

# DESIGN AND ANALYSIS OF ASME BOILER AND PRESSURE VESSEL COMPONENTS IN THE CREEP RANGE

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To our wives  
Dixie and Betty



# PREFACE

Many structures in chemical plants, refineries, and power generation plants operate at elevated temperatures where creep and rupture are a design consideration. At such elevated temperatures, the material tends to undergo gradual strain with time, which could eventually lead to failure. Thus, the design of such components must take into consideration the creep and rupture of the material. In this book, a brief introduction to the general principles of design at elevated temperatures is given with extensive references cited for further in-depth understanding of the subject. A key feature of the book is the use of numerous examples to illustrate the practical application of the design and analysis methods presented.

The book is divided into seven chapters. The first chapter is an introduction to various creep topics such as allowable stresses, creep properties, elastic analog, and reference stress methods, as well as a few introductory topics needed in various subsequent chapters.

Chapters 2 and 3 cover structural members in the creep range. In Chapter 2, the subject of members in axial tension is presented. Such members are encountered in pressure vessels as hangers, tray supports, braces, and other miscellaneous components. Chapter 3 covers beams and plates in bending. Components such as piping loops, tray support beams, internal piping, nozzle covers, and flat heads are included. A brief discussion of the requirements of ANSI B31.1 and B31.3 in the creep region is given.

Chapters 4 and 5 discuss stress analysis of shells in the creep range. In Chapter 4, various stress categories are defined and the analysis of various components using “load controlled limits” of ASME section III-NH is discussed. Comparisons are also given between the design criteria in VIII-2 and III-NH and the limitations encountered in VIII-2 when designing in the creep range. Chapter 5 covers the analysis of pressure components using “strain and deformation controlled limits.” Discussion includes the requirements and limitations of the “A Tests” and “B Tests” outlined in III-NH.

Cyclic loading in the creep-fatigue regime is discussed in Chapter 6. Both repetitive and non-repetitive cycles are presented with some examples illustrating the applicability and intent of III-NH in non-nuclear applications.

Chapter 7 covers the issues related to buckling of components. Axial members as well as cylindrical and spherical shells are discussed. Simplified methods are presented for design purposes. The assumptions and limitations required to derive the simplified methods are also given.

The two appendices included in the book are intended as design tools. Appendix A discusses the derivation of the Bree diagram, used in Chapter 5, and the assumptions made in plotting it. Understanding the derivations will assist the designer in visualizing the applicability of the various regions in the Bree diagram to various design situations. Appendix B lists some conversion factors for English and metric units.

The design approaches illustrated in this book are based on the experience of the authors over the past 40 years, with assistance from colleagues. It is the intent of the authors that the methodology shown in the book will help the engineer accomplish a safe and economical design for boiler and pressure vessel components operating at high temperatures where creep is a consideration.

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# NOTATIONS

Some of the symbols used in this book are defined below

$A$	= area of structural member
$A$	= ASME designation for compressive strain in heads and shells
$B$	= ASME designation for compressive stress in heads and shells
$c$	= corrosion allowance
$C$	= flat head bending factor in ASME, VIII-1
$d$	= diameter
$D$	= $Et^3/12(1 - \mu^2)$
$\mathcal{D}$	= force-deflection matrix of a member
$\frac{D}{D_{cf}}$	= factor to account for the interaction of creep and fatigue damage
$D_i$	= inside diameter
$D_o$	= outside diameter
$E$	= modulus of elasticity
$E_H$	= modulus of elasticity at hot end of cycle
$E_L$	= modulus of elasticity at cold end of cycle
$E_o$	= joint efficiency factor in ASME, VIII-1, and ligament efficiency in ASME-I
$E_t$	= tangent modulus
$f$	= triaxiality factor
$f$	= stress reduction factor in pipes
$f'$	= thickness factor for expanded tube ends in ASME, Section I
$F$	= force in axial members and beams
$F$	= equivalent peak stress in plates and shells
$F'$	= peak stress in plates and shells
$G$	= multiaxiality factor
$I$	= moment of inertia
$k$	= $P/EI$
$k'$	= constant
$\mathcal{K}$	= stiffness matrix of an element
$K$	= plastic shape factor
$K_t$	= creep shape factor. Approximate value adopted by the ASME for a rectangular cross section = $(1 + K)/2$
$K_{sc}$	= stress concentration factor
$K'$	= constant
$K'_v$	= plastic Poisson ratio adjustment factor
$l$	= effective length of column
$L$	= length of member
$n$	= creep exponent, which is a function of material property and temperature
$n_c$	= number of applied cycles
$N_d$	= number of allowable cycles
$P$	= pressure
$P_a$	= ASME allowable external pressure for heads and shells
$P_b$	= equivalent primary bending stress
$P'_b$	= primary bending stress

$P_L$	= equivalent local primary membrane stress
$P'_L$	= local primary membrane stress
$P_m$	= equivalent general primary membrane stress
$P'_m$	= general primary membrane stress
$Q$	= equivalent secondary stress
$Q'$	= secondary stress
$r$	= radius of gyration = $(I/A)^{0.5}$
$R_i$	= inside radius
$R_m$	= mean radius of shell
$R_o$	= outside radius
$R_w$	= weldment reduction factor based on type of weld rod
$S$	= allowable stress for I, VIII-1, and VIII-2 construction
$S_a$	= alternating cycle stress
$\bar{S}_m$	= $(1.5S_m + 0.5S_t)/3$
$S_m$	= allowable stress in III-NH
$S_{mt}$	= membrane stress. It is the lower value of $S_m$ and $S_t$ obtained from III-NH
$S_j$	= the initial stress level for cycle type $j$
$S_o$	= Design stress values. The values are taken as equal to $S_m$ except for a few cases at lower temperatures, where values of $S_{mt}$ at 300,000 hours exceed the $S_m$ values. In those limited cases, $S_o$ is equal to $S_{mt}$ at 300,000 hours
$S_r$	= stress to rupture strength given in Table I-14.6 of III-NH
$\bar{S}'_r$	= relaxed stress level at time $T$ adjusted for the multiaxial stress state
$\bar{S}_r$	= relaxed stress level at time $T$ based on a uniaxial relaxation model
$S_t$	= time-dependent stress intensity values obtained from III-NH
$S_y$	= yield stress
$S_{yH}$	= yield stress at the high temperature end of a cycle
$S_{yL}$	= yield stress at the low temperature end of a cycle
$t$	= thickness
$T$	= time
$\mathcal{T}$	= temperature
$X$	= primary stress/ $S_y$
$y$	= temperature coefficient in ASME, Section I
$Y$	= secondary stress/ $S_y$
$Z$	= section modulus
$Z$	= dimensionless effective creep parameter. It represents core stress values
$\alpha$	= coefficient of thermal expansion
$\epsilon_c$	= creep strain
$\beta$	= $[3(1 - \mu^2)/R_m^2 t^2]^{0.25}$
$\gamma$	= $R_o/R_i$
$\gamma_1$	= $R_i/R_o$
$\Delta\epsilon_{max}$	= maximum equivalent strain range
$\Delta\epsilon_{mod}$	= modified maximum equivalent strain range that accounts for the effects of local plasticity and creep
$\epsilon_t$	= total strain range
$\mu$	= Poisson's ratio
$\sigma_c$	= elastic core stress at a cross section
$\sigma_{cH}$	= elastic core stress at the high temperature end of a cycle

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$\sigma_{cL}$	=	elastic core stress at the low temperature end of a cycle
$\sigma_L$	=	longitudinal stress
$\sigma_r$	=	radial stress
$\sigma_R$	=	reference stress
$\sigma_y$	=	yield stress
$\sigma_\theta$	=	circumferential (hoop) stress
$\sigma_1, \sigma_2, \sigma_3$	=	principal stresses

# ABBREVIATIONS FOR ORGANIZATIONS

AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
API	American Petroleum Institute
ASM	American Society of Metals
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BS	British Standard
EN	European Standard
MPC	Materials Properties Council
UBC	Uniform Building Code
WRC	Welding Research Council

# CONTENTS

<b>Preface</b> .....	v
<b>Acknowledgement</b> .....	vii
<b>Notations</b> .....	ix
<b>Abbreviations for Organizations</b> .....	xii
<b>Chapter 1</b>	
<b>Basic Concepts</b> .....	3
1.1 Introduction.....	3
1.2 Creep in Metals.....	3
1.2.1 Description and Measurement .....	3
1.2.2 Elevated Temperature Material Behavior.....	4
1.2.3 Creep Characteristics .....	7
1.3 Allowable Stress.....	10
1.3.1 ASME B&PV Code.....	10
1.3.2 European Standard EN 13445 .....	12
1.4 Creep Properties .....	15
1.4.1 ASME Code Methodology.....	15
1.4.2 Larson-Miller Parameter .....	15
1.4.3 Omega Method.....	17
1.4.4 Negligible Creep Criteria.....	17
1.4.5 Environmental Effects .....	19
1.4.6 Monkman-Grant Strain.....	19
1.5 Required Pressure Retaining Wall Thickness .....	19
1.5.1 Design by Rule .....	19
1.5.2 Design by Analysis .....	20
1.5.3 Approximate Methods.....	20
1.6 Effects of Structural Discontinuities and Cyclic Loading .....	25
1.6.1 Elastic Follow-Up .....	25
1.6.2 Pressure-Induced Discontinuity Stresses.....	28
1.6.3 Shakedown and Ratcheting .....	29
1.6.4 Fatigue and Creep-Fatigue .....	34
1.7 Buckling and Instability .....	37
<b>Chapter 2</b>	
<b>Axially Loaded Members</b> .....	41
2.1 Introduction.....	41
2.2 Design of Structural Components Using ASME Sections I and VIII-1 as a Guide .....	45

2.3	Design of Structural Components Using ASME Section NH as a Guide — Creep Life and Deformation Limits.....	51
2.4	Reference Stress Method .....	57
<b>Chapter 3</b>		
<b>Members in Bending.....</b>		
3.1	Introduction.....	61
3.2	Bending of Beams .....	61
3.2.1	Rectangular Cross-Sections.....	62
3.2.2	Circular Cross-Sections.....	63
3.3	Shape Factors .....	66
3.3.1	Rectangular Cross-Sections.....	66
3.3.2	Circular Cross-Sections.....	68
3.4	Deflection of Beams.....	69
3.5	Piping Analysis — ANSI 31.1 and 31.3 .....	72
3.5.1	Introduction .....	72
3.5.2	Design Categories and Allowable Stresses .....	73
3.5.3	Creep Effects .....	75
3.6	Stress Analysis .....	75
3.6.1	Commercial Programs.....	81
3.7	Reference Stress Method .....	81
3.8	Circular Plates .....	83
<b>Chapter 4</b>		
<b>Analysis of ASME Pressure Vessel Components:</b>		
<b>Load-Controlled Limits.....</b>		
4.1	Introduction.....	87
4.2	Design Thickness.....	89
4.2.1	Section I .....	90
4.2.2	Section VIII.....	91
4.3	Stress Categories.....	93
4.3.1	Primary Stress .....	93
4.3.2	Secondary Stress, $Q'$ .....	95
4.3.3	Peak Stress, $F'$ .....	95
4.3.4	Separation of Stresses.....	95
4.3.5	Thermal Stress.....	99
4.4	Equivalent Stress Limits for Design and Operating Conditions.....	99
4.5	Load-Controlled Limits for Components Operating in the Creep Range .....	105
4.6	Reference Stress Method .....	113
4.6.1	Cylindrical Shells.....	114
4.6.2	Spherical Shells .....	121
4.7	The Omega Method .....	122
<b>Chapter 5</b>		
<b>Analysis of Components: Strain- and Deformation-Controlled Limits.....</b>		
5.1	Introduction.....	127
5.2	Strain- and Deformation-Controlled Limits.....	127
5.3	Elastic Analysis .....	128
5.3.1	Test A-1 .....	128

5.3.2	Test A-2.....	130
5.3.3	Test A-3.....	130
5.4	Simplified Inelastic Analysis.....	137
5.4.1	Tests B-1 and B-2.....	141
5.4.2	Test B-1.....	141
5.4.3	Test B-2.....	141
5.4.4	Test B-3.....	142
<b>Chapter 6</b>		
<b>Creep-Fatigue Analysis.....</b>		
6.1	Introduction.....	151
6.2	Creep-Fatigue Evaluation Using Elastic Analysis.....	151
6.3	Welded Components.....	174
6.4	Variable Cyclic Loads.....	174
6.5	ASME Code Procedures.....	175
6.6	Equivalent Stress Range Determination.....	175
6.6.1	Equivalent Strain Range Determination — Applicable to Rotating Principal Strains.....	175
6.6.2	Equivalent Strain Range Determination — Applicable When Principal Strains Do Not Rotate.....	176
6.6.3	Equivalent Strain Range Determination — Acceptable Alternate When Performing Elastic Analysis.....	176
<b>Chapter 7</b>		
<b>Members in Compression.....</b>		
7.1	Introduction.....	183
7.2	Design of Columns.....	183
7.2.1	Columns Operating at Temperatures below the Creep Range.....	183
7.2.2	Columns Operating at Temperatures in the Creep Range.....	187
7.3	ASME Design Criteria for Cylindrical Shells under Compression.....	191
7.3.1	Axial Compression of Cylindrical Shells Operating at Temperatures below the Creep Range.....	191
7.3.2	Cylindrical Shells under External Pressure and Operating at Temperatures below the Creep Range.....	192
7.3.3	Cylindrical Shells Subjected to Compressive Stress and Operating at Temperatures in the Creep Range.....	195
7.4	ASME Design Criteria for Spherical Shells under Compression.....	198
7.4.1	Spherical Shells under External Pressure and Operating at Temperatures below the Creep Range.....	198
7.4.2	Spherical Shells under External Pressure and Operating at Temperatures in the Creep Range.....	199
<b>Appendix A</b>		
<b>Background of the Bree Diagram.....</b>		
		201
<b>Appendix B</b>		
<b>Conversion Table.....</b>		
		212
<b>References.....</b>		
		213
<b>Index.....</b>		
		217

