Lifecycle of the ESS Moderator and Reflector System

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Abstract. The European Spallation Source (ESS) will be a 5 MW class spallation neutron research facility. An important part of the target station is the Moderator and Reflector (MR) System including structure and handling. The primary function of the MR Plugs is to efficiently reflect and moderate fast neutrons from the spallation target to thermal and cold neutrons suitable for the neutron scattering systems. However, the MR System need to fulfil many operational functions as well, which include cooling of radiation heat in liquid and metal bodies, positioning and structural support, capability of handling of active components and confinement, shielding and avoidance of streaming. Depending on the design, the accumulated neutron flux and irradiation induced material degradation mechanism limit the lifetime of the MR Plug. At full beam power of 5 MW, the MR Plugs need to be changed yearly. That imposes high demands on logistics, manufacturing and handling on the system. This paper presents the lifetime criteria of the MR System, in view of radiation induced material degradation. The complete MR System lifecycle is presented, which ranges from purchase of raw materials (aluminium alloy, stainless steel and beryllium), manufacturing, factory acceptance test (FAT), transport, delivery control, pre-installation test until a new MR System is ready for installation.

1. Moderator and Reflector (MR) System
The primary function of the Moderator and Reflector System is to reflect and moderate fast neutrons from the spallation target to thermal and cold neutrons suitable for the neutron scattering systems. The MR Plugs are located in close vicinity of the target wheel. One MR Plug is positioned above the target wheel and the other below. The MR System consists of a pre-moderator, a cold moderator, a thermal moderator, a beryllium reflector and the support structure including cooling pipes as shown Figure 1. In order to facilitate replacement of the MR Plugs without interactions with the target wheel, the MR Plugs can be rotated to clear the wheel. They can then be lifted straight up.

2. Motivation
Dependent on the design, the accumulated neutron flux and the different irradiation material effects the lifetime of the MR Plugs is limited. The current ESS design is based on the assumption of exchanging the MR System each year during the summer down time. That puts particular demands on logistics, manufacturing, transport and handling on the system.
At this early stage the aim is to get an understanding, when it is needed to start final design, purchase and manufacturing of a second MR Systems during initial operation and finally to establish a schedule for sustainable series production of MR Systems during normal ESS operation.

3. Expected Lifetime of Moderator and Reflector System

The maximum lifetime of the MR System is estimated to be 7000 hours as illustrated in Figure 2. The deterioration leading to the end of lifetime in the MR System is the irradiation damage of the aluminium alloy Al 6061 T6 located close to the target centre. The irradiation damage mechanisms relevant for the aluminium parts of the MR System are thermal neutron induced silicon transmutation caused embrittlement and fast neutron caused radiation damage.

The maximum local thermal neutron flux in the MR Plugs is about $6.8 \times 10^4 \, \text{n}_\text{th}/\text{cm}^2\cdot\text{s}$, which amounts to the total annual fluence of $1.36 \times 10^{22} \, \text{n}_\text{th}/\text{cm}^2$ for 5400 hours of 5 MW operation at ESS. The green line in Figure 2 is showing the thermal neutron fluence versus time. The maximum value given in the RCC MRx code [1] (A3.2A.32) for negligible irradiation is $1.8 \times 10^{22} \, \text{n}_\text{th}/\text{cm}^2$ @ 20°C. Beyond $1.8 \times 10^{22} \, \text{n}_\text{th}/\text{cm}^2$ rules for irradiation damage must be applied. According to RCC MRx, a maximum fluence of $6.7 \times 10^{22} \, \text{n}_\text{th}/\text{cm}^2$ is allowed. However, the design code focuses on the material degradation in view of thermal neutron induced silicon transmutation caused embrittlement only. Considering that the ESS moderators are exposed to a high level of fast neutron flux, a more stringent lifetime criteria is needed. But, the RCC MRx provides with a robust design guideline, which is complemented with

![Figure 1. Moderator and Reflector System (Twister) consisting of cold, thermal moderator, beryllium reflector, piping and supporting structure](image1)

![Figure 2. Expected Lifetime of MR System](image2)
additional lifetime criteria based on fast neutron based radiation damage.

As the pre-moderator is located next to the spallation source, the relatively high fast neutron fluences induces a high radiation damage rate of about 28 dpa for 5400 hours of annual operation at 5 MW. For reference, the operating experience at HFIR (High flux isotope reactor), Oak Ridge National Laboratory shows that aluminium alloy Al 6061 T6 is able to withstand up to 40 dpa of irradiation [2]. Taking the nominal lifetime limit of 40 dpa, the ESS water pre-moderator should be replaced every 7000 hours (Figure 2). For the future, as the displacements and the point defects in the aluminium self-anneals at a moderately elevated temperature [3], there is still potential for further relaxation of the dpa-based lifetime limit.

4. Lifecycle Stages of the First Moderator and Reflector System

Until today a long development of the MR System is done. Currently the end of final design and start of manufacturing is reached. The Technical Design Report (TDR) was issued in April 2013 and the MR System ready for installation will be achieved in summer 2018 after 5 years.

The main features of the TDR concept have been: cold and thermal volume moderators and a 25 ton backpack for remote handling of the MR System. After 2 years of extensive iterations the Preliminary Design Review (PDR) was held in June 2015. In order to improve neutronic performance, now the MR System now consists of a butterfly 2 (BF2) flat moderator and a rotating Twister structure for remote handling.

The final design is done by the in-kind partner Forschungszentrum Jülich. With CFX and FEM analysis the outcome of the preliminary design was confirmed and improved. According to manufacturing possibilities and restrictions the design was adapted and detailed. For critical parts or processes mock-ups were built and tests were done. The final outcome of the detailed design ready for manufacturing is shown in Figure 1. The duration of the final design was 16 month for the cold, thermal moderator and reflector. For the Twister the final design lasted 18 + 6 month. 6 month design work was added due to the change to replace the lower MR Plug (still shown in Figure 1) with a water-cooled steel structure.

The make phase consist of material purchase, manufacturing and testing of sub-assemblies and the complete MR System. With the exception of the MR System shaft the manufacturing is done in-house in Forschungszentrum Jülich’s own workshops. Because of this, the time to build and test the cold, thermal moderator and reflector can be squeezed to about 6 month and the time to build the complete MR System is about a year. The major procurements for the MR System are the raw materials: aluminium alloy, stainless steel and beryllium. Whereas stainless steel 1.4306 and aluminium Al 6061 T6 are standard materials still with a delivery time of up to 20 weeks, the beryllium with high purity demands is a very special material with limited availability and a time for delivery of about one year.

Testing is done for sub-assemblies and the complete MR System. The final test will be conducted in a factory acceptance test (FAT). Testing comprises: visual inspection, He leak test, dye penetrant test, x-ray examination and pressure test. The cold moderator will even be tested cold with liquid nitrogen, combined with a He leak test before and after the moderator was cryogenic cold. The overall testing is estimated to take about 1 month, assuming that sub-assembly tests have been conducted before.

5. Moderator and Reflector System Replacement

To understand replacement scenarios a very generic sequential schedule for a new built MR System is sketched in Figure 3 based on the experience described above. Without any integration or optimization a new MR System ready for installation could be done: with 6 month final design work, 1 year raw material purchase (due to the long delivery time of beryllium), 1 year of making and testing including FAT and finally 3 month for delivery and pre-installation site testing.

According to the replacement schedule the second MR System is planned for installation in 2024. Already today it is decided to do a major design change. For the second MR Plug the intention is to have a butterfly 1 (BF1) cold moderator design. With the experience from the preliminary and final
design the change is estimated to take about 6 month of design work before manufacturing can start. The manufacturing time is expected to be the same as for the first MR System, 1 year. Special for the second MR Plug is, that beryllium is available and need not to be purchased. That is due to the late change during construction to remove the lower MR Plug, as the beryllium for the component was already ordered. Under this conditions the second MR System could be built in about 18 to 20 month depending on the purchase and delivery time of aluminium alloy and stainless steel. That would mean the concept to go for final design must be decided latest in December 2022.

The third MR System is planed for summer 2025. That means after one year of operation of the second MR System exposed to irradiation damage corresponding to full 5 MW proton beam. But, even without any design work, the purchase of the beryllium for the third MR System must be started in July 2023, long before the second MR system is installed. About 6 month may be saved if machining would start without having beryllium delivered.

![Sequential Schedule for MR System Replacement](image)

**Figure 3. Sequential Schedule for MR System Replacement**

### 6. Conclusions

Still there are possibilities for time optimization for MR System replacement, but it can be concluded that the yearly replacement of MR Systems is very challenging because of beryllium delivery time, machining time and workshop capacities. Furthermore, time for design changes is very limited or need to be done before operation experiences are available.

Regarding the beryllium purchase it seems to be necessary to develop a longer-term strategy to have beryllium available but not restrict flexibility for design changes. The high cost of beryllium needs to be considered as well. The manufacturing workshop needs to establish a concept for series production for MR System manufacturing and testing.

### References

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