CENF - LBNF cryostat Relevant safety codes

O. Beltramello

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LBNF warm vessel is considered a **low pressure cryostat**, i.e. P<500 mbar

The design of the warm vessel is based on **Finite Elements Analysis (FEA)** method (ANSYS code).

The design approach is to generate a detailed Finite Element Model of the pressure vessel and to perform a detailed stress analysis of each component.

As a consequence, we refer to **ASME code section VIII, division II** and **Eurocode III**
Note: *the most conservative requirements among the two codes will be adopted.*

Part 5 of ASME sect. VIII, div. II provides the so-called "**design by analysis requirements**": i.e. requirements for design of vessels and components using finite element analysis methods.

LBNF vessel structure design is guided by the detailed design procedures provided in **ASME VIII, Div.2, Part 5**

- Failure modes considered: **plastic collapse**, **local failure**, **buckling**

- **Maximum material allowable stress S** is the minimum of $S_T/2.4$ and $S_Y/1.5$ as prescribed in **ASME section II, Part D**

        where S_T is the material minimum tensile strength
        and S_Y is the material minimum yield strength
        Material data provided and guarantied by manufacturer

- The calculations are performed using an **Elastic Stress Analysis method**

- **Design Loads combination**:
  (1) P + D
  (2) 0.6 D + 0.7 E
  (3) 0.9 P + D + 0.7 E
where: P: hydrostatic pressure from the LAr + vessel overpressure (nom. or acc.)
           D: self-weight of the structure including insulation and membrane
           E: seismic load

The seismic loads contribution is determined considering **ASME Sect VIII, div.2, ASCE 7-10 and IBC15.**
The **DUSEL site seismic hazards** to support seismic analysis and design are provided in "*The deep underground science and engineering Lab (DUSEL) – historic, earthquakes, faults and seismic hazard*" -Golder Associate"

Plastic collapse - verification for Elastic Stress FEA analysis (ASME Sect VIII, div.2)

$$P_m < S$$
$$P_L < 1.5\,S$$
$$P_L + P_b < 1.5\,S$$

where the beam stresses are categorized following the 3 categories below:

P_m - General primary membrane equivalent stress

P_L - Local primary membrane equivalent stress

P_b - Primary bending equivalent stress

Local failure verification

$$\sigma1+\sigma2+\sigma3 \leq 4S$$

where

σ_1, σ_2, σ_3 : 3 direction equivalent stress values for local primary membrane plus bending

Buckling verification

Each point of the structure is verified via a numerical Finite Element linear bifurcation buckling analysis (all buckling modes considered)

A **design factor of 4** is considered in the calculations

> design factor 2 for the shell elements recommended by ASME code section VIII div.2.

Bolted connections
ASME, sect VIII, div. part 5, "supplemental requirements for bolts":

Maximum allowable service stress (S_s) in the bolt, averaged across the bolt cross section and neglecting stress concentrations, shall verify:

$$S_s < 2/3\ S_y$$

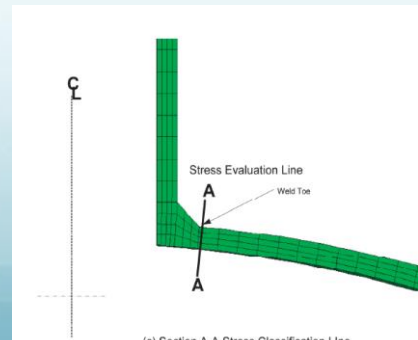Note: S_s are produced by a combination of preload, pressure, differential expansion .

All bolted connections are also verified using the **EUROCODE III** methods.

Welded connections
Stresses are extracted at Classification Line (CL) from the Finite Element models following the recommendations of **ASME Annex 5-A "Linearization of stress results for stress classification"**.

Stresses characterization and comparison
with bolt material allowable stresses
as defined for beam structures.

All welds will be fully examined and tested as prescribed

Stress Evaluation Line
A
Weld Toe
A

(c) Section A-A Stress Classification LIne

Shell Model at Mean
Radius of Nozzle and Shell

Nozzle Thickness

Weld Leg

Weld Throat Thickness (see Note 1)

Stress Evaluation Point

Head Thickness