# Feedback to the MQXFA03 Structure & Loading Review Committee

Soren Prestemon, Dan Cheng, Heng Pan

May 28, 2019

**Question from the committee:**

The charge for the MQXFA03  review asked if all the recommendations of previous reviews had been followed.  One of the recommendations from the AP02 review concerns several technical areas that need to be considered when using a FAD safety margin of 1.2 as compared to 1.5.  These areas were not specifically addressed in the talks. The A03 review committee requests that you send a note discussing these areas.  The AP02 report reads as follows:

*“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 KIC 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 analyses/models were 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.”*

**Response by the MQXFA Structures team:**

The primary elements associated with our use of a safety margin of 1.2 on the Al shells are indeed:

1. Detailed FEA analysis
2. Measured K1c data, at the appropriate temperature
3. Flaw inspection of the material

Along with proper quality control and assurance through material certification and material properties assessment during sourcing.

## FEA Analysis

For FEA analysis, significant effort has been taken to properly assess the 3D fields, to properly evaluate stress concentrations via grid refinement and via sub-scale modeling, and to validate subscale model assumptions prior to evaluating the safety margin. These details are described in some detail in the presentation by Giorgio Vallone and Heng Pan (see “The analysis process applied to the Al shells” at the MQXFAP2 Al-Shell Issue and Lessons Learned Indico site <https://indico.fnal.gov/event/19886/>, as well as in a ASC 2018 publication “Failure Assessments for MQXF Magnet Support Structure With a Graded Approach”, accepted for publication: IEEE TAS, Vol. 29, No. 5, August 2019). It is our understanding from the feedback from the Review of the MQXFAP2 Al-Shell Issue and Lessons Learned committee that the analysis approach taken by the MQXFA team is indeed at the level needed to justify the use of a safety margin of 1.2.

## Measurement of K1c on relevant samples

For the measurement of K1c at cryogenic temperatures, the expertise of the materials properties measurement team at the NHMFL, led by Bob Walsh, has been leveraged. The shells are loaded in circumferential tension, and for cracks initiated in the cutout areas, the primary crack propagation direction is along the length of the shell; the corresponding sample orientation is denoted C-L. In the case of the weld-strip cutouts, the initial crack propagation direction is radial, hence the sample orientation of consideration is C-R. Both samples have been evaluated with two samples to-date; additional samples are planned to develop proper statistics. Sample values measured are shown in Table 1. Based on the data received to date, we have used a K1c=24 for all FAD plots and for our evaluation of safety margin. The additional samples being prepared for testing will allow us to refine the level of safety margin in the future.

Table 1. Measured K1c data for shell material at croygenic temperature.

|  |  |  |  |
| --- | --- | --- | --- |
| **Sample** | **Orientation** | **Crack orientation** | **K1c** |
| LBL T6 C-L 11 | C-L | L | 30.5 |
| LBL T6 C-L 6 | C-L | L | 26.7 |
| LBL T6 C-R 7 | C-R | R | 23.8 |
| LBL T6 C-R 8 | C-R | R | 27.0 |

## Shell flaw inspection

Based on the Design Criteria, and in accordance from feedback from the Design Criteria review committee, we have strengthened our flaw inspection regiment to include both enhanced ultrasonic flaw inspection (at the AA level) of every shell forging, and post-machining dye-penetrant inspection to identify surface flaws, e.g. that emanate from machining operations. Examples from these inspections were presented at the MQXFA03 Structure & Loading Review, in the presentation by Katherine Ray (see slide #11). The AA ultrasonic inspection technique should identify flaws of dimension >1.2mm; we have conservatively assumed a flaw size of 2mm in our evaluation of safety margin.

Concerning fatigue crack growth rate, we evaluated the possibility in detail by a) measuring the crack growth rate at cryogenic temperature of relevant material samples (performed by Bob Walsh at the NHMFL), and b) evaluating the Paris Law (as recommended by the Design Criteria Review committee) for relevant load cases. The results of the analysis were presented at the Review of the MQXFAP2 Al-Shell Issue and Lessons Learned (<https://indico.fnal.gov/event/19886/>) in the presentation by Soren Prestemon (see slides 16-18). Based on the analysis and the relatively small change in stress associated with the primary cyclic load (energizing of the magnets), fatigue crack growth is not a primary concern for the shell material.