TE/MSC/CMI Section meeting

Guidelines for mechanical design and fabrication of cryostats

Conformity with pressure regulations

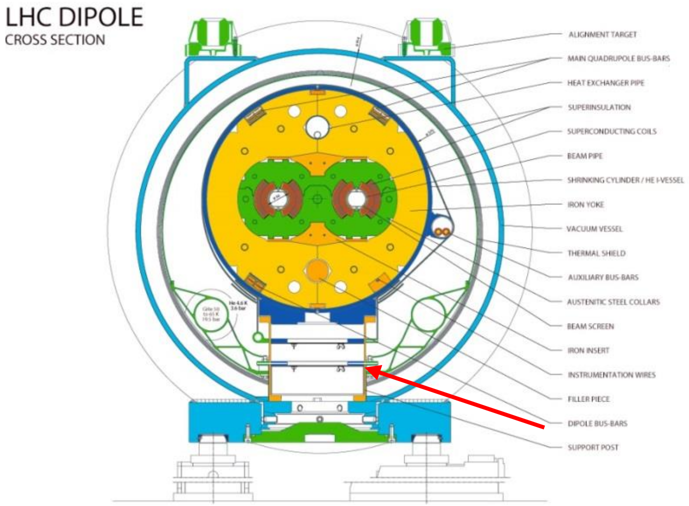
May 21, 2013

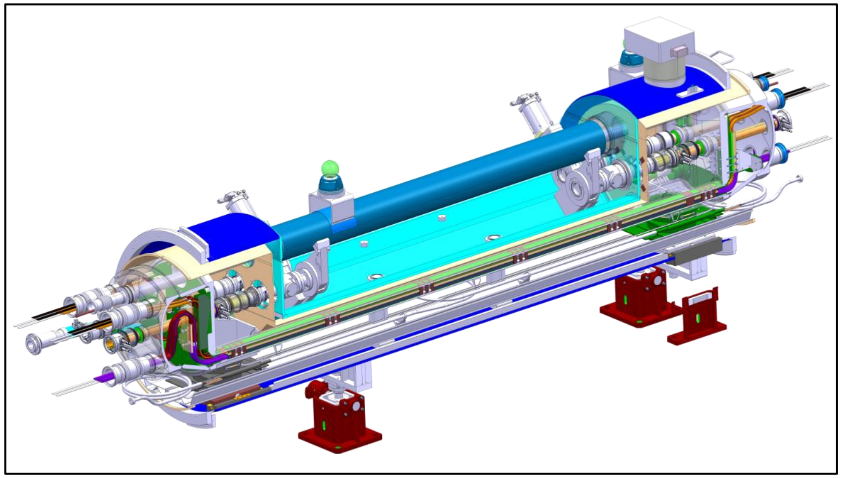
by D. Ramos

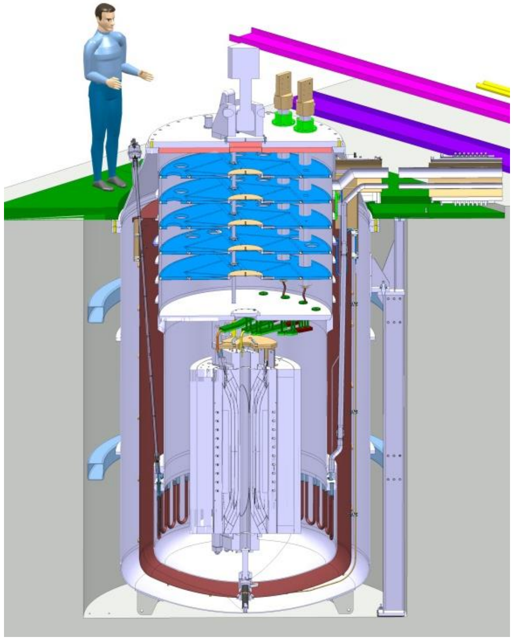
Scope and Outline

- Why are cryostats bound to regulations and their implications
- Designing and checking the design
- Specifying the right material
- Welding specification, qualifications and inspection
- Fabrication tolerances
- Cleaning and packaging
- Leak testing
- Pressure testing

What are we talking about: Vacuum insulated vessels

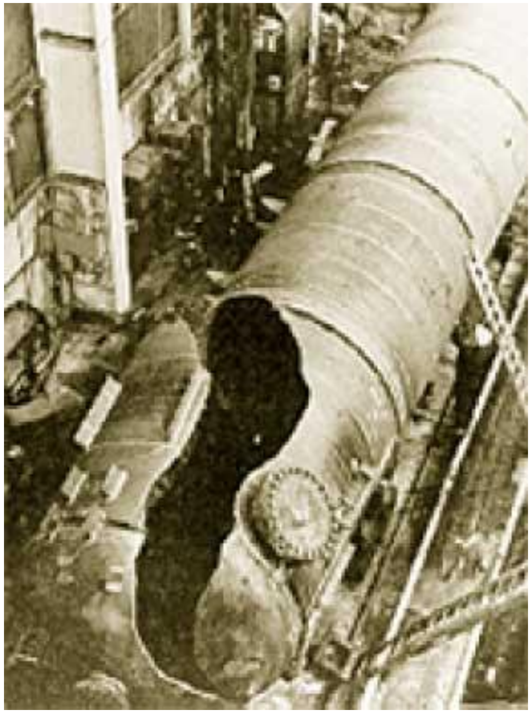




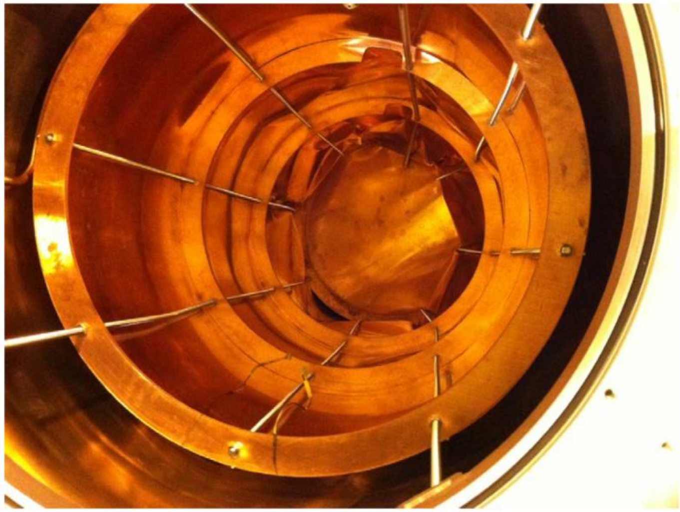


Cryostats for accelerators often determined by deformation and not strenght, nevertheless regulations apply anyway…

Failure from internal pressure



Failure from external pressure



Regulations for pressure bearing equipment

- Some examples of legislation for pressure equipment around the world
  - Pressure European Directive 97/23/EC (often called PED), obligatory in the EU **since 2002**
  - ASME BPVC(USA), first published in **1915**
  - CODAP (France)
  - AD Merkblatt (Germany)
  - PD 5500 (UK)

Where national law before EU directives. These standards are still in use but the PED requirements must be fullfiled.

- **At CERN we have our own rules**. In general:
  - Rules at CERN impose the aplication of EU directives whenever possible
  - A classification of special equipment applies to equipment excluded from EU directives or "equipment of special safety relevance"
- **Think of them from the beginning**: they restrict not only **what you can do** but also **how you can do it**!
- Common misconceptions:
  - **An overpressure test before putting into service is not enough to ensure safe operation over the lifetime of the equipment!**
  - **Neither a calculation alone, even with "large safety factor"!**

Safety Rules at CERN

https://espace.cern.ch/Safety-Rules-Regulations/en/rules/byDomain/Pages/cryogenic.aspx

Unit > CERN Safety rules > Home English Sign In |

HSE
Occupational Health & Safety
and Environmental Protection Unit

All Sites

ome | Rules | Definitions | FAQ | Regulatory watch

HSE Unit > CERN Safety rules > Home > Rules > By Keywords > Cryogenics

Safety rules: Cryogenics

The CERN Safety rules and related documents listed below relate and apply to cryogenics.

No CERN Safety rules' revision process is currently foreseen for mechanical structures.

For any information and/or questions relating to cryogenics, please contact Gunnar Lindell or in his absence Claudia Parente. You can also use the generic email address: Safety.Info@cern.ch.

(Note that you should be logged in to access the regulatory watch (Copyright) and FAQ!).

Safety Regulation

SR-M - Mechanical equipment en fr
This Safety Regulation defines standard equipment and special equipment. It lists the binding general requirements for mechanical equipment during its life-cycle, from design to decommissioning.

Safety Instruction

IS 47 - The use of cryogenics fluids (1998) en fr
The cooling and operation of superconducting RF cavities and magnet systems for particle accelerators and magnets for detectors require large quantities of cryogenic fluids. These fluids may generate health hazards for cryogenic personnel (asphyxiation, burns, etc.). A number of precautions or measures must be taken to prevent accidents and injuries, for instance: protective clothing, vent lines, alarm and shutdown systems or pressure relief devices.

General Safety Instruction

GSI-M2 - Standard Pressure Equipment en fr
This General Safety Instruction defines binding general requirements for standard pressure equipment during its life-cycle. Standard pressure equipment must comply with the Standards defined by the European Union as "Harmonised European Standards", which are a specific subset of the European Standards (EN).
This General Safety Instruction refers and is based on European Directives 97/23/EC, 87/404/EEC and 99/36/EC.

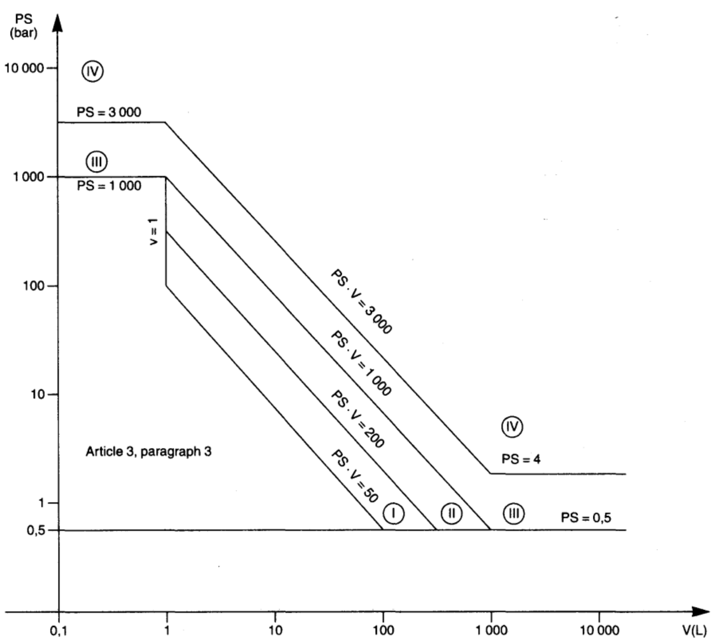
GSI-M3 - Special Mechanical Equipment en fr
This General Safety Instruction defines binding general requirements for special mechanical equipment during its life-cycle.
It applies to mechanical equipment not falling within the scope of the applicable European Directives or which, due to its designated function, cannot comply with European Directives.
It also applies to metallic structures not falling within the scope of Eurocodes or standard mechanical equipment classified by the Department as equipment of high Safety relevance.

Safety Guideline

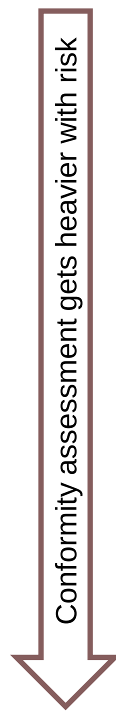
Safety Guildeline M-2-0-1 - Flowchart pressure equipment at CERN en
Flowchart - General Safety Instruction GSI-M2 - Pressure equipment

Pressure European Directive

- Applies to **internal pressure ≥ 0.5 bar**
- Vessels must be designed, fabricated and tested according to the essential requirements of Annex I (Design, safety accessories, materials, manufacturing, testing, etc)
- Establishes the conformity assessment procedure depending on vassel category. The category depends on the stored energy (which relates to risk), expressed as **Pressure x Volume in bar.L**
- Design your system to fall in the lowest possible category: minimise pressure, fluid volume or both



For vessels with non-dangerous gases (cryogenic liquids are treated as gas)



Category	Conf. assessment module	Comment
SEP	None	The equipment must be designed and manufactured in accordance with sound engineering practice. No CE marking and no involvement of notified body.
I	A	CE marking with no notified body involvement, self-certifying.
II	A1	The notified body will perform unexpected visits and monitor final assessment.
III	B1+F	The notified body is required to approve the design, examine and test the vessel.
IV	G	Even further involvement of the notified body.

PED Harmonised codes and standards

These are often called "product standards" or "codes" as they give rules for the design and fabrication of a complete equipment.

- Harmonised standards give **presumption of comformity with the PED**, within their scope. Uselful standards for cryostat design and fabrication:
  - EN 13458-1:2002 Cryogenic vessels - Static vacuum insulated vessels - Part 1: Fundamental requirements
  - EN 13458-2:2002 Cryogenic vessels - Static vacuum insulated vessels - Part 2: Design, fabrication, inspection and testing + EN 13458-2:2002/AC:2006
  - EN 13458-3:2003 Cryogenic vessels - Static vacuum insulated vessels - Part 3: Operational requirements + EN 13458-3:2003/A1:2005
  - EN 13445-1:2009 Unfired pressure vessels - Part 1: General
  - EN 13445-2:2009 Unfired pressure vessels - Part 2: Materials
  - EN 13445-3:2009 Unfired pressure vessels - Part 3: Design
  - EN 13445-4:2009 Unfired pressure vessels - Part 4: Fabrication
  - EN 13445-5:2009 Unfired pressure vessels - Part 5: Inspection and testing
  - EN 13445-8:2009 Unfired pressure vessels - Part 8: Additional requirements for pressure vessels of aluminium and aluminium alloys
- Other codes such as CODAP or ASME can be used, *but proof of comformity is at the charge of the manufacturer*.

Best practices

- **Using a coherent set of standards** throught the lifecycle of the cryostat is the simplest and safest approach. As an example when using only EN harmonised standards:
  - **Error margins** of pressure relief devices are taken into account in the design rules
  - The design rules are only applicable if the material has enough **ductility**
  - **Materials** certified for pressure vessels have measured minimum fracture thoughness
  - **Safety factors** inclued in buckling formulae take into account **shape imperfections** up to the allowable toleraces layed out on the manufacturing section of the standards
  - The extent of **welding inspection** must be compatible with the joint coefficient used in thickness **calculations**
  - Coherence of **test pressure** and testing procedure with the **design rules**

Design Loads

- See **EN 13458-2 section 4.2.3** for a detailed list of load cases to be considered in the design of the vacuum vessel and inner vessel. Some examples:

- Inner vessel
  - Pressure during operation (with and without liquid)
  - Reactions at the supports (including seismic loads)
  - Loads imposed by piping
    - Cooldown: inner vessel warm – piping cold
    - Filling and withdrawal: Inner vessel cold – piping cold,
    - Storage: inner vessel cold – piping warm
  - Pressure test
  - Shipping and handling
  - Outer pressure due to leak in insulation vacuum space

- Vacuum vessel
  - External pressure: 1 bar
  - Internal pressure: safety valve set pressure
  - Support reactions (incl. wind seismic, etc)
  - Loads imposed by piping
  - Loads and the inner vessel support points during cooldown and operation
  - Shipping and handling
  - External loads (wind, seismic, etc)
  - Gross mass

- Other loads may have to be taken into account (e.g. particular warm-up or cool-down cases, magnet quenches, Lorentz forces, etc.).
- A risk analysis (imposed by CERN rules) can be very useful to avoid overlooking important load cases

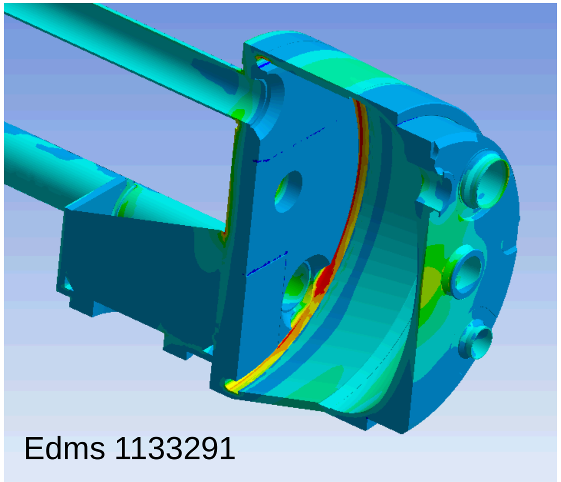
Exceptional load cases

- **Reduced safety factors** can be used for exceptional load cases: typically 1.05 instead of 1.5 for normal load cases.
- Limited **plastic deformations** can be expected.
- Not allways obvious to determine or decide if a load can be taken as exceptional, but one should keep in mind:
  - An exceptional load event must be followed by an **inspection before restarting operation**.
  - Ex: Is a magnet quench an exceptional load? Even if it is not expected to occur everyday, we don’t want to warmup for inspection every quench! Better to treat a quench pressure as normal load.

Calculations*

- By formula
  - The most standard approach and easiest to cross check
  - Not always straightforward to understant how the formula was derived
  - Often long and tedious calculation procedures: spreadsheets and comercial software packages are a must
  - Only deals with pressure loads
  - Rarely enough to calculate a magnet cryostat or a cryomodule (weight, interface loads, particular geometry, etc.)
- Stress analysis (ex: EN 13458-2 Annex A or EN 13445-3 Annex C)
  - Evaluation of stresses using a finite element code
  - Linear elastic analysis
  - Decomposition of stresses in primary, secondary, membrane, bending etc.
  - Comparison with different allowable stresses depending on the load classification
- Design by analysis – Direct route (EN 13445-3 Annex B)
  - Applicable to any component under any action
  - When manufacturing tolerances specified by the code are exceeded
  - Finite element models including material and geometrical non-linearities

Example of stress analysis: He vessel of the QTC cryostat



Example of direct route: HFM vacuum vessel, edms 1278597

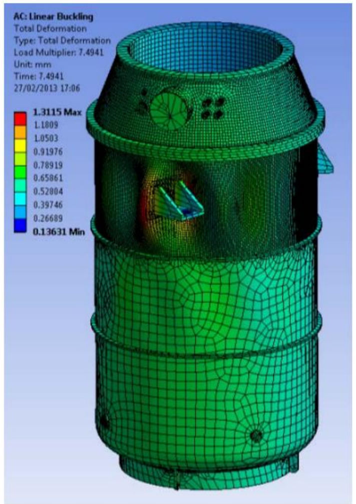


Figure 15 Buckling mode Nr 1

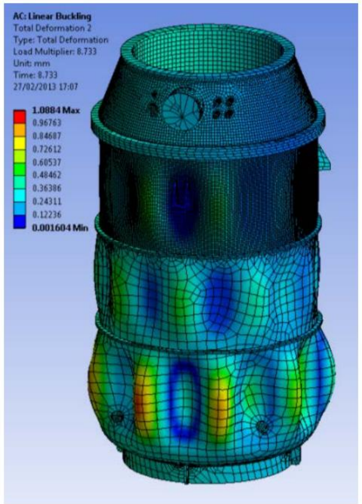


Figure 16 Buckling mode Nr 2

* "Design checks" is actually a better term. The verification of the final design **must** be done through one of these routes but it may be practical to use other formulas/methods during the preliminary design phase.

Material selection for pressure bearing parts

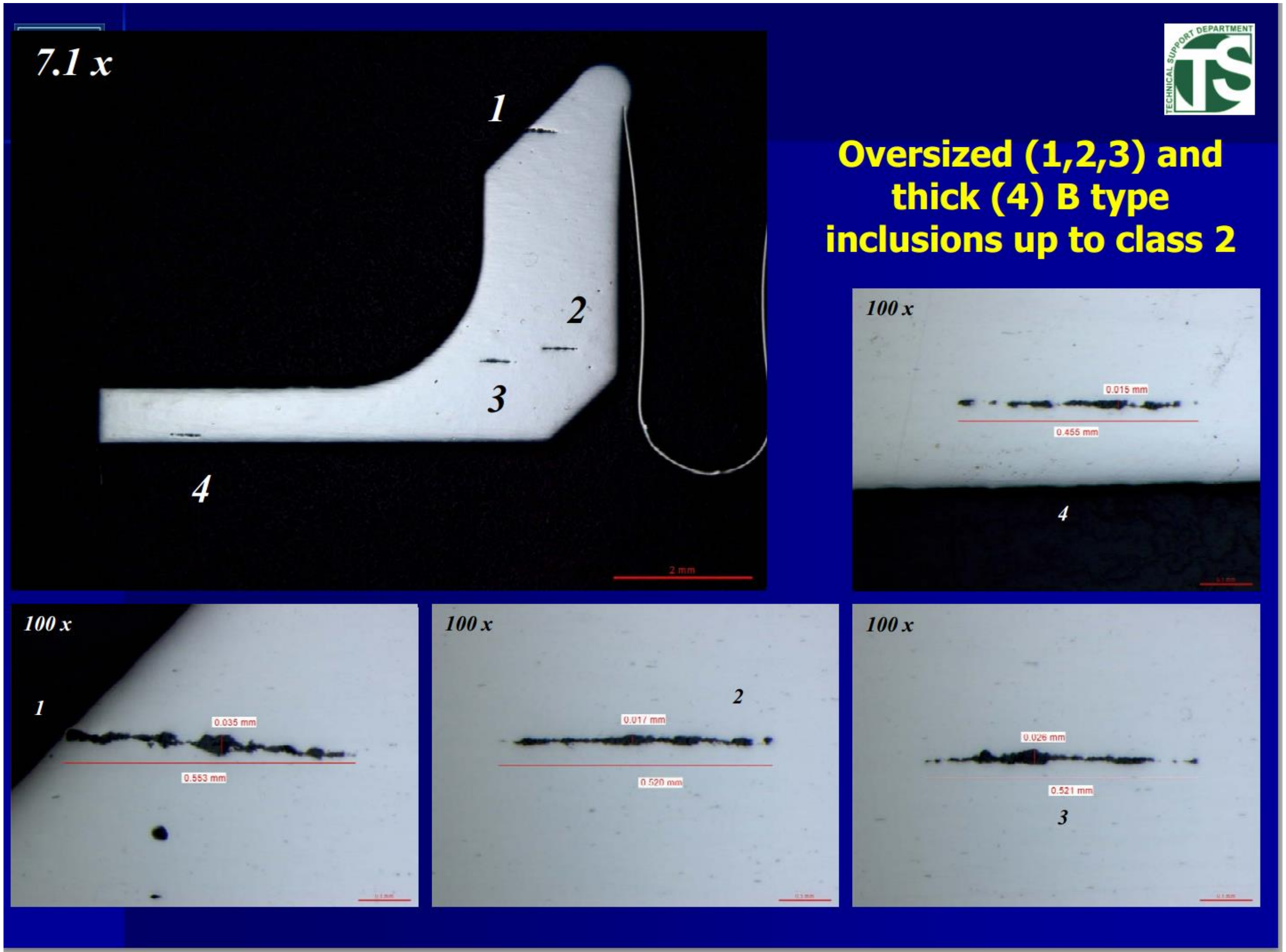
- Proper materials shall be selected to ensure minimum ductility and fracture toughness throughout the specified temperature range.
- A useful list of standards is given below. Materials specified according to these standards confer presumption of conformity, within their scope, with the related essential requirements of the PED:

Plates and sheets	• EN 10028-1:2007+A1:2009 Flat products made of steels for pressure purposes - Part 1: General requirements • EN 10028-3:2009 Flat products made of steels for pressure purposes - Part 3: Weldable fine grain steels, normalized • EN 10028-7:2007 Flat products made of steels for pressure purposes - Part 7: Stainless steels
Tubes	• EN 10216-5:2004 Seamless steel tubes for pressure purposes - Technical delivery conditions - Part 5: Stainless steel tubes • EN 10217-7:2005 Welded steel tubes for pressure purposes - Technical delivery conditions - Part 7: Stainless steel tubes
Forged blanks	• EN 10222-1:1998 Steel forgings for pressure purposes - Part 1: General requirements for open die forgings • EN 10222-5:1999 Steel forgings for pressure purposes - Part 5: Martensitic, austenitic and austenitic-ferritic stainless steels
Castings	• EN 10213:2007 Steel castings for pressure purposes
Pipe fittings	• EN 10253-4:2008 Butt-welding pipe fittings - Part 4: Wrought austenitic and austenitic-ferritic (duplex) stainless steels with specific inspection requirement
Bars	• EN 10272:2007 Stainless steel bars for pressure purposes
Aluminium	• EN 12392:2000 Aluminium and aluminium alloys – Wrought products – Special requirements for products intended for the production of pressure equipment (choose materials included in the list given in EN 13445-8 section 5.6)

Material selection (contin.)

- EN 13458-2 Annex K gives a list of base **materials approved** for use in cryostats.
- Mechanical **property values** used in the design shall be the minimum values given by the **material standards**. **Usage of actual property values is usually not allowed**.
- **Physical properties** of steels are given in EN 13445-3 Annex O, including corrections for temperature.
- EN 13458 refers to EN 1252 for requirements on **toughness properties** of base materials and welded joints, depending on the operating temperature:
  - EN 1252-1:1998 Cryogenic vessels - Materials - Part 1: Toughness requirements for temperatures **below -80°C** (Austenitic stainless steels: Only welds impact tested; test at saturated liquid N_2 even if working temperature is lower)
  - EN 1252-2:2001 Cryogenic vessels - Materials - Part 2: Toughness requirements for temperatures **between -80°C and -20°C** (Austenitic stainless steels: Only welds impact tested, and only if ferrite content of filler metal >10%)
- All pressure bearing materials shall be procured with **inspection certificates type 3.1 or 3.2 according to EN 10204**, and **traceability** must be ensured throughout the fabrication process.

Pressure vessel materials, yes, but not allways enough!



Courtesy S. Sgobba

Specifications developed for vacuum applications at CERN

- Some cryostat components demand for even more strict requirements. Ex: absence of **macroinclusions**, limitations to size and amount of **microinclusions**, imposed **manufacturing processes**, minimum **quality assurance** tests, etc.
- Some materials at the CERN stores are procured with traceability and specifications to avoid leaks across the material and minimise welding deffects:

CERN specification	EDMS no.	Usage
316LN_sheets_English_ed_4	790774	
316LN_blanks_English_ed_4	790775	3D-Forged blanks for Conflat flanges
316LN_bars_English_ed_4	790773	
304L_bar_English_ed_5	790544	
304L_sheets_English_ed_5	790767	
316L_bellows_English_ed_4	790771	Thin foil for bellows convolutions

Presently these CERN specifications do not require conformity with PED harmonised standards but the conformity is often stated by default in the material certifcates.

Design stresses for some materials

- Design stresses for plates less than 12 mm thick applicable to membrane stress (safety factor 1.5 included) according to EN 13445-3
- For stainless steels:

$$f = \frac{R_{p1.0}}{1.5} \qquad f_{test} = \frac{R_{p1.0}}{1.05}$$

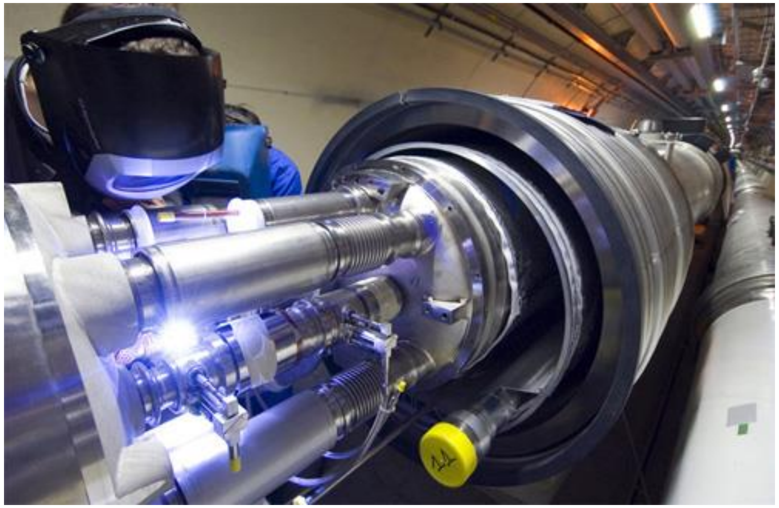
Material	$R_{p1.0}$ (MPa)	f (MPa)	f_{test} (MPa)
1.4306 (304L)	240	160	228
1.4435/1.4404 (316L)	260	173	247
1.4406/1.4429 (316LN)	320	213	304

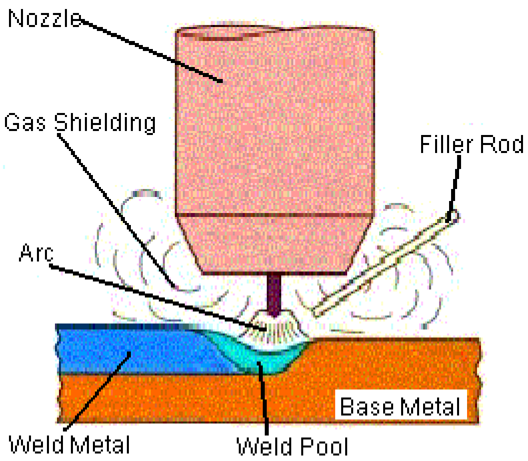
- For aluminium-magnesium alloys:

$$f = \min\left(\frac{R_{p0.2}}{1.5}, \frac{R_m}{2.4}\right) \qquad f_{test} = \frac{R_{p0.2}}{1.05}$$

Material	$R_{p1.0}$ /R_m (MPa)	f (MPa)	f_{test} (MPa)
AW 5083-O/H111	125/270	83	119

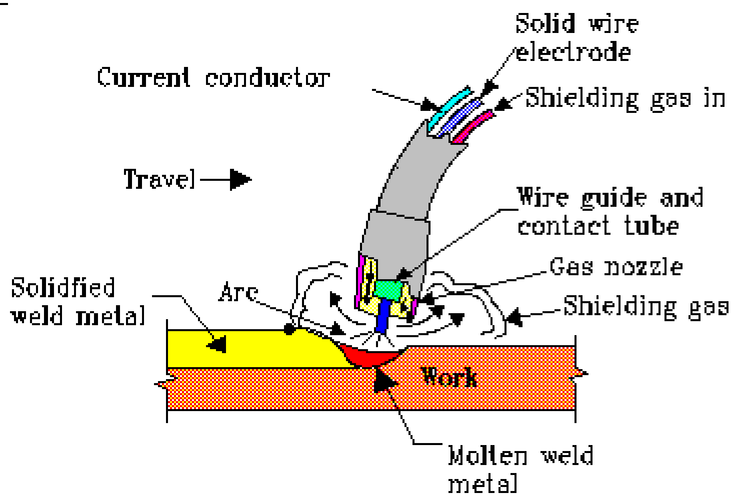
Welding





Tungsten inert gas welding

- Tungsten Inert Gas (TIG) and Metal Inert Gas Welding (MIG) are the most commonly used processes in cryostat fabrication
- Full quality assurance of welds involves:
  - Specification of **quality levels** for imperfections suitable to the application
  - Qualification test of **welding procedures** and **welders**
  - Welding **inspection**



Metal inert gas welding

Quality levels for imperfections

FA132996 ISSN 0335-3931

norme européenne **NF EN ISO 5817**
Novembre 2007

norme française

Indice de classement : **A 89-231**

ICS : 25.160.40

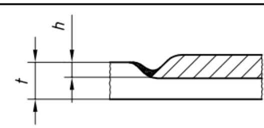
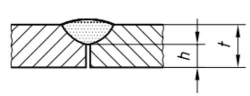
Soudage

Assemblages en acier, nickel, titane et leurs alliages soudés par fusion
(soudage par faisceau exclu)

Niveaux de qualité par rapport aux défauts

- Current practice at CERN is to specify quality **level B** for leak tight welds
- **EN 13445 and EN 13458** give their own quality level specifications: in general, **less demanding** than ISO 5817 level B

Tableau 1 — Limites des défauts

N°	Référence ISO 6520-1	Désignation du défaut	Remarques	t mm	Limites des défauts pour les niveaux de qualité D	C	B
1 Défauts superficiels							
1.1	100	Fissure	—	⩾ 0,5	Non autorisé	Non autorisé	Non autorisé
1.2	104	Fissure de cratère	—	⩾ 0,5	Non autorisé	Non autorisé	Non autorisé
1.3	2017	Piqûre	Dimension maximale d'une piqûre isolée pour — soudures bout à bout — soudures d'angle	0,5 à 3	$d \leqslant 0,3\ s$ $d \leqslant 0,3\ a$	Non autorisé	Non autorisé
			Dimension maximale d'une piqûre isolée pour — soudures bout à bout — soudures d'angle	> 3	$d \leqslant 0,3\ s$, mais max. 3 mm $d \leqslant 0,3\ a$, mais max. 3 mm	$d \leqslant 0,2\ s$, mais max. 2 mm $d \leqslant 0,2\ a$, mais max. 2 mm	Non autorisé
1.4	2025	Retassure ouverte de cratère		0,5 à 3	$h \leqslant 0,2\ t$	Non autorisé	Non autorisé
				> 3	$h \leqslant 0,2\ t$, mais max. 2 mm	$h \leqslant 0,1\ t$, mais max. 1 mm	Non autorisé
1.5	401	Manque de fusion (collage)	—	⩾ 0,5	Non autorisé	Non autorisé	Non autorisé
		Micromanque de fusion (microcollage)	Uniquement détectable par micro-examen		Autorisé	Autorisé	Non autorisé
1.6	4021	Manque de pénétration à la racine	Uniquement pour les soudures bout à bout d'un seul côté 	⩾ 0,5	Défauts courts: $h \leqslant 0,2\ t$, mais max. 2 mm	Non autorisé	Non autorisé

…see the standard for the complete table…

Qualification of welding personnel and welding procedures

Some examples of applicable standards:

	Steel	Aluminium
Welding procedure approval	**EN ISO 15614-1:2004** Specification and qualification of welding procedures for metallic materials - Welding procedure test - Arc and gas welding of steels and arc welding of nickel and nickel alloys	**EN ISO 15614-2:2005** Specification and qualification of welding procedures for metallic materials - Welding procedure test - Arc welding of aluminium and its alloys
Qualification of welders	**EN 287-1:2004** Qualification test of welders - Fusion welding - Steels	**EN ISO 9606-2:2004** Qualification test of welders - Fusion welding - Aluminium and aluminium alloys
Qualification of welding operators	**EN 1418:1998** Welding personnel - Approval testing of welding operators for fusion welding and resistance weld setters for fully mechanized and automatic welding of metallic materials	

Welding inspection

- From EN 13458: Visual inspection of all welds to **EN 970**, is required. X-ray examination is required for the inner vessel and shall be carried out in accordance with **EN ISO 17636-2:2013**. Volumetric inspection is not required on the outer jacket (vacuum vessel)*.
- Non-destructive testing personnel shall be qualified for duties according to **EN ISO 9712** (replaces EN 1435). It is common at CERN to ask for **level 2** as a minimum.
- The following table shows a possible specification for welding inspection of a cryostat in stainless steel:

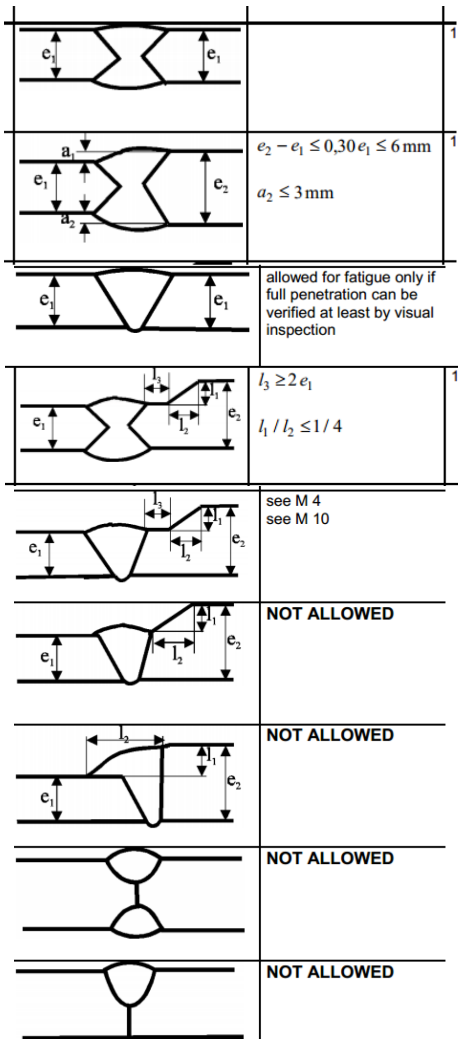
Vacuum vessel/ Inner vessel	Surface imperfections	Volumetric imperfections
Method	Visual inspection	X-rays
Extent of examination	100 % / 100 %	None / as per EN 13458-2, section 6.3.3
Covered by	EN ISO 17637 (replaces EN 970)	EN ISO 17636-2:2013 (replaces EN 1435)
Qualification of personnel	Required competence but certification is not mandatory	EN ISO 9712, NDT level 2 (Replaces EN 473)
Acceptance levels	EN 5817, quality level B	

* But may be recommended in particular cases (ex: HIE-Isolde cryomodule)

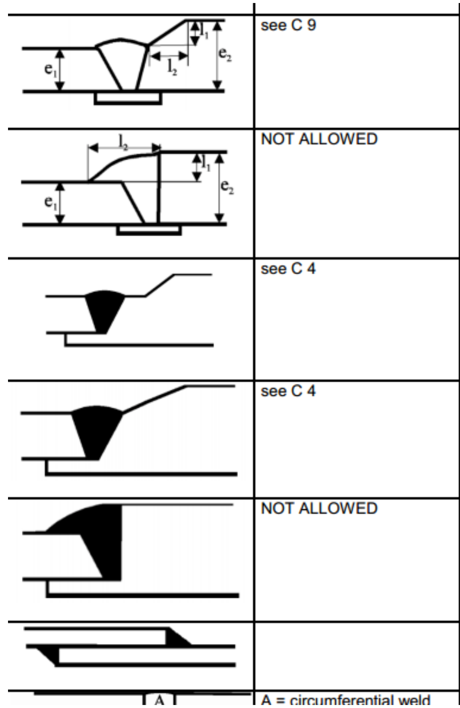
Design of pressure bearing welds

- EN 13445-3 annex A is a good reference for designing pressure bearing welds. EN 1708-1 is also a useful hamonised standard. Some examples:

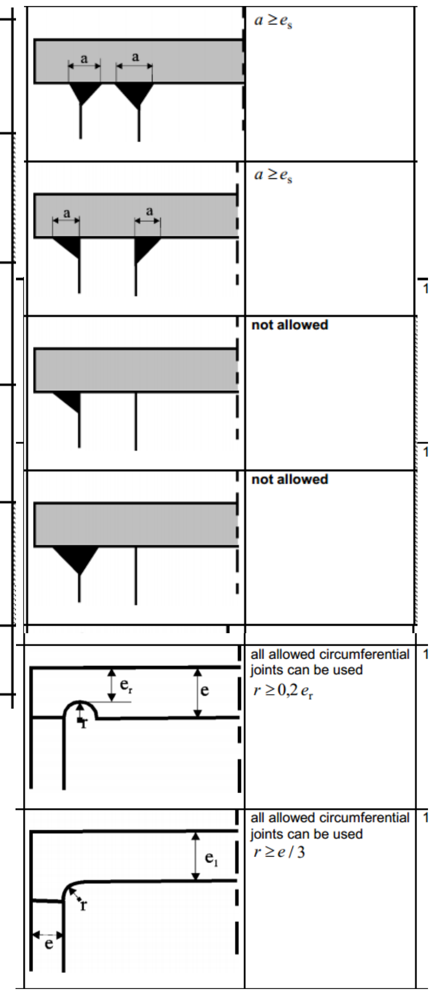
Longitudinal welds



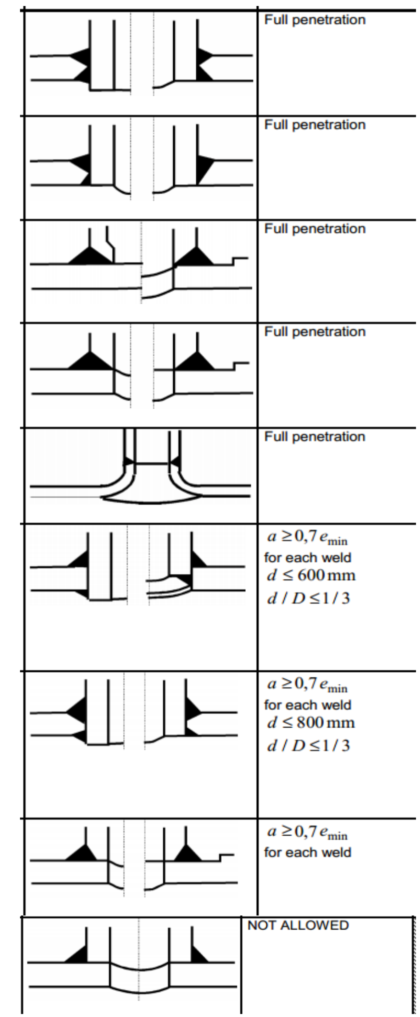
Circular welds



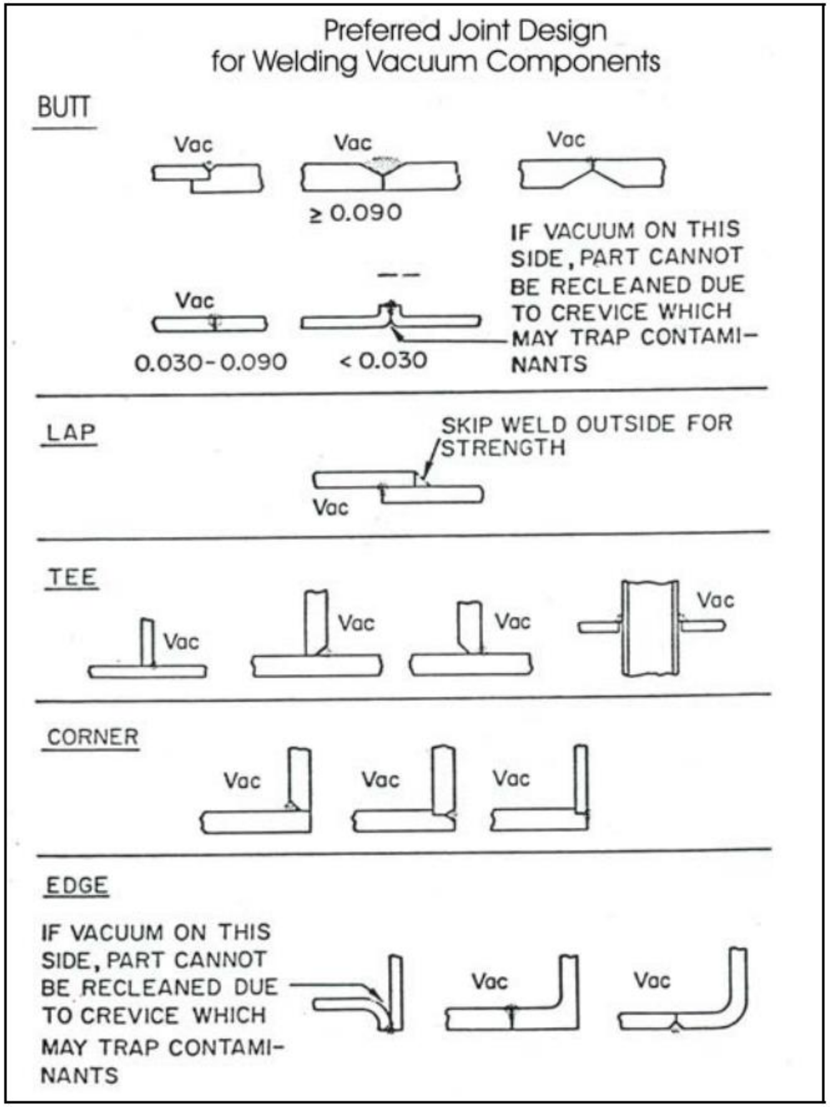
Flat ends

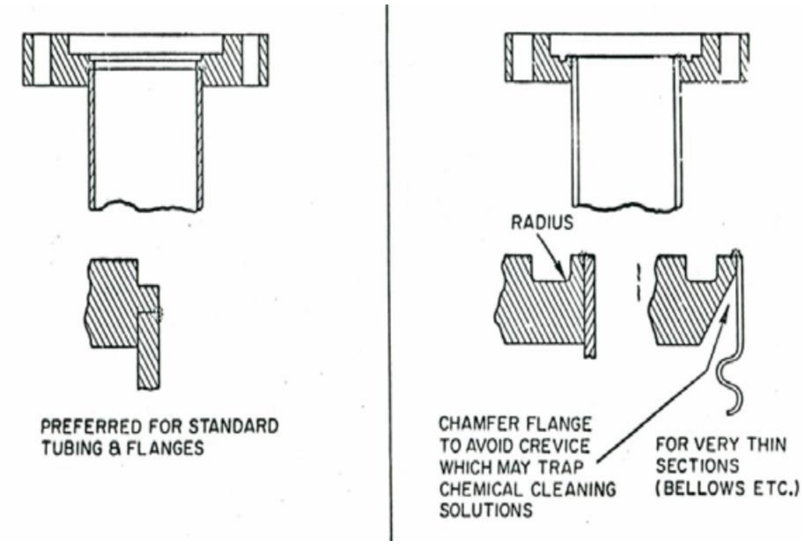


Nozzles



Design of vacuum facing welds

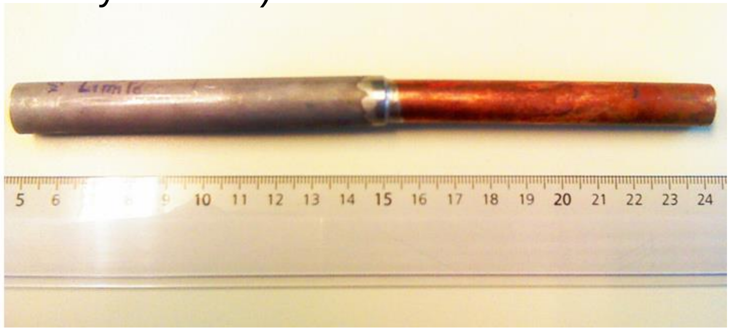


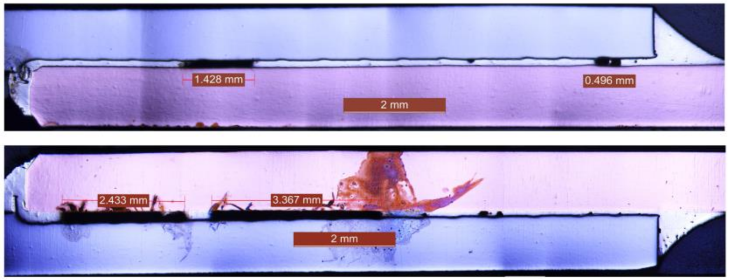


Brazing

- Often the solution to **join different materials** (ex: copper to stainless steel; stainless steel to ceramics…)
- Vacuum brazing (no flux required) gives the most reliable joints, but at a cost
- **Thorough cleaning** after brazing with flux is mandatory. Poor cleaning often results in the development of leaks in stainless steel due to corrosion!

Example of flame brazed stainless steel to copper transition for a thermal shield cooling circuit (HIE-Isolde cryomodule)

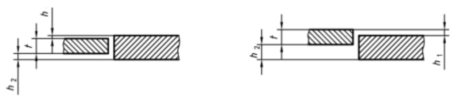




- Useful standards for brazing specification and execution:
  - EN 13134:2000 Brazing - Procedure approval
  - EN 13133:2000 Brazing - Brazer approval
  - EN 12797:2000 Brazing - Destructive tests of brazed joints
  - EN 12799:2000 Brazing - Non-destructive examination of brazed joints
  - EN ISO 18279:2003 Brazing - Imperfections in brazed joints

Fabrication tolerances

- Formulas for external pressure stability and finite element models using the “direct route” assume a maximum deviation from nominal shape
- Tolerances in the drawings must be coherent with the standard used in the calculations!
- Some examples from EN 13458-2 section 5.5:



Key

h, h_1, h_2 is the surface misalignments
t is the thickness of the thinner plate
e is the distance from the surface of the thicker plate to the centreline of the thinner plate

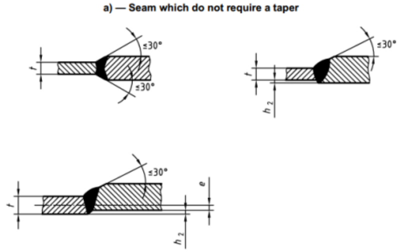
For longitudinal seams:

$h_1 \leq 0{,}15\ t$ and $h_2 \leq 0{,}15\ t$

For circumferential seams:

$h_1 \leq 0{,}25\ t$ and $h_2 \leq 0{,}25\ t$

a) — Seam which do not require a taper



For longitudinal seams:

$h \leq 0{,}15\ t$ and

$e = \frac{t}{2} - h \geq 0{,}35\ t$

For circumferential seams:

$h_2 \leq 0{,}25\ t$ and

$e = \frac{t}{2} - h \geq 0{,}25\ t$

b) — Seams which do require a taper

Figure 27 — Plate alignment

5.5.4 Cylinders

5.5.4.1 The actual circumference shall not deviate from the circumference calculated from the specified diameter by more than ± 1,5 %.

5.5.4.2 The out of roundness u calculated from the expression:

$$\text{out of roundness } u = \frac{200(D_{max} - D_{min})}{D_{max} + D_{min}} \quad \text{in \%} \qquad (35)$$

shall be not more than the values shown in Table 1.

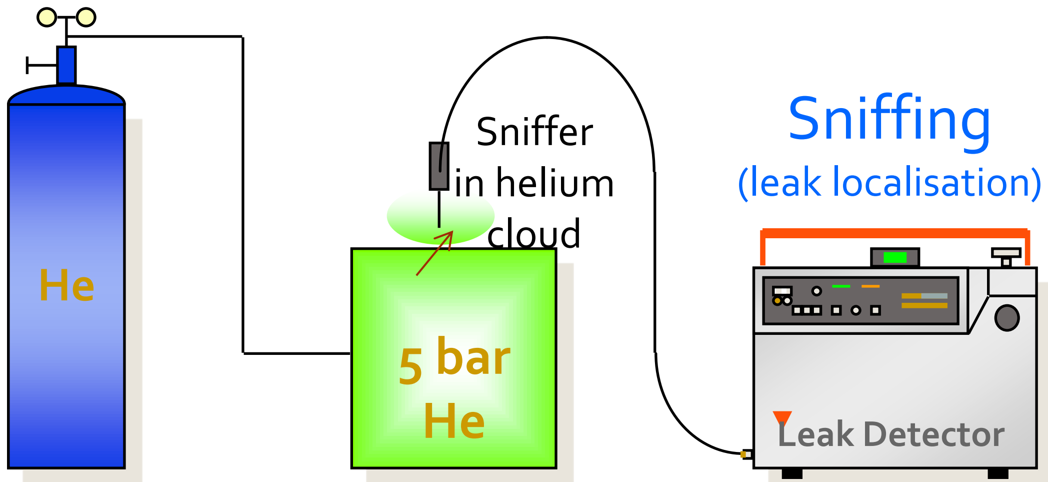
Table 1 — Permitted out of roundness

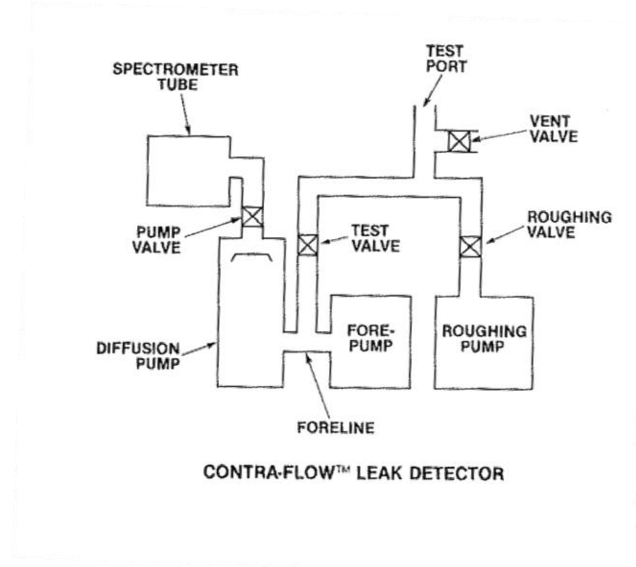
Wall thickness to diameter ratio	Permitted out of roundness for	
	internal pressure	external pressure
$s/D \leq 0{,}01$	2,0 %	1,5 %
$s/D > 0{,}01$	1,5 %	1,5 %

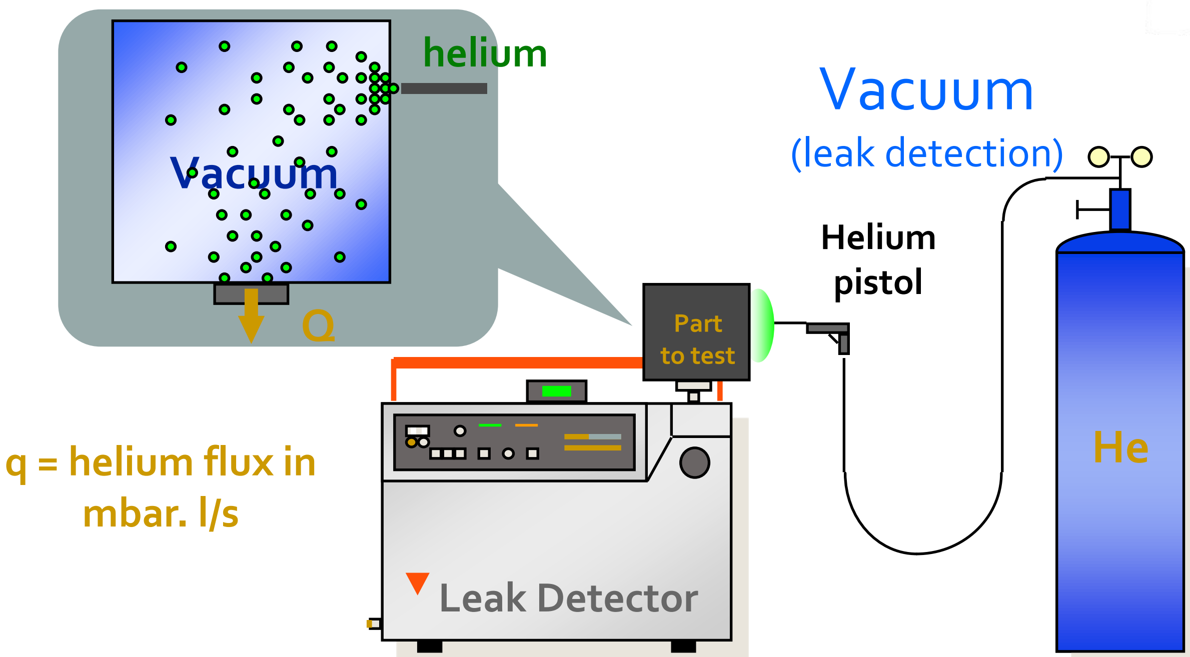
Cleaning

- Example of cleaning procedure specification for the HIE-Isolde vacuum vessel:
  - *All internal surfaces shall be delivered in a clean condition, compatible with ultra-high vacuum applications. Cleaning shall be performed following a written procedure, including as a minimum:*
    - *Degreasing in a detergent solution with ultrasonic agitation.*
    - *Rinsing with demineralized water according to ASTM D1193-99 Type II, at a temperature higher than 30 ºC, first with a water jet and then by immersion in a bath with ultrasonic agitation.*
    - *Drying in clean air.*
  - *External surfaces shall be cleaned following a written procedure, including as a minimum:*
    - *Cleaning with high-pressure spray of detergent solution.*
    - *Rinsing with demineralised water jet.*
    - *Drying.*
- Some reference standards:
  - EN 12300:1999 Cryogenic vessels - Cleanliness for cryogenic service
  - ISO 15730:2000 Metallic and other inorganic coatings – Electropolishing as a means of smoothing and passivating stainless steel.

He leak detection methods







Courtesy of P.Cruikshank

Leak testing

- Example of leak testing specification (HIE-Isolde vacuum vessel):
  - *All parts shall be leak tested according to EN 13185, by evacuation of the internal volume (**EN 13185, technique A.1**) and using helium as tracer gas. The final test shall be performed on clean components, after electropolishing.*
  - *Testing shall be performed with a calibrated helium leak detector with sensitivity better than 2x10-11 Pa m3 s-1. The calibration certificate shall be included in the inspection certificate.*
  - *The test protocols that the contractor intends to follow must be submitted to CERN for approval before the tests are carried out.*
  - *An automatic recorder shall be used to produce a chart showing the complete evolution over time of the vacuum leak test. This chart shall be included in the leak test report.*

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European standard

French standard

NF EN 13185
November 2001

Classification index: **A 09-492**

ICS: 19.100

Non-destructive testing

Leak testing

Tracer gas method

F : Essais non destructifs — Contrôle d'étanchéité — Méthode par gaz traceur
D : Zerstörungsfreie Prüfung — Dichtheitsprüfung — Prüfgasverfahren

Pressure testing

- According to EN 13458-2 the test pressure shall be the higher of

$$\begin{cases} 1.43(PS + 1\ bar) \text{for hydrostatic test, or } 1.25(PS + 1\ bar) \text{ for pneumatic} \\ 1.25(PS + P_L + 1\ bar)\dfrac{K_{20}}{K_{design}}, \text{where } \mathrm{P_L} \text{ is the hydrostatic pressure} \end{cases}$$

- The test procedure is given in EN 13458-2 section 6.5.

Where the test is carried out hydraulically the pressure shall be raised gradually to the test pressure holding it there for 30 min. Then the pressure shall be reduced to the design pressure so that a visual examination of all surfaces and joints can be made. The vessel shall not show any sign of gross plastic deformation or leakage. The test may be carried out pneumatically on a similar basis. As pneumatic testing employs substantially greater stored energy than hydraulic testing, it shall normally only be carried out where adequate facilities and procedures are employed to assure the safety of inspectors, employees and the public.

Some standards for accessories and components

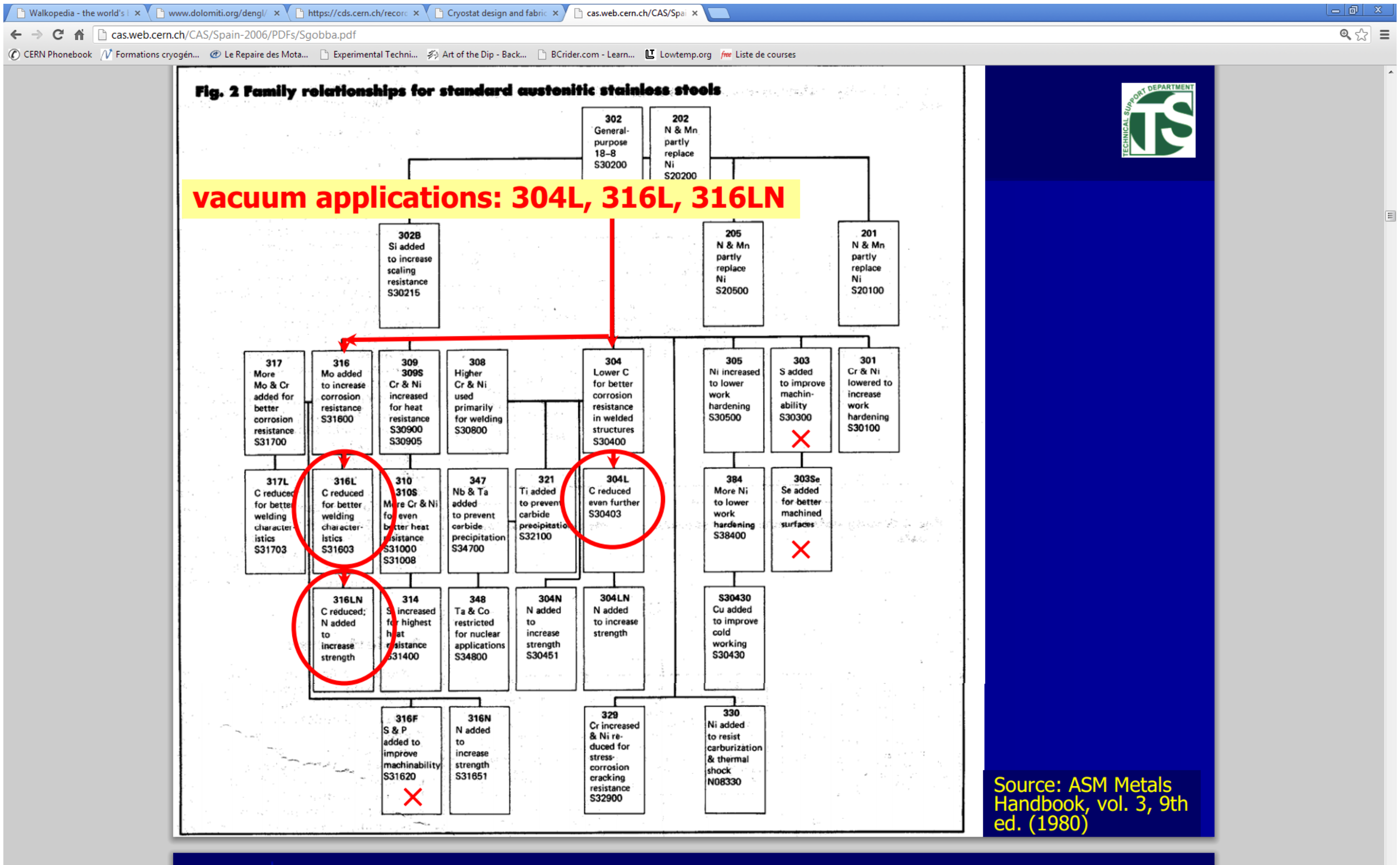
- EN 14917:2009 Metal bellows expansion joints for pressure applications
- EN 12434:2000 Cryogenic vessels - Cryogenic flexible hoses
- EN 13371:2001 Cryogenic vessels - Couplings for cryogenic service
- EN 1626:2008 Cryogenic vessels - Valves for cryogenic service
- ISO 1609 Vacuum Technology – Flange dimensions
- ISO 3669 Vacuum technology – Bakable flanges – Dimension

Thank you!

Questions?

Useful textbooks

- Chattopadhyay, Pressure vessels – Design and practice, CRC press, 2005
- Zeman, Pressure vessel design – Direct route, Elsevier, 2003


cas.web.cern.ch/CAS/Spain-2006/PDFs/Sgobba.pdf
Fig. 2 Family relationships for standard austenitic stainless steels
302 General-purpose 18–8 S30200
202 N & Mn partly replace Ni S20200
vacuum applications: 304L, 316L, 316LN
302B Si added to increase scaling resistance S30215
205 N & Mn partly replace Ni S20500
201 N & Mn partly replace Ni S20100
317 More Mo & Cr added for better corrosion resistance S31700
316 Mo added to increase corrosion resistance S31600
309 309S Cr & Ni increased for heat resistance S30900 S30905
308 Higher Cr & Ni used primarily for welding S30800
304 Lower C for better corrosion resistance in welded structures S30400
305 Ni increased to lower work hardening S30500
303 S added to improve machin-ability S30300
301 Cr & Ni lowered to increase work hardening S30100
317L S31703
316L C reduced for better welding character-istics S31603
310 310S S31000 S31008
347 Nb & Ta added to prevent carbide precipitation S34700
321 Ti added S32100
304L C reduced even further S30403
384 More Ni to lower work hardening S38400
303Se Se added for better machined surfaces
316LN C reduced; N added to increase strength
314 S31400
348 Ta & Co restricted for nuclear applications S34800
304N N added to increase strength S30451
304LN N added to increase strength
S30430 Cu added to improve cold working S30430
316F S & P added to improve machinability S31620
316N N added to increase strength S31651
329 Cr increased & Ni re-duced for stress-corrosion cracking resistance S32900
330 Ni added to resist carburization & thermal shock N08330
Source: ASM Metals Handbook, vol. 3, 9th ed. (1980)