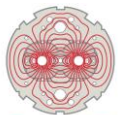




Structural Design Criteria Discussion

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Design criteria meeting 2017-10-28



LARP

Outline

- What exists that we can simply refer to
- Where and why would we deviate
- Should include references to standards
- Address use of 'Brittle' materials

Recommendations from the Review Committee to the Project Team:

- 1) Create & Approve (Structural & Electrical) Design Criteria, including criteria for **brittle materials**, prior to CD-2/CD-3b.
- 2) Secure external review of these criteria prior to or during CD-2/CD-3b.

Design Criteria used by other projects

Structural

<u>System</u>	<u>Criterion</u>
Superconducting Circuit	FIRE (NSTX)
MagLab Cryostat	ASME B&PVC Sec. VIII, div. 2
Resistive Magnet	MagLab RES/MAG
Plumbing	ASME B31 (Pressure Piping)
Lifting and Turning	ASME B30.20 (BTH)
Human Occupied Structures	ANSI/AISC 360 (SSSB)

Usually documented in critical lift notes—defined by institute, but specify

Electrical

Superconducting Circuit
Power

ITER
National Electric Code

Comparison of example design criteria docs

ITER Structural Design Criteria

- Exists, is well written, copies or refers to large sections of existing standards
- Good balance in definition of limits and loads—we would need to define independently
- Perhaps too much emphasis on welded structures which are adequately covered in B&PVC
- Treatment of Linear Elastic Fracture Mechanics (LEFM) but with an emphasis on fatigue not fracture
- Some good values and points—should steal where appropriate (appropriate where appropriate)
- **~60 pages, + appendices**

NSTX Design Criteria

- Simpler formulation, similar in tone to what we should probably produce
- Tends to be more rule based than analysis based—we generally always have FEA results so should identify what we would 'only hand calculate'
- Does not include significant treatment of LEFM, uses S-N curves and cumulative damage for Fatigue...
- Does have some good section ideas, e.g. defining allowables for differing kinds of materials e.g. insulators etc.
- **~28 pages, + appendices**

Boiler & Pressure Vessel Code and Pressure Equipment Directive

- Generally rely on high margins against yield
- Provide conservative material properties to use and define/document source of properties
- Rely generally on tough, typically weldable alloys (alternate materials have limited treatments, e.g. composites)
- References are outside of code for brittle or flawed structures, e.g cracks
- Do not usually cover material common in our structures, e.g. 7000 Al, Iron, low-carbon steel

Excerpts from BPVC VIII Division 2

Alternative Rules

3.11.2.8 Establishment of the MDMT Using a Fracture Mechanics Methodology.

(a) In lieu of the procedures in 3.11.2.1 through 3.11.2.7, the MDMT may be established using a fracture mechanics

approach. The fracture mechanics procedures shall be in accordance with [API 579-1/ASME FFS, Part 9, Level 2 or Level 3](#).

(b) The assessment used to determine the MDMT shall include a systematic evaluation of all factors that control the susceptibility to brittle fracture, e.g., stresses from the applied loadings including thermal stresses, flaw size, fracture toughness of the base metal and welded joints, heat treatment, and the loading rate.

(c) The reference flaw size used in the fracture mechanics evaluation shall be a surface flaw with a depth of $a = \min [t/4, 25\text{mm}]$ and a length of $2c = 6a$ where t is the thickness of the plate containing the reference flaw.

If approved by the user, [an alternative reference flaw size may be used based on the weld joint geometry and the NDE](#)

that will be used and demonstrated for qualification of the vessel (see Part 7).

(d) The material fracture toughness shall be established using the exemption curve for the material (see Notes to

Figures 3.7 and 3.8) and MPC Charpy impact energy correlation described in [API 579-1/ASME FFS-1](#), Appendix F,

F.4. If approved by the user, an alternative material fracture toughness may be used based on fracture toughness test results.

(e) The MDMT established using a fracture mechanics approach shall not be colder than that given in 3.11.2.3(e).

MDMT: Min Design Metal Temp: for elevated temp performance— Level 2 or Level 3 described later.

5.11 FRACTURE MECHANICS EVALUATIONS

Fracture mechanics evaluations performed to determine the MDMT in accordance with 3.11.2.8 shall be in accordance with [API/ASME FFS-1](#). Residual stresses resulting from welding shall be considered along with primary and secondary stresses in all fracture mechanics calculations.

BPVC references Fitness for Service standards for fracture

- Part 3 of BPVC_VIII-2 is on material properties
- Part 4 is design by Rule
- Part 5 is the Design by Analysis requirements (what we do)
- Nominally Division 2 is for vessels between 3,000-10,000psi
- That's not us, but gives clearest guidance on how to approach calculations conservatively
- Provides some guidance on inspection as well
- Does not explicitly discuss Fracture
- Excellent ref for Plastic Collapse

More from BPVC VIII Div 2

**Table 5.1
Loads and Load Cases to Be Considered in a Design**

Loading Condition	Design Loads
Pressure testing	<ul style="list-style-type: none"> (1) Dead load of component plus insulation, fireproofing, installed internals, platforms, and other equipment supported from the component in the installed position (2) Piping loads including pressure thrust (3) Applicable live loads excluding vibration and maintenance live loads (4) Pressure and fluid loads (water) for testing and flushing equipment and piping unless a pneumatic test is specified (5) Wind loads
Normal operation	<ul style="list-style-type: none"> (1) Dead load of component plus insulation, refractory, fireproofing, installed internals, catalyst, packing, platforms, and other equipment supported from the component in the installed position (2) Piping loads including pressure thrust (3) Applicable live loads (4) Pressure and fluid loading during normal operation (5) Thermal loads
Normal operation plus occasional [Note (1)]	<ul style="list-style-type: none"> (1) Dead load of component plus insulation, refractory, fireproofing, installed internals, catalyst, packing, platforms, and other equipment supported from the component in the installed position (2) Piping loads including pressure thrust (3) Applicable live loads (4) Pressure and fluid loading during normal operation (5) Thermal loads (6) Wind, earthquake, or other occasional loads, whichever is greater (7) Loads due to wave action
Abnormal or start-up operation plus occasional [Note (1)]	<ul style="list-style-type: none"> (1) Dead load of component plus insulation, refractory, fireproofing, installed internals, catalyst, packing, platforms, and other equipment supported from the component in the installed position (2) Piping loads including pressure thrust (3) Applicable live loads (4) Pressure and fluid loading associated with the abnormal or start-up conditions (5) Thermal loads (6) Wind loads

NOTE:

(1) Occasional loads are usually governed by wind and earthquake; however, other load types such as snow and ice loads may govern, see ASCE-7.

DEFINE LOAD CASES and DEFINITIONS

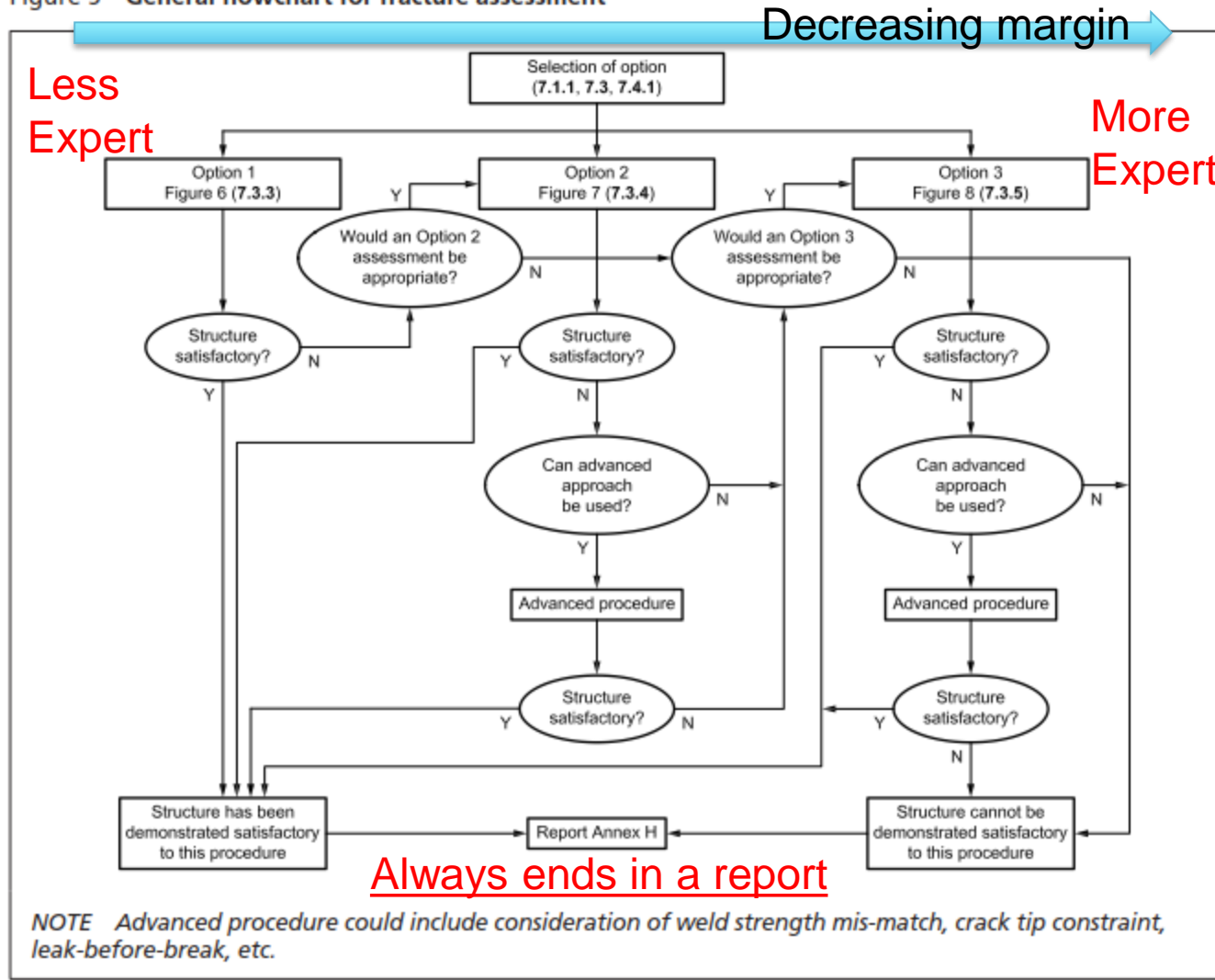
This is something we do already, but haven't documented well

Fitness for Service

- Devised by energy sector to assess damaged equipment (also considers defects from mfg)
 - Aimed at extending life or allowing use
 - Similar discipline to Damage Tolerant Design used in aerospace—assumes ‘flaws’ are present in structure
- Based on inspection and evaluation of flaws
 - Graded approach, from ‘hand calculations’ to FEA, simple LEFM to EPFM—in order of complexity
 - Each grade uses more of the ‘strength criteria’ of the material or structure—allowing higher usable loads
 - Each grade decreases conservatism
- It is up to us to establish the thresholds between each of the steps of the graded approach
 - This is where our design criteria document is useful and important...

Excerpt BS 7910:2013+A1:2015

Figure 5 General flowchart for fracture assessment



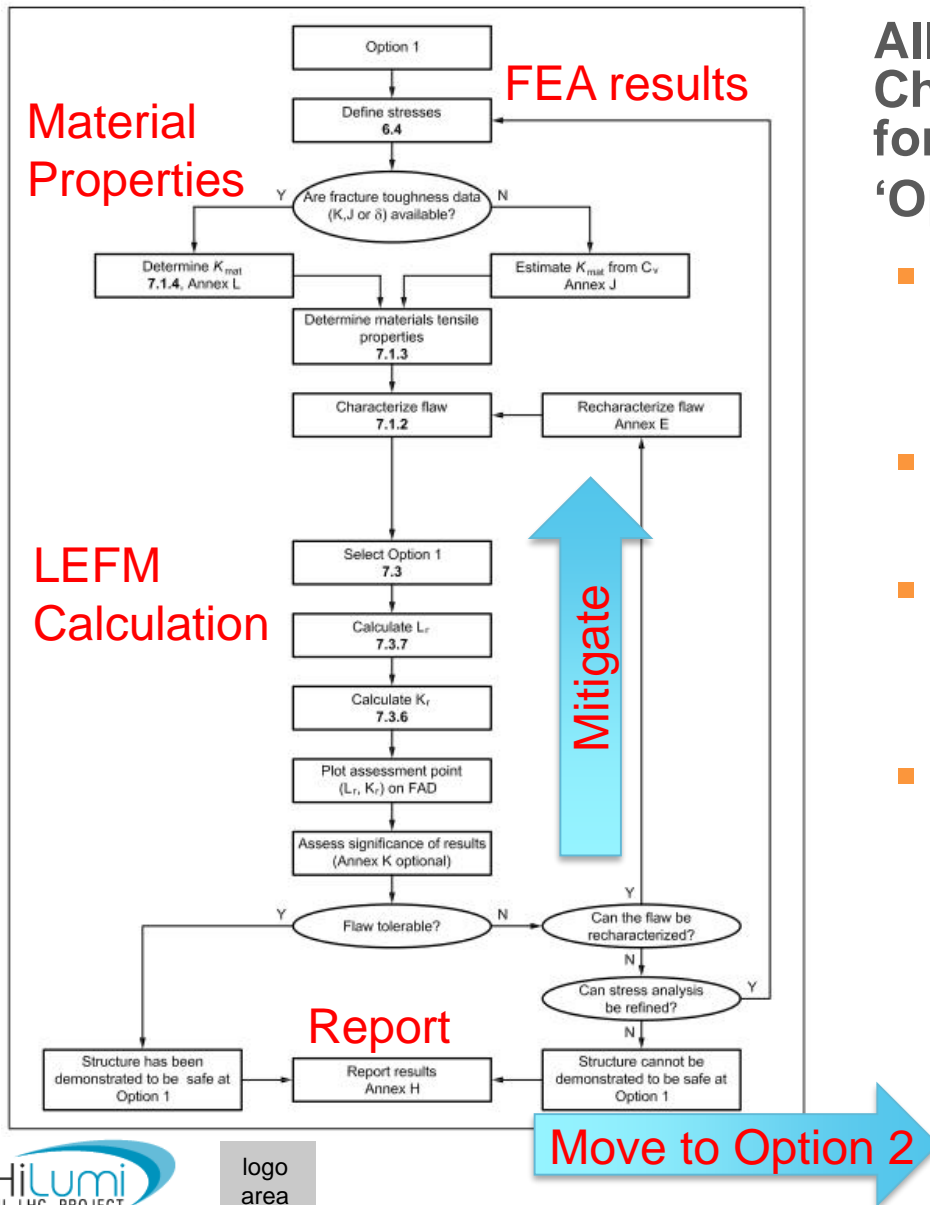
NOTE Advanced procedure could include consideration of weld strength mis-match, crack tip constraint, leak-before-break, etc.

Graded Approach can start simple

- Options 1 can be as simple as $FoS > 4$ Done
- Move to option 2 if simple change can't meet criteria specified in option 1
- Move to next level if say $FoS < 2$, require more analysis, maybe relevant material test data, etc
- LEFM is just one of the later levels
 - It should be stated that some auxiliary checks should be defined e.g. if X material property is lower than some threshold, Level X analysis is required (skipping lower levels)
 - Ratio of Yield to Ultimate, ductility below some threshold, K_{Ic} etc.
- This is why some replication of the various standards is useful in a design criteria document so that its distilled and more accessible to engineers on the project(s)
- None of the divisions of the standards is less than 700pages long, and not always easy to access.
 - Either excerpt or point directly at relevant section of accessible documents...

Flow Chart for flawed structure assessment

Flowchart for Option 1 fracture assessment



All Options have the same Flow Chart, become more complicated for higher levels

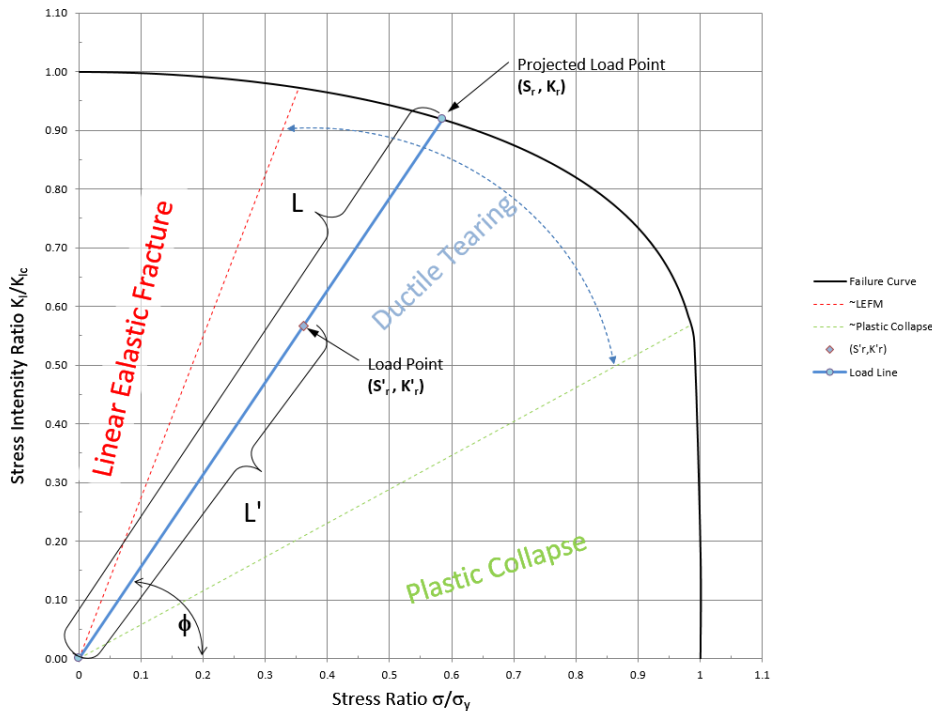
‘Options’ defined from FFS-1

- The LEFM calculation is aimed at assessing a load point on a Failure Assessment Diagram (FAD)
- The Option 1 FAD depends on only K_{IC} and Yield (at temp)
- Option 2 FAD requires also plastic flow data--full stress-strain data at relevant temps (try to avoid)
- Option 3 FAD is based fully on experimentally failed samples of relevant temp, geometry and residual stress (we shall avoid)

Option 1 (section 3 of FFS-1) uses LEFM

Failure Assessment Diagram

R-6 Failure Assessment Diagram
Method for calculating "Load Factor" (L/L')



R6 is a useful method to assess complex failure envelopes

- Predicts well LEFM and Plastic Collapse on one figure
- If under curve on FAD, safe, if outside mitigation is required
- Can set Limits on Load Factors, e.g. 1.1-1.5 are suggested for different load severities in the ITER SDC
- Here the FAD is normalized to K_{Ic} and S_y , for materials with significant strain hardening significant margin above S_y is available
- I propose we do not use that, but do take advantage of higher S_y at cryo temperature
- SU-1005-6694 is a decent summary of the method outlined in R6 and BS7910 which is a ref for FFS-1

Section 9 is fully Elasto-Plastic Fracture

Methodology of Part-9 of API-579 RP for Crack-Like Flaws: FAD

FAD combines the effects of stress field and stress intensity factor into one assessment point

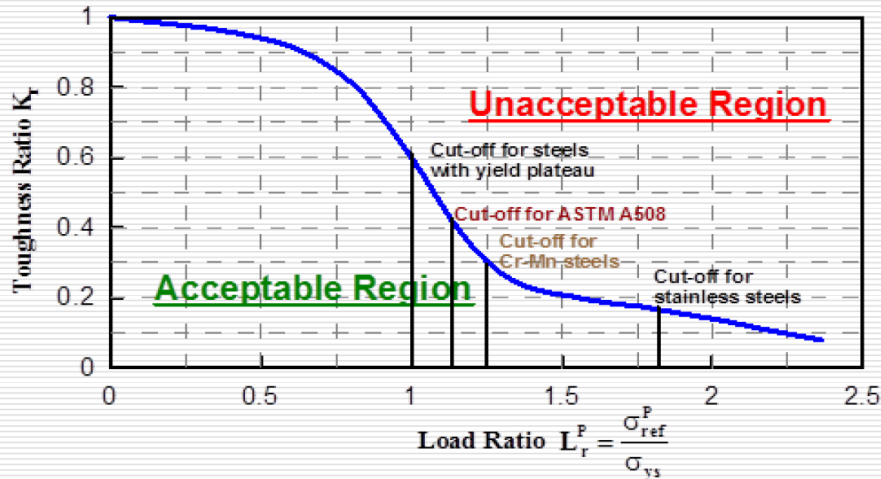


Figure from talk on API 579-1/ASME FFS-1
Mohammad M. Megahed
Mohammad S. Attia
Faculty of Engineering – Cairo University – Egypt

Significant residual strength lies beyond $S_y = 1...$

- Part-9 FAD (Option 3) extends to higher plastic collapse values
- Curves as aggressive as this are only used with actual data to define the envelopes—methods presented in BS7910/FFS-1
- Option 2 is more benign but propose that we stay conservative and design well within the Option 1 FAD
- Can better flesh this out, but may help to read the previously mentioned engineering note on the shell.

How we propose to move forward

- Leverage existing codes where appropriate
 - ITER, FFS, NSTX, etc
- Develop a “simple” document specific to MQXF that...
 - provides custom guidance for our application
 - leverages/duplicates as much as possible from existing codes
 - provides a graded approach for straightforward guidance to design & analysis
 - Is kept **short and focused** on our application
- Check our analysis of each major element of the MQXF magnet wrt the draft code
- Review the draft code within LARP
- Convene external reviewers
- Make modifications as necessary prior to CD2 and/or CD3b

A draft timeline for the development and implementation of the design criteria document

Develop skeleton of the draft Design Criteria	~November 10 th , 2017
Flesh out the graded criteria and associated analysis techniques	~December 1 st , 2017
Check analysis of all critical components wrt design criteria	Dec. 20 th , 2017
Finalize draft document	January 12 th , 2018
Review draft document within LARP	January 19 th , 2018
Convene external review of document	February/March 2018
Address feedback from external review	March/April 2018

Draft Document exists—beginning to write

Document outline prepared and beginning to flesh out sections that can be appropriated from other design criteria documents, codes, etc.

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Conclusion

- Fitness for Services methodology seems a well structured approach to build design criteria
- The R6 FAD is a method that should allow us to adequately assess 'brittle' materials for use in magnet structures
- Should extend to other 'brittle' materials such as insulators, coils, G11, etc
 - Need to investigate further failure criteria in composites (Mil HDBK 17)
- Should re-write SU-1005-6694 to be more consistent with FFS-1 (also need to get K_{Ic} data for shell at cold)