Preliminary thoughts and feedback from Oct 5 review meeting on the Review of Structural Design Criteria Using Al 7075-T65 in MQXF

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General Comments

To develop a structural design criteria for Al 7075-T65 component in MQXF, it may not be practical for LBNL to develop generalized design guidelines/criteria applied for all magnet structures since the structural component for each magnet might be different in materials, different in operating and loading conditions, and also different in flaw size distribution. Therefore, it is our opinion that this particular design criterion is developed specifically only for Al 7075-T65 shell in MQXF.

In reality, all materials are considered to contain flaws/microcracks due to inclusions and voids too small to be "seen". The size and distribution of microflaws are dependent upon the material and its processing. Fracture Mechanics based approach to design application (Fracture Control Plan) is intended for use, given material and structure geometry with known or assumed flaw sizes, in assessing whether the subject structure under known loading and operating conditions would be safe without catastrophic failure, thus it is a fail-safe design concept ("Design against Failure (DaF)"). With this understanding, our initial/general observation/suggestion is that the Berkeley Lab uses the proposed Design against Failure Criteria and although it can borrow or benefit from other types of design criteria in other industries (e.g. ASME B&PV Codes) it shouldn't be strictly tied to such standards. For example, referencing this criteria so closely with B&PV Code and borrowing all of its acceptability standards (load combinations, factors of safety…) may be too restrictive and possibly not warranted based on at least:

- manufacturing quality control standards (we understand you have much tighter QA/QC requirements compared to a part being made in power industry)

- consequences of failures of the part in question (aluminum ring/shell), which, as we discussed, is primarily of financial nature or interruption in business while B&PV addresses human/safety concerns in addition to financial/business considerations.

Therefore, you may want to consider/call this a DaF Criteria with its own reasonable requirements and only use other standards that were used to help develop your criteria as references.

The above is also based on our understanding that this Al shell/ring is NOT a true "pressure vessel" (the Al shell behaves more like a press-fit cylinder which might have self-limiting load with increased compliance from crack growth). Based on this, we suggest you also consider not de-convoluting your stress profiles into "membrane" and "bending," a common approach for pressure vessels. Although not a significant difference in results, we propose that your stress profiles be considered on their own merit and used to evaluate against failures.

For avoiding failure, we understand you're considering net section collapse (plastic) and fast fracture (critical flaw size) conditions. In fact you are proposing to use an "R6" equivalent approach, which considers a failure envelope (FAD) based on these two extreme (as well as the intermediate ductile tearing – J-integral/EPFM – condition). The approach at this time seem reasonable (as it is very comprehensive including three different failure modes), but we reserve the final judgement upon seeing and reviewing material behavior at the operational temperatures (where highest stress conditions exist). For example, if the material shows significant loss of ductility at its LC2 (load case 2 under cool down) operating condition (provided it can also be shown that LC2 is the "governing" loading/stress condition), fast fracture (using LEFM) evaluation may be a more appropriate criterion for evaluation. Of course net section collapse still needs to be evaluated especially for those loading/operating conditions (e.g. shipping/handling, etc.) during which the material behaves more ductile. Overall, an approach similar to R6 will still be quite prudent for any condition although it requires more analysis. We would, however, suggest not using R6 terminology but maybe calling it Failure Envelope Criteria. This may also eliminate the perceived need to use R6 type design/safety factors common for pressure vessels. In fact, based on the loading conditions (normal, accident, etc.), method of analysis (I, II, etc.), and how the material behavior is obtained (literature, limited tests, comprehensive testing program…), you may be able to define your own, and more reasonable but yet conservative factors. A conceptual use of such factors (let's call them "load/design factor" and "factor of safety") is given below:

Analysis Method	**Loading Condition**	**Load/Design Factor**
I	Normal	xx
	Accident (?)	yy
II		

Material Property Determination	**FoS (Factor by which material properties t be reduced)**
Literature	
Limited testing (3-5 samples) using Min., mean, or mean-xStdDev values	Three values here…
Extensive testing (>?? samples) using Min., or Mean or Mean-xStdDev value	Xxy, or xyz or xxzz

Now, considering some of the initial analytical results and test data on this material, we gather that the part is at ~4^{o}K during its highest stress condition (LC2). In fact this is the loading condition that sees about 3 times more stresses compared to the next highest loading (LC1b). If this condition proves to be the governing condition and if the material behaves very brittle in this environment, a Fracture Control Plan approach using LEFM may suffice to assure its failure prevention for this loading (still need to check for stress/strength criteria as well).

CRACK GROWTH CONSIDERATION:

Regarding crack growth, based on the simulation results provided during the meeting (stress range of <~10MPa and <5000 cycles), assuming the Al 7075- T65 material behavior at 4K doesn't show any abnormality compared to its reported behavior at higher temperatures (27K, 77K, etc.) and the C and n parameters in the Paris Law do not change much in cryogenics temperature, then the fatigue issue can be reasoned away (ignored). For this purpose, a comparison of limited test data on crack growth at operating temperature are recommended to be performed to validate that material still acts within reason. More discussion on this to follow after test data becomes available.

FLAW DETECTION CRITERIA:

Regarding flaw detection methods/requirements, we suggest requiring non-destructive examination (NDE) after the part has been finished to its final form and prior to being accepted by the Berkeley Lab. This may still require an additional NDE after the part has been forged and before it has been finished (this to be decided by the outfit doing the finishing) but from Lab's perspective, we suggest, the part in its final form needs to be qualified/tested (NDE). Considering (assuming) the brittle nature of the material during its high stress conditions, NDE should be targeted to find surface and sub-surface flaws of given min sizes (TBD) in directions normal to operating stresses. For the worst case, longitudinal flaws at or near the root of machined sections with stress concentrators are to be characterized. Based on analytical evaluations, a table listing "acceptable" (to be detected) flaw sizes and orientations for different locations can be established. An example of such table is shown below:

Location	**Orientation**	**Assumed flaw location/geometry**	**Min. Flaw Size detection (mm or in)**
General (shell away from discontinuities)	Longitudinal	Surface/elliptical or semi-circular	Xxyyzz
		Subsurface/…	Xyzyzy
	Circumferentia		Xxuuzz
			Yyzz
Near discontinuity	Longitudinal		Yyzzz

Some further comments from the review session:

- Grade III calls for sub-modelling technique for magnet structure, sub-modelling approach may not be necessary as computers/software nowadays are quite powerful and capable of detailed modeling/analyses of, the entire structural component.
- Based on the comments from Flaw Detection discussion above, we recommend adding surface flaw detection (e.g. dye penetrant test) on final shell parts to identify any surface flaws, as a complement to the current ultrasonic inspections.
- Failure Assessment Diagram (FAD) incorporates two "independent" failure criteria (brittle fracture and plastic collapse) with interaction between them in one diagram. The developed curve represents the locus of predicted failure points. The structure is considered safe for operation if its assessment point is located within the boundary of the

curve. In the LBNL design criteria, Sm = 0.8 S_y (Yield Strength) with 3 sigma standard deviation on S_y was used. In B&PV code, the limiting stress value is limited to 2/3 S_y but min value of S_y was used. The resulting multiplier (factor) for S_y might just be approximately the same (*though this point needs to be checked to confirm*).

- With evidence of adequate stress analysis, proper crack growth analysis during operation (if needed), sufficient material properties measurements (e.g. for K_{IC} at lowest operating temperature), and accurate post fabrication flaw detection on component, the conservative margin of safety used in other codes can be reduced. Thus the use of a static stress limit of 80% and its further use of 80% on the load factor for the FAD would seem reasonable. (If the Lab decides to use our proposed tables for load factors/FoS, this and the next paragraphs can be transferred to those tables)
- From the US HL-LHC AUP MQXF Design Criteria Review Committee Final Report (p.13), the review committee suggests increasing the safety margin to 1.5 on the K_{IC} using FAD approach. If the fracture toughness test data measured at 4K (1.8K?) were reasonably consistent among the test samples, the finite element stress analysis model was accurate, fatigue crack growth was not an issue, and the NDE measurements were thorough and reliable, then the FAD safety margin could be confidently reduced to 1.2. The state of the structure would still be located within the safe zone of the FAD.
- On page 19 of the Review Committee Final Report, "In other magnet codes, the Paris integral evaluation uses a factor of 1.5 on fracture toughness, 2 on flaw size and 2 on life." We are not familiar with other magnet codes and can't comment on this point at this moment. However, in lieu of what has been discussed above, a FoS of 1.2 (1/0.8) on plastic collapse (stress/strength) and fast fracture (K_I/K_{IC}) seem reasonable to us. This translates to a FoS of ~1.5 on initial flaw size, so for flaw size/detection, an additional FoS of 1.5 (combination would provide ~2) would be reasonable. If there was fatigue crack growth considerations as well, we would suggest a FoS of 2 on crack growth rate to be reasonable.

- Per our conversation, because of brittleness, we highly recommend mitigating (minimizing and/or removing) stress concentrators within the geometry – especially at its higher stress locations and directions. We understand such is being already implemented but it may be beneficial to include a statement in the Design Criteria for that effect – e.g. requiring a min root radius, etc.
- Finally, while we recognize all applicable loading conditions have been considered during the design, we wanted to make sure no transient/sudden type events can exist that can, even for a very short time, cause "shock" type loading. We believe a statement to that effect may be prudent…
- We look forward to reviewing the K_{IC} test results once they become available.