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

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 *Maan H. Jawad*
January 2018

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 *Maan H. Jawad*
Barberton, OH, USA *James R. Farr*
June 1988

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 in to 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.

Part4 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 — *Maan H. Jawad*
Barberton, OH, USA — *James R. Farr*
September 1983

Acknowledgements

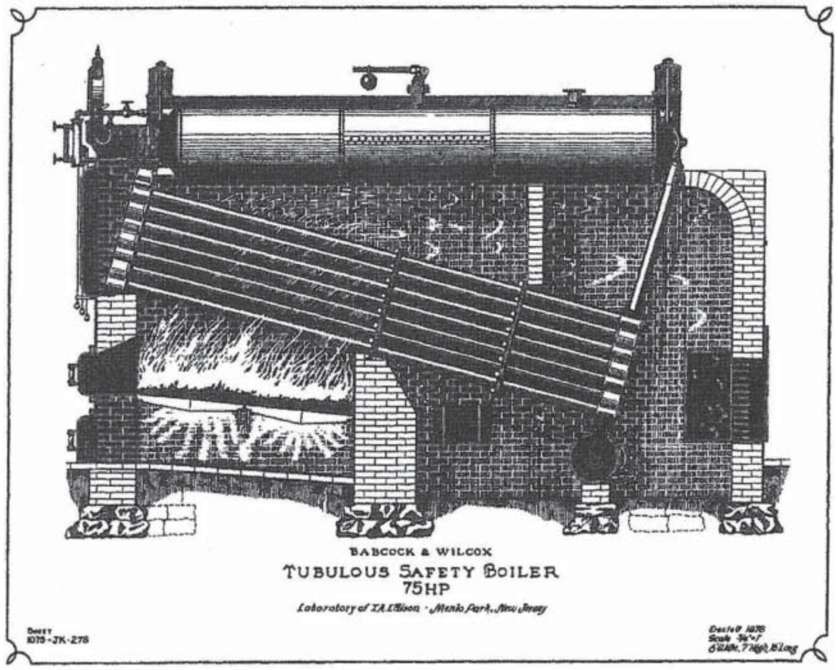
Thanks to the many people and organizations that helped during the rewrite of the third edition. Special thanks are given to the following people for helping with the international standards: Dave I. Anderson for the British code, Anne Chaudouet for the French code, Susumu Terada for the Japanese code, 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.

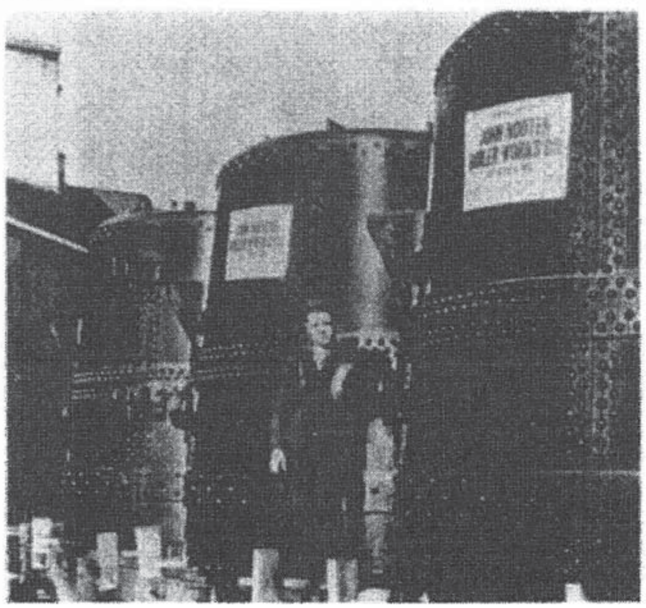
The Nooter Corporation of St. Louis, Missouri, is acknowledged for its continual support of the author in publishing this book as well as participating in other standards' activity.

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

Structural Analysis and Design of Process Equipment, Third Edition. Maan H. Jawad and James R. Farr.

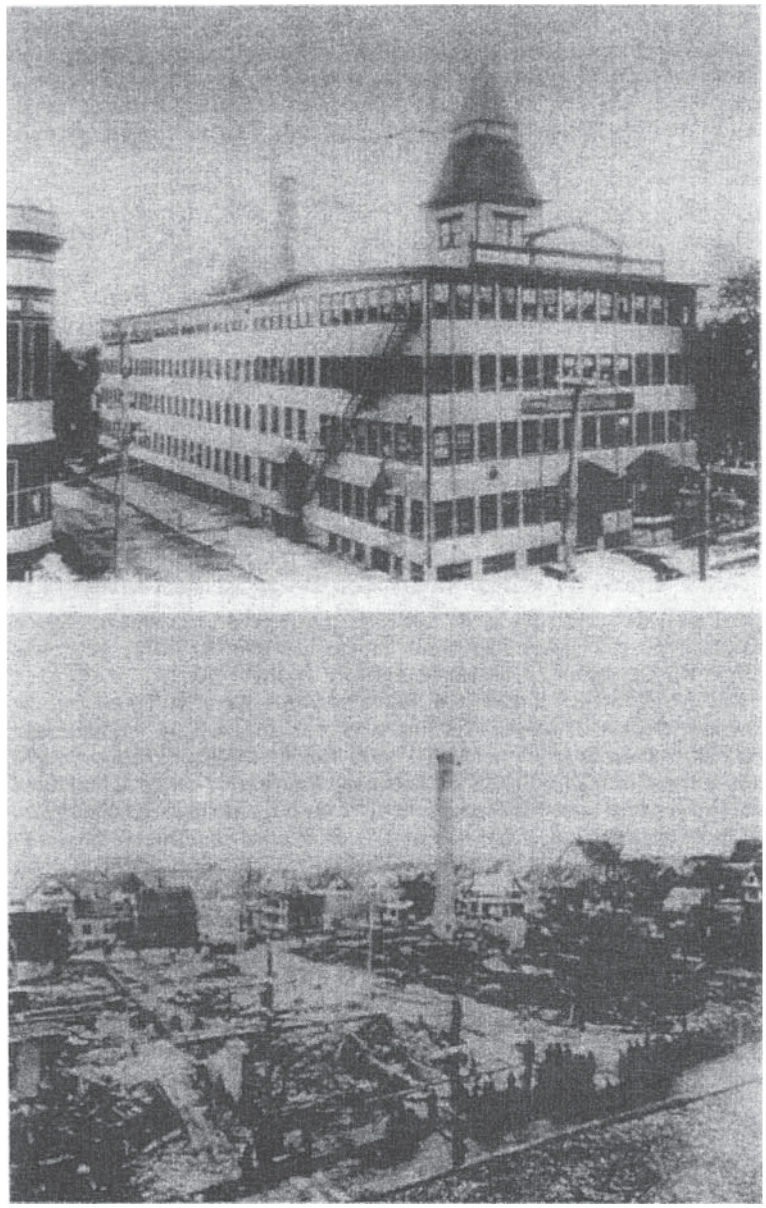


Figure 1.1 Firetube boiler explosion in shoe factory in Brockton, Massachusetts in 1905. *Source*: Courtesy Hartford Steam Boiler Inspection and Insurance Co., Hartford, Ct.

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.

Standards of the Expansion Joint Manufacturers Association, 10th ed., Expansion Joint Manufacturer's Association, New York.

A number of standards are available in the United States for repairing and altering existing boilers and pressure vessels. Frequently, the repairs and alterations involve design considerations that are outside the scope of ASME Sections I and VIII. Some of these standards are as follows:

National Board Inspection Code. National Board of Boiler and Pressure Vessel Inspectors, Ohio.

Fitness-for-Service. API 579–1/ASME FFS-1, American Society of Mechanical Engineers, New York.

Pressure Vessel Inspection Code. API-510, American Petroleum Institute, Washington, D.C.

1.6 Worldwide Pressure Vessel Codes

In addition to the ASME Boiler and Pressure Vessel Code, which is used worldwide, many other pressure vessel codes have been legally adopted in various countries. Difficulty often occurs when vessels are designed in one country, built in another country, and installed in still another country. This is often the case.

The following list is a partial summary of some of the various codes used in different countries:

Australia. Pressure Equipment: AS 1200. Standards Association of Australia. Sydney, Australia.

China. Pressure Vessel Standard GB 150. China National Institute of Standardization (CNIS). Beijing, China.

European Union. Countries belonging to the European Union (EN) including France, Germany, Italy, and the United Kingdom use the European Pressure equipment Directive (PED) for the design of boilers and pressure vessels. Hence, Standard EN 12953 is used for boilers and Standard EN 13445 is used for pressure vessels. Local codes are also used when specific rules are not covered by these two standards. These include CODAP in France, A. D. Merkblatter in Germany, and BS 5500 in the United Kingdom.

Japan. In Japan, the Japanese Industrial Standard for pressure vessels is JIS B 8265, 8266, and 8267. For boilers, the standard is JIS B 8201.

More complete details, discussions of factors of safety, and applications of the codes mentioned are given in Section 2.12.

References

1. (2017). *ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, Rules for Construction of Pressure Vessels*. New York: American Society of Mechanical Engineers.
2. API Standard 620 (2013). *Design and Construction of Large, Welded, Low-Pressure Storage Tanks*," ANSI/API Std. 620. Washington, D.C.: American Petroleum Institute.
3. (2017). *ASME Boiler and Pressure Vessel Code, Section I, Rules for Construction of Power Boilers*. New York: American Society of Mechanical Engineers.
4. API-ASME Code (1951). *Unfired Pressure Vessels for Petroleum Liquids and Gases*, 5ee. New York: American Society of Mechanical Engineers and American Petroleum Institute.
5. ASME Code for Pressure Piping B31 *Power Piping*, ANSI/ASME B31.1,. New York: American Society of Mechanical Engineers.
6. ASME Code for Pressure Piping B31 *Chemical Plant and Petroleum Refinery Piping*, ANSI/ASME B31.3. New York: American Society of Mechanical Engineers.
7. *ASME Boiler and Pressure Vessel Code, Code Cases, Boilers and Pressure Vessels*. New York: American Society of Mechanical Engineers.
8. ASME Boiler and Pressure Vessel Code *Interpretations* (issued periodically). New York: American Society of Mechanical Engineers.

Further Reading

Steel Tanks for Liquid Storage. In: *Steel Plate Engineering Data*, 1976the, vol. 1. Washington, D.C: American Iron and Steel Institute.

Design standards.

2

Selection of Vessel, Specifications, Reports, and Allowable Stresses

2.1 Selection of Vessel

Although many factors contribute to the selection of pressure vessels, the two basic requirements that affect the selection are safety and economics. Many items are considered, such as materials availability, corrosion resistance, materials strength, types and magnitudes of loadings, location of installation including wind loading and earthquake loading, location of fabrication (shop or field), position of vessel installation, and availability of labor supply at the erection site.

With increasing use of special pressure vessels in the petrochemical and other industries, the availability of the proper materials is fast becoming a major problem. The most usual material for vessels is carbon steel. Many other specialized materials are also used for corrosion resistance or the ability to contain a fluid without degradation of the material's properties. Substitution of materials is prevalent, and cladding and coatings are used extensively. The design engineer must be in communication with the process engineer in order that all materials used will contribute to the overall integrity of the vessel. For those vessels that require field assembly (in contrast to those that can be built in the shop), proper quality assurance must be established for acceptable welding regardless of the adverse conditions under which the vessel is made. Provisions must be established for radiography, stress relieving, and other operations required in the field.

For those vessels that will operate in climates where low temperatures are encountered or that contain fluids operating at low temperatures, special care must be taken to ensure impact resistance of the materials at low temperatures. To obtain this property, the vessel may require a special high-alloy steel, nonferrous material, or some special heat treatment.

2.2 Which Pressure Vessel Code is Used

The first consideration must be whether or not there is a pressure vessel law at the location of the installation. If there is, the applicable codes are stated in the law. If the jurisdiction has adopted the American Society of Mechanical Engineer (ASME) Code, Section VIII, the decision may be narrowed down to selecting whether Division 1 or Division 2 is used.

There are many opinions regarding the use of Division 1 versus Division 2, but the "bottom line" is economics. In the article "ASME Pressure-Vessel Code: Which Division to Choose?," [1] the authors have listed a number of factors for consideration. Division 1 uses approximate formulas, charts, and graphs in simple calculations. Division 2, on the other hand, uses a complex method of formulas, charts, and design by analysis, which must be described in a stress report. Sometimes, so many additional requirements are added to the minimum specifications of a Division 1 vessel that it might be more economical to supply a Division 2 vessel and take advantage of the higher allowable stresses.

2.3 Design Specifications and Purchase Orders

Currently, all ASME code sections, with the exception of VIII-1, require user design specifications (also called user design requirements) as part of the code requirements. These codes require a User Design Specifications to be prepared and certified by a registered professional engineer experienced in pressure vessel design. This certification by the professional engineer is given on the ASME Manufacturer's Data Report. The manufacture is responsible for retaining the user's Design Report for a specified number of years.

For the ASME Code, VIII-1, there is no specific statement that any design specifications are required. The only indication of some sort of design specifications is the list of minimum loadings in UG-22 that is considered for all construction. The Manufacturer's Data Report, Form U-1 for the ASME Code, VIII-1, requires many items to be listed, which means that most of the basic design information must be given in a design

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