Design and optimisation of the ISIS TS1 Project target

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Abstract. The ISIS spallation neutron source is developing a new target, reflector and moderator assembly for its first target station (TS1). The TS1 Project will increase useful neutron output without increasing the beam power, by using modern software and analysis techniques to redesign these components for improved neutronic efficiency. The design and development of the TS1 Project spallation target is presented here. The final design represents a trade-off between the conflicting demands of neutronic efficiency, engineering reliability and manufacturability. It is essential that the TS1 project does not compromise the reliability of the facility; detailed finite element analysis has been carried out to demonstrate that the TS1 Project target will operate within specified design limits. The new design bears many similarities to the current TS1 target; it is still a plate target, made from tungsten clad in tantalum, cooled by heavy water and contained in a stainless steel vessel. However, the total mass is 60% lower than the current TS1 target. This will improve neutron output, while reducing material cost and the volume of radioactive waste produced.

1. Background
The ISIS spallation neutron source operates two target stations, TS1 and TS2. TS1 has been in operation since 1984, originally with a depleted uranium target. The target material was changed to tantalum in the early 1990’s, then to tantalum-clad tungsten from 2001 to present. TS2 was opened in 2008, again using a tantalum-clad tungsten target. The TS1 target consists of 12 plates and operates at 160kW beam power, whereas the TS2 target is a solid rod target operating at 32kW beam power. The TS1 Project refers to ongoing efforts to develop a new target, reflector and moderator (TRAM) assembly for TS1. The project will increase useful neutron output without increasing the beam power, by improving neutronic efficiency using modern software and analysis techniques, along with lessons learned from the development of TS2. This will include the development of a new spallation target, referred to here as the ‘TS1 Project target’. Figure 1 shows a comparison of the targets.

The scope of the project is limited to changing the TRAM components only; the new TRAM assembly must be compatible with the existing accelerator, beam transfer lines, neutron beamlines and instruments. The proton beam will remain at 800MeV energy, 200µA, with a circular Gaussian beam profile with 17.9mm sigma. The possibility of changing to an elliptical beam profile was investigated but found to be incompatible with the existing beam transfer infrastructure. The new target must be compatible with the existing target infrastructure including diagnostics and coolant pumps. It is critical that the TS1 Project does not compromise the high level of operational reliability which TS1 currently
achieves. The new target must also be manufacturable at a reasonable cost. The ISIS neutronics and manufacturing groups were consulted throughout the design process to ensure their requirements were met. In many cases a trade-off was required between the conflicting demands of neutronic efficiency, engineering reliability and manufacturability.

Figure 1. Comparison of ISIS Targets. From left to right: current TS2, TS1 Project, and current TS1.

2. Overview of TS1 Project target

A detailed view of the proposed TS1 project target is shown in Figure 2. The primary neutron producing material is tungsten, clad in tantalum to improve corrosion resistance. Both materials have a high neutron yield plus good mechanical properties at elevated temperatures, and have been used extensively at ISIS and at other spallation neutron sources around the world [1] [2]. The target core is split into plates to improve cooling and reduce thermal stress. The coolant is heavy water, which is contained in a stainless steel pressure vessel and flows between the target plates in parallel. The materials and basic geometry bear many similarities to the current TS1 target, as the initial design study concluded that these were still the best options based on the ISIS proton beam parameters.

Compared to the current TS1 target, the TS1 Project target is much smaller and lighter. The total mass was reduced by 60%, as shown in Table 1. Neutron production only occurs in the core of the target, which interacts with the proton beam, plus a narrow region around this where secondary interactions take place. Any material away from the core such as the pressure vessel and cooling manifolds will absorb more neutrons than it produces, and should be minimised. Therefore the TS1 Project target cross section is circular, to match the circular cross section of the proton beam. The circular cross section is also a standard shape which is easy to manufacture. Reducing the volume of target material also reduces material cost and the volume of radioactive waste produced at the end of the target lifetime.

| Mass of material (kg) | Current TS1 target | TS1 Project target | Reduction |
|-----------------------|--------------------|--------------------|-----------|
| Stainless Steel       | 73.8               | 8.1                | 89.0%     |
| Tantalum              | 32.7               | 6.9                | 79.0%     |
| Tungsten              | 47.3               | 46.0               | 2.8%      |
| Total                 | 153.8              | 61.0               | 60.3%     |
3. Design and optimisation

3.1. Target core

The target core must be split into plates to manage temperature and thermal stress. However each additional plate increases the volume of tantalum and heavy water, which is bad for neutron production, and also increases the number of manufacturing operations. Therefore the number of plates should be minimised. ANSYS Workbench finite element analysis (FEA) software [3] was used to optimise the design of the target core. A parametric model of the target core was built, which allowed the simulated plate thicknesses to be easily varied, and output the peak core temperature, surface temperature, and the peak stress in tantalum and tungsten for each plate. The current ISIS targets were simulated using a similar process to give a basis for comparison. Table 2 shows the results for each target, and the design limits which were set. The core temperature is unlimited; it is only a problem due to the thermal stresses it creates. The surface temperature is limited to 100°C to avoid damaging adjacent components such as the moderators. Tungsten stress is limited to half the tensile strength, which is estimated to be 550MPa. Tantalum stress is limited to the simulated stress level in the current TS1 target, as we know this target is reliable. Core temperature, heat flux and tungsten stress for the TS1 Project target are slightly higher than for current TS1, but lower than current TS2 and well within design limits. The optimisation goal was to use the smallest possible number of target plates without exceeding any of the limits. The analysis concluded that 10 plates were required, compared to 12 plates in the current target. The limiting factor was tantalum stress for the front 4 plates and surface temperature for the remaining 6 plates.

Table 2. Summary of finite element analysis results for ISIS targets.

| Parameter                       | Current TS1 | Current TS2 | TS1 Project | Design Limit |
|---------------------------------|-------------|-------------|-------------|--------------|
| Peak Core Temperature (°C)      | 184         | 249         | 196         | N/A          |
| Peak Surface Temperature (°C)   | 35          | 35          | 88          | 100          |
| Peak Heat Flux (MW/m²)          | 2.0         | 2.4         | 2.1         | 3.0          |
| Peak Tungsten Stress (MPa)      | 89          | 157         | 96          | 275          |
| Peak Tantalum Stress (MPa)      | 116         | 90          | 112         | 116          |
3.2. Fluid flow
The target coolant is heavy water, as it absorbs fewer neutrons than regular water. Nonetheless, heavy water anywhere in the target has an adverse effect on neutronic performance, so the volume should be minimised. Heavy water between the target core and the moderators (or pre-moderators) has a particularly large effect and should be avoided entirely if possible. The TS1 project target design achieves this by supplying the heavy water from manifolds either side of the target, with no direct cooling on the moderator-adjacent faces. CFX software within ANSYS Workbench was used to simulate fluid flow through the target. Various manifold geometries were tried before the current version was adopted. It is designed to distribute flow as evenly as possible between all plates, while minimising the volume of coolant and complying with the pressure drop and flowrate limits imposed by the existing pumps and water circuit.

3.3. Pressure vessel
The pressure vessel should safely contain the pressurised coolant, but in order to improve neutron output the volume of steel should be minimised. Stainless steel 316L was chosen as the pressure vessel material, as it has good corrosion resistance, weldability and structural properties. The current TS1 target pressure vessel was designed to cope with the original uranium target plates overheating, so is very over-engineered for tungsten plates and would not be a suitable comparison when designing the new vessel. To ensure integrity without making comparison to the previous target, the new vessel was designed to meet the requirements of British pressure vessel design code PD5500 [4].

3.4. Beam window
The beam window, located at the front of the target, is an integrated part of the pressure vessel and made from the same stainless steel 316L. It must withstand both heat deposition by the proton beam and pressure from the heavy water. The window is curved so as to be thin in the centre where the beam passes through, but thicker at the edges to resist the fluid pressure. A very thick window would absorb a lot of energy from the proton beam and experience high thermal stress, whereas a very thin window would not be able to withstand the fluid pressure. A design study was carried out to determine the optimum window dimensions, using a parametric model coupled to a genetic algorithm in ANSYS DesignXplorer. The current TS1 target has a similar thickness beam window, so unlike the rest of the vessel, the beam window stress can be compared to the current TS1 target, and is found to be lower in the TS1 Project target. The window also meets the requirements of PD5500.

4. Conclusions
The new design is fundamentally quite similar to the current TS1 target; it is still a plate target, made from tungsten clad in tantalum, cooled by heavy water and contained in a stainless steel vessel. The target core contains a similar volume of tungsten to the current TS1 target. However, the volume of additional material (e.g. pressure vessel and cooling manifolds) has been substantially reduced. This will reduce neutron re-absorption in the target, material cost, and the volume of radioactive waste produced. Detailed finite element analysis has been carried out to demonstrate that despite this material reduction the target will operate within all required design limits, ensuring reliability.

References
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