DEVELOPMENT OF CALCULATION FORMULAE FOR CYLINDER WALL THICKNESS

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EIGA

DEVELOPMENT OF CALCULATION FORMULAE FOR CYLINDER WALL THICKNESS

ECMA
EUROPEAN CYLINDER MAKERS ASSOCIATION

This publication is based upon TI 002 *Development of calculation formulas for cylinder wall thickness* issued by the European Cylinder Makers Association,(ECMA) and was prepared by Herr Gerhard Koenig. Herr Koenig worked for Heiser Cylinders, which then became Worthington Cylinders. Following this he became the General Secretary of ECMA. This career extended over fifty years and this publication captures a small part of Gerhard's knowledge on the development of calculation formulae for cylinder wall thickness. It is hoped future generations of cylinder specialists will find this publication of immense use, and EIGA is grateful to ECMA to use their publication, TI 002 *Development of calculation formulas for cylinder wall thickness* as the basis of this publication.

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1 Introduction

This publication explains the historical background to the formulae used to calculate the minimum design wall thickness of seamless steel and aluminium alloy cylinders and the differences between them.

The publication is based on Technical Information TI 002, *Development of calculation formulas for cylinder wall thickness* [1][1] prepared by the European Cylinder Makers Association, ECMA. This publication has been formatted to align with the EIGA publication style, and EIGA thanks ECMA for the permission to reproduce their text. All material contained in this publication remains the copyright of ECMA.

2 Scope and purpose

2.1 Scope

This publication is limited to the following formulae which are used to calculate the minimum design wall thickness of seamless steel and aluminium alloy cylinders:

- Bach Clavarino formula;
- Mean diameter formula; and
- Lamé von Mises formula.

2.2 Purpose

To detail the design formulae that are used for seamless steel and aluminium alloy cylinders such that the reasons for their use are understood.

3 General

Over the years three main formulae have been used to calculate the sidewall thickness of gas cylinders. These are:

- Bach Clavarino formula (used in the United States Department of Transportation, (DOT) regulations)

$$S = \frac{[P_h(1{,}3D^2 + 0{,}4d^2)]}{D^2 - d^2}$$

$$a = \frac{D}{2} * \left(1 - \sqrt{\frac{S - 1{,}3 * P_h}{S + 0{,}4 * P_h}}\right)$$

- Mean Diameter formula (used in EEC Directives 84/525/EEC [2], 84/526/EEC [3], ISO4705 *Refillable seamless steel gas cylinders* [4] and many other national standards/codes/regulations in Europe)

$$a = \frac{P_h * D}{20 * R_{eg} * F + P_h}$$

[1] References are shown by bracketed numbers and are listed in order of appearance in the reference section.

- Lamé von Mises formula, (used in ISO designs)

$$a = \frac{D}{2} * \left(1 - \sqrt{\frac{10 * F * R_{eg} - \sqrt{3} * P_h}{10 * F * R_{eg}}}\right)$$

where the value of F is the lesser of $\frac{0,65}{R_{eg}/R_{mg}}$ or 0,85.

Whereby the symbols have the following meaning:

a	calculated minimum wall thickness in mm (in inches for the Bach Clavarino formula)
D	outside diameter of the cylinder in mm (in inches for the Bach Clavarino formula)
d	inside diameter of the cylinder in inches
P_h	hydraulic test pressure in bar (in psi for the Bach Clavarino formula)
R_{eg}	minimum guaranteed value of yield stress in MPa
R_{mg}	minimum guaranteed value of tensile strength in MPa
F	design stress factor
S	wall stress in psi Volumetric expansion test

4 Historical background and evaluation of design formulae by ISO/TC58/SC3

In 1947 a Technical Committee of the International Organization for Standardization, ISO/TC58, was established to develop international standards in the field of gas cylinders. This committee created a Sub-Committee ISO/TC58/SC3 which is responsible for the development of cylinder design standards.

The first ISO standard for seamless steel gas cylinders was published in 1983, ISO 4705 [4]. This standard used the Mean Diameter formula to calculate wall thickness. However, it was evident that two other formulae were also used worldwide to calculate wall thickness. Each formula resulted in slightly different wall thicknesses. As a consequence, ISO/TC58/SC3 established a working group, WG-8, in 1981, (under the leadership of the British Standards Institute) to investigate which of the three formulae most accurately reflected the actual stresses in the side walls of gas cylinders.

Cylinders with exactly defined wall thicknesses and mechanical properties, were produced and strain measurements were taken at increasing applied pressures up to and beyond test pressure to cause elastic failure.

The research project can be summarized as follows:

The general conclusion was that over the range of materials and cross-sectional geometries investigated, the Lamé von Mises formula was able to most closely predict elastic failure, and that this formula is therefore the preferred one for deriving required wall thickness of gas cylinders in terms of equivalent stress distribution.

The Bach Clavarino formula tends to overestimate internal pressure causing elastic failure, and the mean diameter formula tends to underestimate pressure to promote elastic failure for thin walls and overestimate for thick walls.

In more detail, the outcome showed that gas cylinders can be categorized as:

- Thin-walled cylinders ($D_{external}$ / $D_{internal}$ around 1,06), are best calculated by the Lamé von Mises formula and is most applicable.

- Thick-walled cylinders with a diameter ratio $D_{external}$ / $D_{internal}$ around 1,16 – 1,20 such as aluminium alloy or normalized mild steel cylinders, are best calculated by either the Mean Diameter or Lamé von Mises formula..
- Whereas, the Bach Clavarino formula results in slightly underestimated wall thicknesses (see graph below).

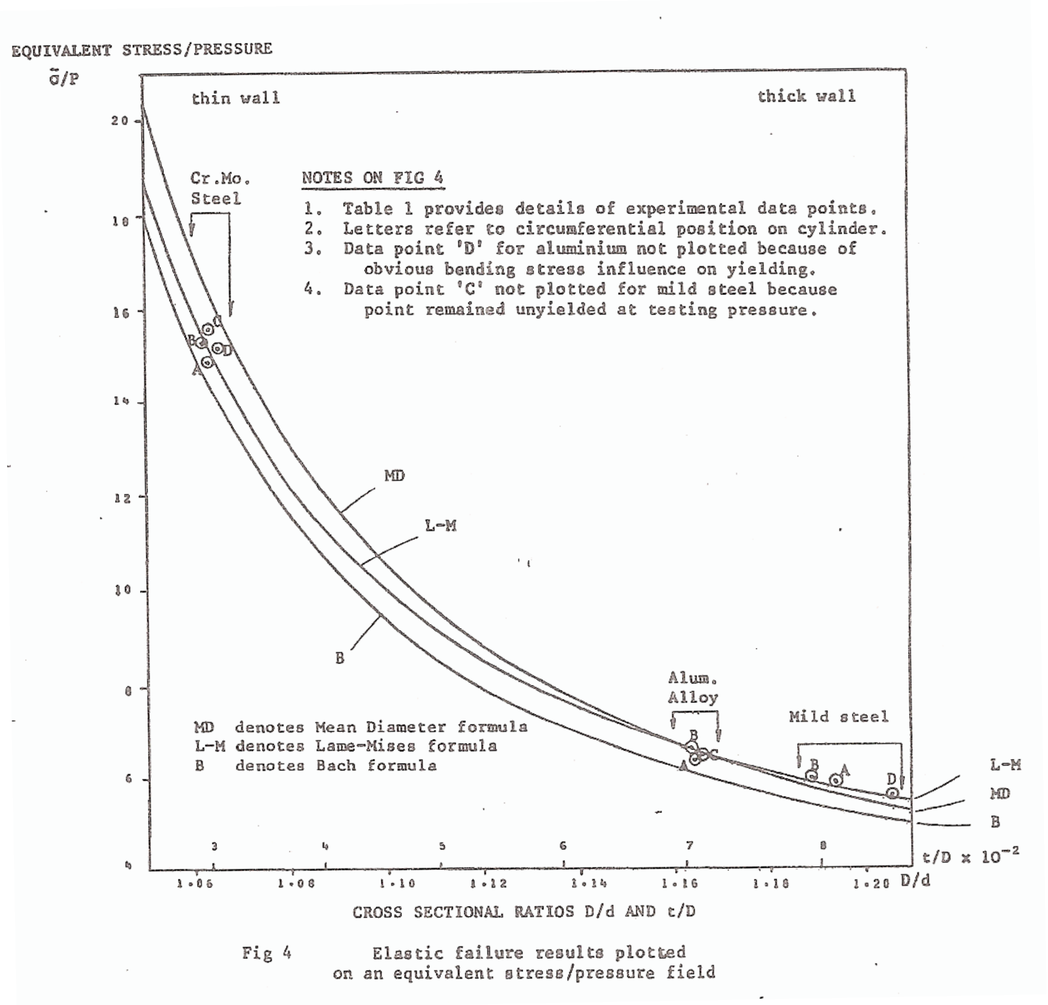

Figure 1 Equivalent failure results: (Source ISO TC 58 SC3 WG 8)

Four examples of wall thickness calculations, using the three different design formulae, for cylinders having the same test pressure, diameter and mechanical properties can be found in Annex A to see the different influence on the minimum calculated wall thickness.

5 Conclusion

As a result of the studies by ISO/TC58/SC3 it was agreed to use the Lamé von Mises formula in all future ISO cylinder design standards.

Industry experience over more than 15 years has shown that the Lamé von Mises formula to be satisfactory for the design of seamless high-pressure aluminium alloy and steel gas cylinders

6 References

Unless otherwise stated the latest edition shall apply.

[1] TI 001; *Description of the pressure test methods used during cylinder manufacture* www.ecma.org

[2] Council Directive 84/525/EEC of 17 September 1984 *on the approximation of the laws of the Member States relating to seamless, steel gas cylinders* www.europa.eu

[3] Council Directive 84/526/EEC of 17 September 1984 *on the approximation of the laws of the Member States relating to seamless, unalloyed aluminium and aluminium alloy gas cylinders* www.europa.eu

[4] ISO4705: *Refillable seamless steel gas cylinders* www.iso.org

[5] ISO 9809-1, *Gas cylinders - Refillable seamless steel gas cylinders - Design, construction and testing - Part 1: Quenched and tempered steel cylinders with tensile strength less than 1 100 MPa* www.iso.org

[6] DOT 3AA, 49 CFR 178.37 - Specification 3AA and 3AAX seamless steel cylinders

7 Other references

Paper regarding the test programme carried out by ISO TC58/SC3/WG-8:

Design Formulae for Transportable High Pressure Gas Cylinders UK Test Programme for ISO/TC58/SC3/WG8 F McQuilken, Senior Scientific Officer, National Engineering Laboratory

Report from the research work carried out by ISO TC58/SC3/WG-8:

Design Wall Thickness of Transportable High Pressure Gas Cylinders Comparison of Experiment and Theory John A Walters, Bsc PhD, T.I. Chesterfield Limited

ANNEX A - Calculation examples for cylinders in accordance with the Bach Clavarino formula, the Mean Diameter formula and the Lamé von Mises formula

The following example calculations demonstrate the difference in the calculated minimum wall thickness for steel cylinders made of the same material with the same mechanical properties (same heat treatment, quenched and tempered), the same test pressure and same diameter when calculated in accordance with (see table 1):

- the Bach Clavarino formula using the wall stress requirements of DOT 3AA (Example 1*)
- the Mean Diameter formula
  - using the F factor requirements of ISO4705 (Example 2.a)
  - using the F factor requirements of EEC Directive 84/525/EEC (Example 2.b)
- the Lamé von Mises formula using the F factor requirements of ISO 9809-1 [5] (Example 3)

Specified parameters for calculation:

D = 229 mm (= 9,015748 inches)

P_h = 300 bar (= 4350 psi)

R_{mg} = 720,3477 MPa (= 104477,6 psi), see explanation in example 1.

Table 1: Summary of results of wall thickness calculations for gas cylinders with the same mechanical properties, test pressure and diameter for each of the three design formulae

Example no.	Design formula	Standard	Wall thickness in mm
1	Bach Clavarino formula	DOT 3AA (*Note that test pressure is 5/3 service pressure)	6,07
2a	Mean Diameter formula	ISO 4705 [4]	6,69
2b	Mean Diameter formula	EEC Directive 84/525/EEC [2]	7,25
3	Lamé von Mises formula	ISO 9809-1 [5]	6,54

Example 1 – Bach Clavarino formula (DOT 3AA [6])

$$a = \frac{D}{2} * \left(1 - \sqrt{\frac{S - 1{,}3 * P_h}{S + 0{,}4 * P_h}}\right)$$

DOT3AA, §178.37 (f) (2) requires that the maximum specified wall stress S at test pressure shall not exceed 67% of the minimum tensile strength and must be not over 70000 psi. Therefore the following calculation is based on a specified minimum tensile strength of 70000/0,67=104477,6 psi (=720,3477 MPa).

$$a = \frac{9{,}015748}{2} * \left(1 - \sqrt{\frac{70000 - 1{,}3 * 4350}{70000 + 0{,}4 * 4350}}\right) = 0{,}2387167\ inches$$

a = 6,07 mm

Example 2.a - Mean Diameter formula (ISO 4705 [4])

$$a = \frac{P_h * D}{20 * R_{eg} * F + P_h}$$

The standard ISO4705 requires a yield/tensile strength ratio of max. 0,9, consequently the following minimum specified yield stress is taken: R_{eg} = 0,9 * R_{mg} = 648,3129 MPa

$$F = \frac{1}{1,3} = 0,76923$$

$$a = \frac{300 * 229}{20 * 648,3129 * 0,76923 + 300} = 6,687\ mm$$

a = 6,69 mm

Example 2.b - Mean Diameter formula (EEC Directive 84/525/EEC [2])

$$a = \frac{P_h * D}{20 * R_{eg} * F + P_h}$$

The EEC Directive requires a yield/tensile strength ratio of max. 0,85, consequently the following minimum specified yield stress is taken: R_{eg} = 0,85 * R_{mg} = 612,2955 MPa

$$F = \frac{3}{4} = 0,75$$

$$a = \frac{300 * 229}{20 * 612,2955 * 0,75 + 300} = 7,243\ mm$$

a = 7,25 mm

For F-factor see 84/525 EEC [x]

Example 3 - Lamé von Mises formula (ISO 9809-1 [5])

$$a = \frac{D}{2} * \left(1 - \sqrt{\frac{10 * F * R_{eg} - \sqrt{3} * P_h}{10 * F * R_{eg}}}\right)$$

R_{eg} = 0,9 * R_{mg} = 648,3129 MPa

$$F = \frac{0,65}{R_{eg}/R_{mg}} = \frac{0,65}{648,3129\ /720,3477} = 0,722$$

$$a = \frac{229}{2} * \left(1 - \sqrt{\frac{10 * 0,722 * 648,3129 - \sqrt{3} * 300}{10 * 0,722 * 648,3129}}\right) = 6,54\ mm$$

a = 6,54 mm