ABSTRACT.

In publication 2018-19.03 with interest in the safety of pressure vessels we carried out studies on the historical evolution of the legislative framework that regulates the design and the structural calculation by making in appendix an application of the rules that determine the calculation models to be adopted for the realization of a pressure vessel considered safe throughout the work cycle.

Keywords: pressure vessels, design of pressure vessels.

Member States of the European Union shall take all appropriate measures to ensure that pressure receptacles may be placed on the market and used only if they do not compromise the safety of persons, pets or property, in the case of installation, proper maintenance and Use according to their intended use. In the US the first pressure vessel code was developed starting in 1911 and released in 1914, starting the ASME Boiler and Pressure Vessel Code (BPVC). In 1920s and 1930s the BPVC included welding as an acceptable means of construction, and welding is the main means of joining metal vessels today. Many other countries have adopted the BPVC as their official code. There are, however, other official codes in some countries (some of which rely on portions of and reference the BPVC), Japan, Australia, Canada, Britain, and Europe have their own codes. Regardless of the country nearly all recognize the inherent potential hazards of pressure vessels and the need for standards and codes regulating their design and construction.

In the context of the European Community, the need to implement general laws that were not intended to become obsolete and hinder the technological development of the sector over time, led to the resolution of the European Council of 7 / 5/1985, to a new orientation. The new approach resulted in the implementation of a series of "harmonized" directives, characterized by greater flexibility and aimed at encouraging the free market of persons, goods and services within the Community. This avoided the spread of directives aimed at specific products, thus giving greater homogeneity to the whole European technical and legislative context.

The new orientation is applied in the field of pressure equipment through Directive 87/404 / EEC on "Simple Pressure Containers". The Directive defines simple receptacles, equipment and parts thereof under pressure when the maximum working pressure of the vessel is less than or equal to 30 bar and the pressure vessel capacity of the vessel (PS V) reaches a maximum of 10 000 bar. Liter, the minimum operating temperature shall not
be less than -50 °C and the maximum operating temperature shall not exceed 300 °C for steel and 100 °C for aluminum or aluminum alloy. In Italy, the design and manufacturing criteria remain unchanged at national level, except those specified in the VSR, VSG, M, S collections, while certification procedures are still adhering to those previously used in individual countries. A substantial change has taken place with Directive 97/23/EC, also known as the PED (Pressure Equipment Directive) directive on the design, manufacture and assessment of conformity of vessels and equipment (and parts thereof), in pressure no simple, pressure at a relative pressure greater than 0.5 bar. In Directive 97/23/EC, pressure equipment is considered as "containers, piping, safety accessories and pressure accessories, including the elements attached to pressurized parts such as flanges, fittings, sleeves, supports and movable fins". In general, the Directive excludes all equipment for which pressure does not constitute a risk factor, in addition to pumps, compressors, turbines, internal combustion engines and those already covered by other product directives (Directive on simple receptacles Pressure, Machine Directive, Low Voltage, Elevators, etc.).

The main feature of this directive is the classification of pressure equipment in four categories of risk defined by type (pressure vessel, steam generator, piping), the energy contained therein in the form of pressure, volume and fluid used. Through the use of 9 diagrams, the classification category of the equipment is defined and, accordingly, different procedures (13 "modules") are proposed, with which the manufacturer can face the assessment of compliance with the essential safety requirements covered by the Directive. Directive 87/404/EEC of 25 June 1987 on the approximation of the laws of the Member States relating to simple pressure vessels has undergone, over the next two decades, substantial changes resulting from technological developments, from the increased security required for a wider use of pressure equipment, requiring coding to streamline the substantial changes through Directive 2009-105-EC on simple pressure vessels subsequently repealed by Directive 2014/29/EU on harmonization of the laws of the Member States relating to the making available on the market of simple pressure receptacles. Directive 97/23/EC on pressure vessels and equipment (no simple) has undergone substantial modifications until 2014, when the European Parliament of the Council recasts the same legislation and its amendments by adopting Of Directive 2014/68/EU for reasons of clarity.

In the design of pressure vessels, the ASME code "Boiler & Pressure Vessel Code" is applied. It was born at the beginning of the nineteenth century on
the initiative of an American Society of Mechanical Engineers, as a result of the need to standardize the legislation of many of the states of the US Confederation on pressure equipment (especially boilers). To date, it is used in more than 100 countries beyond the United States and Canada, it is the world’s most widely used standard for the safety calculation of pressure vessels. The ASME Code is divided into twelve sections and each of them covers particular areas. Five sections of the ASME Code concern pressure vessels, pressure vessels:

1. Section I - Power Boilers: Provides the requirements for all construction methods for power boilers and miniature boilers, high temperature water boilers used in fixed service and power boilers used in locomotive, portable and service boilers traction.


3. Section V - Non-Destructive Testing: Determines the rules and procedures for all non-destructive controls: radiographic, ultrasonic, penetrating liquid, magnetic particles and leak tests.

4. Section VIII - Pressure Containers: It is divided into three divisions: **Division 1** - Provides requirements for the design, manufacture, inspection, testing, and certification of pressure vessels operating at internal or external pressures greater than 15 psi. **Division 2** - Alternative Rules provides requirements for the design, manufacture, inspection, testing and certification of pressure equipment operating at internal or external pressures greater than 15 psi. However, the higher intensity values of project stresses are permitted. **Division 3** - alternative rules for construction in high pressure vessels, provides requirements applicable to the design, manufacture, inspection, testing and certification of pressure vessels, working with internal or external pressures generally over 10,000 psi.

5. Section IX - Qualification for Welding and Brazing: Provides Qualification Procedures Requirements, Qualification of Welder, Solder Operator and procedures Brazing, Welders, Brazing, and Welding and Brazing Operators.

In the appendix we have performed a sizing of a pressure vessel using the DBF approach provided by ASME VIII and in compliance with CE harmonized standards, with particular reference to Directive 2015/68 / EU, which excludes
the possibility of applying a Experimental design method and therefore without sizing calculations, pursuant to Annex 1, the **essential safety requirements** of the same Directive in points 2, 2.2.1, 2.1.1 and 2.2.2.
APPENDIX.

Pressure vessel.

In the dimension design of the pressure vessel, the most common load conditions should be considered:

- Internal and external pressure, own weight, actions transmitted by the weight of any equipment: machines, internals, actions transmitted by the container motion,
- Supports, cyclical and dynamic actions produced by variations in pressure and temperature, wind, snow,
- Impulsive actions, such as those due to "blow" (is a hydraulic phenomenon that occurs in a conduit when a flow of liquid moving in it is abruptly stopped by the sudden closing of a valve or when a closed conduit in Under pressure is opened suddenly),
- Temperature gradients and differential thermal expansion, pressurization test.
- It is, however, the responsibility of the manufacturer to identify all actions that may be expected to take place during the operating life, which may be relevant for safety,
- Including those resulting from any reasonably foreseeable misuse of the equipment itself.

Often the pressure component includes welded joints whose presence tends to reduce the permissible voltage values of the component itself by means of a coefficient called "efficiency" of the weld. The welding efficiency generally depends on the following factors: welding type (pp head, corner angle, etc.), NDE or NDD ("Non Destructive Examination" or "Non Destructive Testing" US, X-ray, etc.) After welding, the thicknesses of the welded parts, the working temperatures, the type of base material, must be evaluated.

The operating conditions determine the safety coefficient to be taken and may cause variations in structural calculations with variations.

PED Directive, Pressure Equipment Directive, standards for the design of pressure vessels

The PED Directive refers to harmonized standards (eg EN 13445) for the design and construction of pressure equipment; It is understood that PED’s safety requirements are deemed to be satisfied if it complies with
the design and construction requirements of EN 13445.
- Category I: for less dangerous equipment, EC certification is subject to the "self-certification" of the manufacturer.
- Category II: CE certification is obligatory through a notified body which, without entering into the merit of the design, carries out production monitoring in the manner selected by the manufacturer;
- Category III: CE certification is obligatory through a notified body. If the manufacturer has not certified his quality system, including the design, the in-depth testing of the prototype to be certified by CE is also foreseen;
- Category IV: requires the highest level of control of design and production.

Sizing methods used in the project

- **Design by Formulas (DBF)**: Sizing and checking of the container are based on pre-packed formulas (formulas) designed to cover, with adequate safety coefficients, all the main situations encountered in the design of a pressure vessel; When formulas are usually based on simple or semi-empirical models that are not very accurate, so the security coefficients tend to be higher.

- **Design by Analysis (DBA)**: sizing and checking the pressure vessel are based on accurate analysis of the actual voltage state, usually only available with Finite Element Method (FEM) bases. The DBA approach is necessary for cases not covered by DBF relationship, but is also used as an alternative to the latter, unless simple analytical models are sufficient. By providing the DBA approach more accurate analysis, so the security coefficients used tend to be lower.

Principal regulations used for the design of pressure vessels

- ASME VIII
  - Div. 1 – Approach DBF
  - Div. 2 – Approach DBF+DBA

- EN 13445 – Approach DBF+DBA
Criteria for structural security verification:
The different regulations differ for criterion used for the calculation of the equivalent sigma $\sigma_{eq}$ defined as $\sigma_{id}$ in this calculation:

**ASME VIII - Div. 1 (DBF) : Lamé criterion (max. Normal voltage)**

$$\sqrt{\sigma^2 + \tau^2} = \sigma_{eq}$$ used for less ductile materials.

**ASME VIII - Div. 2 (DBF) : Criterion of Tresca (max. Tangential tension)**

$$\frac{|\sigma_i - \sigma_j|}{2} \max = \tau_{max}$$

$$2 \cdot \tau_{max} = \sigma_{eq}$$

Where that in this publication is $\sigma_{id}$. Criterion used for ductile materials.

**ASME VIII - Div. 2 (DBA) : Criterion of Von Mises (Distortion Energy)**

$$\sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1 \sigma_2 - \sigma_1 \sigma_3 - \sigma_2 \sigma_3 + 3(\tau_{12}^2 + \tau_{13}^2 + \tau_{23}^2)} = \sigma_{eq}$$

Where with $\sigma_3 = 0$ it is $\sqrt{(\sigma_1 - \sigma_2)^2 + 3\tau}_{12}^2 = \sigma_{eq}$ Compared to the Tresca criterion, an approximation is used for excess in the
calculation of $\sigma_{eq}$. The Von Mises verification criterion is used for ductile materials.

**EN13445 (DBF+DBA) : Criterion of Tresca (max. Tangential tension)**

$$\frac{|\sigma_i - \sigma_j|_{\text{max}}}{2} = \tau_{\text{max}}$$

$$2 \cdot \tau_{\text{max}} = \sigma_{eq}$$

Where that in this design calculation is $\sigma_{id}$. Criterion used for ductile materials.
Sizing the pressure vessel in the side view below.

The container has a cylindrical configuration with internal diameter $D = 2100$ mm, closed with semipherical bottoms, it is placed on two A and B saddles at a distance of $LAB = 7000$ mm and extends length $L0 = 2000$ mm on both sides. Contains a liquefied gas at pressure $p = 5$ bar. The density of the liquid is $\rho = 0.80$ kg / dm$^3$. A project calculation is made to measure the thickness of the cloak and the funds, assuming that the degree of safety is at least 2.

Material data

$$\sigma_R = 570 \frac{N}{mm^2} \quad \sigma_S = 250 \frac{N}{mm^2}$$

The $\sigma_{amm}$ will have to be the last value before breaking up, so at most equal to $\sigma_R$. 
Calculation of the permissible voltage.
Since the safety degree is not less than 2, the safety coefficient $\gamma$ is equal to 2 so that the permissible voltage is:

$$\sigma = \frac{\sigma_s}{\gamma} = \frac{250}{2} = 125 \frac{N}{mm^2}$$

Pressure calculation
The point of greater stress is identified.
In any section of the cylinder, at point C the pressure appears to be:

$$p_c = 5 \text{ bar} = 500 \ 000 \ Pa = 0.5 \ MPa$$

At point D above the pressure, the pressure due to the weight of the fluid is added:
\[ p_D = p_c + \rho gh = 500\ 000 + 800 \cdot 9.81 \cdot 2.1 = \\
= 0.516\ \text{Mpa} \]

\[ P_D \approx 0.52\text{MPa} \text{ essendo } 1\ \text{MPa} = 1 \frac{N}{mm^2} \]

allora \[ P_D \approx 0.52 \frac{N}{mm^2} \]

**Dimensioning of cylindrical cloak**

In a pressure vessel, with thin walled, the voltages can be calculated using the following relationships

\[ \sigma_m = \frac{p \cdot r}{2s} \quad \sigma_n = \frac{p \cdot r}{s} \quad \sigma_r = -p \]

The calculation will be made by reference to the pressure on the bottom, ie the pressure \( p_D \), using the Tresca method as the criterion for structural safety verification, is obtained
In this dimension the minimum voltage is $\sigma_r$ while the maximum voltage is $\sigma_m$

$$\sigma_{id} = \sigma_{max} - \sigma_{min}$$

$$\sigma_{id} = \frac{p \cdot r}{s} - (-p) = \frac{p \cdot r}{s} + p$$

for the calculation of the thickness, the structural stability equation is used

$$\sigma_{max} \leq \sigma_{amm}$$

Where $\sigma_{max} = \sigma_{id}$ replacing, i have

$$\frac{p \cdot r}{s} + p \leq \sigma_{amm}$$

$$\frac{p \cdot r}{s} \leq \sigma_{amm} - p$$

From which the resulting thickness is derived:
\[
s \geq \frac{p \cdot r}{\sigma_{amm} - p}
\]

being the radius half the diameter of 1050 mm, replacing it is obtained

\[
s \geq \frac{0,516 \cdot 1050}{125 - 0,516} = 4,35 \text{ mm}
\]

so it is appropriate to choose a thickness of 5 mm from the application of Directive 2014/29 / EU repealing Directive 2009/105 / EC, rationalization of EC Directive 404/1987 adopted in Italy by Legislative Decree No. 82 of 19 May 2016. For the presence on the longitudinal sealing vessel realized by a non-automatic welding process, the thickness is multiplied by the coefficient 1,15. Having, the pressure vessel, being the product between maximum operating pressure for volume greater than 6000 bar. liter can be realized with a project in which the thickness of the pressure parts is calculated in accordance with Directive 2014/68 / EU (adopted in Italy by Decree Law No 26 of 15 February 2016) excluding the possibility of applying the experimental method (Without calculation) that would determine the thickness to allow the vessel to withstand, at room temperature, a pressure equal to at least 5 times the maximum working pressure, with a permanent circumferential deformation of not more than 1%. 

It should be noted that the structural calculation project, obligation imposed by the directive, carried out by an authorized
technician (authorized engineer), achieves considerable material savings in accordance with the highest security requirements.

$S = 5 \text{ mm}$

Semi-spherical bottom dimensioning

In this case the relations for the calculation of voltages are:

$$\sigma_m = \frac{p \cdot r}{2s}, \quad \sigma_n = \frac{p \cdot r}{2s}, \quad \sigma_r = -p$$

Applying Tresca's criterion for structural safety verification, i have:

$$\sigma_{id} = \frac{p \cdot r}{2 \cdot s} - (-p) = \frac{p \cdot r}{2 \cdot s} + p$$

From which the thickness is equal to

$$S \geq \frac{p \cdot r}{2(\sigma_{amm} - p)} = \frac{0,516 \cdot 1050}{2(125 - 0,516)} = 2,18 \text{ mm}$$

The calculation determines a choice for the bottoms semi-sphere of 2 mm.
Being a receptacle, the same thickness will be used both for the bottom and the mantle and equal to $S = 5\, mm$.

**Note:**

In the construction of thin-walled pressurized vessels, in the absence of structural constraints, the semisphere bottom is chosen because it results in reduced metal reduction being able to have a slender thickness respect cloak up to half; A choice that is not used for thin-walled pressure vessels where the same thickness is used for both the cloak and the semi-spherical bottoms. It is to be considered that the metal of 4 to 5 millimeters represents the thickest used for the production of cylindrical pressure vessels in practice. When structural constraints do not allow the use of spherical funds, eg the use of flat funds, the thickness to be used for the funds is about three times greater than the thickness of the mantle.

**Action of fluid and container weight.**

The weights of the fluid and cloak operate as a continuous load $q$ which is however constant in the cylindrical area, but variable in the two bottoms.
The volume of a spherical segment proportional to weight is given by the report

\[ V_f = \pi \cdot h^2 \left( r_i - \frac{h}{3} \right) \]

the trend of which is shown in the graph.

Assuming the two bottom as the cylinder, the design safety is increased beyond the simplification of the calculations, so that the tank becomes a cylinder with a length \( L_t = 11 \) mm with an inner diameter of 2100 mm and an outer diameter of \( D_e = 2110 \) mm.

The volume of the fluid turns out to be:

\[ V_f = \pi \cdot r_i^2 \cdot L_t \]

its weight is:

\[ Q_f = m_f \cdot g = \rho \cdot V_f \cdot g \]

\[ Q_f = \rho \cdot \pi \cdot r_i^2 \cdot L_t \cdot g = \]

\[ = 800 \cdot \pi \cdot 1,05^2 \cdot 11 \cdot 9,81 = 298,855 \ N \]
by dividing the total weight, of the fluid, for the total length, the equivalent continuous load is obtained:

\[ q_f = \frac{Q_f}{L_t} = \frac{298,855}{11} = 27,169 \frac{N}{m} = 27,169 \frac{N}{mm} \]

The weight of the coat is:

\[ V_f = 2 \cdot \pi \cdot r_i \cdot s \cdot L_t \]
\[ Q_m = \rho_m \cdot 2 \cdot \pi \cdot r_i \cdot s \cdot L_t \cdot g = 7500 \cdot 2 \cdot \pi \cdot 1,05 \cdot 0,005 \cdot 11 \cdot 9,81 = 26 \ 683 \ N \]

the total load is the sum of the two weights:

\[ Q_t = Q_f + Q_m = 298855 + 26683 = 325538 \approx 326 \ 000 \ N \]

by dividing the total weight for the total length, the equivalent continuous load is obtained:
**Calculation of voltages**

The most stressed section is identified by calculating the moment at which it reaches the maximum intensity, in sections A and B and in the
middle of the middle that we call E.
In sections A and B, for the symmetry of the system, moments take on the same intensity:

\[ M_B = -q \frac{L_A^2}{2} = 29,64 \frac{2100^2}{2} = -65356200 \text{ Nmm} \]

In section E it is calculated:

\[ M_E = q \frac{L_{A,E}^2}{2} + R_B \cdot L_{BE} = -29,64 \frac{5500^2}{2} + \frac{321000}{2} 3500 = \]

\[ = 113445000 \text{ Nmm} \]

To calculate the maximum voltage indicated by the constant bending resistance modulus is calculated throughout the section:

\[ W_f = \frac{\pi D_e^4}{32} - \frac{\pi D_i^4}{64} = \frac{\pi}{32} \cdot \frac{2110^4 - 2100^4}{2110} = 17350658 \text{ mm}^4 \]
Being the maximum bending moment in section E, in module, it is possible to calculate the maximum voltage in E through the calculation below:

\[ \sigma_{f_{\text{max}}} = \frac{M_{FE}}{W_F} = \frac{113445000}{17350658} = 6.54 \ \frac{N}{mm^2} \]

The tension state in the section is represented in the red figure, where at point A generates a maximum compression value \( \sigma_{f_{\text{max}}} \) and in the point B a traction of value \( \sigma_{f_{\text{max}}} \).

Calculating the tension now \( \sigma_n \), the maximum voltage generated by the fluid pressure is obtained:

\[ \sigma_n = \frac{pr}{s} = \frac{0.516 \cdot 1050}{5} = 108.36 \ \frac{N}{mm^2} \]

So at point B there is a maximum voltage \( \sigma_{mt} \) (Sigma cylindrical mantle) calculated as follows:

\[ \sigma_{mt} = \sigma_n + \sigma_{f_{\text{max}}} = 108.36 + 6.54 = 114.9 \ \frac{N}{mm^2} \]
The pressure sizing design is considered to be completed by applying the Tresca criterion

$$\sigma_{id} = \sigma_{\text{max}} - \sigma_{\text{min}} = \sigma_{mt} - \sigma_r \equiv \sigma_{ntf}$$

the resulting ideal voltage $\sigma_{id} \equiv \sigma_{mt}$ is inferior to the tension of sliding, beyond which the metal begins to warp or plastic deformation that precedes breakage. The sigma limit is indicated by sigma R defined as breakdown voltage.

S thickness of 5 mm is the thickness for which the pressure vessel with cylindrical wall and two bottom semi-spherical, meets the design safety requirements (operating conditions, maximum operating pressure, maximum temperature and minimum operating pressure, vessel motion ...).

1) NB-370, National Board Synopsis United States. The National Board Synopsis of Boiler and Pressure Vessel Laws, Rules and Regulations is a compilation of jurisdiction laws, rules, and regulations set forth in a concise, easy-to-read format. It features the prevailing requirements, detailed contact information, and regulatory history for each jurisdiction.


7) Union de Normalisation de la Mécanique, Nation France. EN 13445 "Unfired pressure vessels". Background to the rules in Part 3 Design.

8) Course clipboard Construction of Machines, Prof. ing. A. De Iorio, University of Engineering, Federico II, Naples, Italy.
