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**Materials R&D needs for the ESS target station**

E. Noah1, M. Butzek2, A. Class3, S. Domingo4, D. Ene1, U. Fischer3, C. Kharoua1, L. Massidda5, F. Mezei1, V. Moreau5, E. Platacis6, F. Plewinski1, P. Sabbagh1. P. Sievers7, F. Sordo4, K. Thomsen8, J. Wolters2.

1ESS AB (European Spallation Source, SE-22100 Lund, Sweden)

2FZJ (Forschungszentrum Jülich GmbH, 52425 Jülich, Germany)

3KIT (Karlsruhe Institute of Technology, 76021, Karlsruhe, Germany)

4ESS Bilbao (ESS-Bilbao, 48160 Derio, Spain)

5CRS4 (CRS4, 09010 Pula, Italy)

6IPUL (Institute of Physics of the University of Latvia, Salaspils, LV-2169, Latvia)

7CERN (European Organization for Nuclear Research, CH-1211 Geneva, Switzerland)

8PSI (Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland)

**Abstract**

The ESS target will be chosen from a set of tried and tested solutions close to 1 MW (SNS, J-SNS, MEGAPIE, SINQ) or from alternatives such as rotating or windowless concepts. Materials issues associated with an extrapolation from 1 MW to 5 MW for liquid metal loops are presented, taking into consideration target lifetime. Prospects for solid rotating targets are presented with water- and helium-cooled systems.

**Keywords:** spallation neutron source, high power target, liquid metal, rotating target.

# Introduction

The selection of a site to host the European Spallation Source at the end of May 2009 has triggered a renewed interest in the technical implementation of such a facility. The main parameters which formed the basis of the design of the Linac, target station and instruments for the study described in this document, March-December 2010, were the following (latest end December 2010 values in brackets):

* 5 MW average beam power,
* 2.5 GeV proton energy,
* 1 ms (2 ms) proton pulse length,
* 16.67 Hz (20 Hz) proton beam repetition frequency.

Whereas the previous incarnation of the ESS project [1] foresaw two target stations receiving on one a short pulse (1.4 s, 50 Hz) and on the other a long pulse (2 ms, 16.67 Hz), the current version is strictly only one long pulse target station motivated by higher neutron fluxes in the thermal and cold neutron energy range (wavelength > 0.9 A) [2]. This move away from the short pulse target station along with operational experience gained in the last decade on MW-class spallation targets prompted a re-evaluation of potential target concepts for the ESS. Though it was always likely that a concept would be chosen amongst those studied over 50 years of R&D in the field of spallation neutron sources [3,4], it was decided that some features of seemingly exotic solutions could be investigated as the more classical solutions would be reviewed in order to choose the final design.

The main targetry concern for pulsed spallation neutron sources (ESS, SNS, JSNS) in the last decade centered on the effects and mitigation of the pressure wave caused by the quasi-instantaneous deposition of large amounts of energy (60 kJ in ~1 s) in a few litres of Hg, with a large experimental programme led by the ASTE collaboration [5]. The focus of materials R&D for ESS has shifted away from these effects towards the other parameters that affect the lifetime of critical components such as hardening and embrittlement caused by prolonged exposure to the spallation radiation spectrum, corrosion in systems with flowing coolants (liquid metal, water or helium) and fatigue due to thermo-mechanical cycling of structural components.

Following a discussion of target lifetime, the different concepts considered for the ESS are described, highlighting materials issues. These concepts are classified independently of design maturity into two groups: stationary targets and rotating targets.

# Target lifetime

For this study, the operational schedule for ESS is defined on the basis of 5000 hrs/yr beam availability for users and must account for regular linac, target and instrument maintenance. The availability of neutron beams to users is quoted to be 5000 hrs/yr, corresponding to 25000 MW.hr/yr at ESS.

As an example of target reliability, at SNS the target was reported to contribute only 1.1 % in 2009 towards unscheduled downtime with the major contributors being proton accelerator components >80%. Depending on the chosen concept at ESS, target lifetime could offset expected improvements in Linac reliability and play a far more significant role in neutron availability to users. It is one of the main factors relevant in evaluating the feasibility of a target concept along with heat removal capacity, layout and environmental impact and licensing. Frequent target exchange interventions mobilize resources and increase the risk of unscheduled downtime.

Table 1: Recorded and predicted (p) lifetime of targets at various facilities. An operation year is 5000 hrs at full power for most facilities, i.e. 57% of a year at full power. SNS targets were changed before their design lifetime to fit a maintenance schedule. Estimations of lifetime with and without cavitation are given for JSNS.

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| Facility | Target | Damage | Int. Beam | Max. Power | Max. current density | Max. charge density | Time online |
|  |  | [dpa] | [MW.hr] | [MW] | [A/cm-2] | [C.cm-2] | [weeks] |
| SINQ | Cannelloni | 25 | 6840 | 0.86 | 31.4 | 900 | 104 |
| MEGAPIE (p) | 6 | 1368 | 0.72 | 31.4 | 214 | 20 |
| MEGAPIE | 6.8 | 1678 | 0.78 | 31.4 | 243 | 18 |
| SNS | Hg (p) | 10 | 5000 | 1.0 | 12.5 | 225 | 52 |
| Hg Target 1 | 7.5 | 3055 | 0.85 | 12.5 | 162 | 144 |
| Hg Target 2 | 7.2 | 3215 | 1.0 | 12.5 | 145 | 52 |
| Rotating (p) | 10 | 75000 | 1.5 | 27.2 | 4900 | 520 |
| JSNS | Cavitation (p) | 2 | 2500 | 1.0 | 15.5 | 140 | 26 |
| No cav. (p) | 5 | 6400 | 1.0 | 15.5 | 357 | 67 |
| ESS | Hg-2003 (p) | 10 | 7320 | 5.0 | 79.6 | 420 | 15 |
| Hg-2010 (p) | 10 | 10000 | 5.0 | 42.5 | 306 | 21 |

The peak accumulated proton charge density (max. current density × operation time) is shown in Table 1 for several facilities. Without accounting for differences in concepts, materials and beam profiles, Figure 1 maps roughly lifetime at different facilities and points to an apparent limit between 200 and 300 C.cm-2. The notable exception is the cannelloni target at PSI that is routinely operated up to 900 C.cm-2. There are essentially four possibilities to increase target lifetime:

* adopt different materials (lighter structural materials),
* adopt different concepts (windowless, rotating),
* adopt different design criteria (design into the brittle domain),
* decrease the proton beam maximum current densities by spreading the beam more evenly over a wider area (flat profile or wobbling/rastering).

With the exception of the windowless targets, stationary targets have short lifetimes at high power so that frequent target exchanges must be planned into the facility schedule. At 2.5 GeV and for a Gaussian beam profile with *x* = 50 mm, *y* = 15 mm, as a rule of thumb the maximum dpa rate in steels is 1 dpa per 1000 MW.hr. Taking 10 dpa as a limit for the target container vessel to ensure sufficient ductility and toughness remain for safe and reliable operation [6], a stationary target would have to be changed every 21 weeks, or more than twice a year, which remains acceptable for 5 MW beam power provided the maintenance schedule is compatible with the operation schedule, Figure 2. By spreading radiation damage over a much wider area, a rotating target can dilute the maximum neutron and proton radiation damage rate by a factor 30 or so and significantly increase target lifetime.

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| Figure 1: Peak proton charge density cumulated over lifetime of several stationary targets. The horizontal axis shows the beam energy. Targets at 575 MeV are from PSI, those at 1 GeV are from SNS, that at 1.334 GeV is from ESS2003, that at 2.5 GeV is from ESS2010 and finally those at 3 GeV are from JSNS. The point labeled “No cavitation” indicates the predicted lifetime if cavitation were not a lifetime-limiting process. |

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| Figure 2: Maintenance timeline for a stationary target. The duration of one operational cycle is set to 42 days, with typically 5 to 6 cycles per year. |

# Stationary targets

Stationary targets here refer to targets that do not have moving structural components but include concepts where the dense spallation material itself could be flowing such as the heavy liquid metal targets. The different targets considered in this family are the following:

* contained liquid metal targets (enclosed in a leak-tight vessel),
* windowless liquid metal targets,
* stationary solid targets cooled with liquid metals, helium or water.

## Heavy liquid metal target materials

Heavy liquid metal target materials fulfill both the role of neutron production and that of coolant. Radiation damage in the liquid metal is not an issue since it does not have a structural role, although radioisotopes and stable elements are produced in large enough quantities to potentially alter its chemical and physical properties.

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| Figure 3: Neutronics performance of ESS target concepts out of the moderator for a 1 ms pulse length. |

The liquid metals considered are mercury and pure lead or lead-based alloys such as lead-bismuth eutectic (LBE) or lead-gold eutectic (LGE). Mercury is liquid at room temperature which greatly simplifies its technical implementation compared with the Pb-based alloys. It has a relatively high absorption cross-section for thermal neutrons, an advantage at the operating short-pulse spallation sources SNS and JSNS since the flux of slower thermal neutrons from the target is significantly reduced, fast neutrons are incident on the moderators leaving a sharper/narrower cold neutron pulse for users. The constraints on neutron pulse width are less severe at a long pulse facility allowing for slower neutrons into the moderators. Figure 3 shows the moderated neutron flux from a mercury target to be lower than that from a lead target despite the higher density of mercury due to significant re-absorption of thermal neutrons within the mercury volume. Concerning physical properties, mercury has a boiling point of 357°C, much lower than that of lead at 1740°C, which translates into reduced margins for operation at 5 MW. Moreover mercury is highly volatile with a vapour pressure of 22 Pa at a typical operating temperature of 90°C compared with 2e-3 Pa for pure lead at 500°C, leading to increased risks of release of radioisotopes during normal operation, planned maintenance or accidental scenarios.

When comparing the different Pb-based options, LBE stands out as the liquid metal for which the most relevant experience exists. The ~1 MW LBE MEGAPIE target that operated for 4 months at PSI provided a proof of principle for the feasibility of such a target as a spallation source. Additional experience comes from the operation of Russian submarines of the ALFA class operated with LBE-cooled fast breeder reactors of 155 MW power for 80 operational years. However, LBE has two considerable drawbacks:

* production of radiotoxic (-emitting) polonium-210.
* Expansion by re-crystallisation after solidification.

The evaporation behaviour of 206Po was measured and found to be similar in pure lead, LBE and LGE [7]. Results show a good retention of Po in the Pb-based liquid metals up to 600-700°C. Although Po evaporation is not expected to be significant for normal operating conditions, reducing the source term is one of the more fundamental goals when licensing a spallation facility to demonstrate the safety case can be handled in accidental scenarios. With 100 to 1000 times less Po produced in pure lead or LGE, these two options have been proposed as alternatives to LBE.

Comparative studies on the corrosion behaviour of LGE and LBE in contact with SS316L on two separate but identical loops showed LGE to be far more corrosive. The concentrations of dissolves species in the LGE (m.p. 212°C) was significantly higher, especially for Ni but also Fe and Cr, when compared with LBE (m.p. 125°C), at two different test temperatures of 400°C and 450°C [8]. Further work is required to identify a structural material (e.g. T91) with acceptable LGE corrosion resistance.

Since pure lead it is not an alloy its properties under irradiation with uncontrolled cooling and heating rates do not introduce the additional uncertainties of those of LBE or LGE. One disadvantage of Pb is the high melting point leading to the highest operation temperature range of the liquid metals being compared here. Although a higher operating temperature can lead to faster self-annealing of radiation damage in structural components exposed to proton and neutron fluxes, it accelerates corrosion in the entire loop, decreases yield strength, and increases creep and release of radioactive species.

The choice of one Pb-based target material over another must be made weighing available data, carefully estimating the safety implications and establishing realistic R&D requirements. LBE is well known and its drawbacks can be extrapolated to the ESS case early in the design phase. LGE offers at first glance an attractive alternative although more knowledge must be acquired of its corrosion effects on structural materials, and of the complex radiochemistry (e.g. much larger production rates of the highly volatile mercury isotopes). Pure lead has its challenges which are mostly of a technical nature, i.e. operating an entire loop above 400°C.

## Cross-flow enclosed liquid metal target

Preliminary fluid dynamics calculations of LBE targets to keep the beam entrance window at an acceptably low temperature whilst ensuring removal of the heat in the target bulk show that it is feasible to operate a stationary liquid metal target at 5 MWb. As an example, for 2.25 MW deposited in a LBE target with a LBE mass flow rate of 155 kg.s-1 and inlet temperature of 200°C, first results of the optimization of a cross-flow target with flow guides and horizontal inclined plates show promising results: a maximum fluid and structural temperature of 350°C (Figure 4), a maximum velocity of 3.55 m.s-1 at the beam entrance window and a pressure drop of 0.3 bar (a factor 5 lower than the 1.5 bar of the ESS2003 Hg design). The high flow velocities would be a corrosion concern requiring further analysis. Transient simulations show a stable flow field with no significant fluctuations in the temperature distribution. For comparison, the SNS target operates routinely with a mass flow rate of 330 kg.s-1. Increasing the flow rate of the LBE target described here would provide a good margin for operation at 5 MWb and allow for operation beyond this beam power level.

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| a) | b) |
| Figure 4: LBE cross-flow target layout and internal positioning of vertical flow guides and horizontal inclined plates a) and target vessel temperature profile b). | |

## Windowless liquid metal target

Windowless targets have been proposed for a number of spallation applications, with studies such as those for PDS-XADS (600 MeV, 6 mA, 3 MWe, 2.6 MWth) and EFIT (800 MeV protons, 20 mA, 16 MWe, 11 MWth). Investigations of a windowless target for MYRRHA were also carried out, although the latest preferred solution is a design with a window. With the accumulated experience in this field and improvements in simulation tools, a windowless target option was studied for ESS. A modular design was proposed with separate target, pump and heat exchanger modules. The proton beam enters the target containment through a double safety window, so that although the target is windowless in the sense that there is no structural element directly in contact with the liquid metal at the point where the beam is incident on it, a safety window is present further upstream, Figure 5.

Transient thermohydraulic simulations were carried out to estimate the mean flow and temperature distributions within the target module using RANS (Reynolds averaged Navier Stokes) with the following conditions:

* average jet velocity 1-2 m/s,
* LBE inlet temperature: 200°C,
* Boundary conditions: adiabatic walls, no slip at walls, free surface
* LBE properties are a function of temperature (,,).

The results show a stable supercritical free surface with an acceptable maximum fluid temperature of 434°C (356°C at 2 m/s average jet velocity). The channel walls stay at a reasonably low temperature, with an operation temperature range between 280 and 350°C.

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| Figure 5: Left. Windowless target module schematic, showing PbBi flow direction, incident horizontal beam path, 15° inclination of the free surface and flow guides required to regulate the flow. Right. Neutron flux distribution (no units). | |

MCNPx (version 2.7a, with the CEM cascade model) simulations with nominal beam parameters for a PbBi target enclosed in a SS316 frame show that the side walls reach the highest level of damage. The side walls reach 14 dpaNRT/fpy (here 1 fpy = 5000hrs), 200 appm of He and 1000 appm of H, Table 2. A dedicated program was established to extend dpa cross-sections using the binary collision approximation method up to 2.5 GeV for Fe, Cr, Ni and He. Using the same model yielded 4 dpaBCA/fpy for the side walls. The bottom wall has a direct view of the beam so hydrogen and helium production rates in the side and bottom walls are essentially the same. The dpaNRT rate per MW.hr is a factor ~ 3 lower for a windowless target compared to a stationary enclosed “window” target at 2.5 GeV and opens up the possibility of operating such a target for over 1 yr.

Table 2: Comparison of displacement damage, hydrogen and helium production rates in the windowless 2010 design with values for the “window” 2003 study and for an ADS target.

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| Parameter | Units | ADS | ESS 2003 Study | | ESS 2010 Study | |
| Proton energy | GeV | 0.6 | 1.3 | | 2.5 | |
| Beam current | mA | 2.46 | 3.75 | | 2 | |
| Beam power | MW | 1.5 | 5 | | 5 | |
| Position | - | BEW | Target | Reflector | Side wall | Bottom wall |
| Damage rate | dpaNRT/fpy | 32 | 33 | 10 | 14 | 7 |
| Hydrogen | appm/fpy | 9000 | 50000 | 360 | 1000 | 900 |
| Helium | appm/fpy | 1400 | 1000 | 60 | 190 | 180 |
| appm H/dpa | - | 280 | 300 | 36 | 70 | 128 |
| appm He/dpa | - | 44 | 30 | 6 | 14 | 27 |

## Helium-cooled solid stationary target

Helium-cooled targets made of tungsten spheres were first proposed for 4 MW neutrino factories where the proton beam time structure is challenging (50 Hz, 3.3 s pulse duration) [9]. The motivation was that the dynamic response of the spheres would be acceptable since pressure pulses and vibrations would be greatly reduced. For the ESS case, the proton pulse length of 1-2ms is much larger than the propagation time for a pressure wave in a cm-sized sphere. Assuming a tungsten porosity of 26%, 13.7 g.cm-3, the peak power density (for an averaged porous medium) is 2.31 kW.cm-3. This value is estimated considering the medium as uniformly made of tungsten. If considering a full density tungsten block, the maximum power density is 3.3 kW.cm-3, equivalent to 9 J.g-1.pulse-1. This will induce a *T* of 60 K.pulse-1 for the centered sphere.

For spheres with 1 cm diameter, assuming a heat transfer coefficient for forced convection of 1 W.cm-2.K-1 the time constant for cooling is ~420 ms, a factor 8 larger than the 50 ms between pulses so that cooling remains feasible, with temperatures of the hottest sphere oscillating between 340 K and 400 K above the helium temperature at that point.

In order to better match the cooling requirements to the energy deposition profile along the beam axis, it was proposed to split the flow of helium into three separate zones, with helium at 15 m.s-1 and 40 bars at the front, 7.5 m.s-1 and 35 bar in the middle and 2 m.s-1 and 30 bar at the rear. Figure 6 shows the temperature profile in the helium for such a setup.

Transient simulations on a single sphere with 3 s of pulsed beam operation followed by 3 s of beam switched off show that stress levels due to the pulsed beam are small ( = 4 MPa, see Figure 8: stress ratio = 0.9) compared to those due to a beam trip ( = 67 MPa, see Figure 8: stress ratio=0), Figure 7. Taking DENSIMET 185 tungsten alloy as an example, theoretical Wohler curves, Figure 8, indicate that the material should withstand more than 108 beam trips (large stress amplitude), well above operational conditions.

The tensile strength of DENSIMET 185 falls from ~800 MPa at room temperature to 400 MPa at 800°C. It is important to remain below 800 °C for the most stressed sphere, located at the center of the target where the power deposition is greatest (and so is its internal ∆T). This sphere is not the hottest, which is located further away towards the outlet of the helium. The failure of a sphere should not impair the operation of the target, as it will result in cracks on the sphere surface.

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| Figure 6: Temperature distribution in the helium coolant of a tungsten sphere target. A quarter of the target is cut out to better visualize the temperature profile. |

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| Figure 7: Transient simulations of stress in the hottest sphere. The proton beam is sent to the target for the first 3 seconds and then switched off for the remaining 3 seconds. |

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| Figure 8: Stress range (difference between the maximum stress and the minimum stress during one cycle) against the number of cycles. Theoretical SN curve for DENSIMET 185, obtained from GRANTA database CES2009. |

## Water-cooled solid stationary target: cannelloni

The “cannelloni” target [10] has been successfully operated at SINQ-PSI under cw beam conditions at up to 1 MW. In the cannelloni target concept, an array of zircaloy hollow rods filled with lead is cooled with flowing water. First results show that this target is technically feasible at 5 MW [11]. At 2.5 GeV, 5 MW and a peak current density of 42.4 A.cm-2, the peak energy deposited is 1.95 kW.cm-3 or roughly twice as much as is currently deposited at SINQ with 590 MeV protons at ~ 1 MW which incidently has a very similar proton current density approaching 40 A.cm-2. The current density at SINQ accidentally reached 70 A.cm-2 in October 2004 [12] and although the coolant flow was not optimized for these conditions, no damage was observed on any of the zircaloy tubes filled with lead.

As a basis for initial calculations, the well known heat transfer coefficients as a function of heat flux and temperature for cooling a single tube in water flowing at 0.75 m.s-1 were used [13]. A crucial consideration is enhanced cooling due to the rise time of the surface temperature: above 150°C, sub-cooled boiling leads to heat fluxes above 3.5 MW.m-2 and heat transfer coefficients well above 0.03 MW.m-2.K-1. Figure 9 shows the temperature distribution in a tube with water flowing in a cross-flow configuration in the most stressed tube in the center of peak energy deposition. The peak temperature in the lead is around 900°C, well above its melting point of 327°C. The average contact temperature between lead and zircaloy is ~500°C and the zircaloy is at ~200°C on its outer surface.

The thermal contact between lead and zircaloy is guaranteed because if the lead were to heat up excessively through the absence of a thermal path to the coolant, it would melt and thus automatically re-establish thermal contact.

Past experience at a continuous 1 MW source has demonstrated that safety, cost and reliability are positive features of this concept. The main drawback is that although target compactness can be relaxed at a long pulse spallation target, the diluted density of the neutron production material leads to significantly lower neutron yields compared to most other concepts described here. It must also be re-evaluated for use at a pulsed spallation source.

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| Figure 9: Axisymmetric model of the most loaded tube, reference beam conditions, safety factor of 1.5 on heat generation and 1.25 on heat transfer coefficient; “Aussenseite” refers to the surface temperature of the zircaloy tube, “Kontakt” to the interface tube/lead, and “Zentrum” to the temperature maximum in the center, from [11]. |

## Sodium-cooled solid stationary target

Liquid metal-cooled solid targets have been proposed in the past. They can be divided into 2 categories: high Z liquid metals where the LM contributes to the spallation process (e.g. MTS, the Materials Test Station proposed at LANL and consisting of tungsten blocks cooled with LBE) and low Z liquid metals. Here, a low Z Na-cooled solid Tungsten target is proposed, motivated by the requirement to keep the spallation volume as compact as possible, hence combining the best neutron production material with the most efficient cooling fluid. The following points were considered in choosing Na:

1. it does not adversely affect neutronic performance,
2. it has excellent cooling properties, especially when compared to water,
3. handling during maintenance is less constrained, especially compared to heavy LM systems such as the Hg targets at SNS and JSNS where irradiated mercury sticking to the circuit walls imposes additional constraints during the maintenance,
4. the safety cases, mainly the sodium water and sodium air reactions, are a concern but could be manageable, due to the relatively small total amount of sodium and heat removal requirements compared with operational Na-cooled reactors.
5. all the necessary technology associated with sodium loops in a nuclear environment is used and proven for more than 50 years.

Neutron fluxes feeding the moderators will be optimized if the global compactness of the target leads to a density close to that of pure W. An average density of a Na-W target could be as high as 17 g.cm-3, 20% higher than a water-cooled rotating tungsten target. In addition, the thermal neutron capture cross-section is low, 0.51 b, compared for example with 374 b for Hg.

In forced convection conditions under normal operation, a simulation of a Na-cooled tungsten target for a compactness of 74% (W rod diameter of 1 cm) gives (Figure 10):

* an operating temperature for Na between 200 °C and 360 °C,
* a maximum W temperature under 550°C (no cladding, pure W),
* a very low pressure drop (approximately 0,08 bar).

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| Figure 10: Left - CFD simulation for compacted W rods of 1 cm of diameter, cooled by liquid Na 1.25. Right – VM stresses in W rods. | |

Compatibility of sodium and tungsten is excellent under non-irradiated conditions [14]. Nevertheless, it should be investigated further under a spallation environment where compatibility issues could arise. If this were the case, cladding/canning could be considered as a back up solution, in order to minimise W fragment release into the Na coolant. Na could also be used between W and cladding/canning material to ensure good thermal contact and thus lower the maximum W temperature. This solution might allow the reuse of irradiated W blocks if their lifetime is longer than that of the steel containment.

Due to its low Z, the range of radionuclides produced in Na in a spallation environment is far more limited when compared to the high Z liquid metals (Hg, Pb, LBE). Although Na is well known under thermal and fast neutron fluxes, it will be necessary to test it under proton irradiation (GeV range). It is expected that activation will be less severe compared with high Z LM circuits. Impurities adsorbed on the circuit walls or modifying Na surface tension should be limited. Procedures for flushing the Na out of the loop and into storage tanks have been developed for fast reactor technologies and are mature. This would allow a complete and efficient draining of the loop during maintenance periods. The important implication is that only a relatively small volume of the target subjected to the proton beam would require remote handling for maintenance and waste conditioning. A light transport cask could then be used to transport this element to a hot cell that need not be located close to the target monolith. The other parts of the Na circuits could be maintained and operated “hands on” when drained in the basement. The target systems layout inside the monolith is represented in figure 11 below.

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| Figure 11: Target systems layout inside the monolith. Monolith center: W container with its lateral remote access trace of the proton beam represented coming from the back side of the monolith. Lower rooms under the monolith: Solid Na storage tanks (lower room) and main components of the Na circuits (upper room incl. pumps, heat exchanger). |

# Rotating targets

The lifetime and heat removal limitations of stationary targets motivated the original SNQ rotating target concept of the 80ies. Since then, many derivatives have been proposed, the most widely studied of which have been water-cooled tungsten targets. However, since tungsten corrodes in the presence of water and because of tungsten oxidation at high temperatures (>500oC), other cooling mechanisms based on helium or liquid metals have been suggested.

The critical components in rotating targets are:

* **tungsten or one of its alloys:** it must operate below a determined temperature limit to avoid excessive oxidation in contact with oxygen-containing environments (such as air or steam) especially in accidental scenarios where above 800oC, WO3 is particularly volatile and can act as a vector to propagate other radioactive species in and away from the target station.
* **Seals:** the seals in a rotating system must remain leak tight throughout their design life.
* **Bearings:** bearings must be designed to be operational under the radiation environment they will be submitted to.

## Water-cooled rotating targets

Water-cooled options must ensure that the tungsten is not in contact with water:

* cladding tungsten with a thin layer of tantalum.
* edge-cooling of an aluminium plate connected to the tungsten.
* inserting tungsten rods in Zircaloy canisters with a layer of lead between the tungsten and the canister to ensure good heat transfer. [15]

A water-cooled rotating (30 rpm) target has been explored for ESS. It is a compact design, with an outer radius of 75 cm and height of ~10 cm and consists of six concentric rows of tungsten bricks connected top and bottom to aluminium plates into which 10 mm-wide cooling water channels are machined. Thermo-mechanical studies assuming perfect contact between tungsten and aluminium, and a heat transfer coefficient for the water cooling system of 68 kW/m2, show that the hottest tungsten brick located on the outermost rim of the wheel reaches a peak temperature of 450°C for a steady state analysis, the water is at 30°C and the aluminium plates approx. 60°C. For the geometry shown in Figure 12 left, the top and bottom plates each dissipate 4 kW of heat. Transient simulations show the peak temperature varies between 420 and 500°C, Figure 12 right. Slightly higher values still of 450°C/540°C were obtained when a more rigorous analysis of the beam incidence on the target was carried out. Essentially, because the target only rotates by 9° between pulses, the tungsten brick modeled would partially be subjected to two consecutive beams and in addition would not receive in exactly the same spot the beam 2s later.

For comparison, an alloy of tungsten, DENSIMET 176, was also modeled. It showed poorer thermal performance with higher temperature peaks: although the thermal conductivity of DENSIMET 176 increases with temperature, which is the opposite trend to that of pure tungsten, its starting value at room temperature is almost a factor 3 lower. SS316 was also modeled as the cooling plate material, but due to its lower thermal conductivity, it was a less efficient system for heat removal, the peak temperature reaching 650°C.

By both increasing the wheel radius to 100 cm and decreasing the height to 6.5 cm, the peak temperature in the tungsten would vary between 180°C and 260°C.

With a rotating wheel, radiation damage is spread across a much larger volume in the target. The aluminium would receive 3.5 dpa/fpy (5000 hrs at 5 MW) and the tungsten 1.4 dpa/fpy, indicating that the target would have a lifetime in excess of 4 yrs.

The promising preliminary results of this design raise the question of how to implement the contact between tungsten and aluminium. Since the contact surfaces are fairly large and planar, explosive bonding is a potential bonding technique. Further from the beam interaction zone, critical components require detailed investigations, namely seals, bearings and drives. In addition, very little data exist on the properties of irradiated tungsten. In order to address the many uncertainties related to a rotating target, a two-stage approach has been proposed of using multiple quasi-stationary cannelloni-type targets on a rotating wheel configuration as illustrated in Figure 13. The wheel does not rotate during normal operation so that the beam is incident on one cannelloni target. When it reaches the end of its service life, the wheel is rotated by a fraction of a turn to expose a new target. This approach combines a tried and tested target solution with a new layout (shaft or trolley), since moderators and other stationary components may need replacing more frequently than the target.

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| Figure 12: Left. Temperature profile for the hottest brick. Dimensions are width: 60mm, height ~100mm, depth 39mm. Right, peak temperature in the outermost tungsten brick as a function of time. | |

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| Figure 13: Multi-body cannelloni target on a rotating wheel platform, from [11]. |

## Helium-cooled rotating targets

The requirements on a helium cooling circuit for a rotating granular target are rather modest: 10 bar pressure, 5 m/s velocity. For the hottest sphere, its temperature difference with the helium inlet temperature is less than 500 K. The local peak helium temperature is below 700 K. Pulsed peak stresses inside spheres would be well below 10% of the yield strength of W. Since stresses are much lower compared with a stationary granular target, it is possible to consider rods. With 10 cm height, 2 cm diameter W rods arranged in a horizontal target ring with an outer diameter of 150 cm and an inner diameter of 50 cm, the temperature difference between rod surface and helium is 246 K, Table 3. The maximum temperature and stress are 812 K and 102 MPa respectively, Figure 14. The pressure drop across the target is negligible (442 Pa for case 1 in table 3 and 885 Pa for case 2 in table 3). Leak tightness of Helium seals will have to be assessed, as well as the interaction of helium with tungsten under these temperature, stress and flow conditions.

Table 3: Summary of simulation parameters for a rotating He-cooled W rod target.

|  |  |  |  |
| --- | --- | --- | --- |
| Property | Case 1 | Case 2 | Case 3 |
| Pressure [bar] | 10 | 20 | 10 |
| Temperature [K] | 500 | 500 | 500 |
| Density [kg/m3] | 0.96 | 1.92 | 0.96 |
| Mass flow rate [kg/s] | 20 | 6 | 6 |
| Velocity in channel [m/s] | 132 | 19.8 | 39.7 |
| T in flow [K] | 28.9 | 96.3 | 96.3 |
| T between surface and fluid [K] | 34.7 | 246 | 246 |

|  |  |
| --- | --- |
|  |  |
| Figure 14: Maximum temperature and stress in the rotating He-cooled W rod target. | |

# Discussion

The liquid metal target material retained for further study under ESS conditions is LBE based on the extensive experience gained on its use in a spallation environment. It would be implemented as a stationary target, with both fully enclosed and windowless options being considered. As was mentioned earlier, there are substantial challenges to be met for a stationary liquid metal target. The structural material in contact with the LBE will be subjected to a hostile combination of irradiation environment and high flow velocities causing hardening, embrittlement and significant corrosion. These will determine the lifetime of the target module, which will require frequent changes that must be planned into the facility schedule. The upgrade path for a stationary target appears limited as it should balance the technical feasibility limit (maximum admissible temperatures, velocities and hydrostatic pressures) with the practical limit of number of target exchanges per year.

Amongst the rotating targets based on tungsten, both water-cooled and helium-cooled options are to be further studied. The choice of grade of tungsten or one of its alloys is yet to be made. Databases on tungsten properties at room temperature exist but at higher temperatures under irradiation, relevant properties are scarce. For the design phase, knowledge of the temperature and irradiation dependence of relevant properties is mandatory even though the tungsten would not necessarily fill a determining structural role on the rotating target module. When comparing different tungsten alloys, the variation of properties (unirradiated) as a function of density can be taken as a good indicator. As an example, DENSIMET and INERMET alloys are compared here. An increase in density benefits neutron production and many physical properties such as thermal expansion coefficient, and thermal conductivity. The most significant exception to this rule is tensile strength, with a parabolic dependence on density for both INERMET and DENSIMET alloys and a peak for a density of 17.6 g.cm-3. INERMET alloys present better thermal conductivity values, 30% higher than DENSIMET alloys. However, DENSIMET alloys have better compressive strengths, tensile properties, fracture elongation and hardness. The evolution of material properties during irradiation and their activation (e.g. INERMET and DENSIMET have a high Ni content, leading to significant 60Co production) must be assessed in the selection process.

The use of engineering codes in the design of ESS target station components would ensure these meet safety standards. Existing codes used in nuclear engineering do not cover the spallation domain. Adapting these codes would require data from materials testing in spallation environments. This would be an iterative process: initially data from previous spallation tests could be reviewed. Further testing of already irradiated components or new irradiation programmes would then be carried out to provide the required additional data.

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