Cryogenic Moderator Design for the ISIS TS1 Project

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Abstract. A project to improve the neutronics and serviceability of the ISIS Target Station One TRAM (Target, Reflector, and Moderators) is being carried out. This includes a redesign of the cryogenic methane and hydrogen moderators to improve functionality with the new target and reflector, whilst accommodating new water pre-moderators. Both moderators consist of a high pressure, low temperature fluid vessel contained within a vacuum vessel. Finite Element Analysis along with Parametric Optimisation has been used to design and optimise all the moderator vessels. Buckling analysis was investigated as a method of verifying the moderator vacuum vessels and used to show that the vacuum vessels are conservatively designed.

1. Introduction
The ISIS Target Station One (TS1) project is currently in the design and implementation phase. The project includes a redesign of the cryogenic methane and hydrogen moderators. This paper will cover the design challenges encountered and the computer modelling used to support the design process. This includes the optimisation carried out on the moderator fluid vessels and an investigation into the potential use of computational buckling analysis.

1.1. TS1 Project Cryogenic Moderators
ISIS TS1 employs two cryogenic hydrogenous moderators; one containing liquid methane, the other containing liquid hydrogen (Figure 1). Both of these moderators consist of a high pressure, low temperature fluid vessel contained within a vacuum vessel. The hydrogen moderator also employs a tertiary containment vessel. As can be seen in Figure 1; both moderators are positioned directly below the tantalum/tungsten target. As part of the project, water pre-moderators are being introduced between the cryogenic moderators and the target. The hydrogen moderator supplies neutrons to instruments on one side of the target station, whereas the methane moderator supplies neutrons to both sides of the target station. To prevent back scattered neutrons passing through the methane moderator, two gadolinium poison foils are placed in the centre of the moderator.

Figure 1: A section of the ISIS TS1 TRAM showing the hydrogen (1.) and methane (2.) cryogenic moderators.
1.2. Moderator Design Process
The neutronic design team established ideal moderator dimensions. These dimensions provided a starting point for the engineering design process to work from. The design was adjusted from the ideal moderator dimensions to improve the manufacturability and usability of the moderator vessels before being passed back to the neutronics team. This iterative process can be continued until a final, highly optimised design is produced. As part of the engineering design process, the Finite Element package ANSYS was used to ensure the peak stress and maximum deflection met the specification. Parametric Response Surface Optimisation was also used to further optimise the dimensions of the moderator vessels. Due to the variable wall thickness of the moderator fluid vessels, a hex-dominant volumetric mesh was used for all the analysis of the fluid vessels. The vacuum and tertiary vessels have a near constant wall thickness therefore shell elements were used as a reasonable simplification.

2. Parametric Optimisation
The moderator designs were optimised using Parametric Optimisation with the FEA package ANSYS. This process uses a statistical model between the key geometric parameters (e.g. the wall thickness or internal radius) and the key output parameters; in this case the peak stress and maximum deflection. Figure 2 shows the relative influence each parameter has on the peak stress. As expected, the wall thickness is the most significant input parameter and is inversely related to the peak stress. An allowable wall thickness was agreed with the neutronic design team therefore the internal radii (the second most significant factor shown on Figure 2) became a focus of the optimisation.

During parametric optimisation the statistical model is used to determine the specific set of input parameters which result in the required output, as defined by the specification. Figure 3 shows the theoretical relationship between wall thickness, internal radius, and peak stress according to the statistical model. Figure 4 shows specific design points within this range with the constraints applied; each coloured point represents a feasible set of parameters for the design. By applying the allowable limits to every parameter, a highly optimised design which meets the specification can be selected.

Figure 2: A bar chart showing the influence each parameter has on the peak stress within the methane moderator fluid vessel.

Figure 3: A surface plot of the relationship between wall thickness, internal radius, and peak stress.

Figure 4: Specific design points with the wall thickness, internal radius, and peak stress constraints applied; a coloured point represents a feasible design.
2.1. Optimised Designs

The process of parametric optimisation (Section 2) allowed the geometry of all the moderator vessels to be optimised while ensuring the design met the specification. The specification stated that the peak stress within all moderator vessels must be lower than 83MPa, in accordance with PD5500 for the Aluminium Alloy 5083-O used for moderator vessels at ISIS [1]. The limit of 83MPa has previously been used for the computational verification of moderator vessel designs at ISIS; and therefore was also deemed suitable for this analysis. As part of the geometry optimisation the internal radii were decreased in order to minimise the apparent wall thickness around the edges of the vessel, and therefore reduce unnecessary beam-loss in these areas. However, as can be seen in Figure 5 and Figure 6, the internal radii of the fluid vessel are also the areas experiencing peak stress. The optimisation process allowed designs to be produced with minimal internal radii without exceeding the maximum allowable stress. This process was repeated for all the internal and external radii, as well as the radius of the top and the bottom of the vessel itself. The curvature of the top of the vessels was also reduced in order to accommodate the water pre-moderators that have been introduced as part of the TS1 project.

The current design provides a nominal 4mm gap between the undeformed cryogenic vessel and the vacuum containment vessel. The maximum deformation at this point was limited to less than 0.5mm in the centre of the moderator face so as to prevent thermal contact between the internal cryogenic vessel and the surrounding vacuum vessel during peak deformation of both vessels. An example of the predicted deformation of the methane fluid vessel under maximum operating pressure is shown in Figure 7.

3. Buckling Analysis

The vacuum vessels were verified in ANSYS to ensure they would not fail in buckling. Computational analysis has not previously been used at ISIS for buckling analysis of moderator vessels; however it has the potential to allow less conservative designs, therefore has been investigated here.

3.1. Eigenvalue Buckling

The specific buckling analysis used was eigenvalue buckling within ANSYS. This method assumes that the material behaves linearly elastically up until the point of buckling, which generally leads to an
overestimating of the load which the moderator can withstand before buckling occurs [2]. Due to the fact that computational analysis has not been used for this purpose at ISIS before, some validation of the method was carried out first.

3.2. Validation
Previous vacuum vessel designs have been verified using PD5500; considering the external surface of the moderator vessel to be a section of a cylinder under external pressure [1]. By ensuring that the critical buckling pressure for this cylinder is greater than the max operating pressure of the vacuum vessel, the vessel has been deemed safe. When this method was replicated by analysing the same cylinders using ANSYS the elastic instability pressure was found to agree with the hand calculations to within 10% for all designs. This was taken as a demonstration that the eigenvalue buckling analysis method can predict the elastic instability pressure consistently with the previously used methods.

3.3. Analysis Results
Figure 8 and Figure 9 show the primary buckling mode for the methane and hydrogen vacuum vessel respectively. In these cases the elastic instability pressure is 7.3Bar and 14.9Bar, which equates to pressures 1.5 times greater than the pressure calculated previously using PD5500. This reassures the previous assumptions that the vacuum vessels are a conservative design, and that less conservative designs could be investigated in the future, however less conservative designs would require further analysis and testing before use due to the overestimation typical of eigenvalue buckling analysis [2].

4. Conclusions
The cryogenic moderator designs for the TS1 project have been parametrically optimised to closely match the ideal neutronic design while meeting the engineering specification for all the vessels. The peak stress within all the moderator vessels is below 83MPa as required to prevent structural failure. The max deformation of all the vessels will not produce thermal contact between the cryogenic vessel and the surrounding vacuum vessel. Buckling analysis has been investigated and shown to agree with the PD5500 standard when analysing a conservative simplification of the vacuum vessels. Finally, when considering a non-conservative analysis of the moderator vessel geometry, an instability pressure at least 1.5 times greater was predicted. This suggests further optimisation is possible, however it would require physical testing to verify.

References
[1] PD 5500:2015 Specification for unfired fusion welded pressure vessels (The British Standards Institution: 2015)
[2] Kurowski, PM. Kurowski, TP. Buckling Analysis with FEA (Machine Design, London, Ontario, Canada: 2011)