Air		550	201	3164.7	30.1	90.6	1.28E-03
JAEA	FUF6A7	Plate	F2	Air		550	191	9851.3	25.4	86.7	3.14E-04
JAEA	FUN7A4	Plate	F2	Air		550	191	8116.7	24.2	87.9	4.88E-04
JAEA	FUF6B0	Plate	F2	Air		550	177	22365.8	20.7	82.4	1.08E-04
JAEA	FUF6B4	Plate	F2	Air		600	177	128.1	53.5	91.3	4.13E-02
JAEA	FUF6A2	Plate	F2	Air		600	157	357.9	25.2	90.7	1.12E-02
JAEA	FUF6B7	Plate	F2	Air		600	137	3397.5	32	88.4	9.34E-04
JAEA	FUF6A5	Plate	F2	Air		600	127	7864.8	30.9	86.1	-
JAEA	FUF6A8	Plate	F2	Air		600	118	15716.1	20.3	79.9	1.59E-04
JAEA	FUF6B2	Plate	F2	Air		600	113	10169.7	25.1	83	2.97E-04

Research Laboratories	Test piece name	Product	Heat name	Test condition	Aging Process	Temperature (°C)	Stress (MPa)	Time to rupture (h)	Elongation after rupture (%)	Reduction of area (%)	Steady state creep rate (%/h)
EPRI	EPRI-1	Tube		Air		550	230	2112			
EPRI	EPRI-2	Tube		Air		550	240	672			
EPRI	EPRI-3	Tube		Air		550	260	224			
CRIPi	C-1	Plate		Air		550	320	2	32	85.3	
CRIPi	C-2	Plate		Air		550	280	14	29.6	87.1	
CRIPi	C-3	Plate		Air		550	240	165	26.3	86.5	
CRIPi	C-4	Plate		Air		550	220	384	21.7	88.7	
CRIPi	C-5	Plate		Air		550	200	3940	21.4	87.6	
CRIPi	C-6	Plate		Air		550	180	13077	23.4	90.9	
ORNL	CONN-1	Plate		Air		538	276	1181	14	84	
ORNL	CONN-2	Plate		Air		538	296	610	21	83	
ORNL	CONN-3	Plate		Air		538	310	107	23	86	
NRIM	C-1	Plate	NRIM1	Air		500	319	552	28	84	
NRIM	C-10	Plate	NRIM1	Air		600	137	843	30	90	
NRIM	C-11	Plate	NRIM1	Air		600	127	2791	32	89	
NRIM	C-12	Plate	NRIM1	Air		600	118	6474	33	87	
NRIM	C-13	Plate	NRIM1	Air		650	98	163	55	93	
NRIM	C-14	Plate	NRIM1	Air		650	88	627	55	96	
NRIM	C-15	Plate	NRIM1	Air		650	78	1871	42	92	
NRIM	C-16	Plate	NRIM1	Air		650	69	2639	42	91	
NRIM	C-17	Plate	NRIM1	Air		650	59	6580	25	89	
NRIM	C-2	Plate	NRIM1	Air		500	309	2077	25	84	
NRIM	C-3	Plate	NRIM1	Air		500	299	3453	24	83	
NRIM	C-4	Plate	NRIM1	Air		500	279	6951	26	85	
NRIM	C-5	Plate	NRIM1	Air		500	270	6115	26	84	
NRIM	C-6	Plate	NRIM1	Air		550	240	159	32	88	
NRIM	C-7	Plate	NRIM1	Air		550	221	1950	28	88	
NRIM	C-8	Plate	NRIM1	Air		550	201	3574	28	87	
NRIM	C-9	Plate	NRIM1	Air		600	157	178	40	91	

Table 33 - Mod. 9Cr-1Mo Fatigue Data of JAEA (Temperature is 400°C or more)

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
JAEA	Plate	F6	Air		HTH6C4	450	0.1	0.1	1.204	1710
JAEA	Plate	F6	Air		HTH6B1	450	0.1	0.1	1.003	3596
JAEA	Plate	F6	Air		HTH6A8	450	0.1	0.1	0.689	8178
JAEA	Plate	F6	Air		HTH6B2	450	0.1	0.1	0.495	42639
JAEA	Plate	F6	Air		HTH6G7	500	0.001	0.001	0.5	42271
JAEA	Plate	F6	Air		HTH6G2	500	0.01	0.01	0.505	11618
JAEA	Plate	F6	Air		9CR-54	500	0.1	0.1	1.5	860
JAEA	Plate	F6	Air		HTH6A7	500	0.1	0.1	1.199	1597
JAEA	Plate	F6	Air		HTH6A4	500	0.1	0.1	0.995	2904
JAEA	Plate	F6	Air		9CR-51	500	0.1	0.1	0.99	1739
JAEA	Plate	F6	Air		9CR-57	500	0.1	0.1	0.7	3899
JAEA	Plate	F6	Air		HTH6A1	500	0.1	0.1	0.699	4908
JAEA	Plate	F6	Air		9CR-53	500	0.1	0.1	0.5	13320
JAEA	Plate	F6	Air		HTH6A0	500	0.1	0.1	0.499	16615
JAEA	Plate	F6	Air		9CR-56	500	0.1	0.1	0.4	151736
JAEA	Plate	F6	Air		HTH6H4	500	1	1	0.304	173268
JAEA	Plate	F6	Air		HTH6F4	550	0.0001	0.0001	0.999	1110
JAEA	Plate	F6	Air		HTH6G5	550	0.001	0.001	0.707	2581
JAEA	Plate	F6	Air		HTH6F0	550	0.001	0.001	0.504	15995
JAEA	Plate	F6	Air		HTH6C6	550	0.1	0.1	1.197	1706
JAEA	Plate	F6	Air		HTH6E7	550	0.1	0.1	1.016	1843
JAEA	Plate	F6	Air		HTH6B5	550	0.1	0.1	1.002	2323
JAEA	Plate	F6	Air		HTH6B3	550	0.1	0.1	0.702	5087
JAEA	Plate	F6	Air		HTH6E8	550	0.1	0.1	0.508	12088

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
JAEA	Plate	F6	Air		HTH6B6	550	0.1	0.1	0.504	13016
JAEA	Plate	F6	Air		HTH6G4	550	0.1	0.1	0.291	496412
JAEA	Plate	F6	Air		HTH6H2	550	1	1	0.308	175244
JAEA	Plate	F6	Air		HTH6H7	550	1	1	0.251	3558742
JAEA	Plate	F6	Air		HTH6H5	550	1	1	0.2	21091549
JAEA	Plate	F6	Air		HTH6F2	600	0.001	0.001	0.502	4168
JAEA	Plate	F6	Air		HTH6G1	600	0.01	0.01	0.506	10645
JAEA	Plate	F6	Air		HTH6A2	600	0.1	0.1	1.2	1307
JAEA	Plate	F6	Air		HTH6C1	600	0.1	0.1	0.998	2062
JAEA	Plate	F6	Air		HTH6A5	600	0.1	0.1	0.706	4694
JAEA	Plate	F6	Air		HTH6B0	600	0.1	0.1	0.485	9853
JAEA	Plate	F6	Air		HTH6H3	600	1	1	0.31	36723
JAEA	Plate	F6	Air		HTH6H6	600	1	1	0.202	6772955
JAEA	Plate	F6	Air		HTH6C7	650	0.1	0.1	1.198	1065
JAEA	Plate	F6	Air		HTH6B7	650	0.1	0.1	0.955	1883
JAEA	Plate	F6	Air		HTH6B9	650	0.1	0.1	0.701	3334
JAEA	Plate	F6	Air		HTH6C0	650	0.1	0.1	0.501	9857
JAEA	Plate	F7	Air		HTH1A6	400	0.1	0.1	0.986	3648
JAEA	Plate	F7	Air		HTH1A4	400	0.1	0.1	0.681	11580
JAEA	Plate	F7	Air		HTH1B2	400	0.1	0.1	0.479	109133
JAEA	Plate	F7	Air		GAF-1	500	0.1	0.1	1	2167
JAEA	Plate	F7	Air		T3B1	500	0.1	0.1	1	2239
JAEA	Plate	F7	Air		GAF-2	500	0.1	0.1	0.7	5390
JAEA	Plate	F7	Air		T3B2	500	0.1	0.1	0.7	4550
JAEA	Plate	F7	Air		GAF-3	500	0.1	0.1	0.4	141000
JAEA	Plate	F7	Air		T3B4	550	0.1	0.1	1.03	1020

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
JAEA	Plate	F7	Air		GAF-4	550	0.1	0.1	1	2083
JAEA	Plate	F7	Air		T3B5	550	0.1	0.1	0.71	2721
JAEA	Plate	F7	Air		GAF-5	550	0.1	0.1	0.7	4500
JAEA	Plate	F7	Air		GAF-6	550	0.1	0.1	0.4	60280
JAEA	Plate	F7	Air		T3B6	550	0.1	0.1	0.4	57848
JAEA	Plate	F9	Air		HFF958	500	0.001	0.001	1	1886
JAEA	Plate	F9	Air		HFF949	500	0.001	1	0.996	1652
JAEA	Plate	F9	Air		HFF947	500	0.01	0.01	1.003	1999
JAEA	Plate	F9	Air		HFF948	500	0	1	0.996	1867
JAEA	Plate	F9	Air		HFF917	500	0.1	0.1	1.493	922
JAEA	Plate	F9	Air		HFF942	500	0.1	0.1	1.2	1341
JAEA	Plate	F9	Air		HFF938	500	0.1	0.1	1.003	2574
JAEA	Plate	F9	Air		HFF940	500	0.1	0.1	0.805	4174
JAEA	Plate	F9	Air		HFF936	500	0.1	0.1	0.501	24644
JAEA	Plate	F9	Air		HFF944	500	1	1	0.967	3065
JAEA	Plate	F9	Air		HFF934	550	0.001	1	1.006	856
JAEA	Plate	F9	Air		HFF932	550	0.001	0.001	1	1446
JAEA	Plate	F9	Air		HFF931	550	0.01	0.01	1.003	1381
JAEA	Plate	F9	Air		HFF933	550	0.01	1	1	1260
JAEA	Plate	F9	Air		FB9C05	550	0.1	0.1	1.5	825
JAEA	Plate	F9	Air		HFF909	550	0.1	0.1	1.5	825
JAEA	Plate	F9	Air		FB9C04	550	0.1	0.1	1.2	3179
JAEA	Plate	F9	Air		HFF908	550	0.1	0.1	1.2	1308
JAEA	Plate	F9	Air		FB9C03	550	0.1	0.1	1	1792
JAEA	Plate	F9	Air		HFF905	550	0.1	0.1	0.983	1790
JAEA	Plate	F9	Air		HFF906	550	0.1	0.1	0.793	3106

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
JAEA	Plate	F9	Air		FB9C02	550	0.1	0.1	0.7	2049
JAEA	Plate	F9	Air		FB9C01	550	0.1	0.1	0.5	8856
JAEA	Plate	F9	Air		HFF907	550	0.1	0.1	0.5	17662
JAEA	Plate	F9	Air		HFF930	550	1	1	1	2238
JAEA	Plate	F9	Air		HFF953	600	0.001	1	1.003	773
JAEA	Plate	F9	Air		HFF966	600	0.001	0.001	1.001	1392
JAEA	Plate	F9	Air		HFF950	600	0.01	0.01	1.01	2267
JAEA	Plate	F9	Air		HFF957	600	0.01	1	1.001	984
JAEA	Plate	F9	Air		HFF916	600	0.1	0.1	1.5	757
JAEA	Plate	F9	Air		HFF912	600	0.1	0.1	1.2	1113
JAEA	Plate	F9	Air		HFF913	600	0.1	0.1	1	1504
JAEA	Plate	F9	Air		HFF914	600	0.1	0.1	0.8	2322
JAEA	Plate	F9	Air		HFF915	600	0.1	0.1	0.513	7628
JAEA	Plate	F9	Air		HFF945	600	1	1	0.977	2167
JAEA	Forging	F4	Air		HMH6J6	500	0.1	0.1	1.003	2266
JAEA	Forging	F4	Air		HMH6J0	500	0.1	0.1	0.703	7528
JAEA	Forging	F4	Air		HMH6K1	500	0.1	0.1	0.488	35054
JAEA	Forging	F4	Air		HMH6K2	500	0.1	0.1	0.401	79070
JAEA	Forging	F4	Air		HMH6J9	500	0.1	0.1	0.384	53876
JAEA	Forging	F4	Air		HMH6J1	550	0.1	0.1	1.007	1389
JAEA	Forging	F4	Air		HMH6J5	550	0.1	0.1	0.699	5934
JAEA	Forging	F4	Air		HMH6F6	550	0.1	0.1	0.501	10217
JAEA	Forging	F4	Air		HMH6G3	550	0.1	0.1	0.497	18606
JAEA	Forging	F4	Air		HMH6A2	550	0.1	0.1	0.496	16489
JAEA	Forging	F4	Air		HMH6J4	550	0.1	0.1	0.489	13779
JAEA	Forging	F4	Air		HMH6H5	550	0.1	0.1	0.479	17772

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
JAEA	Forging	F4	Air		HMH6C4	550	0.1	0.1	0.477	10294
JAEA	Forging	F4	Air		HMH6I3	550	0.1	0.1	0.475	18018
JAEA	Forging	F4	Air		HMH6B3	550	0.1	0.1	0.474	7486
JAEA	Forging	F4	Air		HMH6E8	550	0.1	0.1	0.458	21014
JAEA	Forging	F4	Air		HMH6D6	550	0.1	0.1	0.437	10490
JAEA	Forging	F4	Air		HMH6K0	550	0.1	0.1	0.394	72230
JAEA	Forging	F5	Air		HMH9A4	550	0.1	0.1	0.513	14390
JAEA	Forging	F5	Air		HMH9B2	550	0.1	0.1	0.51	20590
JAEA	Forging	F5	Air		HMH9A1	550	0.1	0.1	0.51	14252
JAEA	Forging	F5	Air		HMH9B3	550	0.1	0.1	0.509	10033
JAEA	Forging	F5	Air		HMH9A0	550	0.1	0.1	0.509	20407
JAEA	Forging	F5	Air		HMH9A8	550	0.1	0.1	0.508	14315
JAEA	Forging	F5	Air		HMH9A6	550	0.1	0.1	0.501	11173
JAEA	Forging	F5	Air		HMH9A3	550	0.1	0.1	0.501	15091
JAEA	Forging	F5	Air		HMH9B0	550	0.1	0.1	0.5	15476
JAEA	Forging	F5	Air		HMH9B4	550	0.1	0.1	0.497	10816
JAEA	Forging	F8	Air		S-9	550	0.1	0.1	1.2	1069
JAEA	Forging	F8	Air		S-3	550	0.1	0.1	1.2	1122
JAEA	Forging	F8	Air		S-7	550	0.1	0.1	1	1330
JAEA	Forging	F8	Air		S-1	550	0.1	0.1	1	1704
JAEA	Forging	F8	Air		S-18	550	0.1	0.1	0.7	2545
JAEA	Forging	F8	Air		S-12	550	0.1	0.1	0.7	2452
JAEA	Forging	F8	Air		S-17	550	0.1	0.1	0.5	5300
JAEA	Forging	F8	Air		S-11	550	0.1	0.1	0.5	7180
JAEA	Forging	F8	Air		S-8	550	0.1	0.1	0.4	26815
JAEA	Forging	F8	Air		S-2	550	0.1	0.1	0.4	9300

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
JAEA	Forging	F8	Air		S-10	550	0.1	0.1	0.4	57732
JAEA	Forging	F11	Air		HBM01	550	0.1	0.1	0.5	12704
JAEA	Tube	F2	Air		RUG6C6	450	0.1	0.1	1.65	715
JAEA	Tube	F2	Air		HUH6B0	450	0.1	0.1	1.198	2349
JAEA	Tube	F2	Air		HUH6A4	450	0.1	0.1	0.999	2874
JAEA	Tube	F2	Air		RUG6C7	450	0.1	0.1	0.972	1547
JAEA	Tube	F2	Air		HUS6C0	450	0.1	0.1	0.802	3638
JAEA	Tube	F2	Air		HUH6B7	450	0.1	0.1	0.697	10200
JAEA	Tube	F2	Air		HUS6C1	450	0.1	0.1	0.516	18883
JAEA	Tube	F2	Air		HUH6B8	450	0.1	0.1	0.497	92178
JAEA	Tube	F2	Air		HUS6C2	500	0.1	0.1	1.859	390
JAEA	Tube	F2	Air		HUH6B2	500	0.1	0.1	1.2	1902
JAEA	Tube	F2	Air		HUS6C3	500	0.1	0.1	1.139	962
JAEA	Tube	F2	Air		HUH6A5	500	0.1	0.1	0.999	2546
JAEA	Tube	F2	Air		HUS6C4	500	0.1	0.1	0.77	1214
JAEA	Tube	F2	Air		HUH6B1	500	0.1	0.1	0.699	7432
JAEA	Tube	F2	Air		HUH6B6	500	0.1	0.1	0.498	25806
JAEA	Tube	F2	Air		HUS6C5	500	0.1	0.1	0.412	27450
JAEA	Tube	F2	Air		HUS6C8	550	0.1	0.1	1.663	621
JAEA	Tube	F2	Air		HUH6B3	550	0.1	0.1	1.199	1515
JAEA	Tube	F2	Air		HUS6C9	550	0.1	0.1	1.114	1250
JAEA	Tube	F2	Air		HUH6A8	550	0.1	0.1	1	2294
JAEA	Tube	F2	Air		HUH6A9	550	0.1	0.1	0.698	4938
JAEA	Tube	F2	Air		RUG6C8	550	0.1	0.1	0.666	4203
JAEA	Tube	F2	Air		RUG6C9	550	0.1	0.1	0.592	6682
JAEA	Tube	F2	Air		HUH6B5	550	0.1	0.1	0.497	15996

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
JAEA	Tube	F2	Air		RUG6D4	600	0.1	0.1	1.648	544
JAEA	Tube	F2	Air		HUH6B4	600	0.1	0.1	1.201	994
JAEA	Tube	F2	Air		RUG6D1	600	0.1	0.1	1.044	1721
JAEA	Tube	F2	Air		HUH6A7	600	0.1	0.1	1	1826
JAEA	Tube	F2	Air		HUH6A2	600	0.1	0.1	0.699	4272
JAEA	Tube	F2	Air		RUG6D3	600	0.1	0.1	0.63	3303
JAEA	Tube	F2	Air		HUH6A0	600	0.1	0.1	0.495	11392
EPRI	Tube		Air		EPRI-9	500	0.1	0.1	0.5	8621
EPRI	Tube		Air		EPRI-10	500	0.1	0.1	0.7	2888
EPRI	Tube		Air		EPRI-11	500	0.1	0.1	1	1182
EPRI	Tube		Air		EPRI-12	500	0.1	0.1	1.4	342
EPRI	Tube		Air		EPRI-13	550	0.1	0.1	0.5	1574
EPRI	Tube		Air		EPRI-14	550	0.1	0.1	0.7	1092
EPRI	Tube		Air		EPRI-16	550	0.1	0.001	0.7	1327
EPRI	Tube		Air		EPRI-19	550	0.1	0.001	1	548
EPRI	Tube		Air		EPRI-22	550	0.1	0.001	1.4	218
EPRI	Tube		Air		EPRI-17	550	0.001	0.001	0.7	630
EPRI	Tube		Air		EPRI-20	550	0.001	0.001	1	337
EPRI	Tube		Air		EPRI-23	550	0.001	0.001	1.4	250
EPRI	Tube		Air		EPRI-15	550	0.001	0.1	0.7	2136
EPRI	Tube		Air		EPRI-18	550	0.001	0.1	1	772
EPRI	Tube		Air		EPRI-21	550	0.001	0.1	1.4	361
CRIEPI	Plate		Air		CRIEPI-5	400	0.1	0.1	1.4	1786
CRIEPI	Plate		Air		CRIEPI-6	400	0.1	0.1	1	3076
CRIEPI	Plate		Air		CRIEPI-7	400	0.1	0.1	0.7	8160
CRIEPI	Plate		Air		CRIEPI-8	400	0.1	0.1	0.5	15800

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
CRIEPI	Plate		Air		CRIEPI-9	550	0.1	0.1	1.4	1385
CRIEPI	Plate		Air		CRIEPI-10	550	0.1	0.1	1	3120
CRIEPI	Plate		Air		CRIEPI-11	550	0.1	0.1	0.7	4280
CRIEPI	Plate		Air		CRIEPI-12	550	0.1	0.1	0.5	10960
CRIEPI	Plate		Air		CRIEPI-13	600	0.1	0.1	1.4	2050
CRIEPI	Plate		Air		CRIEPI-14	600	0.1	0.1	1	3600
CRIEPI	Plate		Air		CRIEPI-15	600	0.1	0.1	0.7	4620
CRIEPI	Plate		Air		CRIEPI-16	600	0.1	0.1	0.5	7290
TOKYO Univ.	Plate	Tokyo	vacuum		T-1	600	0.1	0.1	0.482	143499
TOKYO Univ.	Plate	Tokyo	vacuum		T-2	600	0.1	0.1	0.591	91495
TOKYO Univ.	Plate	Tokyo	vacuum		T-3	600	0.1	0.1	0.797	35289
TOKYO Univ.	Plate	Tokyo	vacuum		T-4	600	0.1	0.1	0.986	16331
TOKYO Univ.	Plate	Tokyo	vacuum		T-5	600	0.1	0.1	1.97	3290
TOKYO Univ.	Plate	Tokyo	vacuum		T-6	600	0.01	0.01	0.967	16505
TOKYO Univ.	Plate	Tokyo	vacuum		T-7	600	0.01	0.01	1.989	3334
TOKYO Univ.	Plate	Tokyo	vacuum		T-8	600	0.1	0.01	0.977	13257
TOKYO Univ.	Plate	Tokyo	vacuum		T-9	600	0.1	0.01	1.982	3344
TOKYO Univ.	Plate	Tokyo	vacuum		T-10	600	0.01	0.1	0.986	5941
TOKYO Univ.	Plate	Tokyo	vacuum		T-11	600	0.01	0.1	1.979	1525
TOKYO Univ.	Plate	Tokyo	vacuum		T-12	600	0.001	0.1	0.999	1830
TOKYO Univ.	Plate	Tokyo	vacuum		T-13	600	0.001	0.1	1.982	558
CONNECTICUT	Plate	ORNL	Air	60 hr 60hr+retemper	1	538	0.4	0.4	1	1750
CONNECTICUT	Plate	ORNL	Air		2	538	0.4	0.4	1	1200
CONNECTICUT	Plate	ORNL	Air		3	538	0.4	0.4	1	1450
ORNL	Plate	30394	Air		394-3	538	0.4	0.4	0.5	13786
ORNL	Plate	30394	Air		394-29	538	0.4	0.4	0.5	15455

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
ORNL	Plate	30394	Air		394-6	538	0.4	0.4	0.7	6844
ORNL	Plate	30394	Air		394-24	538	0.4	0.4	0.7	9676
ORNL	Plate	30394	Air		394-38	593	0.4	0.4	0.52	13125
ORNL	Plate	30394	Air		394-53	593	0.4	0.4	0.49	7420
ORNL	Plate	30394	Air	75kh Aging	394-702L	538	0.4	0.4	0.51	10700
ORNL	Plate	30394	Air	50kh Aging	2241	538	0.4	0.4	0.71	6060
ORNL	Plate	30394	Air	50kh Aging	2341	593	0.4	0.4	0.47	5061
NRIM	Plate	NRIM1	Air		F-F-10	500	0.1	0.1	1.76	352
NRIM	Plate	NRIM1	Air		F-F-11	500	0.1	0.1	1.5	458
NRIM	Plate	NRIM1	Air		F-F-12	500	0.1	0.1	1.04	1300
NRIM	Plate	NRIM1	Air		F-F-13	500	0.1	0.1	0.68	5990
NRIM	Plate	NRIM1	Air		F-F-14	500	0.1	0.1	0.5	14000
NRIM	Plate	NRIM1	Air		F-F-15	500	0.1	0.1	0.44	28000
NRIM	Plate	NRIM1	Air		F-C2-1	500	0.001	0.001	1.4	657
NRIM	Plate	NRIM1	Air		F-C2-2	550	0.001	0.001	1	853
NRIM	Plate	NRIM1	Air		F-C2-3	550	0.001	0.001	0.8	1670
NRIM	Plate	NRIM1	Air		F-C2-4	550	0.001	0.001	0.62	3290
NRIM	Plate	NRIM1	Air		F-C2-5	550	0.001	0.001	0.5	3450
NRIM	Plate	NRIM1	Air		F-C2-6	550	0.001	0.001	0.46	9830
NRIM	Plate	NRIM1	Air		F-C1-1	550	0.01	0.01	2	419
NRIM	Plate	NRIM1	Air		F-C1-2	550	0.01	0.01	1.52	773
NRIM	Plate	NRIM1	Air		F-C1-3	550	0.01	0.01	1	1100
NRIM	Plate	NRIM1	Air		F-C1-4	550	0.01	0.01	0.82	2030
NRIM	Plate	NRIM1	Air		F-C1-5	550	0.01	0.01	0.62	3990
NRIM	Plate	NRIM1	Air		F-C1-6	550	0.01	0.01	0.5	8500
NRIM	Plate	NRIM1	Air		F-F-16	550	0.1	0.1	1.42	617

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
NRIM	Plate	NRIM1	Air		F-F-17	550	0.1	0.1	1.02	1490
NRIM	Plate	NRIM1	Air		F-F-18	550	0.1	0.1	0.78	2350
NRIM	Plate	NRIM1	Air		F-F-19	550	0.1	0.1	0.7	1930
NRIM	Plate	NRIM1	Air		F-F-20	550	0.1	0.1	0.58	5860
NRIM	Plate	NRIM1	Air		F-F-21	550	0.1	0.1	0.48	11000
NRIM	Plate	NRIM1	Air		F-F-22	550	0.1	0.1	0.34	73400
NRIM	Plate	NRIM1	Air		F-FA-1	550	0.5	0.5	2.02	337
NRIM	Plate	NRIM1	Air		F-FA-2	550	0.5	0.5	1.64	432
NRIM	Plate	NRIM1	Air		F-FA-3	550	0.5	0.5	1.5	884
NRIM	Plate	NRIM1	Air		F-FA-4	550	0.5	0.5	1	1390
NRIM	Plate	NRIM1	Air		F-FA-5	550	0.5	0.5	0.78	1700
NRIM	Plate	NRIM1	Air		F-FA-6	550	0.5	0.5	0.6	5400
NRIM	Plate	NRIM1	Air		F-FA-7	550	0.5	0.5	0.4	28000
NRIM	Plate	NRIM1	Air		F-C2-10	600	0.001	0.001	0.96	934
NRIM	Plate	NRIM1	Air		F-C2-11	600	0.001	0.001	0.7	1420
NRIM	Plate	NRIM1	Air		F-C2-12	600	0.001	0.001	0.6	2500
NRIM	Plate	NRIM1	Air		F-C2-13	600	0.001	0.001	0.5	4160
NRIM	Plate	NRIM1	Air		F-C2-14	600	0.001	0.001	0.46	2650
NRIM	Plate	NRIM1	Air		F-C2-15	600	0.001	0.001	0.46	5280
NRIM	Plate	NRIM1	Air		F-C2-7	600	0.001	0.001	1.88	345
NRIM	Plate	NRIM1	Air		F-C2-8	600	0.001	0.001	1.5	601
NRIM	Plate	NRIM1	Air		F-C2-9	600	0.001	0.001	0.98	1350
NRIM	Plate	NRIM1	Air		F-C1-10	600	0.01	0.01	0.7	1580
NRIM	Plate	NRIM1	Air		F-C1-11	600	0.01	0.01	0.6	5550
NRIM	Plate	NRIM1	Air		F-C1-12	600	0.01	0.01	0.5	8670
NRIM	Plate	NRIM1	Air		F-C1-7	600	0.01	0.01	1.5	632

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Strain rate [%/s]		Total strain [%]	Cycles to failure
							:Tension	:Compression		
NRIM	Plate	NRIM1	Air		F-C1-8	600	0.01	0.01	1.02	1040
NRIM	Plate	NRIM1	Air		F-C1-9	600	0.01	0.01	0.78	1610
NRIM	Plate	NRIM1	Air		F-F-23	600	0.1	0.1	1.86	320
NRIM	Plate	NRIM1	Air		F-F-24	600	0.1	0.1	1.5	558
NRIM	Plate	NRIM1	Air		F-F-25	600	0.1	0.1	1.22	1210
NRIM	Plate	NRIM1	Air		F-F-26	600	0.1	0.1	0.86	2210
NRIM	Plate	NRIM1	Air		F-F-27	600	0.1	0.1	0.7	2510
NRIM	Plate	NRIM1	Air		F-F-28	600	0.1	0.1	0.6	3910
NRIM	Plate	NRIM1	Air		F-F-29	600	0.1	0.1	0.5	8020
NRIM	Plate	NRIM1	Air		F-F-30	600	0.1	0.1	0.4	12200
NRIM	Plate	NRIM1	Air		F-F-31	600	0.1	0.1	0.34	49400
NRIM	Plate	NRIM1	Air		F-F-32	650	0.1	0.1	1.74	484
NRIM	Plate	NRIM1	Air		F-F-33	650	0.1	0.1	1.18	780
NRIM	Plate	NRIM1	Air		F-F-34	650	0.1	0.1	1.04	1340
NRIM	Plate	NRIM1	Air		F-F-35	650	0.1	0.1	0.7	2260
NRIM	Plate	NRIM1	Air		F-F-36	650	0.1	0.1	0.48	5480
NRIM	Plate	NRIM1	Air		F-F-37	650	0.1	0.1	0.34	16200
NRIM	Plate	NRIM1	Air		F-FA-10	600	0.5	0.5	1	1510
NRIM	Plate	NRIM1	Air		F-FA-11	600	0.5	0.5	0.8	2320
NRIM	Plate	NRIM1	Air		F-FA-12	600	0.5	0.5	0.6	6650
NRIM	Plate	NRIM1	Air		F-FA-13	600	0.5	0.5	0.42	11400
NRIM	Plate	NRIM1	Air		F-FA-8	600	0.5	0.5	1.98	377
NRIM	Plate	NRIM1	Air		F-FA-9	600	0.5	0.5	1.5	623

Table 34 - Mod. 9Cr-1Mo Creep Fatigue Data (Temperature is 400 °C or more)

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Hold time [h]		Strain rate [%/s]		Total strain [%]	Cycles to failure
							Tens.	Comp.	Tensi.	Comp.		
JAEA	Plate	F6	Air		9CR85	500	0.017	0	0.1	0.1	0.5	19468
JAEA	Plate	F6	Air		9CR86	500	0	0.017	0.1	0.1	0.5	8958
JAEA	Plate	F6	Air		9CR92	500	0	0.05	0.1	0.1	0.5	6717
JAEA	Plate	F6	Air		HTH6G3	500	1	0	0.1	0.1	0.507	20686
JAEA	Plate	F6	Air		9CR83	500	0.167	0	0.1	0.1	0.7	6485
JAEA	Plate	F6	Air		9CR58	500	0.167	0	0.1	0.1	1	2070
JAEA	Plate	F6	Air		9CR91	500	0	0.083	0.1	0.1	1.01	1404
JAEA	Plate	F6	Air		9CR82	500	0.017	0	0.1	0.1	1.51	1232
JAEA	Plate	F6	Air		HTH6E6	550	0.1	0	0.001	0.001	0.345	56097
JAEA	Plate	F6	Air		HTL9A5	550	1	0	0.002	0.002	0.361	13012
JAEA	Plate	F6	Air		HTL9A2	550	0	1	0.002	0.002	0.373	7347
JAEA	Plate	F6	Air		HTL9A3	550	0	10	0.002	0.002	0.724	1428
JAEA	Plate	F6	Air		HTH6F5	550	1	0	0.1	0.1	0.494	6453
JAEA	Plate	F6	Air		HTH6D3	550	0.1	0	0.1	0.1	0.498	16093
JAEA	Plate	F6	Air		HTH6E0	550	0	1	0.1	0.1	0.505	3293
JAEA	Plate	F6	Air		HTH6D8	550	1	0	0.1	0.1	0.692	2623
JAEA	Plate	F6	Air		HTH6C8	550	0.1	0	0.1	0.1	0.693	3568
JAEA	Plate	F6	Air		HTH6D1	550	0.1	0	0.1	0.1	0.991	1749
JAEA	Plate	F6	Air		HTH6D7	550	1	0	0.1	0.1	1.003	1266
JAEA	Plate	F6	Air		HTH6F6	600	1	0	0.1	0.1	0.518	3630
JAEA	Plate	F9	Air		HFF961	550	0.333	0	0.1	0.1	1.5	1184
JAEA	Plate	F9	Air		HFF956	550	0.167	0	0.1	0.1	1.49	1065
JAEA	Plate	F9	Air		HFF962	550	0.167	0	0.1	0.1	1.001	1067

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Hold time [h]		Strain rate [%/s]		Total strain [%]	Cycles to failure
							Tens.	Comp.	Tensi.	Comp.		
JAEA	Plate	F9	Air		HFF964	550	0.167	0	0.1	0.1	1.001	1197
JAEA	Plate	F9	Air		HFF955	550	0.333	0	0.1	0.1	0.998	2290
JAEA	Plate	F9	Air		HFF965	600	0	0.333	0.1	0.1	1.001	589
JAEA	Plate	F9	Air		HFF963	600	0.333	0	0.1	0.1	0.996	1452
CRIPI	Plate		AIR		CF-3	550	0.167	0.167	0.1	0.1	1	1142
CRIPI	Plate		AIR		CF-9	550	0.167	0.167	0.1	0.1	0.5	3871
CRIPI	Plate		AIR		CF-1	550	0.167		0.1	0.1	1	1968
CRIPI	Plate		AIR		CF-7	550	0.167		0.1	0.1	0.5	10120
CRIPI	Plate		AIR		CF-6	550	1	1	0.1	0.1	1	734
CRIPI	Plate		AIR		CF-4	550	1		0.1	0.1	1	1885
CRIPI	Plate		AIR		CF-2	550		0.167	0.1	0.1	1	1006
CRIPI	Plate		AIR		CF-8	550		0.167	0.1	0.1	0.5	2822
CRIPI	Plate		AIR		CF-5	550		1	0.1	0.1	1	956
TOKYO Univ.	Plate	Tokyo	Vacuum		T-14	600	0.167		0.1	0.1	0.978	6627
TOKYO Univ.	Plate	Tokyo	Vacuum		T-15	600	0.167		0.1	0.1	1.972	2547
TOKYO Univ.	Plate	Tokyo	Vacuum		T-16	600		0.167	0.1	0.1	1.988	1674
ORNL	Plate	30394	AIR		394-37	538	0.25		0.4	0.4	0.78	3537
ORNL	Plate	30394	AIR		148-31	538	0.5		0.4	0.4	0.5	6975
ORNL	Plate	30394	AIR		394-46	538	0.5		0.4	0.4	0.51	7770
ORNL	Plate	30394	AIR		148-33	593	0.5		0.4	0.4	0.5	3360
ORNL	Plate	30394	AIR		394-47	593	1		0.4	0.4	0.5	3207
ORNL	Plate	30394	AIR		394-49	593	1		0.4	0.4	0.5	2870
ORNL	Plate	30394	AIR		148-35	593	1		0.4	0.4	0.5	2882
ORNL	Plate	30394	AIR		394B60T	538		0.25	0.4	0.4	0.5	8840
ORNL	Plate	30394	AIR	50kh Aging	2242	538	0.25		0.4	0.4	0.76	2894
ORNL	Plate	30394	AIR	50kh Aging	394-698L	538	0.25		0.4	0.4	0.51	4791

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Hold time [h]		Strain rate [%/s]		Total strain [%]	Cycles to failure
							Tens.	Comp.	Tensi.	Comp.		
ORNL	Plate	30394	AIR	75kh Aging	394-700L	538	0.5		0.4	0.4	0.51	3535
ORNL	Plate	30394	AIR	50kh Aging	2243	538	0.5		0.4	0.4	0.78	2590
ORNL	Plate	30394	AIR	50kh Aging	2342	593	0.5		0.4	0.4	0.5	1652
ORNL	Plate	30394	AIR	50kh Aging	2344	593	0.5		0.4	0.4	0.51	1221
ORNL	Plate	30394	AIR	50kh Aging	2343	593	1		0.4	0.4	0.5	2303
ORNL	Plate	30394	Vacuum		148-38	593	0.5		0.4	0.4	0.5	4150
ORNL	Plate	30394	Vacuum		148-44	593	1		0.4	0.4	0.5	2900
NIMS	Plate	NRIM1	AIR		CF-1	550	0.1		0.5	0.5	1.94	339
NIMS	Plate	NRIM1	AIR		CF-11	600	0.1		0.5	0.5	1.86	361
NIMS	Plate	NRIM1	AIR		CF-12	600	0.1		0.5	0.5	1.52	580
NIMS	Plate	NRIM1	AIR		CF-13	600	0.1		0.5	0.5	1.4	596
NIMS	Plate	NRIM1	AIR		CF-14	600	0.1		0.5	0.5	1.04	1180
NIMS	Plate	NRIM1	AIR		CF-15	600	0.1		0.5	0.5	0.8	1340
NIMS	Plate	NRIM1	AIR		CF-16	600	0.1		0.5	0.5	0.52	3910
NIMS	Plate	NRIM1	AIR		CF-17	600	0.1		0.5	0.5	0.46	5840
NIMS	Plate	NRIM1	AIR		CF-2	550	0.1		0.5	0.5	1.52	743
NIMS	Plate	NRIM1	AIR		CF-3	550	0.1		0.5	0.5	1.08	1180
NIMS	Plate	NRIM1	AIR		CF-4	550	0.1		0.5	0.5	0.84	2550
NIMS	Plate	NRIM1	AIR		CF-5	550	0.1		0.5	0.5	0.7	3410
NIMS	Plate	NRIM1	AIR		CF-6	550	0.1		0.5	0.5	0.52	13100
NIMS	Plate	NRIM1	AIR		CF-10	550	1		0.5	0.5	0.72	2420
NIMS	Plate	NRIM1	AIR		CF-18	600	1		0.5	0.5	2.02	291
NIMS	Plate	NRIM1	AIR		CF-19	600	1		0.5	0.5	1.48	398
NIMS	Plate	NRIM1	AIR		CF-20	600	1		0.5	0.5	1.04	1000
NIMS	Plate	NRIM1	AIR		CF-21	600	1		0.5	0.5	0.82	1090
NIMS	Plate	NRIM1	AIR		CF-22	600	1		0.5	0.5	0.74	954

Research Laboratories	Product	Heat name	Test condition	Aging process	Test piece name	Temperature [°C]	Hold time [h]		Strain rate [%/s]		Total strain [%]	Cycles to failure
							Tens.	Comp.	Tensi.	Comp.		
NIMS	Plate	NRIM1	AIR		CF-7	550	1		0.5	0.5	1.94	360
NIMS	Plate	NRIM1	AIR		CF-8	550	1		0.5	0.5	1.46	491
NIMS	Plate	NRIM1	AIR		CF-9	550	1		0.5	0.5	0.98	944

APPENDIX B

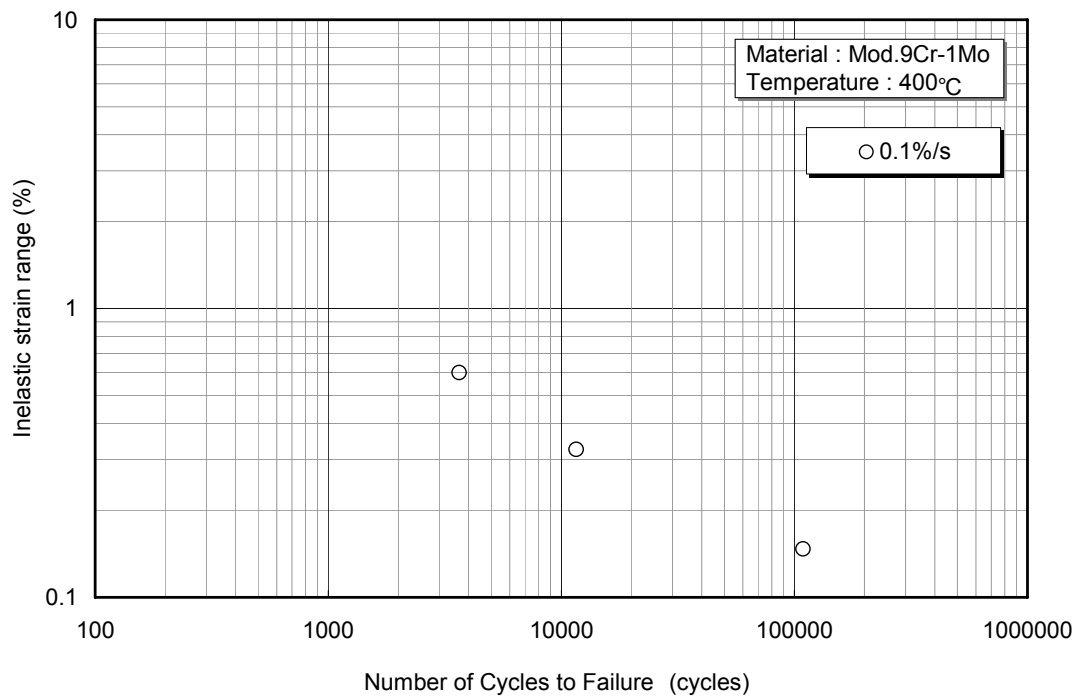


Figure 113 - Relation between Inelastic Strain Range and Fatigue Life at 400°C

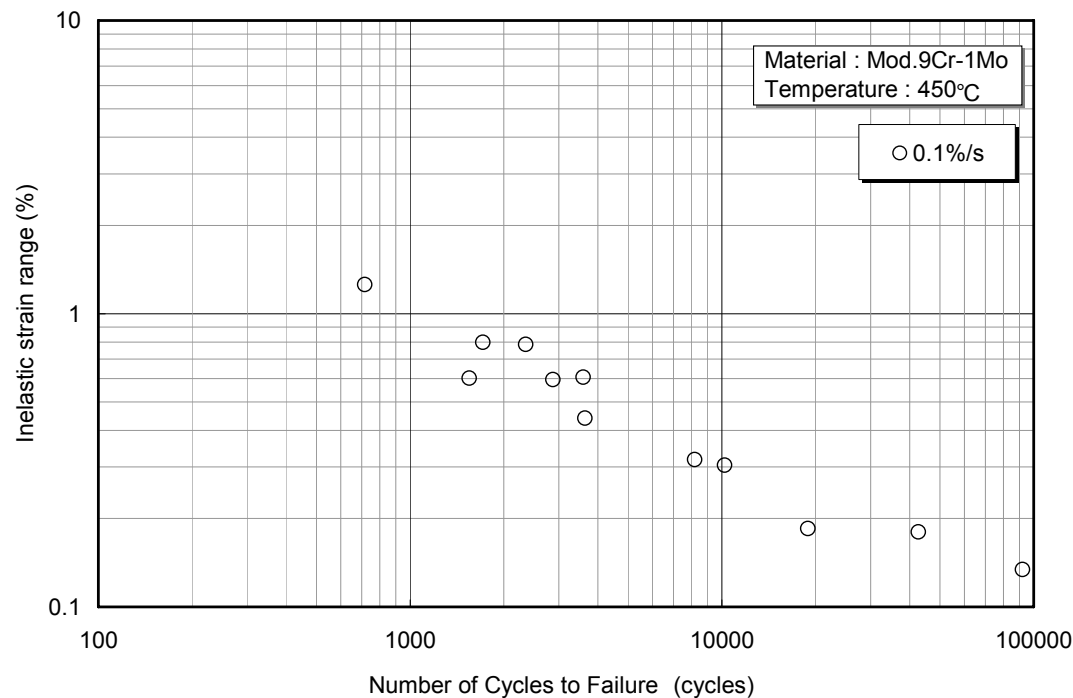


Figure 114 - Relation between Inelastic Strain Range and Fatigue Life at 450°C

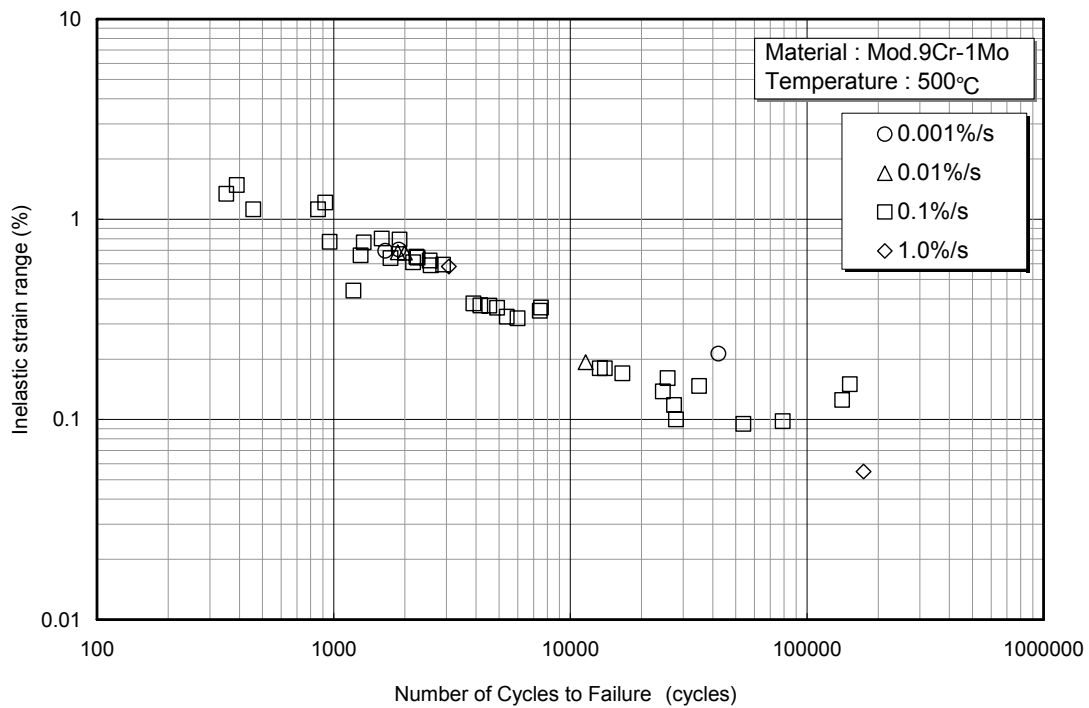


Figure 115 - Relation between Inelastic Strain Range and Fatigue Life at 500°C

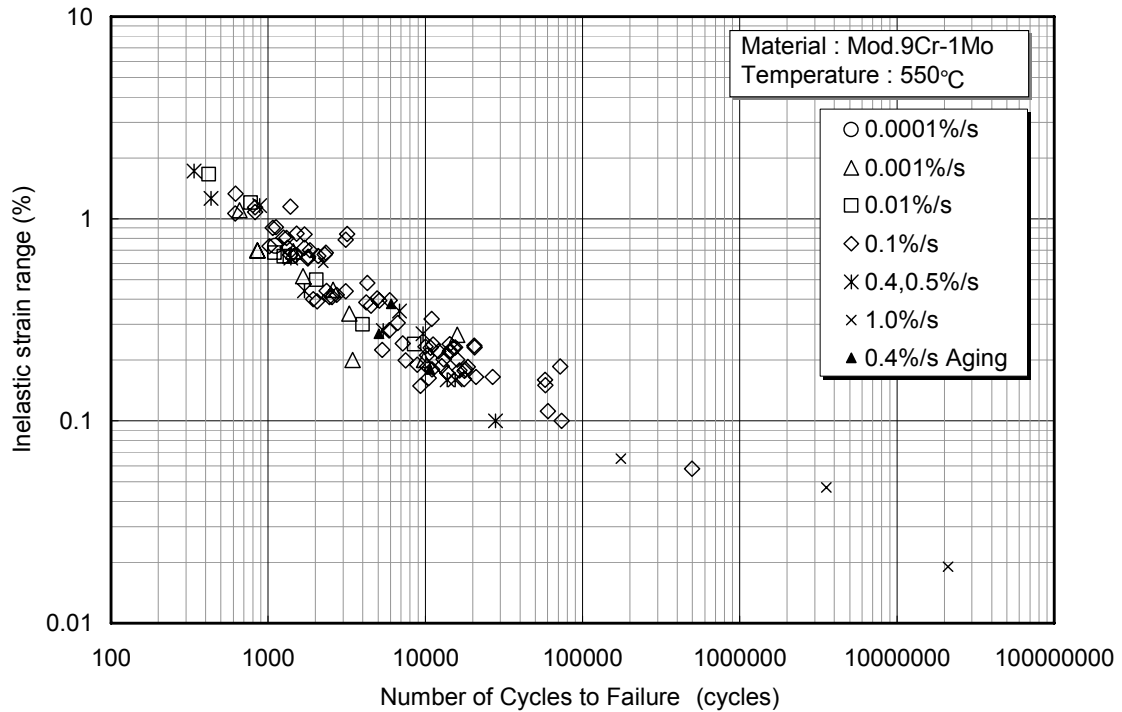


Figure 116 - Relation between Inelastic Strain Range and Fatigue Life at 550°C

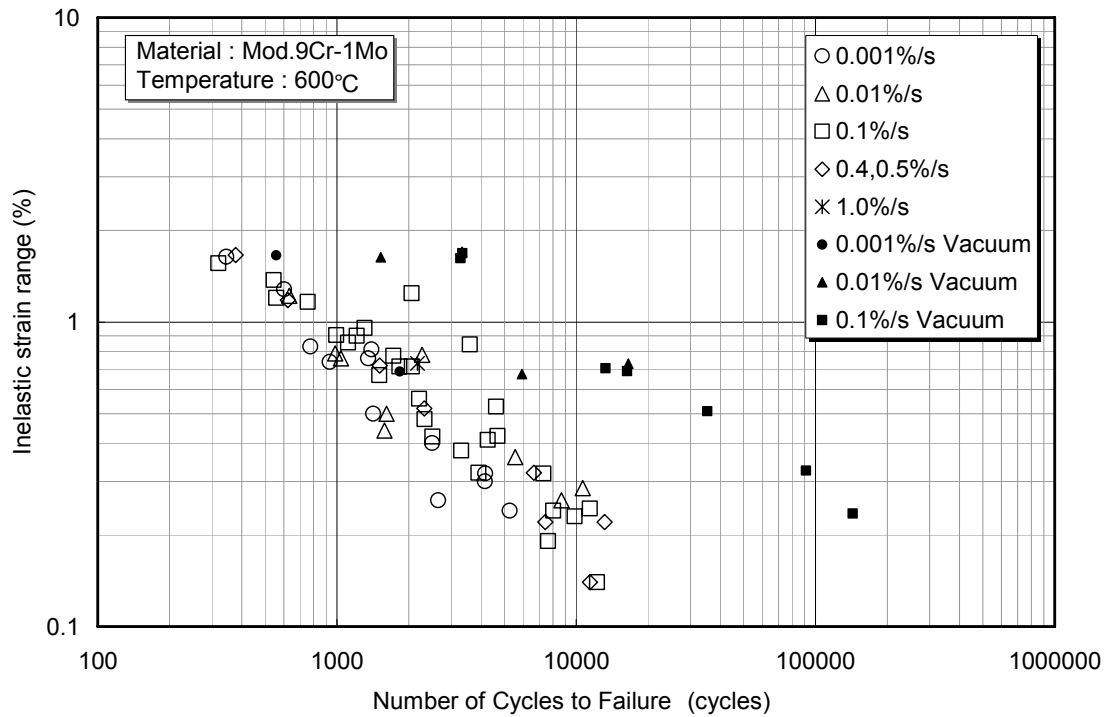


Figure 117 - Relation between Inelastic Strain Range and Fatigue Life at 600°C

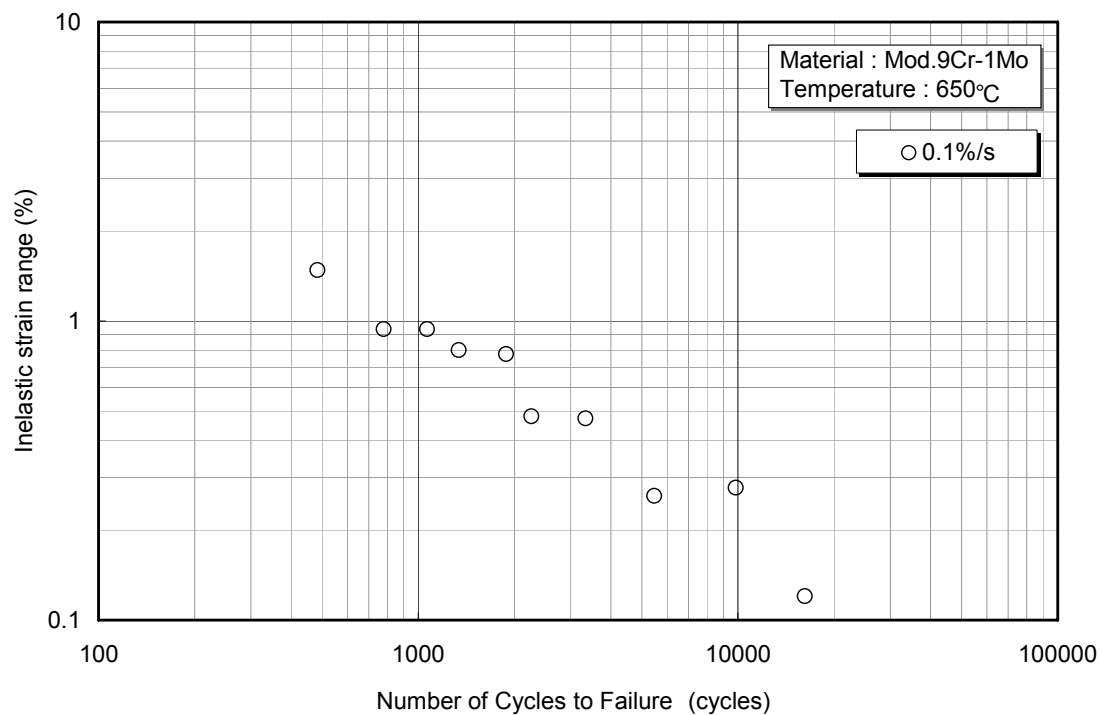


Figure 118 - Relation between Inelastic Strain Range and Fatigue Life at 650°C

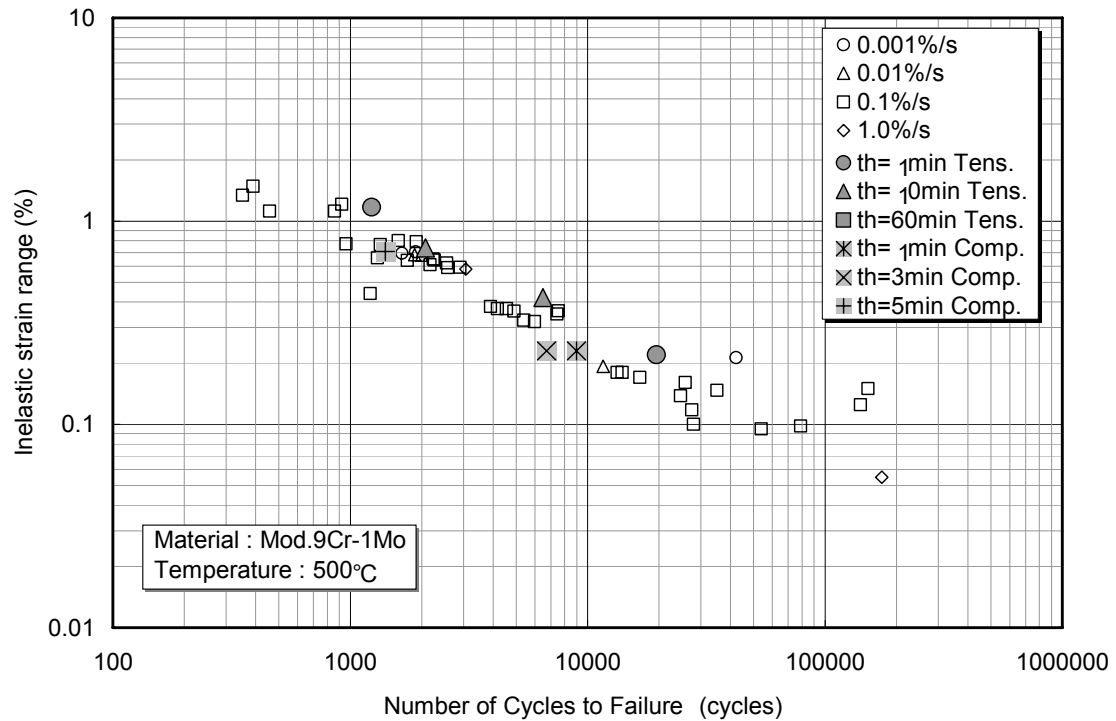


Figure 119 - Relation between Inelastic Strain Range and Creep Fatigue Life at 500°C

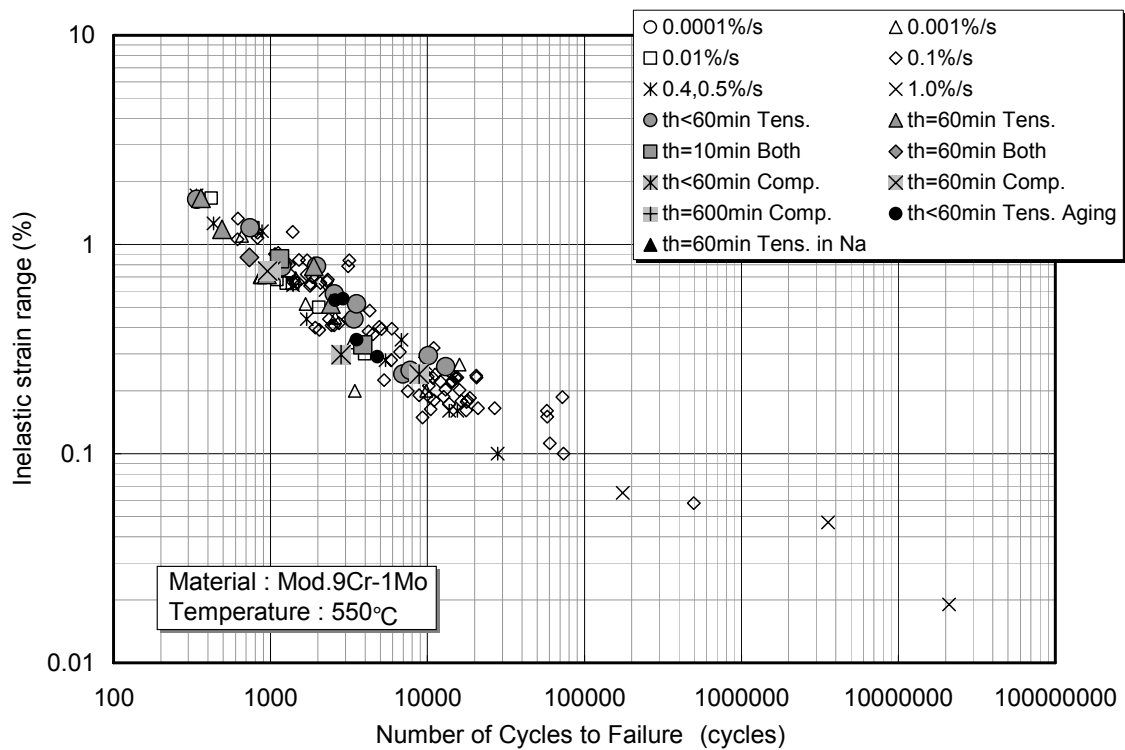


Figure 120 - Relation between Inelastic Strain Range and Creep Fatigue Life at 550°C

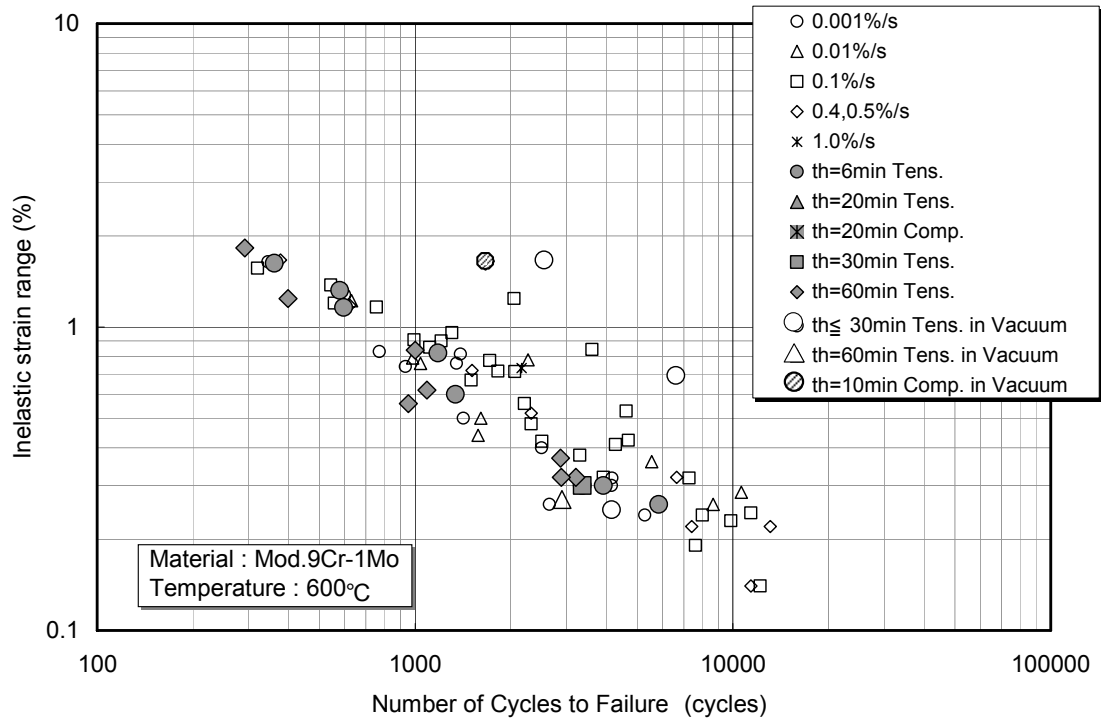


Figure 121 - Relation between Inelastic Strain Range and Creep Fatigue Life at 600°C

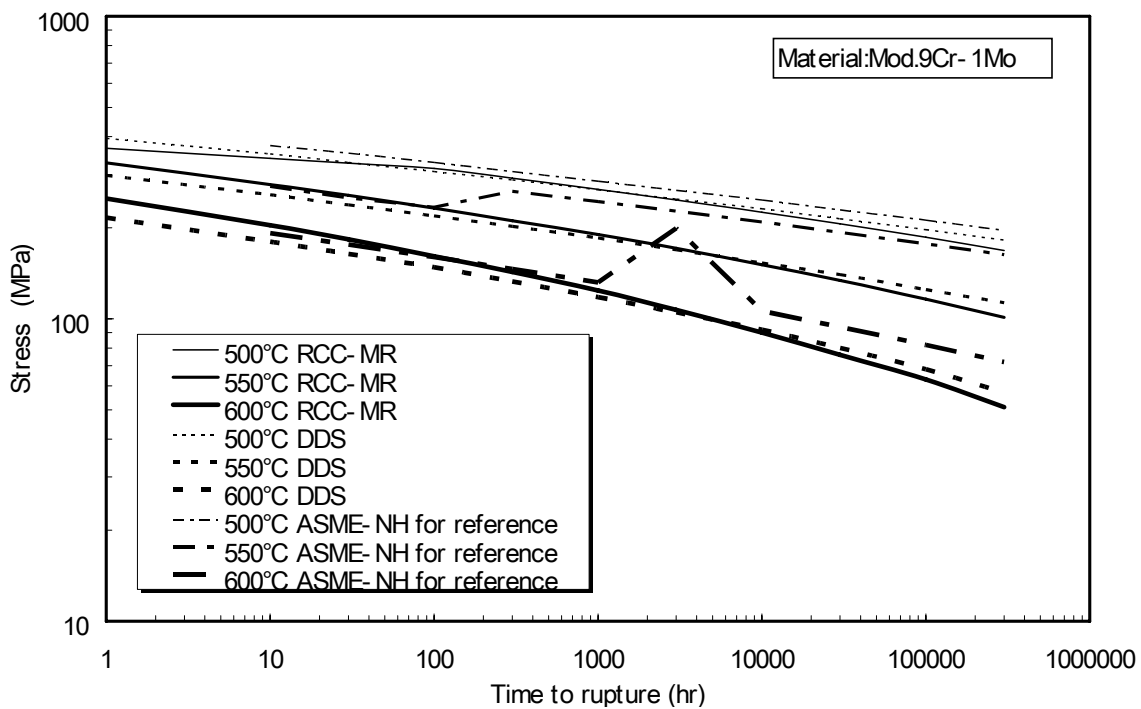


Figure 122 - Comparison of Minimum Rupture Stress between DDS and RCC-MR

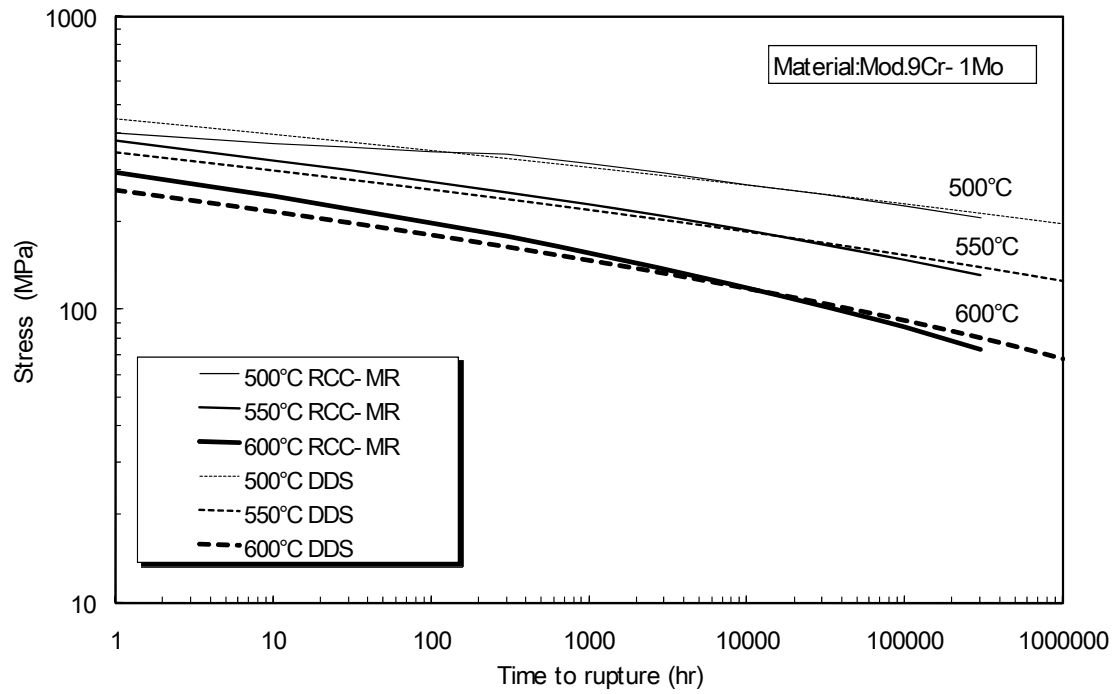


Figure 123 - Comparison of Average Rupture Stress between DDS and RCC-MR

APPENDIX C

2004 SECTION III, DIVISION 1 — NH

04

TABLE I-14.6F
9Cr-1Mo-V, S_p — EXPECTED MINIMUM STRESS-TO-RUPTURE VALUES, MPa (CONT'D)

SI Units										
Temp., °C	10 hr	30 hr	10 ² hr	3 × 10 ² hr	10 ³ hr	3 × 10 ³ hr	10 ⁴ hr	3 × 10 ⁴ hr	10 ⁵ hr	3 × 10 ⁵ hr
375	487	487	487	487	487	487	487	487	487	487
400	475	475	475	475	475	475	475	461	435	412
425	459	459	459	459	459	436	412	390	366	345
450	440	440	440	418	396	374	350	329	308	289
475	419	404	385	361	338	317	295	276	257	240
500	374	353	329	307	285	266	247	229	212	196
525	322	301	278	259	239	222	204	189	173	159
550	274	251	234	264	244	227	209	193	177	163
575	231	213	194	179	163	149	135	122	110	99
600	192	176	160	146	132	119	106	94	82	72
625	159	145	130	117	105	94	81	67	53	42
650	130	117	104	93	81	72	54	44	33	25

TABLE I-14.10 A-1
STRESS RUPTURE FACTORS FOR TYPE 304 STAINLESS STEEL WELDED WITH SFA-5.22 E 308T AND E 308LT;
SFA-5.4 E 308 AND E 308L; AND SFA-5.9 ER 308 AND ER 308L

U.S. Customary Units										
Temp., °F	10 hr	30 hr	100 hr	300 hr	1,000 hr	3,000 hr	10,000 hr	30,000 hr	100,000 hr	300,000 hr
850	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.97	0.97
900	1.00	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.95	0.94
950	1.00	0.98	0.97	0.96	0.95	0.95	0.95	0.95	0.93	0.91
1,000	1.00	0.98	0.96	0.94	0.93	0.93	0.93	0.93	0.91	0.88
1,050	1.00	0.99	0.98	0.97	0.97	0.97	0.97	0.95	0.91	0.85
1,100	1.00	0.99	0.98	1.00	1.00	1.00	0.99	0.95	0.89	0.82
1,150	1.00	1.00	1.00	1.00	1.00	0.99	0.95	0.90	0.81	0.72
1,200	1.00	1.00	1.00	1.00	0.98	0.95	0.88	0.81	0.71	0.60
1,250	1.00	1.00	0.97	0.97	0.92	0.87	0.78	0.69	0.57	0.46
SI Units										
Temp., °C	10 hr	30 hr	100 hr	300 hr	1,000 hr	3,000 hr	10,000 hr	30,000 hr	100,000 hr	300,000 hr
450	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.97	0.97
475	1.00	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.96	0.95
500	1.00	0.98	0.97	0.96	0.96	0.96	0.96	0.96	0.94	0.92
525	1.00	0.98	0.96	0.95	0.94	0.94	0.94	0.94	0.92	0.89
550	1.00	0.99	0.97	0.96	0.95	0.95	0.95	0.94	0.91	0.87
575	1.00	0.99	0.98	0.98	0.98	0.98	0.98	0.95	0.90	0.84
600	1.00	0.99	0.98	1.00	1.00	1.00	0.98	0.94	0.87	0.80
625	1.00	1.00	1.00	1.00	1.00	0.98	0.94	0.89	0.80	0.70
650	1.00	1.00	1.00	1.00	0.98	0.95	0.88	0.81	0.71	0.60
675	1.00	1.00	0.97	0.97	0.92	0.88	0.79	0.70	0.58	0.47

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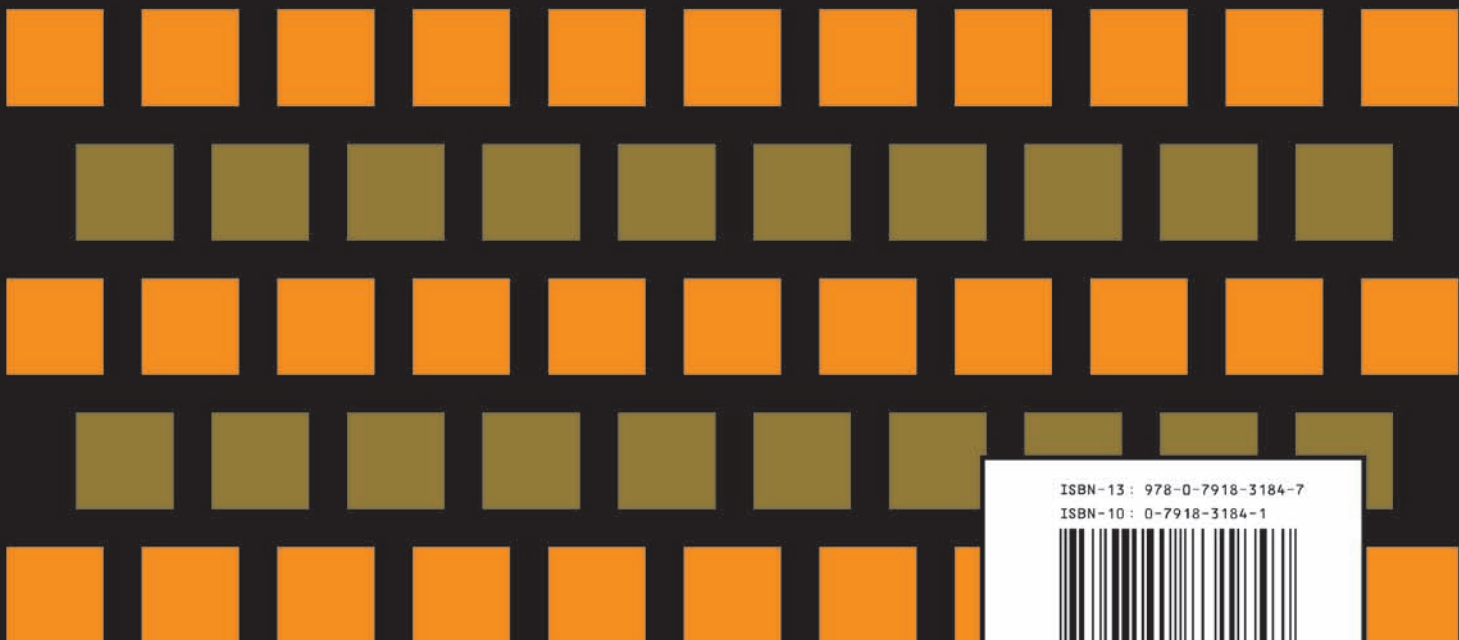
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ABBREVIATIONS AND ACRONYMS

ASME	American Society of Mechanical Engineers
ASME ST-LLC	ASME Standards Technology, LLC
CRIEPI	Central Research Institute of Power Industry in Japan
DOE	U.S. Department on Energy
EPRI	Electric Power Research Institute
FBR	Fast Breeder Reactor
HENDEL	Helium Engineering Demonstration Loop
HTGR	High Temperature Gas-cooled Reactor
HTTR	High Temperature Engineering Test Reactor
IHX	Intermediate Heat Exchanger
JAEA	Japan Atomic Energy Agency
JAERI	Japan Atomic Energy Research Institute
JIS	Japan Industrial Standards
NIMS	National Institute of Material Science in Japan
ORNL	Oak Ridge National Laboratory
VHTR	Very High Temperature Reactor

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