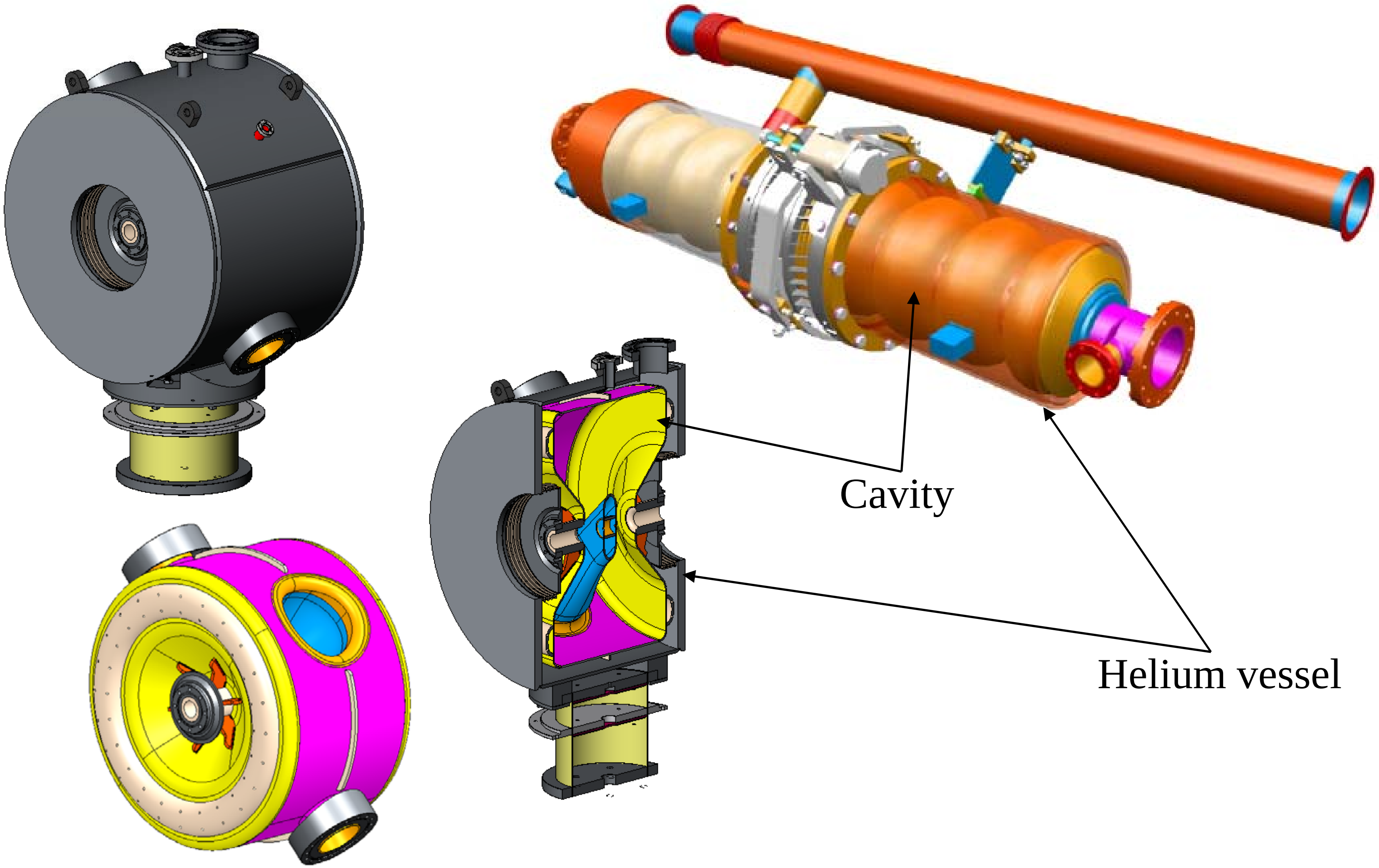
SRF Pressure Safety at Fermilab

Tom Nicol
Technical Division – SRF Department

Topics

- Brief introduction to the mechanical structures
- Goals and (self-appointed) charge
- Materials
- Design and Analysis
- Welding and Brazing
- QA and Documentation
- Testing
- Summary

Single Spoke and Elliptical Cavity Structures



SRF Pressure Safety Committee

- The following is the result of work by a newly formed committee to address pressure safety issues associated with superconducting RF structures. Our first meeting was September 19, 2008.
- Ultimate goal – A consistent set of rules that can be used by Fermilab engineers in the design, construction, review, approval, and use of superconducting RF cavities.
- Scope – Develop a strategy to be used for 1.3 GHz elliptical and 325 MHz spoke cavities. In other words we aren't attempting to address issues affecting all SRF structures.
- Form – A new chapter in the Fermilab ES&H Manual, a revision to an existing chapter or a technical appendix to an existing chapter.
- Precedents – LH_2 targets and thin windows.

SRF Pressure Safety Committee Members

- Harry Carter
- Mike Foley
- Patrick Hurh
- Arkadiy Klebaner
- Kurt Krempetz
- Tom Nicol
- Dan Olis
- Tom Page
- Tom Peterson
- Phil Pfund
- Dave Pushka
- Richard Schmitt
- Jay Theilacker
- Bob Wands

Order of “Acceptability” of Pressure Vessels

1. ASME code-stamped vessel from an outside source.
2. In-house built vessel using and complying with ASME code rules, with well documented material control, material certifications and inspections. Takes full advantage of Code-allowed stresses.
3. In-house built vessel using and complying with ASME code rules, without well documented material control, material certifications and inspections. Requires derating of the allowed stress by a factor of 0.8.
4. Features of the vessel preclude following of the ASME Code, but the same level of safety is provided, i.e. enacting the provision of 10 CFR 851 – *this is what we're currently working toward with SRF pressure safety*.
5. Non-compliance with ASME Code – request special approval.

10 CFR 851

"The research and development aspects of DOE often require that some pressure vessels are built to contain very high pressure that is above the level of applicability of the ASME Pressure Safety Code. Other times, new materials or shapes are required that are beyond the applicability of the ASME Code. In these cases, addressed under Appendix A section 4(c), rational engineering provisions are set to govern the vessels construction and use and assure equivalent safety."

Starting Proposal

- Define a set of material properties for Nb, NbTi, Ti, etc., possibly on a batch-by-batch basis, similar to those established for Code-allowed materials, that result in a comparable level of safety, when used in Code-based analyses or other acceptable analyses options.
- Define a set of manufacturing and inspection procedures, and possibly geometries for use in evaluating electron-beam and TIG welded structures and brazed assemblies.
- Establish a quality assurance program to ensure compliance with the applicable standards.

Materials

Material Acceptance by the Code

- Niobium and Niobium-Titanium are not addressed by the materials section of the ASME Boiler and Pressure Vessel Code.
  - Searching Section VIII, Division 1 and Section II, Part D there are no references to Niobium and Columbium is only mentioned as a component in weld wire and some steel alloys.
- SNS had and maintains hope to develop a code case to address the use of Niobium, but it is on hold due to resources and budget. Their plan is to invest existing resources into redesign of the vacuum vessel. Pursuit of the code case may come later.

Proposed Test Regimen for New Materials at Fermilab

- Tensile and Charpy impact testing.
  - 300 K, 77 K, 4.5 K
    - Longitudinal, transverse (as-received, heat treated) – 3 samples each
      - Yield strength
      - Ultimate tensile
      - Stress strain curves (room temperature only)
    - Weld samples if material will be welded – 3 samples each
      - Yield strength
      - Ultimate tensile
- Elastic modulus (room temperature only).
- Chemical analysis.
- Fabricate a standard vessel for external pressure testing – if applicable.
  - Need to develop a geometry and test criteria.
  - Same material and fabrications processes as cavity (no chemical processing).

St. Louis Testing Laboratory Report

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September 2, 2008
Lab. No.08P-3169
P.O. No. 580734
Page 1 of 6

Attention: Ron Evans

REPORT OF MECHANICAL TESTS

SAMPLE ID: RRR Niobium Plate

Sample ID	Width Inches	Thickness Inches	Area Sq. Inches	Yield Strength PSI	Tensile Strength PSI	Elongation (2.0" Gage Length) In.	%
Transverse-1	0.5100	0.1250	0.0638	10300	26500	0.89	44.5
Transverse-2	0.5100	0.1240	0.0632	10800	26800	0.90	45.0
Transverse-3	0.5100	0.1240	0.0632	10300	27000	0.91	45.5
Transverse-4	0.5100	0.1250	0.0638	10200	26600	0.92	46.0
Transverse-5	0.5100	0.1250	0.0638	13900	26800	0.91	45.5
Average				11100	26740	0.91	45.0

Sample ID	Width Inches	Thickness Inches	Area Sq. Inches	Yield Strength PSI	Tensile Strength PSI	Elongation (2.0" Gage Length) In.	%
Longitudinal-1	0.5100	0.1260	0.0643	9000	27000	0.99	49.5
Longitudinal -2	0.5100	0.1260	0.0643	9100	26800	1.10	55.0
Longitudinal -3	0.5100	0.1260	0.0643	10000	27100	1.00	50.0
Longitudinal -4	0.5100	0.1260	0.0643	9000	26700	0.91	45.5
Longitudinal -5	0.5100	0.1260	0.0643	9300	26600	0.91	45.5
Average				9280	26840	0.98	49.1

Tensile specimens tested at 72°F

Rectangular, reduced section tensiles

Yield taken at .2% offset

Tested in accordance with ASTM E8-06

Identification of tested specimens provided by the client

Karl Schmitz, Director
Materials Testing

KS/art

ACCREDITED
Certificate No. 0397-01
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AN OFFICIAL COPY OF TEST REPORT WILL BE PROVIDED BY THIS LABORATORY ON REQUEST. NOT OFFICIAL WITHOUT THE RAISED SEAL OF ST. LOUIS TESTING LABORATORIES, INC. SEE REVERSE FOR CONDITIONS.

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Attention: Ron Evans

REPORT OF CHARPY IMPACT TEST

MATERIAL (SAMPLE ID): RRR Niobium Plate

SPECIFICATION: ASTM A 370-03a

SPECIMEN TYPE: "A" Vee Notch

SPECIMEN SIZE: 2.5 mm x 10 mm

TEST TEMPERATURE: 72° F

RESULTS:

Test Direction	FOOT LBS.	LATERAL EXPANSION	% SHEAR
Longitudinal-1	24	0.067	100
Longitudinal-2	18	0.047	100
Longitudinal-3	19	0.052	100
Longitudinal-4	17	0.048	100
Longitudinal-5	25	0.052	100
Average	21	0.053	100

Test Direction	FOOT LBS.	LATERAL EXPANSION	% SHEAR
Transverse-1	23	0.057	100
Transverse-2	24	0.047	100
Transverse-3	25	0.046	100
Transverse-4	22	0.050	100
Transverse-5	22	0.049	100
Average	23	0.050	100

Identification of tested specimens provided by client.

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These are room temperature results, but have similar reports for 77 K and 4.5 K.

Derivation of Allowable Stress Values

Mechanical Test Results - Nb Testing from SSR1 Cavities 1 and 2 - St. Louis Testing Laboratories

	Test temperature: 72 F			Test temperature: 77 K			Test temperature: 4 K		
Sample ID	Yield strength (psi)	Tensile strength (psi)	Charpy impact (ft-lb)	Yield strength (psi)	Tensile strength (psi)	Charpy impact (ft-lb)	Yield strength (psi)	Tensile strength (psi)	Charpy impact (ft-lb)
Transverse-1	10300	26500	23	77600	96100	4	102600	107800	2
Transverse-2	10800	26800	24	83900	96500	4	101200	107300	3
Transverse-3	10300	27000	25	79600	95900	4	104000	109200	3
Transverse-4	10200	26600	22	82200	97200	4	99600	106600	2
Transverse-5	13900	26800	22	80300	97300	6	99200	106000	3
Average	**11100**	**26740**	**23.2**	**80720**	**96600**	**4.4**	**101320**	**107380**	**2.6**
Longitudinal-1	9000	27000	24	84400	97700	3	99200	108600	3
Longitudinal-2	9100	26800	18	86000	98800	3	99300	105100	2
Longitudinal-3	10000	27100	19	83900	98700	4	103200	107700	2
Longitudinal-4	9000	26700	17	80300	96900	3	99400	108800	2
Longitudinal-5	9300	26600	25	84300	96300	4	105500	110000	2
Average	**9280**	**26840**	**20.6**	**83780**	**97680**	**3.4**	**101320**	**108040**	**2.2**

	"Code" allowables (psi)		"Code" allowables (psi)		"Code" allowables (psi)	
Direction	Yield*2/3	Tens/3.5	Yield*2/3	Tens/3.5	Yield*2/3	Tens/3.5
Transverse	7400	7640	53813	27600	67547	30680
Longitudinal	6187	7669	55853	27909	67547	30869

	"Code" allowables (MPa)		"Code" allowables (MPa)		"Code" allowables (MPa)	
Direction	Yield*2/3	Tens/3.75	Yield*2/3	Tens/3.75	Yield*2/3	Tens/3.75
Transverse	51	53	371	190	466	212
Longitudinal	43	53	385	192	466	213

Design and Analysis

Design and Analysis

- Objective
  - To determine how much compliance with Section VIII of the ASME Code can be reasonably expected in the design and analysis of an SRF cavity.
- Conclusions
  - Other than the obvious non-Code materials issues, either Division 1 or 2 rules can be complied with to a great extent.
  - Compliance with either Division would require substantial analysis outside the application of available rules.
  - Using stainless steel and non-electron beam welding wherever possible can greatly reduce required NDE under Division 1 rules.
  - U-2(g) of Division 1 allows the use of details not expressly forbidden by the Code if supported by analysis accepted as adequate by the "Inspector".
  - Division 2, Part 5 gives detailed guidance for analysis, and would be the candidate of choice for satisfying U-2(g).

Welding and Brazing

Welding and Brazing Challenges

- Not all welds are readily accessible for radiography or ultrasonic inspection.
- Dye penetrant is usable in some instances, but is probably not compatible with cleanliness requirements.
- Some material combinations are expressly prohibited by Code rules, for example, welding approved Ti alloys to non-Ti materials is prohibited by Division 1.
- Division 1 requires that all Ti welds be butt welds.
- E-beam welds require 100% ultrasonic inspection regardless of the weld efficiency.
- For brazing, parent metals, e.g. niobium to stainless steel are not readily brazed. Procedures exist, but we still lack experience.

Proposed Welding and Brazing Procedures

- For E-beam welds
  - Establish base set of weld parameters for each joint type by microscopic examination of cut, etched and polished weld samples.
  - By varying the base weld parameters for each joint, develop a range of viable parameters that yield full penetration (single pass weld) or full overlap (dual pass weld).
  - Generate a weld matrix listing the range of acceptable weld parameters developed for each joint.
  - Write a weld procedure specification (WPS) for each weld in the matrix specifying the range of weld parameters verified as acceptable.
- For TIG welds
  - Design all joints to be TIG welded in accordance with the ASME Code.
  - Follow a similar procedure to that described above to develop the base TIG weld parameters.
  - All TIG welds within the pressure boundary of each helium vessel jacket must be subject to NDT to check for porosity.
- For braze joints
  - Design braze geometries using the rules of the ASME Code, Part UB.
  - Establish braze procedure specifications (BPS) for each braze joint type.
  - Maintain procedure qualification records (PQR) for all test coupons.

QA and Documentation

Quality Assurance Issues for Non-Code Pressure Vessels

- Quality Control Plan requirements are listed in Mandatory Appendix 10 for Division 1 and in Annex 2.E for Division 2.
- In general, systems and responsibilities must be put in place to assure that all code requirements are met.

- Authority and Responsibilities
- Organization
- Drawings, Design Calculations, & Specifications
- Material Control
- Examination and Inspection
- Correction of Non-Conformities
- Welding
- NDE
- Heat Treatment
- Calibration
- Records Retention

10 CFR 851 Appendix A section 4(c) Requirements

- Design drawings, sketches, and calculations must be reviewed and approved by a qualified independent design professional.
- Qualified personnel must be used to perform examinations and inspections of materials, in-process fabrications, nondestructive tests, and acceptance tests.
- Documentation, traceability, and accountability must be maintained for each pressure vessel or system, including descriptions of design, pressure conditions, testing, inspection, operation, repair, and maintenance.

The Inspector

- The Inspector plays a key role in checking that all components of a qualified QC plan are in place and working.
  - Code requires that the Inspector is not an employee of the manufacturer unless the manufacturer is the end user.
  - It may be possible to hire an Accredited Inspection Agency to provide a qualified Inspector to inspect the fabrication of non-Code vessels (with instruction to except the non-Code features). However the manufacturer must still create the QC system to Code requirements.
  - It may be advantageous for Fermilab to train its own Inspector to be equivalent to a qualified Code Inspector so that the subtleties and difficulties of SRF cavity/cryomodule fabrication can be accommodated while ensuring the same level of safety afforded by Code.

Pressure Testing

ASME Code References

Test	*Division 1*	*Division 2*
Hydrostatic	UG-99	8.2
Pneumatic	UG-100	8.3

ASME BPV Section VIII Division 1

- Hydrostatic test pressure (UG-99)
  - P_T = 1.3 x MAWP

  Or

  - P_T = 1.3 x calculated pressure per 3-2
- Pneumatic (UG-100)
  - P_T = 1.1 x MAWP x (S_T/S) ← lowest ratio for all materials used
  - In no case shall the pneumatic test pressure exceed 1.1 times the basis for calculated test pressure as defined in 3-2.

ASME BPV Section VIII Division 2

- Hydrostatic test pressure (8.2)
  - P_T = 1.43 x MAWP

  Or
  - P_T = 1.25 x (S_T/S) ← lowest ratio for all materials used
- Pneumatic (8.3)
  - P_T = 1.15 x MAWP x (S_T/S) ← lowest ratio for all materials used
  - The above represents the minimum required pneumatic test pressure. The upper limits of this test pressure can be determined using the method in Part 4, Paragraph 4.1.6.2.b. Any intermediate value may be used.

Summary

What Are Others Doing

- ANL
  - Established a yield strength of 7000 psi and design to keep stress levels at 50% of that value.
  - In-process inspection of welds, fabrication, etc., but not formalized.
- BNL (from Gary McIntyre) (1 single cell and 1 5-cell ~703 MHz cavity for electron gun)
  - Allowed stress is 2/3 of yield where yield is based on material certifications from supplier.
  - Weld samples are tested per code, i.e. tensile, guided beam test, Charpy at room temperature and 77 K. No testing below 77 K due to heat input from testing giving inaccurate results.
- JLab
  - Established an allowable stress of 4200 psi based on 2/3 of yield strength of softest batch of material.
  - Relying on operational experience.
  - Acceptance based on peer review and adherence to 10 CFR 851.
- SNS
  - Doing their own material testing, abandoned pursuit of material-based Code case for now.
  - Redesigning their cryomodule vacuum vessel to serve as the external containment per Code Interpretation VIII-1-89-82 – the heat exchanger tube sheet analogy.

Our Goal

- To develop a consistent set of rules and procedures that can be used by Fermilab engineers in the design, construction, review, approval, and use of 1.3 GHz and 325 MHz superconducting RF cavities that ensures the same level of safety as that provided by the ASME Boiler and Pressure Vessel Code.
- Document these rules and procedures probably in a technical appendix to an existing chapter of the Fermilab ES&H Manual.