

THIRD EDITION

STRUCTURAL ANALYSIS AND DESIGN OF PROCESS EQUIPMENT

MAAN H. JAWAD
JAMES R. FARR

AIChE
The Global Home of Chemical Engineers

WILEY



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To all engineers builders of a better world.

Contents

	Preface to the Third Edition	<i>xv</i>
	Preface to the Second Edition	<i>xvii</i>
	Preface to the First Edition	<i>xix</i>
	Acknowledgements	<i>xxi</i>
	Part I Background and Basic Considerations	1
1	History and Organization of Codes	4
1.1	Use of Process Vessels and Equipment	4
1.2	History of Pressure Vessel Codes in the United States	4
1.3	Organization of the ASME Boiler and Pressure Vessel Code	6
1.4	Organization of the ANSI B31 Code for Pressure Piping	6
1.5	Some Other Pressure Vessel Codes and Standards in the United States	6
1.6	Worldwide Pressure Vessel Codes	7
	References	7
	Further Reading	7
2	Selection of Vessel, Specifications, Reports, and Allowable Stresses	10
2.1	Selection of Vessel	10
2.2	Which Pressure Vessel Code is Used	10
2.3	Design Specifications and Purchase Orders	10
2.4	Special Design Requirements	11
2.5	Design Reports and Calculations	11
2.6	Materials Specifications	11
2.7	Design Data for New Materials	11
2.8	Factors of Safety	12
2.9	Allowable Tensile Stresses in the ASME Code	12
2.10	Allowable External Pressure Stress and Axial Compressive Stress in the ASME Boiler and Pressure Vessel Code	13
2.11	Allowable Stresses in the ASME Code for Pressure Piping	14
2.12	Allowable Stress in Other Codes of the World	14
2.12.1	European Union (EN) Countries	14
2.12.2	Japanese Code	15
2.12.3	People's Republic of China	15
2.12.4	Indian Code	15
2.12.5	Australian Code	16
	References	16
3	Strength Theories, Design Criteria, and Design Equations	18
3.1	Strength Theories	18
3.2	Design Criteria	18

3.3	Design Equations	19
3.4	Stress–Strain Relationships	19
3.5	Strain–Deflection Equations	20
3.6	Force–Stress Expressions	22
	References	23
	Further Reading	23
4	Materials of Construction	26
4.1	Material Selection	26
4.1.1	Corrosion	26
4.1.2	Strength	26
4.1.2.1	Specified Minimum Yield Stress	27
4.1.2.2	Specified Minimum Tensile Stress	28
4.1.2.3	Creep Rate	28
4.1.2.4	Rupture Strength	28
4.1.3	Material Cost	30
4.2	Nonferrous Alloys	31
4.2.1	Aluminum Alloys	31
4.2.1.1	Annealing	31
4.2.1.2	Normalizing	31
4.2.1.3	Solution Heat Treating	31
4.2.1.4	Stabilizing	31
4.2.1.5	Strain Hardening	31
4.2.1.6	Thermal Treating	32
4.2.2	Copper and Copper Alloys	32
4.2.3	Nickel and High-Nickel Alloys	32
4.2.4	Titanium and Zirconium Alloys	33
4.3	Ferrous Alloys	34
4.3.1	Carbon Steels	34
4.3.2	Low-Alloy Steels	34
4.3.3	High-Alloy Steels	34
4.3.3.1	Martensitic Stainless Steels	34
4.3.3.2	Ferritic Stainless Steels	34
4.3.3.3	Austenitic Stainless Steels	34
4.4	Heat Treating of Steels	35
4.4.1	Normalizing	35
4.4.2	Annealing	35
4.4.3	Postweld Heat Treating	35
4.4.4	Quenching	35
4.4.5	Tempering	35
4.5	Brittle Fracture	35
4.5.1	Charpy V-Notch Test (C_V)	36
4.5.2	Drop-Weight Test (DWT)	37
4.5.3	Fracture Analysis Diagram (FAD)	37
4.5.4	Theory of Fracture Mechanics	39
4.5.5	Relationship Between K_{IC} and C_V	41
4.5.6	Hydrostatic Testing	42
4.5.7	Factors Influencing Brittle Fracture	42
4.5.8	ASME Pressure Vessel Criteria	43
4.6	Hydrogen Embrittlement	50
4.7	Nonmetallic Vessels	50
	References	50
	Further Reading	51

Part II Analysis of Components 53

- 5 Stress in Cylindrical Shells 56**
 - 5.1 Stress Due to Internal Pressure 56
 - 5.2 Discontinuity Analysis 60
 - 5.2.1 Long Cylinders 61
 - 5.2.2 Short Cylinders 66
 - 5.3 Buckling of Cylindrical Shells 69
 - 5.3.1 Uniform Pressure Applied to Sides Only 70
 - 5.3.2 Uniform Pressure Applied to Sides and Ends 71
 - 5.3.3 Pressure on Ends Only 72
 - 5.4 Thermal Stress 72
 - 5.4.1 Uniform Change in Temperature 75
 - 5.4.2 Gradient in Axial Direction 76
 - 5.4.3 Gradient in Radial Direction 77
 - Nomenclature 80
 - References 81
 - Further Reading 81

- 6 Analysis of Formed Heads and Transition Sections 84**
 - 6.1 Hemispherical Heads 84
 - 6.1.1 Various Loading Conditions 86
 - 6.1.2 Discontinuity Analysis 88
 - 6.1.3 Thermal Stress 91
 - 6.1.4 Buckling Strength 91
 - 6.2 Ellipsoidal Heads 93
 - 6.3 Torispherical Heads 95
 - 6.4 Conical Heads 95
 - 6.4.1 Unbalanced Forces at Cone-to-Cylinder Junction 96
 - 6.4.2 Discontinuity Analysis 97
 - 6.4.3 Cones Under External Pressure 98
 - 6.5 Nomenclature 99
 - References 100
 - Further Reading 100

- 7 Stress in Flat Plates 102**
 - 7.1 Introduction 102
 - 7.2 Circular Plates 102
 - 7.3 Rectangular Plates 106
 - 7.4 Circular Plates on Elastic Foundations 107
 - Nomenclature 109
 - Reference 109
 - Further Reading 109

Part III Design of Components 111

- 8 Design of Cylindrical Shells 114**
 - 8.1 ASME Design Equations 114
 - 8.2 Evaluation of Discontinuity Stresses 115
 - 8.3 ASME Procedure[2] for External Pressure Design in VIII-1 121
 - 8.4 Design of Stiffening Rings 126
 - 8.5 Allowable Gaps in Stiffening Rings 129

8.6	Out-of-Roundness of Cylindrical Shells Under External Pressure	129
8.7	Design for Axial Compression	132
	Nomenclature	132
	References	133
	Further Reading	133
9	Design of Formed Heads and Transition Sections	136
9.1	Introduction	136
9.1.1	Flanged Heads	136
9.1.2	Hemispherical Heads	136
9.1.3	Elliptical and Torispherical (Flanged and Dished) Heads	136
9.1.4	Conical and Toriconical Heads	136
9.1.5	Miscellaneous Heads	136
9.2	ASME Design Equations for Hemispherical Heads	137
9.3	ASME Design Equations for Ellipsoidal, Flanged, and Dished Heads	139
9.4	ASME Design Equations for Conical Heads	143
9.4.1	Internal Pressure	143
9.4.1.1	Discontinuity Analysis for Internal Pressure	143
9.4.2	External Pressure	145
9.4.2.1	Discontinuity Analysis for External Pressure	145
	Nomenclature	147
	References	148
	Further Reading	148
10	Blind Flanges, Cover Plates, and Flanges	150
10.1	Introduction	150
10.2	Circular Flat Plates and Heads with Uniform Loading	151
10.3	ASME Code Formula for Circular Flat Heads and Covers	153
10.4	Comparison of Theory and ASME Code Formula for Circular Flat Heads and Covers Without Bolting	154
10.5	Bolted Flanged Connections	154
10.6	Contact Facings	155
10.7	Gaskets	155
10.7.1	Rubber O-Rings	155
10.7.2	Metallic O- and C-Rings	155
10.7.3	Compressed Fiber Gaskets	158
10.7.4	Flat Metal Gaskets	158
10.7.5	Spiral-Wound Gaskets	158
10.7.6	Jacketed Gaskets	158
10.7.7	Metal Ring Gaskets	158
10.7.8	High-Pressure Gaskets	158
10.7.9	Lens Ring Gaskets	159
10.7.10	Delta Gaskets	159
10.7.11	Double-Cone Gaskets	159
10.7.12	Gasket Design	160
10.8	Bolting Design	161
10.9	Blind Flanges	163
10.10	Bolted Flanged Connections with Ring-Type Gaskets	164
10.11	Reverse Flanges	170
10.12	Full-Face Gasket Flange	171
10.13	Flange Calculation Sheets	176
10.14	Flat-Face Flange with Metal-to-Metal Contact Outside of the Bolt Circle	177
10.14.1	Classification of Assembly	177
10.14.2	Categories of Flanges	177

10.15	Spherically Dished Covers	177
	Nomenclature	184
	References	184
	Further Reading	185
11	Openings, Nozzles, and External Loadings	188
11.1	General	188
11.2	Stresses and Loadings at Openings	188
11.3	Theory of Reinforced Openings	192
11.4	Reinforcement Limits	193
11.4.1	Reinforcement Rules for ASME Section I	195
11.4.1.1	No Reinforcement Required	195
11.4.1.2	Size and Shape of Openings	195
11.4.2	Reinforcement Rules for ASME Section VIII, Division 1	198
11.4.3	Reinforcement Rules for ASME, Section VIII, Division 2	204
11.4.3.1	Nomenclature	204
11.4.4	Reinforcement Rules for ANSI/ASME B31.1	210
11.4.4.1	No Reinforcement Calculations Required	210
11.4.5	Reinforcement Rules for ANSI/ASME B31.3	212
11.4.5.1	Nomenclature	213
11.5	Ligament Efficiency of Openings in Shells	215
11.6	Fatigue Evaluation of Nozzles Under Internal Pressure	217
11.7	External Loadings	218
11.7.1	Local Stresses in the Shell or Head	218
11.7.2	Stresses in the Nozzle	226
11.7.2.1	Nomenclature	227
	References	230
	Bibliography	231
12	Vessel Supports	234
12.1	Introduction	234
12.2	Skirt and Base-Ring Design	234
12.2.1	Anchor-Chair Design	239
12.3	Design of Support Legs	241
12.4	Lug-Supported Vessels	242
12.5	Ring Girders	243
12.6	Saddle Supports	245
	Nomenclature	248
	References	249
	Further Reading	249
Part IV Theory and Design of Special Equipment		251
13	Flat-Bottom Tanks	254
13.1	Introduction	254
13.2	API 650 Tanks	254
13.2.1	Roof Design	254
13.2.1.1	Dome Roofs	254
13.2.1.2	Conical Roofs	256
13.2.1.3	Small Internal Pressure	256
13.2.2	Shell Design	258
13.2.3	Annular Plates	261

- 13.3 API 620 Tanks 263
 - 13.3.1 Allowable Stress Criteria 266
 - 13.3.1.1 Compressive Stress in the Axial Direction with No Stress in the Circumferential Direction 266
 - 13.3.1.2 Compressive Stress with Equal Magnitude in the Meridional and Circumferential Directions 266
 - 13.3.1.3 Compressive Stress with Unequal Magnitude in the Meridional and Circumferential Directions 267
 - 13.3.1.4 Compressive Stress in One Direction and Tensile Stress in the Other Direction 267
 - 13.3.2 Compression Rings 267
- 13.4 Aluminum Tanks 270
 - 13.4.1 Design Rules 270
- 13.5 AWWA Standard D100 271
 - References 273
 - Further Reading 273

- 14 Heat-Transfer Equipment 276**
 - 14.1 Types of Heat Exchangers 276
 - 14.2 TEMA Design of Tubesheets in U-tube Exchangers 276
 - 14.3 Theoretical Analysis of Tubesheets in U-tube Exchangers 280
 - 14.4 ASME Equations for Tubesheets in U-tube Exchangers 283
 - 14.4.1 Nomenclature 283
 - 14.4.2 Preliminary Calculations 285
 - 14.4.3 Design Equations 288
 - 14.5 Theoretical Analysis of Fixed Tubesheets 291
 - 14.6 ASME Equations for Fixed Tubesheets 293
 - 14.6.1 Nomenclature 293
 - 14.6.2 Preliminary Calculations 294
 - 14.6.3 Design Equations 294
 - 14.7 Expansion Joints 300
 - 14.8 Tube-to-Tubesheet Junctions 303
 - References 305
 - Further Reading 305

- 15 Vessels for High Pressures 308**
 - 15.1 Basic Equations 308
 - 15.2 Prestressing (Autofrettaging) of Solid-Wall Vessels 309
 - 15.3 Layered Vessels 311
 - 15.4 Prestressing of Layered Vessels 315
 - 15.5 Wire-Wound Vessels 317
 - Nomenclature 317
 - References 318
 - Further Reading 318

- 16 Tall Vessels 320**
 - 16.1 Design Considerations 320
 - 16.2 Earthquake Loading 320
 - 16.2.1 Lateral Loads 320
 - 16.2.2 Numerical Method for Calculating Natural Frequency 324
 - 16.3 Wind Loading 331
 - 16.3.1 External Forces from Wind Loading 332
 - 16.3.2 Dynamic Analysis of Wind Loads 332
 - 16.4 Vessel Under Internal Pressure Only 336
 - 16.5 Vessel Under Internal Pressure and External Loading 338
 - 16.6 Vessel Under External Pressure Only 340

16.7	Vessel Under External Pressure and External Loading	341
	References	342
	Bibliography	342
17	Vessels of Noncircular Cross Section	344
17.1	Types of Vessels	344
17.2	Rules in Codes	345
17.3	Openings in Vessels with Noncircular Cross Section	345
17.4	Ligament Efficiency for Constant-Diameter Openings	345
17.5	Ligament Efficiency for Multidiameter Openings Subject to Membrane Stress	349
17.6	Ligament Efficiency for Multidiameter Openings Subject to Bending Stress	350
17.7	Design Methods and Allowable Stresses	352
17.8	Basic Equations	353
17.9	Equations in the ASME Code, VIII-1	356
17.10	Design of Noncircular Vessels in Other Codes	360
17.10.1	Method of the British Code BS 1113	360
17.10.2	Method of the European Standards EN 12952 and EN 13445	360
17.11	Forces in Box Headers due to Internal Pressure	361
17.11.1	Square Headers	362
17.11.2	Rectangular Headers	362
	References	364
	Further Reading	364
18	Power Boilers	366
18.1	General	366
18.2	Materials	366
18.3	General Design Requirements	366
18.3.1	Allowable Stress Values	366
18.3.2	Cylinders under Internal Pressure	366
18.4	Formed Heads under Internal Pressure	368
18.5	Loadings on Structural Attachments	368
18.6	Watertube Boilers	369
18.6.1	Special Design Requirements and Rules	369
18.7	Firetube Boilers	373
18.7.1	Special Design Requirements and Rules	373
	References	373
A	Guide to ASME Code	375
B	Sample of Heat-Exchanger Specification Sheet	383
C	Sample of API Specification Sheets	387
D	Sample of Pressure Vessel Design Data Sheets	393
E	Sample Materials for Process Equipment	407
F	Required Data for Material Approval in the ASME Code	411
G	Procedure for Providing Data for Code Charts for External-Pressure Design	413
H	Corrosion Charts	415

I	Various ASME Design Equations	431
J	Joint Efficiency Factors	433
K	Simplified Curves for External Loading on Cylindrical Shells	445
L	Conversion Tables	453
	Index	455

Preface to the Third Edition

The third edition includes revisions to various chapters due to advancement in technology since the second edition was written over 30 years ago. These advancements include earthquake and wind analysis, fracture mechanics, and creep analysis of equipment operating in high temperatures. Additional changes were also needed due to the reduction of safety factors in various codes and standards in the last three decades. These reductions were due to improvements in material manufacturing, more accurate analyses due to computerized technology, and better inspection methodology. Additional structural analysis methods were added in few chapters to assist the designer in solving complicated problems not covered by the prevailing codes and standards. These include a natural frequency analysis required in earthquake evaluation for vessels with nonuniform cross sections and analysis of vessels with rectangular cross section having sides with different thicknesses and moduli of elasticity.

Many of the chapters in the first and second editions were written by the late James R. Farr. An effort was made in this third edition to preserve these chapters in their original format with only the necessary changes needed to bring them up to date to the current technology and standards.

The tendency of the newer editions of the codes such as the American Society of Mechanical Engineers

(ASME) Boiler and Pressure Vessel Code is to replace existing charts needed in the design of components with equations that are more suitable for computerized programs. These equations are obtained in one of two methods. The first is to go back to the origin of a given chart. If the original chart was drawn from equations, then these equations are now used in the new code edition and the chart deleted. The format of these equations, more often than not, leads to the original derivation or the assumptions made in developing the equations. The second method is to take the charts that were drawn based on experience and/or experimental data with no background equations and simulate these charts with equations obtained from regression analysis. The resulting equations normally have no physical significance even though the results obtained from them are essentially the same as those obtained from the original chart. Accordingly in this book, equations from the first method were incorporated, as much as possible, in the text since they can be traced back to their original derivation. Equations from the second method were not incorporated in order to minimize the confusion regarding their original background.

Camas, WA, USA
January 2018

Maan H. Jawad

Preface to the Second Edition

The second edition includes a number of new topics not included in the first edition, which are useful in designing pressure vessels. A new chapter has been added to the design of the power boilers, which are an integral part of a chemical plant or refinery. Some of the existing chapters have been expanded to include new topics such as toughness criteria, design of expansion joints, tube-to-tubesheet parameters. In addition, portions of three chapters and one appendix have been rewritten to reflect current practice. The first such passage concerns the design of water tanks, where new equations are added in accordance with the revised criteria given in the American Water Works Association (AWWA) Standard. The second concerns the design of tubesheets in U-tube heat exchangers, where simplified equations are used in

lieu of the cumbersome charts shown in the first edition. The third concerns the design of noncircular vessels, where new equations are added to reflect new changes made in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. Appendix J on joint efficiencies has been rewritten to reflect the current criteria of the ASME code, VIII-1.

We thank all of our colleagues for their numerous comments, which promoted us to revise the first edition. Special thanks are given to Mr E. L. Thomas, Jr., and Dr L. J. Wolf for their help.

St Louis, MO, USA
Barberton, OH, USA
June 1988

Maan H. Jawad
James R. Farr

Preface to the First Edition

We wrote this book to serve three purposes. The first purpose is to provide structural and mechanical engineers associated with the petrochemical industry a reference book for the analysis and design of process equipment. The second is to give graduate engineering students a concise introduction to the theory of plates and shells and its industrial applications. The third is to aid process engineers in understanding the background of some of the design equations in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII.

The topics presented are separated into four parts. Part 1 is intended to familiarize the designer with some of the common “tools of the trade.” Chapter 1 details the history of pressure vessels and various applicable codes from around the world. Chapter 2 discusses design specifications furnished in the purchasing process equipment as well as in various applicable codes. Chapter 3 establishes the strength criteria used in different codes and the theoretical background needed in developing design equations in subsequent chapters. Chapter 4 includes different materials of construction and toughness considerations.

Part 2 is divided into three chapters outlining the basic theory of plates and shells. Chapter 5 develops the membrane and bending theories of cylindrical shells. Chapter 6 discusses various approximate theories for analyzing heads and transition sections, and Chapter 7 derives the equations for circular and rectangular plates subjected to various loading and support conditions. These three chapters form the basis from which most of the design equations are derived in the other chapters.

Part 3, which consists of five chapters, details the design and analysis of components. Chapters 8 and 9 derive the design equations established by the ASME Code, VII-1 and -2, for cylindrical shells as well as heads and transition sections. Chapter 10 discusses gaskets,

bolts, and flange design. Chapter 11 presents openings and their reinforcement; Chapter 12 develops design equations for support systems.

Part 4 outlines the design and analysis of some specialized process equipment. Chapter 13 describes the design of flat-bottom tanks; Chapter 14 derives the equations for analyzing heat-transfer equipment. Chapter 15 describes the theory of thick cylindrical shells in high-pressure applications. Chapter 16 discusses the stress analysis of the tall vessels. Chapter 17 outlines the procedure of the ASME Code, VIII-1, for designing rectangular pressure vessels.

To simplify the use of this book as a reference, each chapter is written so that it stands on its own as much as possible. Thus, each chapter with design or other mathematical equations is written using terminology frequently used in the industry for that particular type of equipment or component discussed in the pertinent chapter. Accordingly, a summary of nomenclature appears at the end of most of the chapters in which mathematical expressions are given.

In using this book as a textbook for plates and shells, Chapters 3, 5, 6, and 7 form the basis for establishing the basic theory. Instructors can select other chapters to supplement the theory according to the background and needs of the graduate engineer.

In deriving the background of some of the equations given in the ASME Boiler and Pressure Vessel Code, attention was focused on Section VIII, Divisions 1 and 2. Although these same equations do occur in the other sections of the ASME Code, such as the Power and Heating Coilers, no consideration is given in this book regarding other sections unless specifically stated.

Saint Louis, MO, USA
Barberton, OH, USA
September 1983

Maan H. Jawad
James R. Farr

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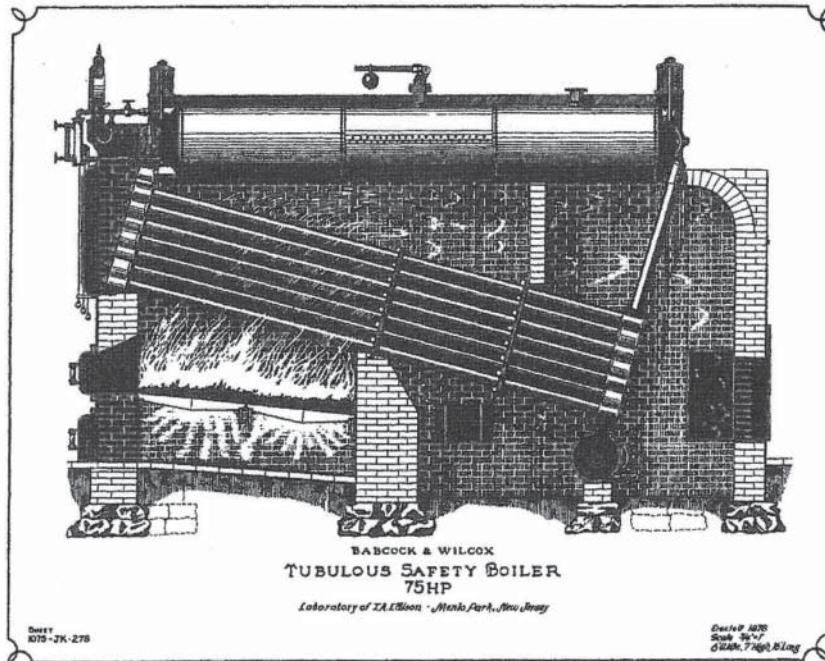
Thanks to the many people and organizations that helped during the rewrite of the third edition. Special thanks are given to the following people for helping with the international standards: Dave I. Anderson for the British code, Anne Chaudouet for the French code, Susumu Terada for the Japanese code, Jay Vattappilly for the Indian code, and Jinyang Zheng for the Chinese code. Thanks are also given to Basil Kattula for his help with the wind load and earthquake requirements of ASCE 7-10.

The Nooter Corporation of St. Louis, Missouri, is acknowledged for its continual support of the author in publishing this book as well as participating in other standards' activity.

Special thanks is also extended to the editors and staff of Wiley for doing an excellent job in editing as well as updating the old charts, figures, and tables from the Second edition to the Third edition.

Part I

Background and Basic Considerations



Old timers. Source: (Top) Courtesy Babcock & Wilcox Company; (bottom) Courtesy Nooter Corporation.

1

History and Organization of Codes

1.1 Use of Process Vessels and Equipment

Throughout the world, the use of process equipment has expanded considerably. In the petroleum industry, process vessels are used at all stages of oil processing. At the beginning of the cycle, they are used to store crude oil. Many different types of these vessels process the crude oil into oil and gasoline for the consumer. The vessels store petroleum at tank farms after processing and finally serve to hold the gasoline in service stations for the consumer's use. The use of process vessels in the chemical business is equally extensive. Process vessels are used everywhere.

Pressure vessels are made in all sizes and shapes. The smaller ones may be no larger than a fraction of an inch in diameter, whereas the larger vessels may be 150 ft. or more in diameter. Some are buried in the ground or deep in the ocean; most are positioned on the ground or supported on platforms; and some actually are found in storage tanks and hydraulic units in aircraft.

The internal pressure to which the process equipment is designed is as varied as the size and shape. Internal pressure may be as low as 1 in. water-gage pressure or as high as 300 000 psi or more. The usual range of pressure for monoblock construction is about 15 to about 5000 psi, although there are many vessels designed for pressures below and above that range. The American Society of Mechanical Engineers (ASME) Boiler and Pressure Code, Section VIII, Division 1 [1], specifies a range of internal pressure from 15 psi at the bottom to no upper limit; however, at an internal pressure above 3000 psi, the ASME Code, VIII-1, requires that special design considerations may be necessary [1]. However, any pressure vessel that meets all the requirements of the ASME Code, regardless of the internal or external design pressure, may still be accepted by the authorized inspector and stamped by the manufacturer with the ASME Code symbol. Some other pressure equipment, such as American Petroleum Institute (API) [2] storage tanks, may be

designed for and contain internal pressure not more than that generated by the static head of fluid contained in the tank.

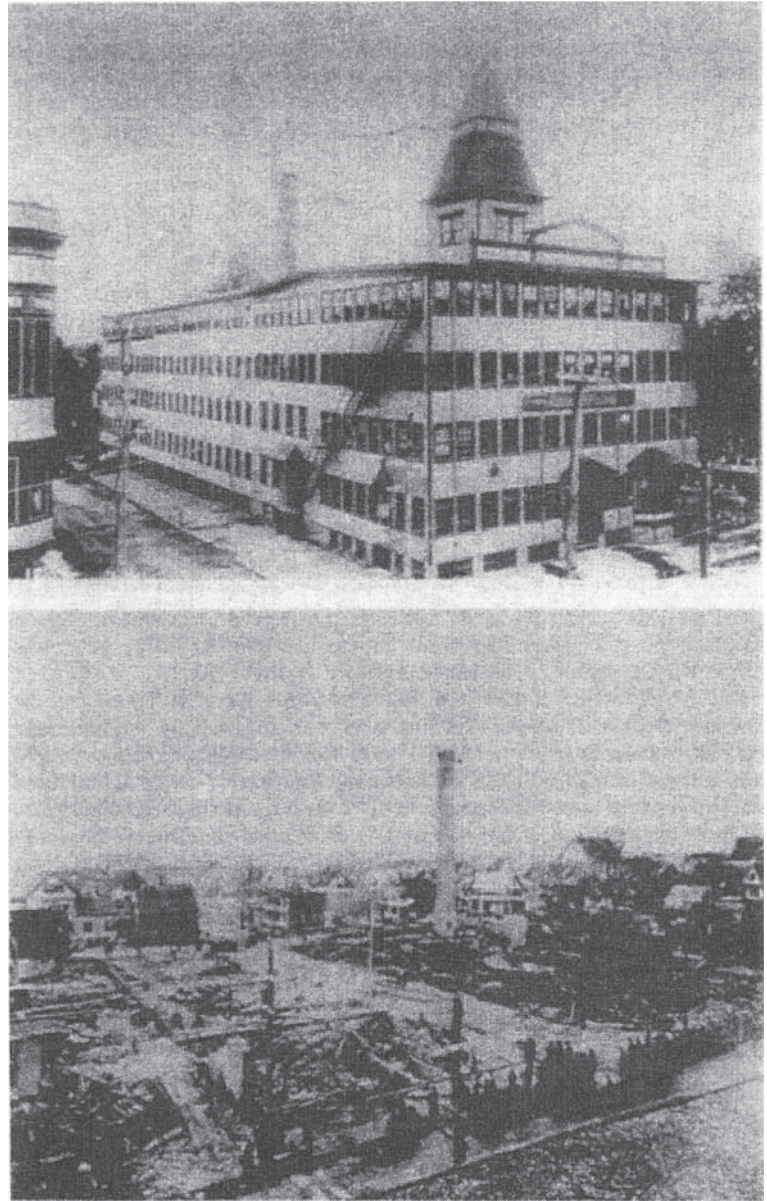
1.2 History of Pressure Vessel Codes in the United States

Through the late 1800s and early 1900s, explosions in boilers and pressure vessels were frequent. A firetube boiler explosion on the Mississippi River steamboat *Sultana* on April 27, 1865, resulted in sinking of the boat within 20 minutes and the death of 1500 soldiers who were going home after the Civil War. This type of catastrophe continued unabated into the early 1900s. In 1905, a destructive explosion of a firetube boiler in a shoe factory in Brockton, Massachusetts (Figure 1.1) killed 58 people, injured 117 others, and caused \$400 000 in property damage. In 1906, another explosion in a shoe factory in Lynn, Massachusetts, resulted in death, injury, and extensive property damage. After this accident, the Massachusetts governor directed the formation of a Board of Boiler Rules. The first set of rules for the design and construction of boilers was approved in Massachusetts on August 30, 1907. This code was three pages long!

In 1911, Colonel E. D. Meier, the president of the ASME, established a committee to write a set of rules for the design and construction of boilers and pressure vessels. On February 13, 1915, the first ASME Boiler Code was issued. It was entitled "Boiler Construction Code, 1914 Edition." This was the beginning of the various sections of the ASME Boiler and Pressure Vessel Code, which ultimately became Section I, *Power Boilers* [3].

The first ASME Code for pressure vessels was issued as "Rules for the Construction of Unfired Pressure Vessels," Section VIII, 1925 edition. The rules applied to vessels over 6 in. in diameter, volume over 1.5 ft [3], and pressure over 30 psi. In December 1931, a Joint API–ASME Committee was formed to develop an unfired pressure vessel code for the petroleum industry. The first edition

Figure 1.1 Firetube boiler explosion in shoe factory in Brockton, Massachusetts in 1905. *Source:* Courtesy Hartford Steam Boiler Inspection and Insurance Co., Hartford, Ct.



was issued in 1934. For the next 17 years, two separate unfired pressure vessel codes existed. In 1951, the last API–ASME Code was issued as a separate document [4]. In 1952, the two codes were consolidated into one code – the *ASME Unfired Pressure Vessel Code*, Section VIII. This continued until the 1968 edition. At that time, the original code became Section VIII, Division 1, *Pressure Vessels*, and another new part was issued, which was Section VIII, Division 2, *Alternative Rules for Pressure Vessels*.

The ANSI/ASME Boiler and Pressure Vessel Code is issued by the ASME with approval by the American National Standards Institute (ANSI) as an ANSI/ASME document. One or more sections of the ANSI/ASME

Boiler and Pressure Vessel Code have been established as the legal requirements in 47 of the 50 states in the United States and in all the provinces of Canada. Also, in many other countries of the world, the ASME Boiler and Pressure Vessel Code is used to construct boilers and pressure vessels.

In the United States, most piping systems are built according to the ANSI/ASME Code for Pressure Piping B31. There are a number of different piping code sections for different types of systems. The piping section that is used for boilers in combination with Section I of the ASME Boiler and Pressure Vessel Code is the Code for Power Piping, B31.1 [5]. The piping section that is often used with Section VIII, Division 1, is the

code for Chemical Plant and Petroleum Refinery Piping, B31.3 [6].

1.3 Organization of the ASME Boiler and Pressure Vessel Code

The ASME Boiler and Pressure Vessel Code is divided into many sections, divisions, parts, and subparts. Some of these sections relate to a specific kind of equipment and application; others relate to specific materials and methods for application and control of equipment; and others relate to care and inspection of installed equipment. The following sections specifically relate to the design and construction of boiler, pressure vessel, and nuclear components:

Sections.

- (I) Rules for Construction of Power Boilers
- (II) Materials
 - Part A. Ferrous Material Specifications
 - Part B. Nonferrous Material Specifications
 - Part C. Specifications for Welding Rods, Electrodes, and Filler Metals
 - Part D. Properties
- (III) Rules for Construction of Nuclear Facility Components
 - Division 1.
 - Subsection NB. Class 1 Components.
 - Subsection NC. Class 2 Components.
 - Subsection ND. Class 3 Components.
 - Subsection NE. Class MC Components.
 - Subsection NF. Supports.
 - Subsection NG. Core Support Structures.
 - Division 5. High-Temperature Reactors.
- (IV) Rules for Construction of Heating Boilers
- (VIII) Rules for Construction of Pressure Vessels
 - Division 1.
 - Division 2. Alternative Rules.
 - Division 3. Alternative Rules for Construction of High Pressure Vessels.
- (X) Fiber-Reinforced Plastic Pressure Vessels
- (XII) Rules for Construction and Continued Service of Transport Tanks

A new edition of the ASME Boiler and Pressure Vessel Code is issued every 2 years. A new edition incorporates all the changes made to the previous edition. The new edition of the code becomes mandatory when it appears.

Code Cases [7] are also issued periodically after each code meeting. They contain permissive rules for materials and special constructions that have not been sufficiently developed to include them in the code itself.

Finally, there are Code Interpretations [8]. These are in the form of questions and replies that further explain the items in the code that have been misunderstood.

1.4 Organization of the ANSI B31 Code for Pressure Piping

In the United States, the most frequently used design rules for pressure piping are the ANSI B31 Code for Pressure Piping. This code is divided into many sections for different kinds of piping applications. Some sections are related to specific sections of the ASME Boiler and Pressure Vessel code as follows:

- B31.1 Power Piping
- B31.3 Process Piping
- B31.4 Pipeline Transportation Systems for Liquids and Slurries
- B31.5 Refrigeration Piping and Heat Transfer Components
- B31.8 Gas Transmission and Distribution Piping Systems
- B31.9 Building Services Piping
- B31.12 Hydrogen Piping and Pipelines

The ANSI B31 Piping Code Committee prepares and issues new editions and addenda with dates that correspond with the ASME Boiler and Pressure Vessel Code and addenda. However, the issue dates and mandatory dates do not always correspond with each other.

1.5 Some Other Pressure Vessel Codes and Standards in the United States

In addition to the ANSI/ASME Boiler and Pressure Vessel Code and the ANSI B31 Code for Pressure Piping, many other codes and standards are commonly used for the design of process vessels in the United States. Some of them are as follows:

ANSI/API Standard 620. *Design and Construction of Large, Welded, Low-Pressure Storage Tanks*, American Petroleum Institute (API), Washington, D.C.

ANSI/API Standard 650. *Welded Steel Tanks for Fuel Storage*, American Petroleum Institute, Washington, D.C.

ANSI-AWWA Standard D100. *Welded Carbon Steel Tanks for Water Storage*, American Water Works Association (AWWA), Denver, Colorado.

UL 644. *Standard for Container Assemblies for LP-Gas*, 9th ed., Underwriters Laboratories, Northbrook, Illinois.

Standards of Tubular Exchanger Manufacturers Association, 9th ed., Tubular Exchanger Manufacturer's Association, New York.