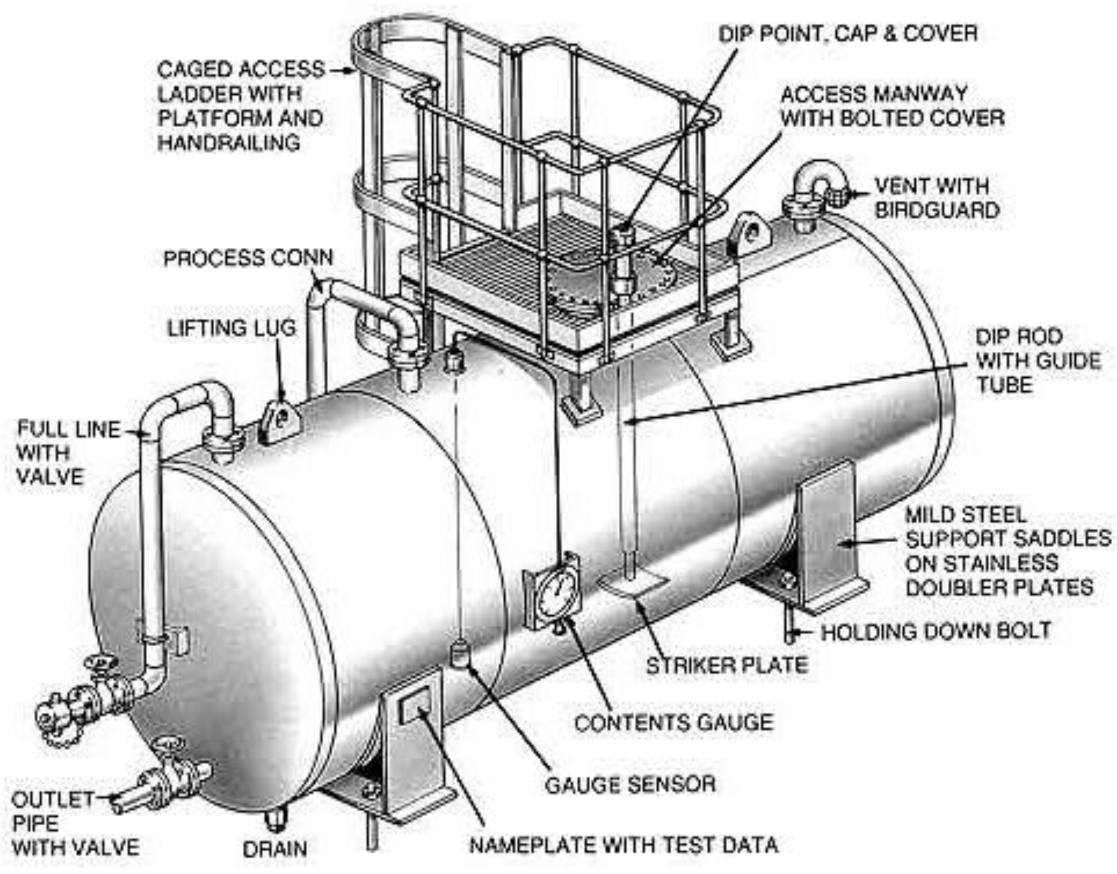
PRESSURE VESSELS, Part I: Pressure Vessel Design, Shell, Head, Nozzle and Basic Flange

STUDY NOTES



arveng
training & engineering

Instructor: Javier Tirenti

training@arvengconsulting.com

www.arvengconsulting.com

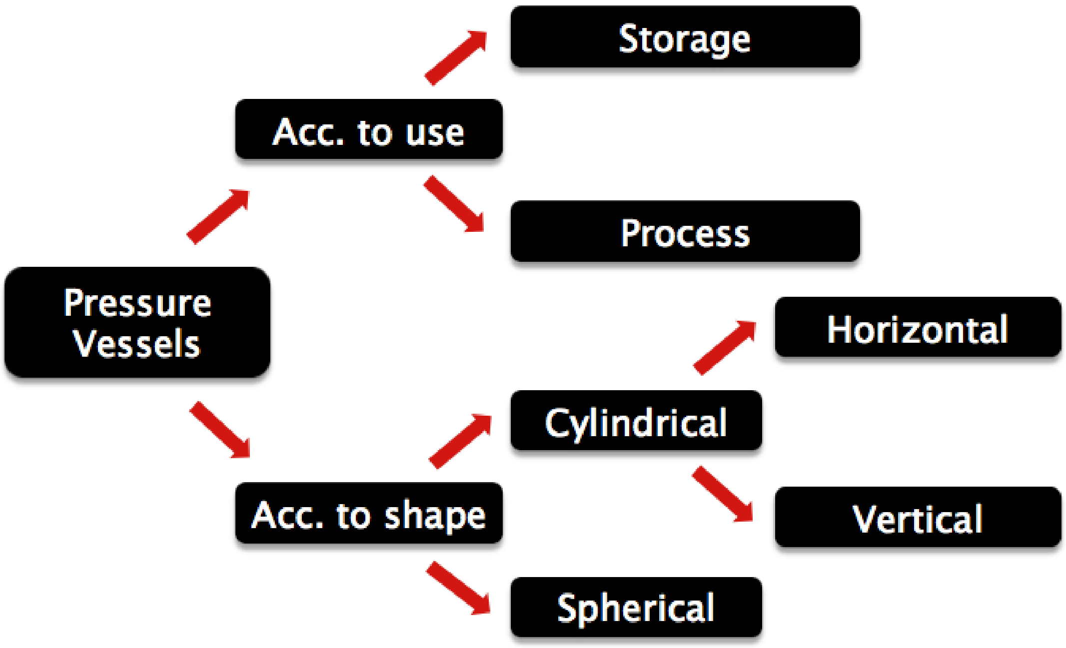
Table of contents

Introduction

A pressure vessel is considered as any closed vessel that is capable of storing a pressurized fluid, either internal or external pressure, regardless of their shape and dimensions. The cylindrical vessels, to which we refer in this volume, are calculated on the principles of thin-walled cylinders.

The first step in designing a container is choosing the best type for the service for which it is intended. **The factors influencing the choice of type are the function of the container, the location, the nature of the fluid that has to be stored, the temperature and operating pressure** and their ability to store the volume needed by the process.

Pressure vessels can be classified according to their intended service, temperature and pressure, materials and geometry. Different types of pressure vessels can be classified as follows:



According to the intended use of the pressure vessel, they can be divided into storage containers and process vessels.

The first classes are only used for storing fluids under pressure, and in accordance with the service are known as storage tanks.

Process pressure vessels have multiple and varied uses, among them we can mention heat exchangers, reactors, fractionating towers, distillation towers, etc.

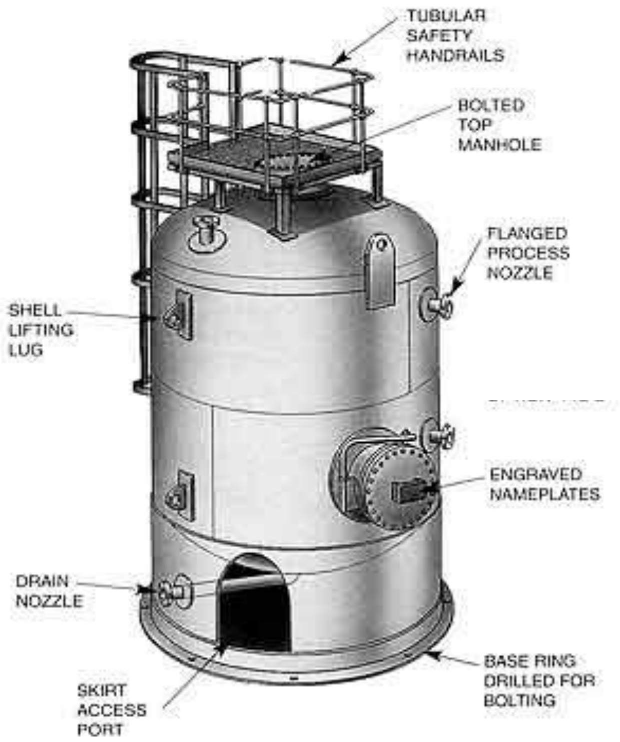
According to the shape, pressure vessel may be cylindrical or spherical. The former may be horizontal or vertical, and in some cases may have coils to increase or lower the temperature of the fluid.

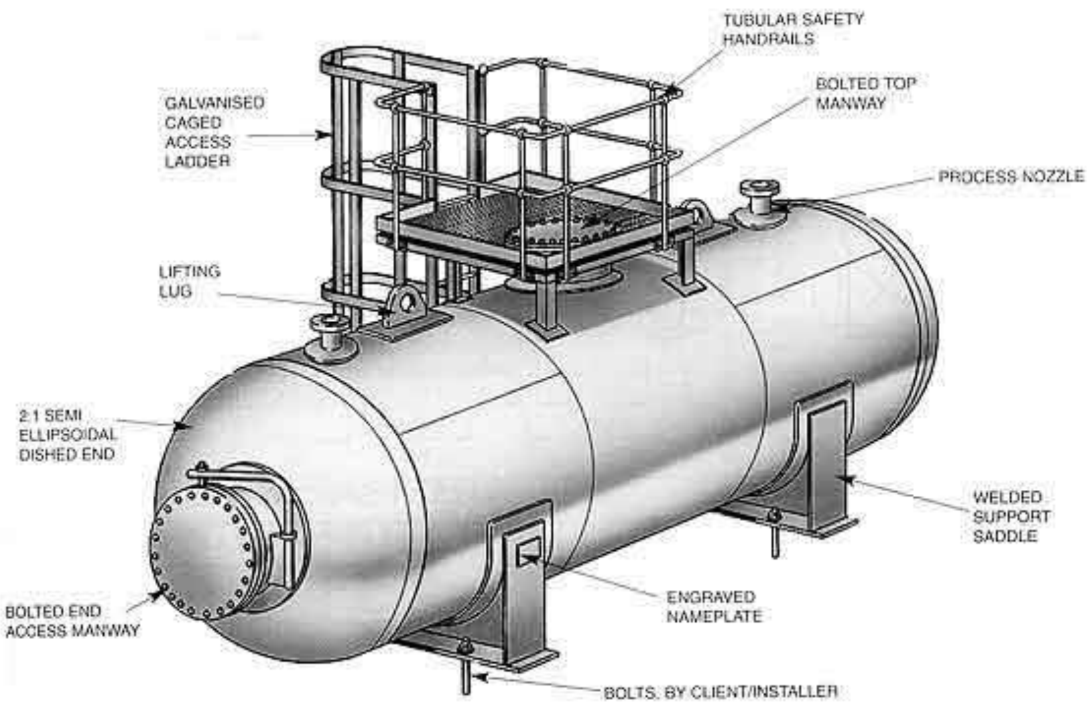
Spherical pressure vessels are usually used as storage tanks, and are recommended for storing large volumes.

Since the spherical shape is the "natural" form bodies adopt when subjected to internal pressure, this would be the most economical way to store pressurized fluids. However, the manufacture of such containers is much more expensive compared with cylindrical containers.

Pressure vessel parts

The following two sample vessels are presented: vertical and horizontal. In both cases the main parts are shown:



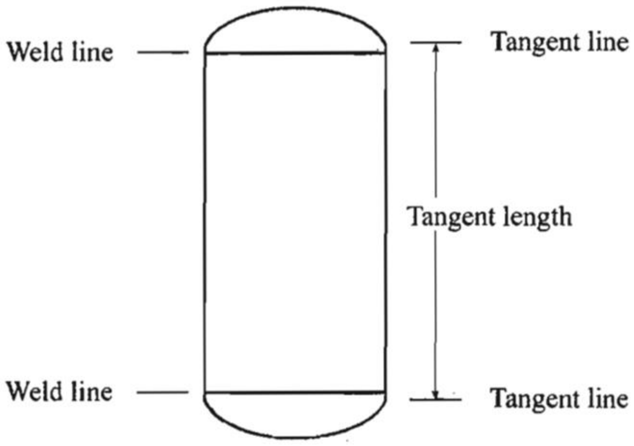


Geometry definition

To define the geometry of a pressure vessel, the inner diameter of the equipment and the distance between tangent lines is used.

The inner diameter should be used, since this is a process requirement.

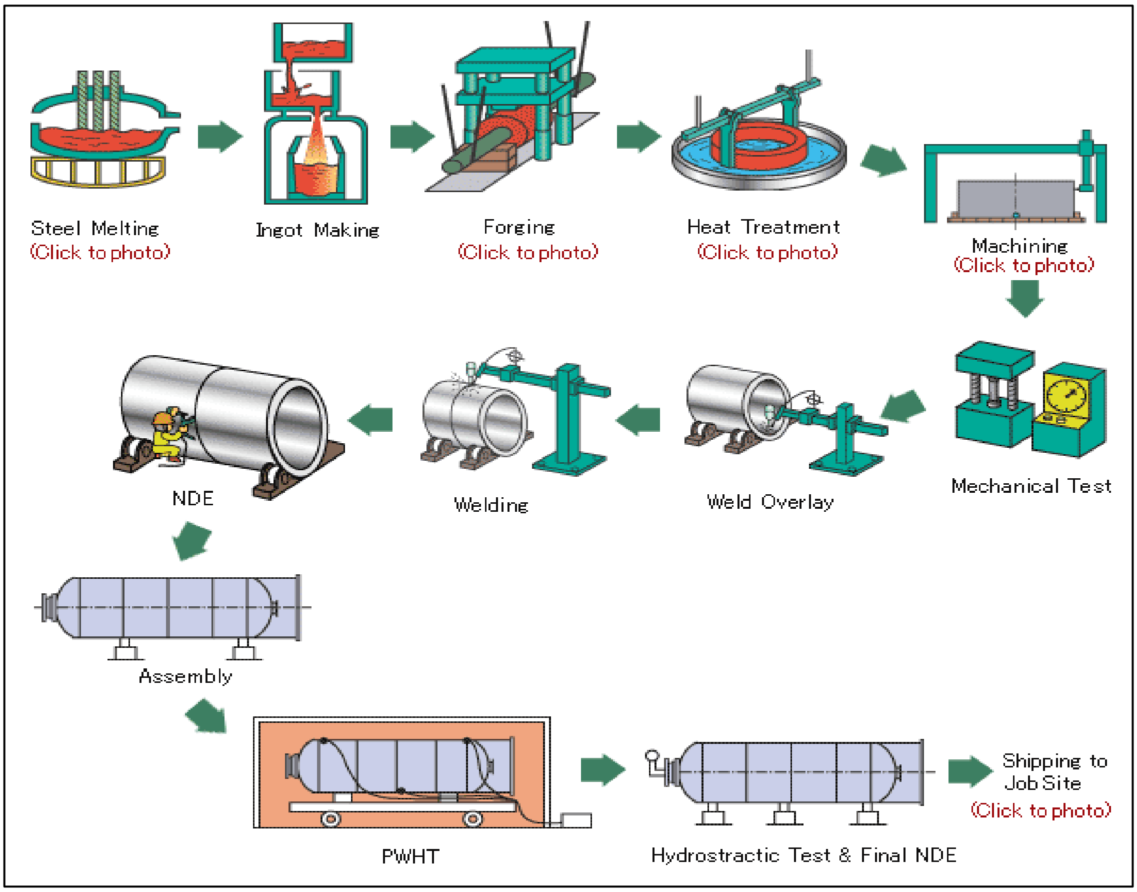
- **Welding line**: point at which the head and shell are welded
- **Tangent line**: point at which the curvature of the head begins



Depending on the head fabrication method, heads come with a straight skirt.

To set the length of the pressure vessel (regardless the type of heads), the distance between tangent lines is used since this distance is not dependent on the head manufacturing method. It is very rare that the weld and tangent lines coincide.

Manufacturing sequence



1. Design codes

The purpose of using design codes is to avoid disasters that can affect humans. Therefore, they comprise a range of experiences and good practices.

While there are several rules that apply, developed by countries with recognized technical expertise in the subject, the code that is the most internationally recognized and the most used is **Section VIII "Pressure Vessels" part of the Boiler and Pressure Vessel Code (BPVC) of the American Society of Mechanical Engineers (ASME).**

Other than the code above, the most commonly codes used for pressure vessels are:

- Europe: **EN-13445**
- Germany: **A. D. Merkblatt Code**
- United Kingdom: **British Standards BS 5500**
- France: **CODAP**
- China: **GB-150**

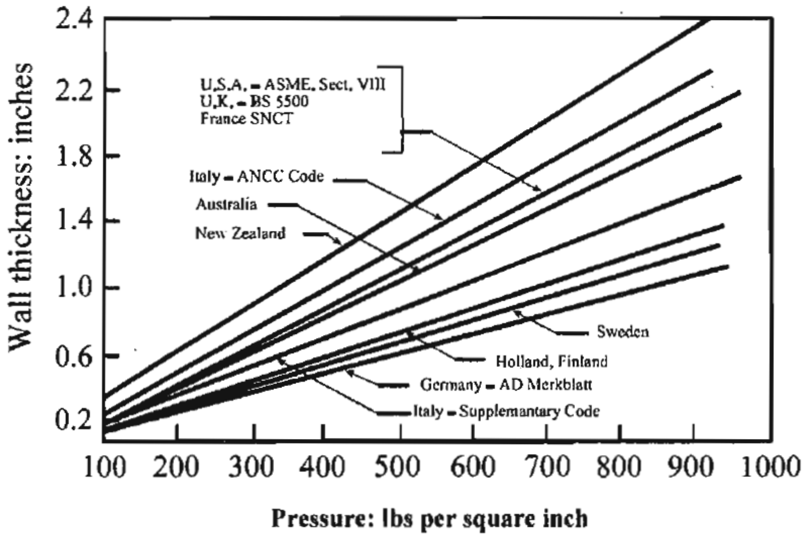
The rules found in the design codes represent many years of experience. If used wisely, the code requirements can:

- Communicate design requirements
- Utilize know-how and technology
- Keep equipment costs low
- Reduce insurance costs
- Provide rules for the design of equipment adequate for design conditions determined by others.
- Do not provide rules or guidance for the determination of design conditions.
- Do not provide rules or guidance for the determination of the required material(s) of construction or corrosion allowance.
- Design scope of most design codes includes new construction only, not revamps, repairs or rerates.

1.1) Codes comparison

Provisions of a design code are an interrelated set of design, fabrication, inspection, and testing requirements. For example, the use of a higher design stress may depend upon use of stringent material, analysis, examination, and testing requirements.

Therefore, different codes can arrive at different resulting wall thickness yet have equivalent degrees of reliability.



Welded Cylindrical Carbon-Steel Shell, 60-inch diameter
100% Radiography

2. ASME BPVC – Boiler and pressure vessel code

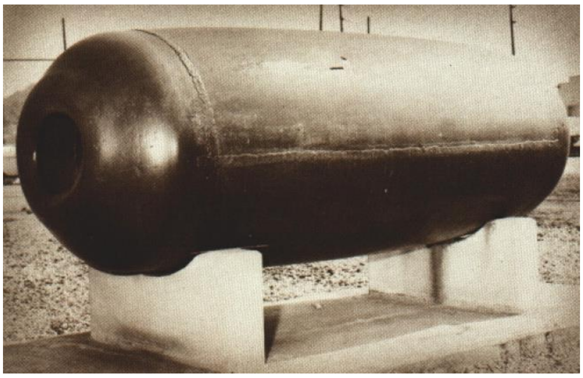
2.1) Historical review

By the end of the 18th century the use of boilers operating at pressures much higher than the atmospheric and the need to protect staff from faults, grew rapidly. In many cases, the result of operating boilers and vessels in those conditions were catastrophic.

Several attempts were made to standardize the design criteria and calculation, but in 1911, due to the lack of uniformity in boiler fabrication, manufacturers and users of boilers and pressure vessels requested advice to the ASME association to correct this situation.

Finally, in 1915, that association published the first ASME Boiler Code (now Section I) in the United States of America. The codes were established to provide manufacturing methods, records and report design data.

Until 1930, when the first welded vessel was manufactured, pressure vessels and boilers were riveted. Joints were made "overlapping" the plates or using strips, placed on the joints, drilling and tightening the rivets. It was estimated that each rivet added pressure in a certain influence area, thus guaranteeing the integrity of the equipment.



Historically, engineers have applied the traditional strength of materials rules for designing pressure vessels. They are still used today, but combined with:

- Nondestructive examination (NDE)

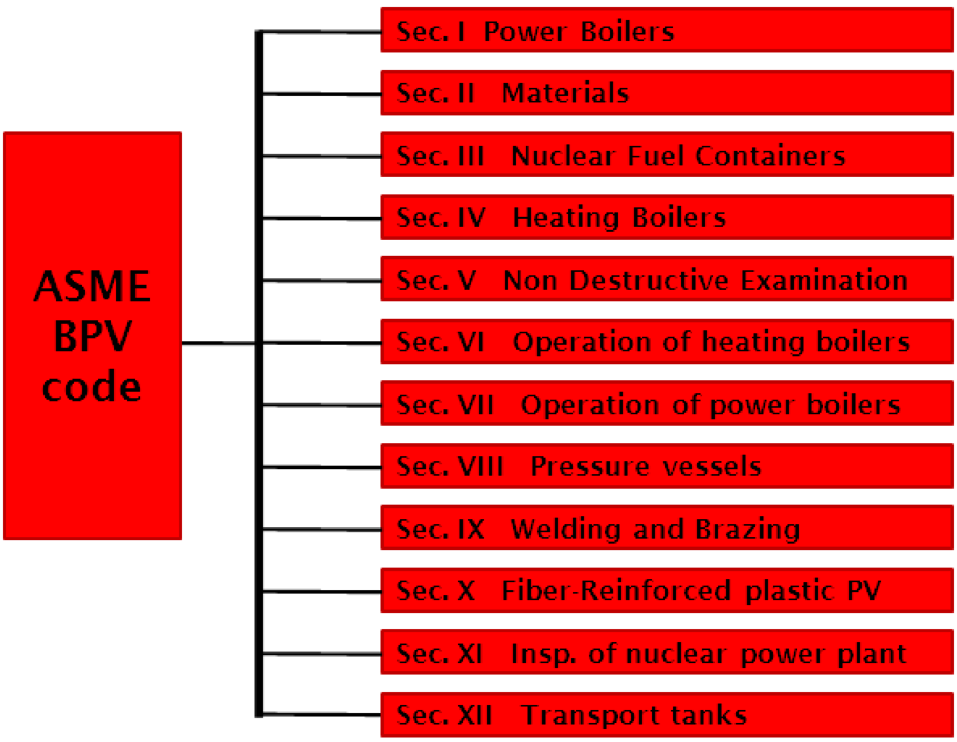
- Safety coefficients
- Lessons learned

The aforementioned includes the classic design of pressure vessels; nowadays checks according to Finite Element Analysis (FEA) are more and more extended with outstanding results, therefore we have to consider using this powerful tool in our designs if necessary.

2.2) BPVC Sections

The ASME BVPC code is a set of standards, specifications, and design rules based on many years of experience, all applied to the design, fabrication, installation, inspection, and certification of pressure vessels.

It was created in the United States of America; several insurance companies demanded a design code in order to reduce losses and casualties. The ASME Boiler and Pressure Vessel is divided into the following sections:



Those shown in the figure above are the twelve sections of the code. To properly design a pressure vessel, it is necessary to understand Section VIII of course, and additionally, the designer will need to be familiar with Sections II, V and IX.

According to the scope of each section, the 12 parts can be grouped as follows:

- Construction codes: Sections I, III, IV, VIII, X & XII
- Reference codes: Sections II, V, IX

- Rules for operating, inspection and in service maintenance: Section VI & VII.

2.3) <u>Section VIII Divisions</u>

The ASME Code Section VIII is a fabrication code. It contains mandatory requirements, specific prohibitions, and rules of construction and non-mandatory appendices. The code does not cover all possibilities related to these activities, therefore, aspects not specifically mentioned should not be considered prohibited.

Anyway, who writes the design codes? The code is written by recognized people from different areas: academics, inspection agencies, owners, users, manufacturers of pressure vessels and notified bodies among others.

What is the most important aspect of the code? The most important aspect of the code is to know its organization and to know where to look things up. WHAT IS EVEN MORE IMPORTANT IS TO **READ UNTIL THE END OF THE PARAGRAPH; EVEN THOUGH IT SEEMS AS IF WE HAVE FOUND WHAT WE WERE LOOKING FOR.**

There are 3 divisions in ASME Section VIII: divisions 1, 2 and 3. Division 3 is used for the calculation and design of high pressure equipment, around 10,000 psig (703 kg/cm2g), while Div.2 and Div.1 are used for the rest of applications.

Equipment design according to Div.1 is based on rules that do not require a detailed assessment of all stresses. There are high secondary stresses and also bending stresses present, but since safety factors are conservative, stresses will be compensated.

When designing according to Div.2 a more detailed analysis is performed, that allows the designer to consider higher allowable stresses and thus get much more real, economic and reliable results.

Another difference between the ASME VIII Div.2 and Div.1 lies in failure theory used to establish the calculation equations. While Div.1 is based on the theory of normal stress, Div.2 is based on the theory of maximum distortion energy (Von Misses).

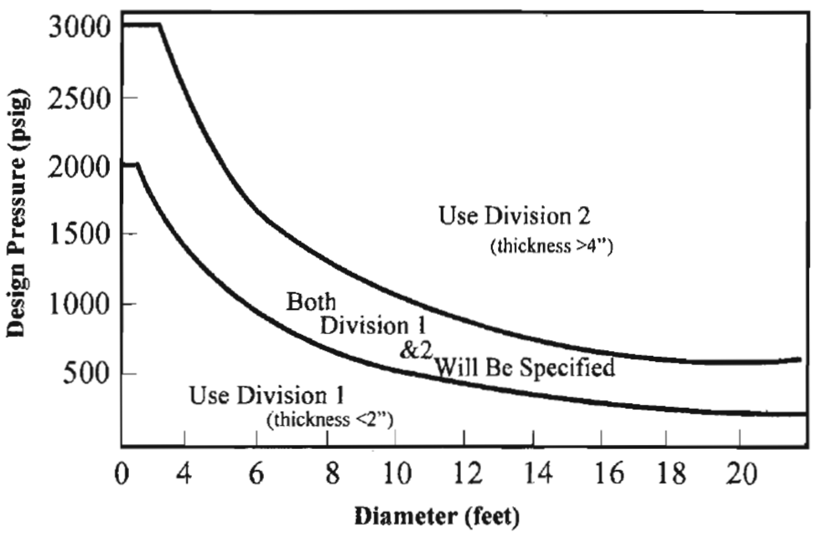
Additionally, the calculation approach is different between divisions; for Div.1 the design is by rules, whereas for Div.2 the design is by analysis, a much more exact method.

The most important limitations of Div.1 are regarding pressure; when the design pressure exceeds 3000 psi (210 Kg/cm2); design according to Div.2 is required. Additionally, Div 1 cannot be used for pressures below 15 psi (1.054 kg/cm2).

Other than the pressure limitation, the scope of both Div.1 and Div.2 is the same, and the main differences are:

- Allowable stresses
- Stress calculations
- Cyclic service design
- General design
- Quality control
- Inspection and fabrication

Now, **can we establish a clear rule that tells us when to use each division? The answer is NO. Each case is different and the designer must analyze all design conditions to determine which division to use.** Whenever the specialist deems appropriate, design shall be carried out according to both divisions to compare results. Even though a general rule cannot be listed, a chart containing some tips is presented below:



Based upon an allowable stress = 17,000 psi

It can be said that Div.1 specifies general conservative design criteria, while Div.2 provides a better design, using stresses close to the real ones. The latter combined with more stringent non-destructive examination, results in an economically more efficient design.

3. <u>ASME BPVC Section VIII, Div.1</u>

3.1) <u>Scope</u>

The extent of coverage of VIII-1 is defined in section U-1. The word "Scope" actually refers to two terms: the type of equipment considered as well as the geometry of the pressure vessel.

Before any design, it is recommended that the designer carefully reviews the paragraph U-1, to determine whether the equipment can be designed according to the code and its implications. The main considerations included in the scope of the code are summarized below:

- **U-1(a) (2) pressure vessels are defined as containers for the "containment" of internal or external pressure.** This definition applies to a very wide range of pressure vessels, some of which have not been considered in the development of the rules. In order to avoid confusion about what kind of pressure vessel is covered by VIII-1, **the Committee preferred to list the equipment <u>"not covered in the development of the rules"</u> instead of making a list of the ones considered.**

- **<u>U-1(c)(2) indicates that VIII-1 is not applicable</u>** for the following pressure vessels:
  - (a) Those included in the scope of **<u>other sections of the ASME Code.</u>**
  - (b) Process tubular heaters.
  - (c) Pressure containers that are integral part of machines (rotating equipment)

- **<u>U-1(c)(2)(d) piping systems are excluded from the scope of VIII-1.</u>**Establishing the difference between a piping system and a pressure vessel sometimes can be complex:
  - (a) If the main purpose of the pressure vessel **<u>is to transfer fluid from one point to another in the system, then it could be considered as a pipeline</u>**, and it must comply with other code's requirements.
  - (b) The main purpose of internal components such us fractionating trays or demisters is not to transfer fluid, they are installed for process reasons, therefore **<u>they must be included in the scope of VIII-1.</u>**

- U-**1(c) (2) (h) defines the scope towards pressure.** If a vessel has an **<u>internal or external pressure less than 100 kPa can be considered outside the scope of VIII-1.</u>**

- **U-1(c) (2) (i) pressure vessels <u>smaller than 152mm regarding internal diameter, width, height or diagonal, are considered out of the scope of VIII-1</u>**, independently from its length or design pressure.

- **U-1(c) (2) (j) <u>Pressure vessels for Human Occupancy (PVHO) are outside the scope of VIII-1</u>.** The design code in this case is ANSI/ASME PVHO-1.

- **U-1(g) <u>some equipment to generate steam are included in the scope of VIII-1.</u>**

  (a) U-1(g)(1): **<u>Unfired Boilers can be fabricated according to Section I or Section VIII-1</u>** (see UG-125(b) and UW-2(c))

  (b) U-1(g)(2) the following pressure vessels, in which steam is generated, are included in the scope of VIII-1.

  - U-1(g) (2) (a): **<u>pressure vessels know as evaporators or heat exchangers.</u>**
  - U-1(g) (2) (b): pressure vessels in which **<u>steam is generated due to heat present in a system or process.</u>**

- **U-1(e) defines the scope in terms of geometry.** The restrictions and limits are according to the following:

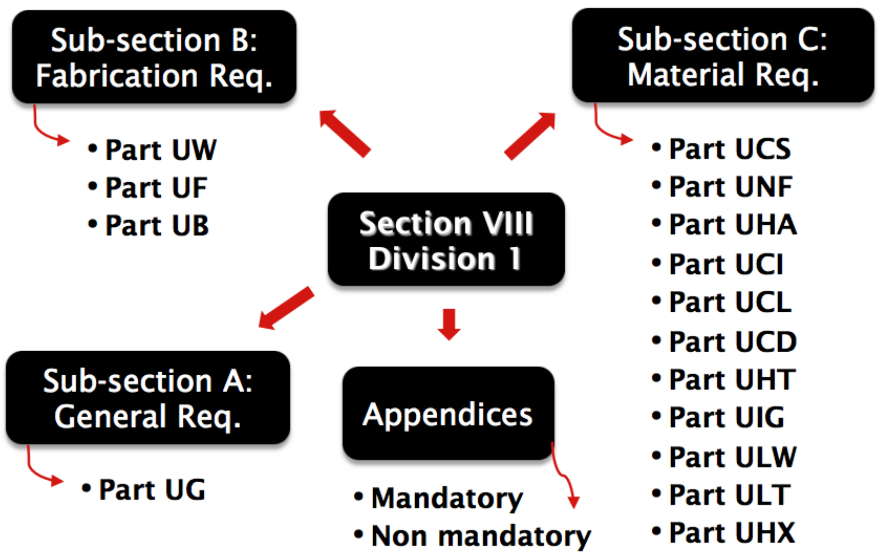
  (c) **<u>Welded nozzles (no flange): the first circumferential joint in the nozzle neck</u>**. The limit might be located in the vessel.

  (d) **<u>Threaded nozzles (no flange): the first thread</u>**.

  (e) **<u>Flanged Nozzles: the first flange face</u>**.

3.2) <u>Code organization</u>

Section VIII, division 1 is organized and divided according to the following:



3.2.1) Sub-section A: general requirements

Part UG

General Requirements for all construction methods and all materials. Paragraphs go from UG-1 to UG-137.

Since they are general requirements, they are the most important part of all. If the goal is to create safe and technically and economically feasible designs, the designer should be familiar with all paragraphs and figures

A simplified summary of the division of this part is as follows:

UG-4 to UG-15: Materials

UG-16 to UG-55: Design

UG-36 to UG-45: Openings and reinforcements

UG-75 to UG-85: Fabrication

UG-90 to UG-103: Inspection and tests

3.2.2) Sub-section B: requirements pertaining methods of fabrication

Part UW

Requirements for pressure vessels manufactured by welding. Paragraphs go from UW-1 to UW-65. Since most pressure vessels are made by welding, this is one of the main parts of the Code.

A simplified summary of the division of this part is as follows:

UW-2: Service restrictions

UW-3: Joint categories

UW-5: Materials

UW-8 to UW-21: Design

UW-11: Radiographic test (RT)

UW-12: Joint efficiencies

UW-26 to UW-42: Fabrication

UW-46 to UW-53: Inspection and tests

Part UF

Requirements for pressure vessels manufactured by forging. Paragraphs go from UF-1 to UF-125. Fully forged containers are very rare. They are used for small applications and for very specific processes.

Part UB

Requirements for pressure vessels manufactured by brazing. The issues range from the UB-1 to UB-60.

As is the case with containers manufactured by forging, this type of welding is very unusual. This is because the arc welding has been technologically improved; on the other hand, "brazing" process is generally more expensive and less productive than the electric arc welding process.

3.2.3) Sub-section C: requirements pertaining classes of materials

Part UCS

Requirements for pressure vessels constructed out of carbon steel and low alloy steel (Cr-Mo, Cr-Mo-V). Points go from UCS-1 to UCS-160.

Since the majority (90%) of pressure vessels are constructed out of carbon and low alloy steel, this section is vital.

A simplified summary of the division of this part is as follows:

UCS-5 to UCS-12: Materials

UCS-16 to UCS-57: Design

UCS-65 to UCS-68: Low temperature operations

UCS-75 to UCS-85: Fabrication

UCS-90: Inspection and tests

Part UNF

Requirements for pressure vessels constructed out non-ferrous materials. Paragraphs go from UNF-1 to UNF-125.

Part UHA

Requirements for pressure vessels constructed out of high alloy materials. Paragraphs go from UHA-1 to UHA-109.

Part UCI

Requirements for pressure vessels constructed out cast iron materials. Paragraphs go from UCI-1 to UCI-125.

Part UCL

Requirements for pressure vessels constructed by means of cladding or weld overlay (linings). Paragraphs go from UCL-1 to UCL-60.

Part UCD

Requirements for pressure vessels constructed out of cast ductile iron. Paragraphs go from UCD-1 to UCD-125.

Part UHT

Requirements for pressure vessels constructed with ferritic steels, which stress have been increased by means of heat treatments. Paragraphs go from UHT-1 to UHT-125.

Part UIG

Requirements for pressure vessels constructed out impregnated graphite. Paragraphs go from UIG-1 to UIG-125

Part ULW

Requirements for pressure vessels constructed in layers. Paragraphs go from ULW-1 to ULW-125.

Part ULT

Alternative rules for pressure vessels construction out of materials with higher allowable stresses at low temperatures. Paragraphs go from ULT-1 to ULT-125.

Part UHX

Rules for shell and tube heat exchangers. Paragraphs go from UHX-1 to UHX-20.

3.2.4) Appendices

Appendices of Section VIII are alternative and supplementary rules and considerations to those indicated in the code itself. These guidelines have been included as appendices since their use is less frequent than other paragraphs of the code.

Mandatory

Mandatory appendices are as important as the code itself. They present alternative rules to the ones included in the body of the code. There are 40 mandatory appendices.

Non-mandatory

Non-mandatory appendices are guidelines and sound engineering practices, they are not a requirement and the designer is not obliged to follow them. Even though they are not obligatory, it is advisable to bear them in mind; they have been verified and tested in many occasions with satisfactory results. Appendices go from A to Y, and from DD to KK.

3.3) ASME stamp

When a pressure vessel is ASME stamped all stages of design, construction, inspection and testing are performed in accordance with the provisions of the code, in addition, a representative of the ASME Code witnesses certain points during the above stages.

A fundamental principle is that the ASME Stamped Pressure vessel must receive an inspection by an authorized “third party" during all the stages mentioned above, to verify compliance with the applicable requirements of the Code. Signature by an authorized third party to the corresponding form in the Code, certifying that the container has been manufactured in accordance with the requirements thereof, is a key step for the acceptance of boilers and pressure vessels, especially by several bodies involved in the legalization process.

Besides inspecting pressure vessel in the abovementioned stages, Authorized Inspectors can also supervise the installation procedures at site. Also, after the equipment has been put into service, they can periodically inspect the compliance with legal requirements defined by local regulations on boilers and pressure vessels.

In addition to all the requirements any stamped boiler or pressure vessel must comply with all aspects of the Code, it must be designed, fabricated and inspected by a manufacturer holding an Authorization Certificate issued by ASME.

A pressure vessel can be designed according to the ASME Code and this does not mean that the equipment is ASME stamped. The stamp requirement it is usually associated with quality level, therefore with the safety. It requires a much more thorough documentation management and stringent fabrication and inspection procedures. It is a requirement of the customer.

There are different ASME stamp types applicable to pressure vessels: “U stamp” for equipment according to ASME VIIIDiv.1 and "U2 stamp” for equipment according toDiv.2.

3.4) Code revisions

A revision of the Code is a change from previous requirements. They can be applied from the date of the new issuance and become mandatory (except for materials) six months after that date (except for vessels contracted before the end of this six months).

3.4.1) Editions cycle

A new version is issued every two years (2011, 2013, and 2015).

The revisions reflect new editions of the Code, and are found in the Summary of Changes, after the preface and the list of people who contributed to the review.

It is strongly recommended to always go directly to the code; it is not prudent to read summaries or abstracts. The code is issued periodically and summaries can easily become outdated.

3.4.2) <u>Interpretations</u>

The Committee on Boilers and Pressure Vessels provides official interpretations of the requirements and intent of the paragraphs of the Code. Interpretations are issued in response to requests made in accordance with the procedure set out in Appendix 16.

3.4.3) <u>Code cases</u>

A code case is an urgent revision of the ASME code to include certain points not contained in current editions or to seek alternatives to the points mentioned in this document. These “revisions" may refer to materials, design, NDE, or manufacturing among others.

Code cases have no expiration date; if they have not been withdrawn or revised (see www.asme.org database), they can be used. **These cases are grouped in a document that is not included in the main body of any of the code sections, it is ordered separately.**

When should we use them? Again, this depends on the complexity of the design and the knowhow of the designer. There are a large number of code cases, covering different issues.

e.g.: Code Case 2235-9: Use of UT in lieu of RT

10. References

This document has been compiled using different books and references. The most important ones are:

-Boiler and Pressure Vessel Code: ASME II, part D

ASME V

ASME VIII, División 1

-Pressure Vessel Design Manual – DENNIS MOSS

-Pressure Vessel Handbook - EUGENE MEGYESY

-Pressure Vessel Design Handbook – HENRY BEDNAR

-Modern Flange Design Bulletin 502 – TAYLOR FORGE