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DESIGN STUDY OF A ROTATING TARGET FOR ESS

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ABSTRACT

In 2002 the ESS TAC (Technical Advisory Committee) recommended to investigate the rotating target option as a backup alternative to the mercury target baseline. In 2009 ESS Bilbao worked out a preliminary design for a rotating target for ESS based on a disc formed by un-cladded tungsten bricks cooled by cold-plates and arranged in a horizontal trolley. This paper describes the general design and underlying concepts and gives a summary of a preliminary assessment of the design. Analysis of cooling under normal operation conditions, evaluation of decay heat and considerations for accidental case assessment, overall drive system design and evaluation of radiation at mechanical elements, and discussion of alternatives for overall layout and maintenance concepts are included.

1. A rotating target for ESS

The rotating target concept was first developed within the SNQ project [1]. More recent work includes the studies done for the Chinese Neutron Source [2] –though finally the decision was made in favour of a stationary target– and the developments for the SNS STS (Second Target Station) [3]. In early 2009 ESS Bilbao launched the design study of a rotating target for ESS as an alternative to the ESS 2002 baseline, which was based on a Liquid Mercury target [4]. Both concepts rely on moving the heated target material from the beam so that it can be further cooled prior to being subjected to another pulse. One of the advantages of the rotating target is that the vessel also rotates and thus its lifetime is significantly enhanced. Another major benefit is that hot cell and cooling loop requirements are largely reduced. Cladding and/or bonding of tungsten to other materials is an important issue that may require prototyping and testing. Another concern is the evolution of tungsten properties –in particular thermal conductivity– during irradiation.

The ESS Bilbao rotating target reference concept presents a 1.5m diameter tungsten disc with horizontal insertion. The disc is formed by un-cladded tungsten bricks with aluminium cold-plates so that target material density is maximized, irradiated water is reduced and no cladding is required. The horizontal insertion arrangement can be integrated in the original ESS target station design with relatively little impact [5]. It requires the use of radiation hard mechanical elements. Alternative disc arrangement / cooling strategies and drive system configurations are also discussed.

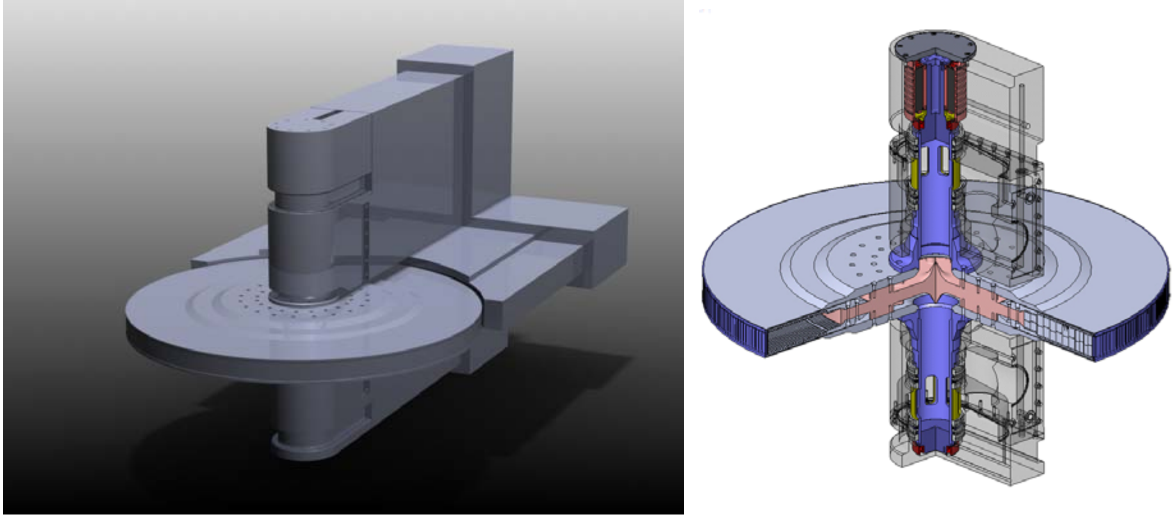

Fig. 1 ESS Bilbao Rotating Target preliminary design.

2. The target disc

2.1. General description of the design

The target preliminary design consists in a 1.5m diameter and 8cm high tungsten disc made up from bricks which are attached to water cooled cold plates. The cold plate configuration has been chosen in order to maximize tungsten disc compactness, avoid the need for tungsten cladding, minimize water in the beam and optimize neutron production. The drawback is the poorer heat removal that potentially leads to higher temperatures in the disc. The design of the tungsten bricks is thus oriented to minimize these problems.

The tungsten disc is built from bricks in order to allow for thermal expansion and minimize stresses. The finned interface between the bricks and the top and bottom diffusers (cold plates) improves the heat transmission and provides the means to attach both elements. Additional vertical cuts (still to be engineered in detail) are performed in the bricks for stress relieve and to reduce the pressure on the diffuser fins.

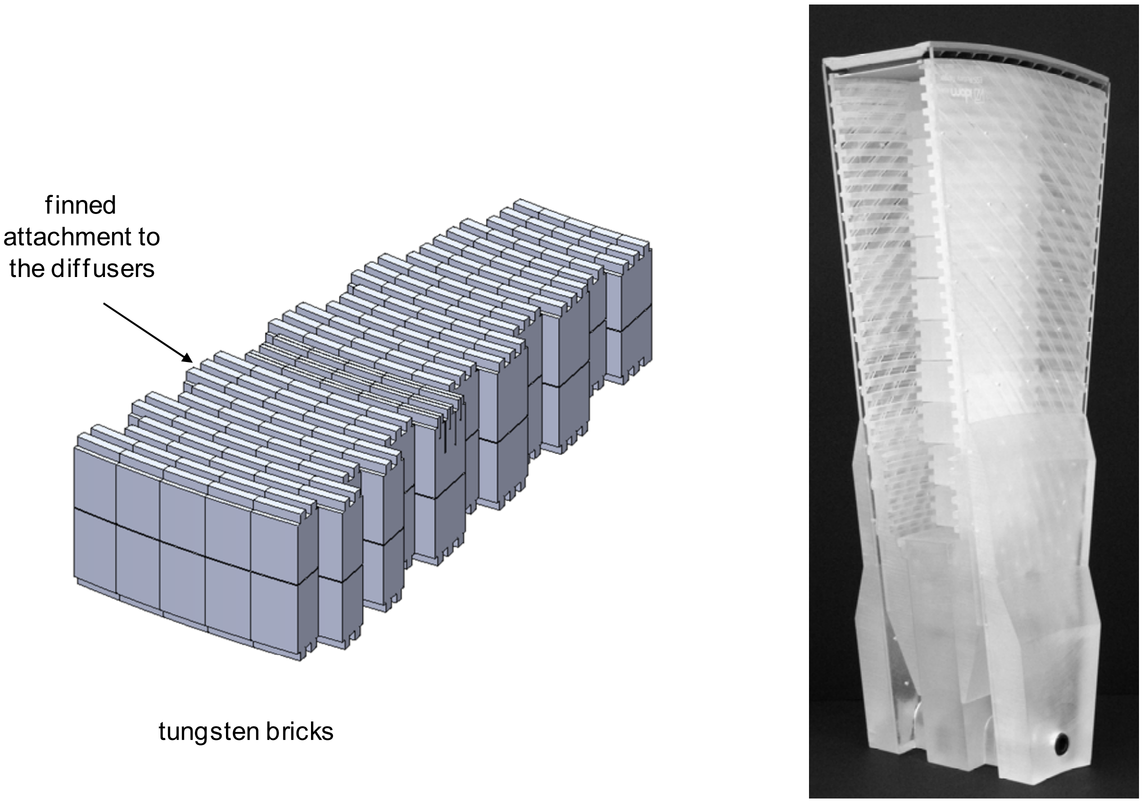

Fig. 2 Tungsten disc arrangement. Left, tungsten bricks; Right, model of a section of the disc.

The diffusers (aluminum or stainless steel) have involute shaped channels on their outer faces to ensure constant flow average velocity of the cooling water. The following figure shows the water flow, entering from the bottom axle, flowing outwards along the bottom diffuser channels, upwards through the perimeter outer channel and inwards along the top diffuser.

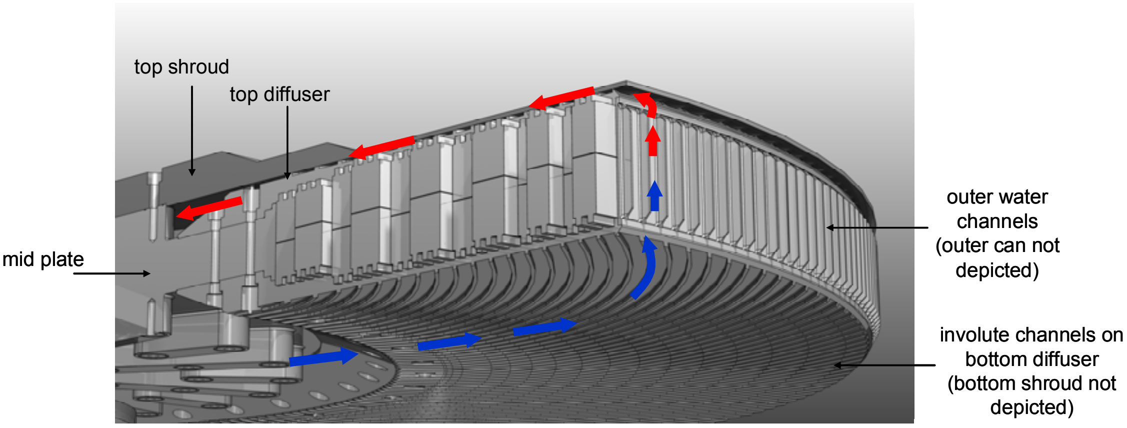

Fig. 3 Cooling water flow along the target disc

2.2. Heat removal for normal conditions

For a ∅1.5m disc and 200mm wide beam footprint with a repetition rate of 16 2/3 Hz a rotation speed of about 30rpm is required to ensure that the maximum heat deposition does not increase due to the overlap of two consecutive pulses. The cooling time for any position is given by the rotation period, i.e. 2s in this case. The radiation damage in the target vessel is reduced by a factor of about 33 relative to a stationary target.

For a preliminary assessment of the cooling strategy the bricks were substituted by cylindrical rods for simplicity of geometry. Temperatures and thermal stresses at tungsten elements were computed for a 5MW 1.3GeV beam of 200×60mm footprint considering both a double parabolic profile as stated in the ESS 2002 project [4] and a 2σ Gaussian profile. The peak deposition in the case of the Gaussian profile is about twice that of the parabolic beam, thus leading to higher temperatures in the peak deposition location. Maximum temperatures are reached in the mid plane of the disc and fall off towards rod ends. For the Gaussian profile, with a water flow of 42 l/s and 3mm thick aluminium plates, the temperature cycle at the maximum heat deposition radius for a given tungsten element is stabilised between 755ºC at beam hit and 565ºC at the end of the 2s cooling cycle in the mid plane of the disc. These temperatures are far below tungsten melting temperature, but are rather close to 800ºC, temperature above which tungsten reacts with water to form hydrogen and a volatile aerosol. The safety case should be further defined and the risk for water leaks into the disc inner volume evaluated in order to set the maximum allowable temperature in the tungsten elements.

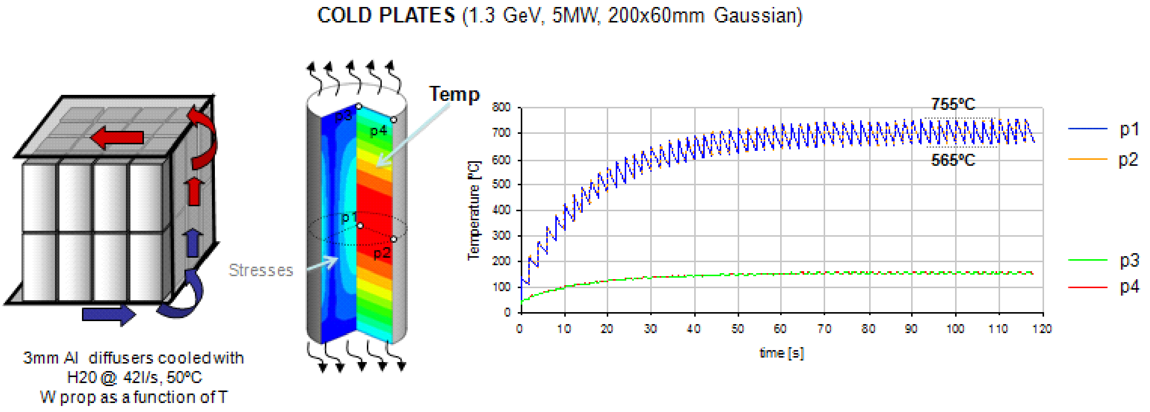
COLD PLATES (1.3 GeV, 5MW, 200x60mm Gaussian)

Fig. 4 Temperatures on tungsten rods cooled at both ends

A rod arrangement with cross-flow cooling has also been analysed for comparison purposes. This option fosters cooling efficiency over other aspects, such as spallation material density and activation. The maximum temperature in the centre of the most loaded rod in a ∅20×80mm rod arrangement with 1.4mm separation, a 1m/s flow and a coolant temperature of 50ºC increases to about 166ºC and gets as low as 53ºC after the 2 s cooling-cycle.

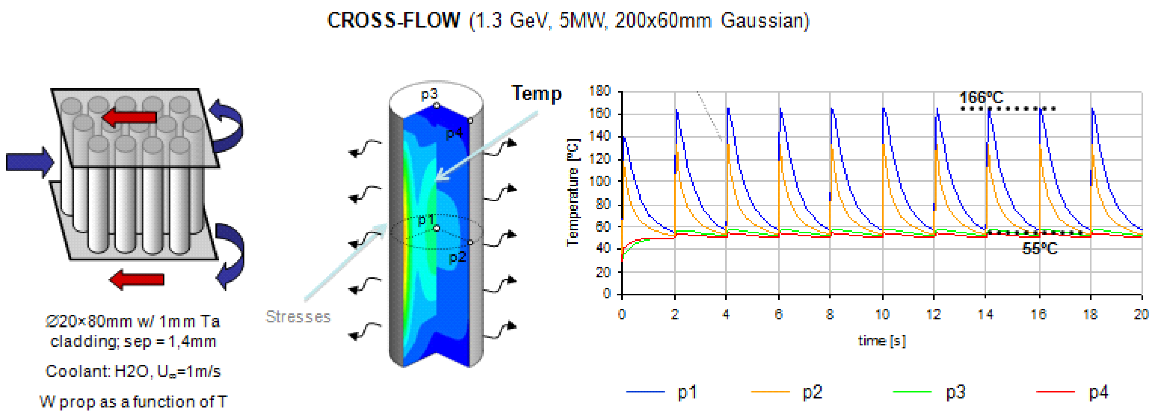

Fig. 5 Temperatures on cladded tungsten rods with cross-flow cooling

In both cooling schemes maximum temperatures at water contact surfaces are above 100ºC. Thus, it is recommended to work with coolant water pressures of about 3-4 bar to prevent *boiling crisis* phenomena.

Differences in thermal stresses are not so significant. In the case of the cold-plate cooling maximum stresses are reached in the centre of the rod and cycle between 62 and 45 MPa. The cross-flow cooling scheme leads to a slightly lower maximum (52 MPa) and a bit larger range (down to 5MPa) in surface points at the mid plane. All these values are well below yield stress and fatigue limit.

For all the calculations tungsten properties evolution with temperature according to [6] was applied.

The cladded tungsten slab design developed for SNS STS (Second Target Station) represents an intermediate option [3]. Large tungsten blocks are directly cooled by water, thus they must be cladded, but the total amount of cladding is significantly reduced compared to the rod arrangement. Also, the reduction on spallation material density is much lower. As for the 3MW case studied by SNS, a central cooling would be required for a 5MW beam. Maximum temperatures in this configuration would be in the range of 150-250ºC. Cooling channels shape and dimensions and flow rates should be carefully studied in order to keep temperatures on the surfaces of the central cooling channels below water boiling temperature.

2.3. Decay heat removal.

Decay heat on a 1.5m un-clad tungsten disc is about 38kW at shutdowns after 5000h of full power operation at 5MW. The predominant isotopes are W187 and W185 with rates of 27% and 24% respectively. After one day and due to a faster decay of W187, W185 accounts for 43% of the total activation.

For these levels of decay heat active cooling is required in order to limit maximum temperatures and to be able to handle the target appropriately. In addition, accidental cases (such as lost of cooling / lost of coolant, etc.) must be defined and analysed. In these cases material damage and other failures to the mechanical systems may be allowed, but release of radioactive products and other hazards must be carefully assessed.

3. Support and drive system

3.1. Overall design

The concept is based on a compact drive system mounted on a horizontal trolley, which could be integrated in the ESS 2002 Target Station design [4] with relatively little impact.

The target axle is supported on both ends into the hinge blocks of the support & shielding plug via ceramic ball bearings mounted on both end shafts. The inlet cooling water enters the disc from below, through the hollow bottom target shaft. The return cooling water is recovered through the top target shaft. A pair of SiC face seals is mounted in each of the rotating joints. The disc is driven by a frameless direct drive -permanent magnets or an induction drive could be used. The ceramic bearings, the proposed drive and the seals are radioactive-hard components that are used in radioactive environments. If necessary, the target shafts can be elongated in order to locate the seals, bearings and drive farther apart from the disc.

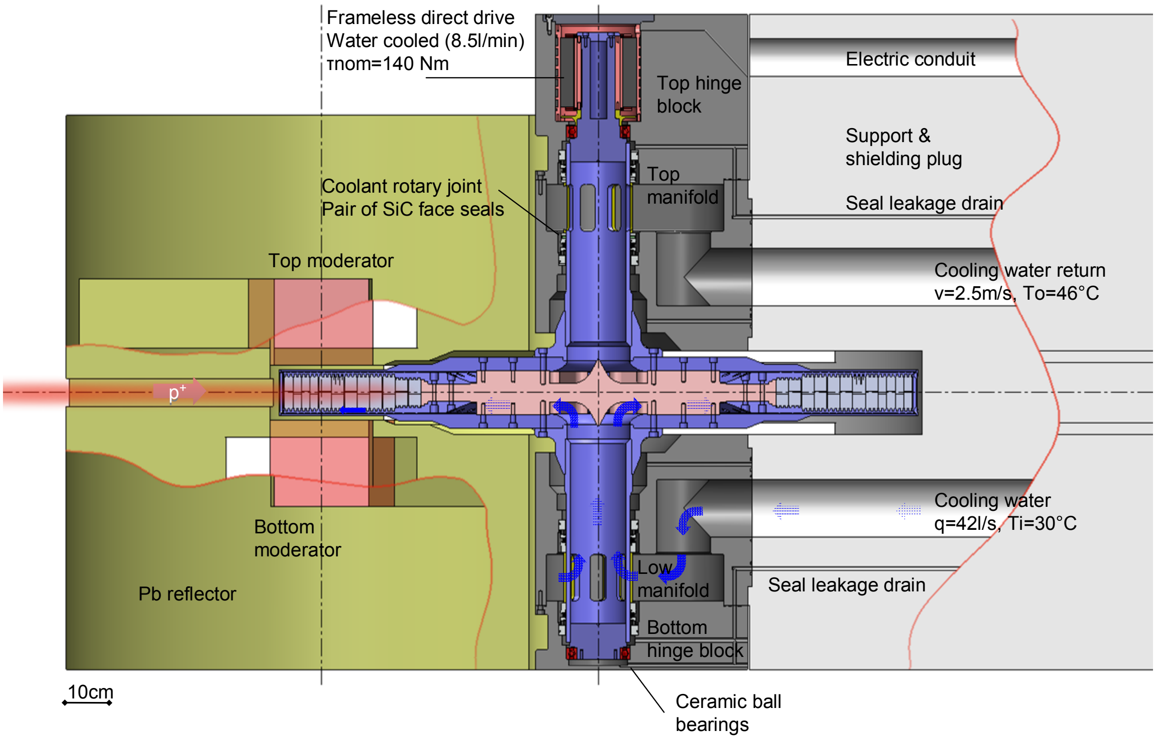

Fig. 6 Rotating target section view

3.2. Radiation dose and damage estimates

Radiation dose for a 5MW beam ranges from above 6000 Gy/s at the beam-target interaction area to about 45 Gy/s at seals location and 5 Gy/s at the motor. The accumulated radiation in a full power year would be 8.1e8 and 9e7 Gy for seals and drive respectively.

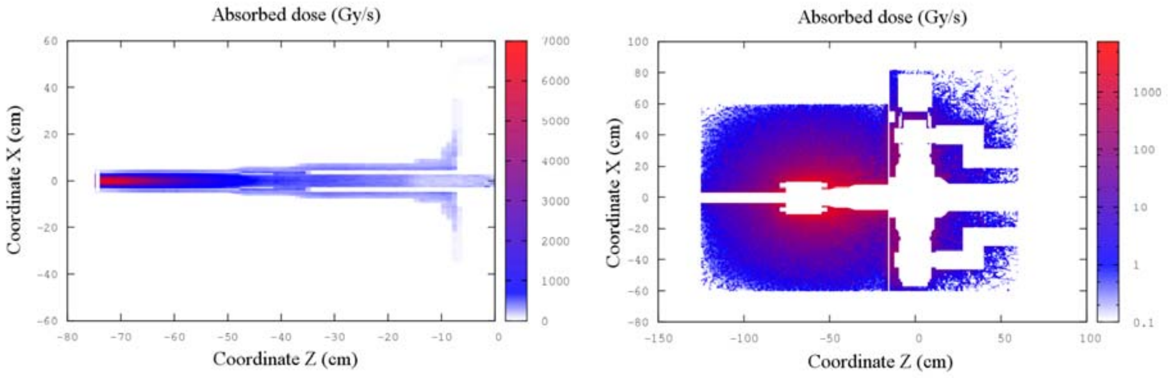

Fig. 6 Absorbed radiation dose at rotating (left) and stationary (right) elements

A radiation resistance of 7e8Gy is reported in [7] for a small size motor formed by a permanent magent drive and non-lubricated Si3N4 ball bearings with no appreciable change of properties for the bearings and certain loss of remanence in the drive probably due to flux of fast neutrons. The applicability of these results to this case must be further assessed.

The dilution effect produced by the rotation of the target is evident in the measurements of radiation damage in terms of displacements per atom and He production, e.g. damage at the target aluminium can is of about 3.5 dpa for 5000 h (1 year) at full power, whilst at the moderator aluminium shroud is 30dpa.

Table I – Radiation damage for a 5MW beam after 5000h operation.

	Material	**dpa/fpy**	**appm He/fpy**
Stationary elements	Moderator Al shroud	30	300
	Lead reflector	16	120
Rotating elements	Target Al can	3.5	14
	Target W disc	1.4	20

3.2. Maintenance concepts

The general arrangement of the target support and drive system is closely related to the maintenance strategies for the TMRA (Target Moderator Reflector Assembly). In the case of a rotating target its lifetime is significantly larger (4-7 years for 5MW) than that of the moderators (a few months). In that case and particularly if moderators are to be replaced 3 or more times a year –which could be the case for ESS– independent handling of moderators and target is recommended. This may be more easily achieved with a horizontally retractable target. The target could be simply removed backwards from the target vessel to allow for moderator replacement either from above or horizontally. An important drawback of horizontal arrangements, however, is that they reduce the available space for instrument lines.

The SNS type vertical long shaft arrangement should also be explored but modifications to the maintenance strategy would be needed to better suit to the more frequent moderator replacement needs. SNS latest design for the STS 1.5MW target station is based on the replacement of the full TMRA by a spare set from above the target vessel. The used TMRA is then processed (cut, stored, rebuilt using the “old” target) in two service cells that are located at the rear of the target station but separated a few metres, which allows for more space for instruments. The period between scheduled shutdowns is sufficient to completely rebuild a new spare set [3].

The final maintenance strategy and general concept study must be accompanied by evaluation of construction and operation costs, number of instruments, time between failures – time to replace – availability, etc.

4. Summary and conclusions

A preliminary design of a rotating target for 5MW has been presented. The main advantages with respect to the liquid metal target are a significantly longer lifetime and a substantial reduction of hot cell and cooling loop requirements.

The reference design is based on an un-clad tunsten disc made of bricks attached to water cooled cold plates. This configuration has been chosen in order to maximize tungsten disc compactness, avoid the need for tungsten cladding, minimize water in the beam and optimize neutron production. The drawback is a poorer cooling efficiency. Maximum temperatures in the bricks for normal operating conditions are about 755ºC compared to 166ºC for a rod arrangement with cross-flow cooling and 150-250ºC for large tungsten slabs with top, bottom and central cooling. In the last two cases the tungsten has to be cladded to avoid direct contact with water. Main R&D issues are: 1) cladding or bonding of tungsten to other materials, which may require prototyping and testing, and 2) the characterization of tungsten properties, in particular thermal conductivity, during irradiation.

Accidental cases must be analysed to complete the trade-off of alternatives. In the case of 1.5m diameter un-clad tungsten disc the decay heat at shutdown after 5000h of operation is about 38kW. With tantalum cladding the decay heat can raise to about 50kW and the decay time will be longer. Heat removal capacity in lost of coolant scenarios must be assessed.

Regarding the drive system, the concept is based on a compact arrangement mounted on a horizontal trolley, which could be integrated in the ESS 2002 Target Station design with relatively little impact. The elements of the drive system, which is located in the vessel, are subjected to 1-10e8 Gy/fpy. Thus, radiation-hard components used in radioactive environments have been chosen. Tests at the JMTR (Japan Materials Testing Reactor) have shown radiation resistance values up to 7e8 Gy for similar drive components.

The general target system arrangement must be studied together with the overall maintenance strategy for target, moderators and reflector. In the case of ESS (5MW) the moderators may have to be replaced about 3 times a year whilst the rotating target lifetime will be of a few (4-7) years. Thus, independent handling of moderators and target is recommended, which may be more easily achieved with a horizontally retractable target. An important drawback of horizontal arrangements, however, is that they reduce the available space for instrument lines.

5. References

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