SRF Pressure Safety at Fermilab

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Outline

- Fermilab Safety Program
- Collaboration with US Labs
- International Collaboration
- Summary

Governing Directives

- Fermilab is managed by Fermi Research Alliance LLC (FRA), a partnership of the University of Chicago and Universities Research Association Inc., a consortium of 89 research universities, for the U.S. Department of Energy Office of Science (DOE). Fermilab is the DOE Contractor
- The Federal Government, its departments and agencies, codifies general and permanent rules using The Code of Federal Regulations (CFR)
- 10 C.F.R. 851: Worker Safety and Health Program - outlines the requirements for a worker safety/health program to ensure that DOE contractors and their workers operate a safe workplace, including Pressure Safety (APPENDIX A , par 4)

10 CFR 851, App A, par 4 (a) - Pressure Safety

- (a) Contractors must establish safety policies and procedures to ensure that pressure systems are designed, fabricated, tested, inspected, maintained, repaired, and operated by trained and qualified personnel in accordance with applicable and sound engineering principles.
- (b) Contractors must ensure that all pressure vessels, boilers, air receivers, and supporting piping systems conform to:
  - (1) The applicable American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (2004); sections I through section XII including applicable Code Cases (incorporated by reference, see § 851.27)
  - (2) The applicable ASME B31 (Code for Pressure Piping) standards as indicated below; and or as indicated in paragraph (b)(3) of this section:
    - (i) B31.1—2001—Power Piping, and B31.1a— 2002—Addenda to ASME B31.1—2001 (incorporated by reference, see § 851.27);
    - (ii) B31.2—1968—Fuel Gas Piping (incorporated by reference, see § 851.27);
    - (iii) B31.3—2002—Process Piping (incorporated by reference, see § 851.27);
    - (iv) B31.4—2002—Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids (incorporated by reference, see § 851.27);
    - (v) B31.5—2001—Refrigeration Piping and Heat Transfer Components, and B31.5a—2004, Addenda to ASME B31.5—2001 (incorporated by reference, see § 851.27);
    - (vi) B31.8—2003—Gas Transmission and Distribution Piping Systems (incorporated by reference, see § 851.27);
    - (vii) B31.8S—2001—Managing System Integrity of Gas Pipelines (incorporated by reference, see § 851.27);
    - (viii) B31.9—1996—Building Services Piping (incorporated by reference, see § 851.27);
    - (ix) B31.11—2002—Slurry Transportation Piping Systems (incorporated by reference, see § 851.27); and
    - (x) B31G—1991—Manual for Determining Remaining Strength of Corroded Pipelines (incorporated by reference, see § 851.27).
  - (3) (3) The strictest applicable state and local codes.

    (c) When national consensus codes are not applicable (because of pressure range, vessel geometry, use of special materials, (etc.), *contractors must implement measures to provide equivalent protection and ensure a level of safety greater than or equal to the level of protection afforded by the ASME or applicable state or local code*. Measures must include the following:

    (1)Design drawings, sketches, and calculations must be reviewed and approved by a qualified independent design professional (i.e., professional engineer). Documented organizational peer review is acceptable.

    (2) *Qualified personnel must be used to perform examinations and inspections of materials*, in-process fabrications, non-destructive tests, and acceptance test.

    (3) *Documentation, traceability, and accountability must be maintained* for each unique pressure vessel or system, including descriptions of design, pressure conditions, testing, inspection, operation, repair, and maintenance.

Fermilab Pressure Safety Program

- Part of the contract between DOE and Fermilab are set of Work Smart (WS) Standards
- Fermilab Environment, Safety and Health Manual (FESHM) contains Fermilab's policies and procedures designed to manage safety, environmental, and health hazards (ESH) in accordance with the requirements of the WS Standards
- For over the last three decades, Fermilab has pressure safety program in place. It's managed under the leadership of the Fermilab ES&H Committee with contributions from the Lab community
- FESHM Section 5000, *"Mechanical, Cryogenic and Structural Safety"* covers policies and procedures for the pressure safety

SRF Cavity Pressure Safety

- Pressure vessels are addressed by FESHM chapter 5031 which is based on ASME Boiler and Pressure Vessel Code Section VIII (the Code)
  - The chapter addresses vessels that are Code stamped, non-Code stamped vessels that are otherwise designed and built to Code, and vessels that do not meet Code requirements
  - Each pressure vessel requires a formal engineering note that is independently reviewed
- Superconducting Radio-Frequency (SRF) cavities containing cryogens under pressure pose a potential rupture hazard to equipment and personnel
- Generally, dressed cavity vessels fall within the scope of the ASME Boiler and Pressure Vessel Code, however, the use of niobium as a material for the SRF cavities is beyond the applicability of the Code

Compliance Issue

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  (3) (3) The strictest applicable state and local codes.

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  (3) *Documentation, traceability, and accountability must be maintained* for each unique pressure vessel or system, including descriptions of design, pressure conditions, testing, inspection, operation, repair, and maintenance.

Pressure Boundary Options

- **Vacuum Vessel Boundary** - the cryomodule vacuum vessel with supply and return end can boundary consists of the outer body of the cryomodule ➔ the outside surfaces of the cryomodule less the penetrations through the outside surface
- **Helium Vessel Boundary** (With Superconducting Cavities) - the helium vessel boundary consisting of the titanium helium vessel, niobium-titanium cavity dish heads and the niobium beam pipes at the ends of each cavity

Boundary	Pros	Cons
Vacuum Vessel	• All materials are listed • Internal components not required code compliance	• Vacuum vessel design (MDMT, thickness, reinforced penetrations, accident protection)
Helium Vessel	• No reinforced penetrations • Carbon steel vacuum vessel	• None listed materials

Fermilab SRF Cavity Pressure Safety

- In 2008, a committee was formed to develop an SRF design guideline and measures that provide equivalent protection and a level of safety afforded by the national consensus standards. Committee worked with other DOE Labs
- In 2011, DOE approval was received as a means for meeting the requirements of 10.CFR.851
- In addition, as a means for meeting the requirements of 10-CFR-851 a new SRF review panel has been formed by the Cryogenic Safety and Mechanical Safety Subcommittees to review new designs in SRF for compliance to the policy and design guideline
- The guidelines addresses concerns specific to SRF cavities in the areas of **materials, design and analysis, welding and brazing, pressure relieving requirements, pressure testing and quality control**

Materials

- Guideline describes the material testing requirements in order to carry out a design consistent with the intent of the the Code
- The required testing includes yield strength, ultimate strength, Young’s modulus, and Charpy impact energy. In addition, the chemical composition of the sample is determined
- The testing is conducted at three points: room temperature, 77K, and 4.5K. A minimum of three samples are required in both the longitudinal and transverse directions for bulk material and welded or brazed material specimens
- The yield and ultimate strength results are used to determine the allowable stress in accordance with Section II, Part D, Mandatory Appendix 1 of the Code
- In addition, the Young’s modulus is required to properly analyze externally pressurized vessels, such as SRF cavities

Design and Analysis

- Overview of the Code in the context of SRF cavity design and one showing how to apply Div. 1 rules to an elliptical and spoke cavity design
- The cavity designer must choose whether the design and analysis is carried out in accordance with Div. 1 or Div. 2 of the Code
- Application of different divisions rules are described in details and examples are presented in appendices
- Discuses the pros and cons of elastic versus elastic-plastic analysis techniques
- Appendices provide an overview of the Code in the context of SRF cavities and the application of Div. 1 rules to elliptical and spoke SRF cavities

Welding and Brazing

- Guidance on the development of a weld procedure specification (WPS) for electron beam and TIG welds based on sample examination using microscopic or scanning electron microscope techniques for procedure verification
- Welding titanium or its alloys to other materials is prohibited by Div. 1, but not by Div. 2. This complicates the use of Div. 1 for any SRF cavity which uses titanium helium containment.
- The Code requires 100% ultrasonic inspection of electron beam welds. It is not uncommon to have the geometry of end joints within a SRF cavity that are impractical to test ultrasonically
- Div. 1 requires that if geometric details are given for a particular joint configuration, then those details must be used in the vessel. There are also several details which are explicitly prohibited by the Code

Pressure Relief Requirements

- Pressure relieving requirements that need to be applied to SRF cavities are discussed in this section of the guideline
- The requirements are based on the Code as well as the Compressed Gas Association (CGA) Pressure Relief Device Standards CGA S-1.3
- SRF cavities typically have large surface area between the beam tube volume and the liquid helium volume. This presents a particularly demanding relieving requirement in the event of a large air in-leak to the beam vacuum volume
- Under this failure mode, air rushes in at sonic velocity and freezes out on the niobium. This results in film boiling of the helium with a large temperature difference.

Pressure Testing

- Concept of having a dual maximum allowable working pressure (MAWP) for SRF cavities is presented
- The MAWP at liquid helium temperature, where the allowable stress in niobium is considerably higher than room temperature
- Above liquid helium temperature, the MAWP is based on room temperature material properties and relieving requirements handled by a smaller lower pressure operational relief valve
- For materials that have higher allowable stresses at cryogenic temperatures, the Code provides a means for pressure testing at room temperature at a lower pressure

Quality Control

- The Code quality control requirements specific to SRF cavities are discussed as related to inspections and the quality control system used in the design, fabrication and testing phases

- The inspector must be certified by the controlling jurisdiction (usually the state uses the National Board commissioning system). If the manufacturer is the end user, then the certified inspector can be an employee of the manufacturer

- Both Div. 1 and Div. 2 include an outline of features for the quality control system, i.e., *Authority and Responsibility, Drawings, Design Calculations, and Specifications, Material Control, Examination and Inspection, NDE, etc.*

Fermilab Cryomodule Pressure Safety

FESHM Chapter	Title	Application
5031.1	Piping Systems	Cryomodules piping
5031.6	Dressed Niobium SRF Cavity	SRF cavities
5034	Pressure Testing	Cavities and piping
5033	Vacuum Vessel Safety	Vacuum vessel and components
4240	Oxygen Deficiency Hazard	Integrated system
5032	Cryogenic System Review	Integrated system
10110	Below the Hook Lifting Devices	Cryomodule

Fermilab Collaboration on LCLS-II

- Argonne, Berkley Lab, Fermilab, JLab, and SLAC partnered to work on the LCLS-II project in late 2013
- SLAC, the host laboratory for the LCLS-II, reviewed the safety and QA programs at the partner laboratories. Common areas determined to be consistent with the SLAC program and therefore became the LCLS-II project requirements
- Unique areas (i.e., Seismic) were identified and addressed. Revised cryomodule stress analysis based on LCLS-II Cryomodule Seismic Design Criteria (LCLSII-4.5-EN-0226) was performed
- Excerpt form the SLAC assessment – LCLS-II document # LCLSII-1.2-EN-0020-R2:

> *"The SLAC Pressure Systems Program Manager reviewed ES&H Manual Chapter 14 against the LCLS-II Partner laboratories pressure systems programs. The goal was to identify differences and determine if changes were needed in SLAC's program. The Program Manager identified that all programs were similar in meeting the 10 CFR 851 requirements. The Partner labs programs addressed non-ASME pressure systems in greater depth than SLAC's. In addition to their pressure systems program,* ***the Partner labs added engineering guidelines to assist designers in meeting the pressure systems programs requirements. For example, Cryogenic System Reviews, Dressed Niobium SFR Cavity Pressure Safety, and Liquid Cryogenic Targets"***

Fermilab collaboration on HL-LHC AUP

- Dressed cavities are subjected to CERN rules:
  - CERN Safety Regulation SR-M - Mechanical equipment safety rules list
  - CERN General Safety Instruction GSI-M-4 – Cryogenic Equipment
- CERN provides specification for non-ferrous materials used for pressure-bearing parts
- The cavity design is based on the EN 13445-3 (Unfired Pressure Vessels) and EN 13458-2 (Cryogenic vessels)
- Cavity manufacturing, inspection and tests is based on the EN 13445-4 and EN 13445-5, considered to be equivalent to the EN 13458-2
- Pressure test level is defined as per pneumatic test pressure of 1.25 times the absolute design pressure

Vacuum Vessel Boundary

- Several National Laboratories have chosen to use vacuum vessel as the pressure boundary → ORNL/SNS, BNL
- The components that make up both these boundaries are all fabricated from austenitic stainless steel and serves as the main boundary around the interior cryogenic components, cavities and piping
- Boundary penetrations include FPC ports, instrumentation ports, maintenance access ports, cryogenic valves penetrations, pressure relief penetrations, beamline penetration, etc.
- Requires Code compliant (UV Stamp) relief system for overpressure protection

Summary

- 10.CFR.851 allows allows US national laboratories use of alternative rules which provide a level of safety greater than or equal to that afforded by ASME codes
- Fermilab approach is based on using helium vessel as a pressure boundary
- Intent of the ASME code is used for materials, design, welding and brazing, pressure relieving requirements, pressure testing and quality control
- Non-listed materials properties are specified by FESHM
- This approach was applied to LCLS-II and LCLS-II HE cryomodules
- CERN approach to SRF pressure safety on HL-LHC AUP is similar to Fermilab's