Chapter 3

Target Station

Chapter abstract

Summary: The main function of the target station is to convert the high-energy proton beam from the accelerator into low-energy neutron beams with the greatest possible efficiency, safety and reliability. This chapter describes three groups of target station subsystems, and the design characteristics that enable them to deliver this key functionality. The first group consists of the target monolith and the components it houses, including among others the target wheel, the moderator-reflector and the beam extraction systems. The second group is made up of fluid systems. The third group includes the handling and logistics subsystems for radioactive components of the target station operation.

Target monolith and associated subsystems. The first group of subsystems will interact directly with protons and/or neutrons. It includes the proton beam window, the rotating target wheel system, the moderator-reflector assembly and the beam extraction system. The target station safety system is also a crucially important part of this group. The target material (tungsten) will transform high-energy protons to fast neutrons. The moderator-reflector system surrounding the target will transform the fast neutrons into slow neutrons, which will be guided to neutron scattering experimentalists via the beam extraction system. These neutronically active subsystems will be housed in the target monolith, which is composed of 7000 tons of steel shielding. The target monolith is designed to contain the highly-penetrating gamma and fast neutron radiation that will be created by the spallation and radioactive decay processes. The baseline technology chosen for the target is a rotating tungsten wheel cooled by inert helium gas. The surface area of the wheel is large enough that, in the event of a loss of power and/or coolant, passive cooling would prevent unsafe target temperatures with a significant safety margin.

Fluid systems. The second group of subsystems consists of fluid systems, including the closed cooling circuits and the radioactive gaseous effluents and confinement system.

Handling and logistics subsystems. The third group of subsystems includes active cells, casks and remote handling systems. These subsystems transport, exchange, maintain, process, package, store and release the used radioactive components from the target station operation.

Fallback and comparative target technologies. Two other target concepts are explored, in order to provide a complete and robust technical underpinning for the ESS design. A water-cooled rotating tungsten target is the designated back up option, while a lead-bismuth-eutectic (LBE) target is used as a comparative option, primarily to assess environmental impact.

Target station interfaces with the rest of the facility are complex. Chapters 5, 8 and 9 detail ESS integration strategies.

Target design support. Advanced multi-physics simulations of target subsystem components are used in an iterative fashion, to optimise neutron beam performance, to address issues of technical realisation and operation, and to ensure a robust and cost-effective design. A database of the characteristics of the irradiated and un-irradiated materials used in the target system provides a crucial underpinning for the engineering design of target system components.
CHAPTER 3. TARGET STATION

3.1 General description

3.1.1 Summary of basic requirements and design choices

The function of the target station is to convert the intense proton beam from the accelerator into a number of intense neutron beams. This conversion is achieved by the interplay of a number of basic functions. The heavy metal target absorbs the impinging proton beam radiation from the accelerator and transforms it via the spallation process into fast neutrons as the useful product, while generating a large amount of heat, radioactive isotopes and prompt radiation as unavoidable by-products. The moderator-reflector assembly surrounding the target transforms the fast neutrons emitted by the target into slow neutrons, which are the final form of useful radiation provided by the neutron source, while further radioactive waste is produced by the absorption of neutrons by various target structures. (Here, “fast” means neutrons with velocities in the range of 10% of the velocity of light and “slow” means velocities comparable to the speed of sound.) These two neutronically active systems are surrounded by a radiation shielding system of approximately 7000 tons of steel, in order to contain the extreme level of highly penetrating gamma and fast neutron radiation created in the target and its vicinity. The beam extraction system provides intense slow neutron beams through beam guides which traverse the target shielding. These neutron beam guides are accessible at the surface of the shielding, for delivery to and use at the neutron-scattering instruments facing the beam ports at variable distances. The proton beam window separates the high vacuum in the accelerator from the atmospheric-pressure inert helium gas inside a large container vessel, in which all of these systems are housed. They form, together with the tight container, the target monolith, which takes the shape of a 12 m diameter and 10 m high cylinder.

At ESS, the proton beam will deliver 5 MW power in the form of kinetic energy. About 10% of this energy is converted to mass through the nuclear reactions in the spallation process that produces neutrons, other nuclear fragments, isotopes and gamma radiation. The kinetic energy of these particles makes up the remaining 90% of the proton beam energy, and it is almost all deposited within a distance of 1 m from the site of proton beam impact in the target. Different cooling circuits in the target monolith remove this large amount of heat from the target itself (3 MW), from the moderator-reflector assembly (1.2 MW) and from the monolith shielding (0.3 MW). The proton beam window is directly heated by the traversing beam and requires cooling of about 6 kW, though this value is strongly dependent on window design details.

Radiation damage and fatigue limit the lifetime of the three most strongly affected systems: the target, the reflector-moderator assembly and the proton beam window. All of these systems will need to be changed multiple times during the lifetime of the facility, with frequencies ranging between 6 months and 5 years, as conservatively estimated on the basis of available experience at spallation sources. The removed used components represent a considerable amount of radioactive waste. The other part of the radioactive waste consists of gases, volatiles and airborne particles, which will be continuously captured by a variety of efficient filters and traps. (See Chapter 10 for further discussion of emission and waste control, management and disposal.)

These functional properties determine the basic requirements that the target station must fulfil:

1. Maximising the neutron yield from the moderators for a given proton beam energy requires keeping the volume of the target on which the proton beam impinges as small as possible, using a target material of high atomic number and high density. At ESS, the effective proton beam cross section on the target will be 100 cm$^2$, and tungsten has been selected as the affordable, high-density target material. Tungsten is one of the most commonly used and well-established choices at existing spallation sources, albeit of much lower power level than ESS.

2. The optimal design of the moderator-reflector system is the other requirement for providing maximal neutron beam performance. For this purpose, the ESS target station will be built with two state-of-the-art, liquid-hydrogen cold neutron moderators, partially surrounded by a water premoderator and beryllium reflector. For each beamline, provision will be made for extracting both cold and thermal beams within the same neutron guide when appropriate, with the help of the bispectral beam extraction concept successfully developed and implemented at HZB. The moderator-reflector design concept allows for the regular implementation of future technical improvements during the lifespan of the facility, whenever the used reflector-moderator system is exchanged for a new one.

3. The viewed, neutron-beam emitting surfaces of the moderators need to be well coupled to the supermirror-based neutron optical beam extraction systems, both for conventional and bispectral
neutron beam guides. Carefully balancing the need to make room for beam extraction openings against the need to maximise the reflector volume is necessary to achieve the best moderator brightness possible.

4. Providing adequate cooling for the target at the 5 MW power level of ESS requires distributing the heat over a much larger volume than the few litres instantaneously irradiated by the proton beam. This can be achieved by a rotating target, with a total active volume much larger than the one momentarily irradiated by each proton beam pulse. The same goal has been attained by other existing modern high-power spallation sources by using circulating liquid mercury as the target material.

5. Cost efficient operation requires a reasonable target lifetime. The principle of a rotating target also dilutes the radiation damage to the materials constituting the target and provides for an adequately long target lifetime of as much as 5 years, estimated on the basis of existing experience with spallation targets built and operated to date.

6. The radioactivity created in the spallation process must be safely contained both in normal operation and in case of accidents, in order to avoid harm to inhabitants living around the facility, personnel and the environment. The radioactivity of the irradiated target material leads to the phenomenon of afterheat, that is, to the development of heat over an extended period of time in the used target even when the proton beam is switched off. Overheating could lead to the escape of radioactivity, so a key safety requirement is to secure a fully fail-safe mechanism for removing the afterheat in the case of loss of cooling, for example in the case of a loss of electric power.

7. The exchange of used, highly radioactive system components requires careful design, planning and extensive auxiliary equipment for protecting workers and the environment in all phases along the path from removal from the monolith through handling, storage, preparation for transport to the disposal site, transport and disposal.

8. The presence of a considerable radioactive inventory inside the monolith and also in the temporary storage on-site requires extensive safety systems for controlling and mitigating the consequences of both operational accidents and the impact of external natural or man-made disasters (earthquake, airplane crash, etc.).

Fulfilling all of these requirements is crucial for the safety of ESS operation, and it has significant implications for the construction and operating costs of the target station and for its performance in delivery of high intensity neutron beams. Optimisation of the cost-to-benefit ratio is an important design goal, which very strongly impacts the total value delivered by the whole facility. In particular, the target station accounts for only about 9% of the total ESS investment, which implies a high leverage in the impact of investments in target performance on the performance of ESS as a whole. For example, a 10% variation in neutron production efficiency of the target would be equivalent for facility output to a variation in similar proportion of the accelerator power, a parameter with very substantial consequences for the total project costs.

**Target baseline and options**

A helium-gas cooled rotating tungsten target of 2.5 m diameter has been selected as the baseline and a water-cooled rotating tungsten target of the same dimensions as the back-up option. A lead-bismuth eutectic liquid metal target has also been studied as a comparative option for environmental safety assessment. The baseline option offers the highest neutronic performance and the lowest inherent environmental safety risks and mitigation costs for ESS, which will be a spallation source operating at an unprecedented power level. The choice of the target wheel diameter assures distribution of the total heat deposition, activation and afterheat over 33 target sectors forming the circumference of the target wheel, with each sector receiving 1 in every 33 proton beam pulses. The surface area of the target wheel will be large enough that passive cooling by radiation and heat conductivity of stagnant helium gas will preclude dangerous overheating of the target in the case of accidental loss of active cooling, for example, due to loss of electric power. Helium gas cooling has been developed and extensively tested as an option for nuclear power plants.
and it is being developed in fusion research for cooling tungsten diverters at much higher power levels than ESS.

The water-cooled rotating target back-up option is intended to occupy the same space as the baseline target. It would require the use of heavy water coolant to match the neutronic performance of the helium-cooled version. This reliance on heavy water, coupled with the inevitable protective enclosure of the tungsten target material against the corrosive water environment if tantalum (the most common choice) is used for the protective enclosure, result in higher radioactive inventory and significantly higher afterheat. The presence of water vapour makes the target more vulnerable to overheating due to the onset of target vapourisation at about 700°C by exothermic water reduction reaction. Similar behaviour of zircaloy is a well-known issue in nuclear safety.

A liquid metal target is the alternative solution to a rotating wheel for the dilution of the heat deposition and afterheat. In studying liquid metal designs, mercury has not been considered for ESS due to the absence of an established and approved disposal technology for this material after irradiation. The development of such a technology would require too much time to be feasible and its costs could very well prove to be comparable to a large fraction of the construction cost of the entire target station. In contrast, lead-bismuth eutectic is solid at room temperature and is acceptable for irradiated waste disposal. From an environmental point of view, however, its operation creates higher radioactive inventory and involves higher risk of the escape of volatile radioactivity in case of accidental overheating than the rotating tungsten target. It also has different spatial requirements compared to the rotating tungsten target baseline. For these reasons, it was not selected as the preferred back-up option.

Neutron beamlines

The traditional layout scheme of beamlines at pulsed spallation sources is a relatively uniform, pre-determined distribution around the target station covering between 110 degrees and 120 degrees of beam extraction sector on each side of the target monolith, with respect to the proton beam direction. However, the intensity of the neutron beams can be enhanced by reducing the accumulated angle of the beam extraction sectors, that is by minimising the associated removal of reflector material around the moderators. For a given number of beamlines, this implies grouping them in bundles as close to each other as possible. For this reason, about 1.5 degrees of separation is the general practice for beamlines using neutron guides at continuous neutron sources. Target engineering studies have shown that 5 degrees minimum angular separation is feasible for ESS, although it might be too small for a number of short instruments.

Creating a 5 degree grid of possible beam port positions in the target monolith design offers the possibility to flexibly group the beamlines in beam extraction sectors with minimal angular width during the full life-cycle of the facility, as the detailed requirements of early and later instrument suites take shape. For instruments that need more lateral space (primarily short instruments), 10 degrees or 15 degrees of separation with respect to neighbouring beam lines can be selected. For example, of the 22 instruments in the ESS reference suite presented in Chapter 2, 60% are longer instruments with 5 degree beam separations and the rest are shorter instruments requiring 10 degree separations. In this arrangement, the neutron beam intensity will be 15% to 18% higher than it would be using the common approach of predetermined beam positions spread more widely around the monolith.

An additional important feature of beam extraction at ESS is that every beamline will have the option either to use both cold and thermal neutrons by bispectral beam extraction, or to extract only one of these spectra. Experience with the prototype bispectral beam system built at the BER-II reactor in Berlin shows that the unmodified beryllium reflector around the cryogenic liquid hydrogen moderator is by itself a good source of thermal neutrons. Neutronics studies by ESS and collaboration partners demonstrated better thermal neutron performance by using extended viewable surfaces of the water premoderator next to the hydrogen moderators.

The target design choices presented here represent an advanced, but not yet final stage of optimisation. Meeting the April 2019 project milestone to start commissioning the target station with neutron beam production requires that the design be finalised and frozen by the third quarter in 2014. The time until this date will be used to fine-tune, further optimise and demonstrate the engineering design of the target station.
3.1. GENERAL DESCRIPTION

3.1.2 Target station layout

The target station (TS) building is divided into several building parts, with different operational functions and different requirements for confinement and shielding in terms of user access during operation and maintenance. Figure 3.1 illustrates the building part-numbering convention. The monolith (part 1) contains mainly the target, the moderators and the shielding. The utility rooms (part 2) house different target systems connected to the monolith, including the helium cells, the utility cells and the target basement. The accelerator-to-target (A2T) section (part 3) is the interface between the accelerator and the target station. The connection cells (part 4) are located on top of the monolith, where circuits penetrate into it. These target station building parts 1 to 4 mainly house the target station systems related to the proton beam and the neutron beams. Two additional parts, the active cells (part 7), which are used to process radioactive components, and the transport hall (part 8) for the external shipment and reception of large components, are connected to the beams-related systems by the high bay (part 5), which permits all transfers and movements of components. Figure 3.2 gives an overview of the target station building. The two experimental halls (part 6) around the monolith house the short instruments and the neutron guides serving long instruments (located in other buildings), and are connected by a...
passage for personnel and components.

The experimental hall constitutes the reference level for the instruments (ground floor), around which the other main levels are positioned. Tables 3.1 and 3.2 summarise the dimensions, relative heights and absolute altitudes of the main TS parts and levels. The proton beam level is 1.8 m above the ground floor. The two reference levels for the neutron beam guides are located approximately 0.18 m above and below this proton beam level, facing respectively the top and bottom moderators.

The A2T section (TS building part 3) hosts the tune-up dump in the lower room, which is used to tune the linac when the proton beam is not being sent to the target wheel. The lower room is located on the same level as the accelerator tunnel. In the upper room, the A2T hosts the last collimator before the high-β protons pass the opening of the confinement valve of the target monolith. This A2T confinement valve forms a part of the second barrier for the primary radioactive inventory, which is an extension of the monolith liner. Table 3.3 gives barrier definitions. The proton beam tube connects the A2T confinement valve to the proton beam window. During shutdown periods, if activated components (the collimator, the tune up dump, the proton beam tube, the A2T confinement valve, etc.) need to be replaced, their handling will be carried out towards the high bay, for a final transfer to the active cells. A cask will be used for handling if the level of remaining activation makes this necessary. For this reason, the above-mentioned A2T components are designed for remote handling. These systems are shielded below and laterally by steel blocks, and by the concrete structural walls and floors of the A2T itself. The upper shielding is composed of removable parts, and is accessible from the high bay. Specific shielded plugs are foreseen for the A2T confinement valve and proton beam diagnostic systems, which are located downstream of the collimator. These components are designed to allow their exchange during normal maintenance periods.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total building length</td>
<td>133</td>
</tr>
<tr>
<td>Internal building width</td>
<td>22</td>
</tr>
<tr>
<td>Monolith external diameter</td>
<td>12</td>
</tr>
<tr>
<td>Length from monolith centre to upstream building end</td>
<td>18</td>
</tr>
<tr>
<td>Length from monolith centre to downstream building end</td>
<td>115</td>
</tr>
<tr>
<td>Total length of the connection cells</td>
<td>24</td>
</tr>
<tr>
<td>Total length of the helium cells</td>
<td>30</td>
</tr>
<tr>
<td>Total length of the active cells</td>
<td>45</td>
</tr>
<tr>
<td>Total length of the transport hall</td>
<td>18</td>
</tr>
<tr>
<td>Floor slab and wall thickness (current zones)</td>
<td>1.0</td>
</tr>
<tr>
<td>Free space above the experimental hall floor (near monolith)</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Table 3.1: Main target station building dimensions.
3.1. GENERAL DESCRIPTION

<table>
<thead>
<tr>
<th>Target station rooms and floors</th>
<th>Relative height [m]</th>
<th>Altitude [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility rooms (basement)</td>
<td>−5.50</td>
<td>73.1</td>
</tr>
<tr>
<td>Tune-up dump room</td>
<td>−3.80</td>
<td>74.8</td>
</tr>
<tr>
<td>Active cells and transport hall</td>
<td>−3.50</td>
<td>75.1</td>
</tr>
<tr>
<td>Experimental halls, collimator room, utility rooms</td>
<td>0.00</td>
<td>78.6</td>
</tr>
<tr>
<td>Connection cells</td>
<td>5.50</td>
<td>84.1</td>
</tr>
<tr>
<td>High bay</td>
<td>11.50</td>
<td>90.1</td>
</tr>
<tr>
<td>Crane hook maximum height</td>
<td>24.00</td>
<td>102.6</td>
</tr>
</tbody>
</table>

Table 3.2: Target station room and floor heights and altitudes.

The monolith (TS building part 1) is a cylinder made of steel and reinforced concrete, housing the irradiated components during ESS operation, as described in Section 3.3. The steel monolith is encapsulated in a steel liner that isolates the steel shielding from the concrete to assure high quality helium throughout the lifetime of the target station and contains radioactive isotopes inside the monolith in normal and accidental situations. This steel shielding and the reinforced concrete volume inside the monolith are structurally connected. This structural block is anchored both in the supporting slab and in the V-shaped walls of the A2T (upstream of the monolith) and of the utility rooms (downstream of the monolith). The V-shaped walls for the A2T and the utility rooms are symmetrically laid out around the proton beam axis, to allow a flexible distribution of 22 neutron beam guides of the construction phase, among the 48 potential neutron beam ports. From a structural viewpoint, the monolith’s structures are not connected to the connection cells that are located above it. This assures the stability of the monolith during normal and accidental situations, including aeroplane crash and earthquake.

The connection cells (TS building part 4) are located just above the monolith, as shown in Figures 3.1 and 3.3. This is the location in which the permanent circuits are connected to the vertical plugs in the monolith. The functions of the connection cells include confinement, since the cells serve as part of the second confinement barrier, and separation of hazards related to the target station circuits, such as tritium, cryogenics, hydrogen explosion, et cetera. The connection cell walls include a network of horizontal structural beams between the connection cell floor level and the high bay slab level. This entire structure, composed of structural beams, connection cell floors and the high bay slab, is connected to the two V-shaped structural walls.

The utility rooms (TS building part 2) are located downstream of the monolith and connection cells, as shown in Figures 3.1 and 3.3. They contain, from the top to the bottom levels, the helium cells, the utility cells and the target basement. The helium cells contain the helium circuits and associated systems, such as the pressure control system (PCS), and the purification and filtering systems, as discussed in Section 3.4.1. The utility cells host permanent circuits connected to the monolith, the intermediate cooling circuits and their interfaces with conventional facilities (mainly external cooling systems). The target basement houses

<table>
<thead>
<tr>
<th>Inventory type</th>
<th>Barrier number</th>
<th>During powered operation</th>
<th>During maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>1</td>
<td>Target cooling helium circuit</td>
<td>Connection cells, monolith &amp; target cask</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Monolith liner &amp; connection cells</td>
<td>High bay</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>High bay</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td>1</td>
<td>Monolith liner &amp; circuits in utilities block</td>
<td>Connection cells, monolith, utility rooms &amp; casks</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Utility rooms</td>
<td>High bay</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>High bay</td>
<td></td>
</tr>
<tr>
<td>Tertiary</td>
<td>1</td>
<td>Containing circuits, casks</td>
<td>Containing circuits, casks</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>High bay, utility rooms</td>
<td>High bay, utility rooms</td>
</tr>
</tbody>
</table>

Table 3.3: Confinement barrier definitions for primary, secondary and tertiary inventories.
CHAPTER 3. TARGET STATION

Figure 3.3: Target station utility rooms. Top: Plan view of the target station building at the utility room level. Bottom: Side view of the utility rooms, showing the helium cells in green.

additional contaminated systems such as fluid storage systems and is a prolongation of the utility cells. It extends around the monolith and houses the monolith atmosphere system, the contaminated liquid effluent storage and over tanks, and some penetrations in the target station building for the ancillaries provided by the conventional facilities.

The high bay (TS building part 5) spans the A2T, the connection cells and utility rooms, the passage between the two experimental halls, the active cells and the transport hall. The transfer of components from the ground floor is possible. Irradiated components such as internal neutron beam guides and internal supports are mainly transported through the hatches in the high bay slab from the passage joining the two experimental halls, and the non-irradiated components are mainly transported through those from the transport hall. The high bay contains safety-classified ancillary systems and facilities (radioactive gaseous effluents and confinement (RGEC) systems, temporary storage area for irradiated components, etc.), non safety-classified ancillary systems and facilities (external cooling water; heat, ventilation and air conditioning (HVAC) system for the TS building; temporary storage zone for non irradiated components), handling systems (casks, mock-up area for plugs, casks and tooling) and some penetrations in the target station building for the ancillaries provided by the conventional facilities. The high bay floor is flat, so all transfers of heavy components can be made either by the high bay crane at a minimised height above the high bay floor or by rolling devices and casks, in order to avoid major structural damages in case of load fall. Several penetrations are available in the high bay for transferring components to and from the active cells (process cell, maintenance cell and storage pits), by connecting internal shielding casks to lids and sliding doors. A large opening is available above the transport hall to deliver large spare components in the high bay for temporary storage, until they are installed during maintenance periods, as shown in Figure 3.3. A pit in the high bay, located upstream of the monolith and at the level of the connection cells, houses the hydrogen systems for the cold moderators.

The functions and characteristics of the active cells (TS building part 7) are described in Section 3.5. Access to the neutron beam windows (part of the monolith liner, the second confinement barrier), internal inserts and neutron guides is only possible from the experimental halls (TS building part 6). The exchange and maintenance of these internal structures in the monolith are performed during proton beam
3.1. GENERAL DESCRIPTION

Table 3.4: Pressure cascade values in different zones of the target station building during powered operation and during maintenance, relative to atmospheric pressure.

<table>
<thead>
<tr>
<th>Location</th>
<th>During powered operation</th>
<th>During maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas Pressure [kPa]</td>
<td>Gas Pressure [kPa]</td>
</tr>
<tr>
<td>Target system</td>
<td>Helium 200</td>
<td>Air or helium −0.20</td>
</tr>
<tr>
<td>Monolith</td>
<td>Helium −0.30</td>
<td>Air −0.06</td>
</tr>
<tr>
<td>Connection cells</td>
<td>Air −0.30</td>
<td>Air −0.06</td>
</tr>
<tr>
<td>Helium cells</td>
<td>Air −0.30</td>
<td>Air −0.06</td>
</tr>
<tr>
<td>Utility rooms</td>
<td>Air −0.12</td>
<td>Air −0.06</td>
</tr>
<tr>
<td>High bay</td>
<td>Air −0.06</td>
<td>Air −0.06</td>
</tr>
<tr>
<td>Accelerator-to-target</td>
<td>Air −0.12</td>
<td>Air −0.06</td>
</tr>
<tr>
<td>Experimental halls</td>
<td>Air −0.12</td>
<td>Air 0</td>
</tr>
</tbody>
</table>

shutdown periods. When the neutron beam windows are open during the maintenance period, access to the area within a 6 m radial distance from the monolith surface will be subject to the same protective measures as access in the immediate monolith area in the absence of the confinement barrier, as shown in Figure 3.63 and as discussed in Sections 3.3.9 and 3.5.2. The junctions between the additional shielding blocks surrounding the external neutron guides and other components on the experimental lines are specifically designed to avoid any aggression of the shielding blocks on the second confinement barrier (steel liner and neutron beam windows) during an accidental scenario, such as an earthquake, aeroplane crash or shielding block handling accident.

Confinement barrier concept

The confinement barrier concept addresses the risk of dissemination of radioactive contaminants. It considers the different radioactive inventories present in the target station building and their capacity to disseminate in the environment (with different transfer factors for noble gases, volatiles and other elements). For each inventory, this chapter discusses a life-cycle approach for the operation and maintenance phases. The decommissioning phase is treated in Chapter 10. The radioactive inventories are classified into three types. The freshly irradiated spallation target wheel and spallation products are classified as the primary inventory. The other radioactive isotopes in the monolith (and those transported from it by the fluid circuits that traverse it) are classified as the secondary inventory, and the additional minor radioactive inventories that are not connected to the monolith (radioactive liquid effluents, empty transfer casks, etc.) are classified as the tertiary inventory. As these inventories are naturally decreasing with time, they are progressively declassified from one inventory to another during the decay process. As a result, the spallation target material is declassified from the primary to the secondary inventory after a few weeks of decay time. The target station confinement barriers are defined in Table 3.3 [299]. Confinement is assured preferentially by a static confinement or by a pressure cascade maintained dynamically with the radioactive gaseous effluents and confinement (RGEC) systems. Table 3.4 presents the pressure cascade during

Table 3.5: Air pressure cascade values in the active cell rooms and in the transfer hall during normal operation, relative to atmospheric pressure.

<table>
<thead>
<tr>
<th>Location</th>
<th>Air pressure [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process cell</td>
<td>−0.23</td>
</tr>
<tr>
<td>Maintenance cell</td>
<td>−0.20</td>
</tr>
<tr>
<td>Storage pits</td>
<td>−0.20</td>
</tr>
<tr>
<td>Transfer zone</td>
<td>−0.10</td>
</tr>
<tr>
<td>Technical galleries</td>
<td>−0.10</td>
</tr>
<tr>
<td>Transport hall</td>
<td>−0.06</td>
</tr>
</tbody>
</table>
power operation of the neutron source and during its maintenance. For the active cells during normal cells operation, the first confinement barrier is the active cells’ external wall and penetrations, and the second confinement barrier is the high bay. The pressure cascade in active cell rooms and in the transfer hall are presented in Table 3.5.

Shielding concept

The shielding concept addresses the risk of direct radiation exposure to prompt radiation from the interaction of the proton beam with matter, and to decay radiation from radioactive inventories. The shielding concept also addresses contamination transfer issues. It considers the different radioactive inventories present in the target station building and their capacity to irradiate personnel in the vicinity. For each inventory, a life-cycle approach is developed for operation and maintenance phases. During beam operation, the necessary shielding is provided by the monolith structures, the connection cell walls, the high bay floor, the A2T shielding and the utility rooms. The monolith, the connection cells and some cells in the utility rooms (those housing filters or water with $^{16}\text{N}$, for example) are off limits for personnel during beam operation and the decay time immediately following it. The slab above the connection cells (22 m × 22 m) is up to 2 m thick, as shown in Figure 3.3. Additional movable shielding blocks are necessary around the monolith, up to an height of 6 m above the ground floor. During maintenance phases, some shielding only required during beam operation can be removed to maintain or exchange irradiated components. Both adapted shielding structures and remote handling procedures are implemented to minimise the radiological impact on workers during these phases. The shielding concept during beam operation is described in more details in Section 3.3 [300], and the one related to the transfer casks and the active cells is presented in Section 3.5.

Zoning concept

ESS has developed an internal system to zone different areas of the facility in terms of required safety measures. The zoning concept mainly addresses those risks associated with non-radioactive inventory (conventional risks) that have a potential impact on radioactive safety functions. A specific radioactive risk addressed by the zoning concept in the target station building is the risk due to tritium. Although all kinds of conventional risks are potentially concerned, the non-conventional hazards present for the target station are hydrogen explosion, fire and usage of beryllium.

3.1.3 Quality assurance and risk analysis

Quality assurance

Quality assurance for the target station (TS) from the standpoint of nuclear safety is considered in this section. Broader issues of ESS quality management and quality assurance are addressed in Section 8.2. Nuclear safety quality assurance (QA) will be applied to activities related to systems and subsystems that are safety-classified and which can have an impact on nuclear safety, and to activities related to these systems and subsystems. The list of systems and subsystems of concern for nuclear safety QA is defined in the preliminary safety analysis report and safety analysis report. (See Chapter 11 for further discussion of these safety reports.) These are the systems participating in the radioactive confinement functions (first, second and third confinement barriers), including the normal release of radioactive gaseous effluents; the systems participating in evacuation of radioactive effluents (liquid and gaseous) and wastes (solid) outside the target station building; the systems participating in radioactive shielding functions; the systems participating in the shutdown of the proton beam, when this shutdown is required to avoid confinement system damages; and the systems participating in monitoring of the previous systems.

Quality assurance activities are defined in the ESS quality management plan [301]. For the target station, these activities include design, production, testing and storage of QA-related systems and their components; operation and maintenance of QA-related systems (including periodic tests); characterisation and analysis of radioactive inventories and releases; monitoring of QA-related systems; training and qualification for personnel; acceptance and processing of non-conforming situations; and review and feedback for TS processes and its QA-related systems documentation (listing all activities above). The activities performed by TS personnel or by TS subcontractors without their own QA manual will be subject to the
TS quality management plan. When a TS subcontractor has his own quality management plan, the scope of the QA plan must be dealt with on a case-by-case basis.

Risk analysis

For the construction phase of the ESS target station, the risks from the perspectives of the availability of human and financial resources, technical challenges, regulatory frame such as licensing, political environment and organisational issues have been identified and their potential impact on costs, schedule and performances has been analysed [302]. Having identified these risks, an action plan was developed and risk mitigation strategies have been implemented and reviewed since 2011 [302].

3.1.4 Target station operations and maintenance

This section presents the main characteristics of operating cycles, such as the annual number of days of operation, number of annual restarts and shutdowns, or the number of annual maintenance days, for target station design. Only the nominal situation is defined, based on ESS high-level requirements described in Chapter 1. Operation and maintenance conditions such as load cases drive the thermo-mechanical design of the target station components.

Abnormal situations (incidents and accidents), including beyond-design-basis accident scenarios, are addressed in the conceptual design of the target station, which will be further refined as ESS works with Swedish regulatory authorities on its safety analysis report. Details can be found in Chapter 11. To define the different load cases for the detailed design of the target station, an iterative method is used, starting with different operating modes for the ESS facility and progressively honing in on different target station systems in more and more well-defined modes, as the design options are selected. For the machine as a whole, ESS operating cycles will permute among four modes corresponding to specific needs such as machine development and qualification, power ramp-up, neutron production, cooling time and maintenance, as indicated in Figure 3.4. The four modes are:

1. Production mode, which prevails when the facility is delivering stable beam to its scientific users;
2. Maintenance mode, during which broad access to most systems is permitted for preventive and curative maintenance;
3. Studies mode, during which tests, studies, and activities to develop or qualify the accelerator are performed; and
4. Restart mode, which prevails during the transition from very low power to nominal power.

Target station modes for different classes of target station systems

Target station systems fall into two classes. The beam class includes those systems that are directly involved in the production of neutrons, and which become activated as a consequence of that involvement. These encompass all the systems in the monolith, all fluid systems transiting through the monolith, the movable shielding, and all the systems in the A2T area. The enabling class includes the TS systems that do not have direct involvement in neutron production, that is, the active cell systems, the radioactive handling systems, the radioactive liquid storage system, the confinement systems and the storage areas. For each of the four ESS modes described above, the beam-class TS systems operate in one of several TS-specific sub-modes:

1. Production mode is associated with several TS stable nominal power modes, each corresponding to a different level of maximal allowable power.
2. Maintenance mode is associated with TS decay mode (for radioactive and thermal decay of components); TS maintenance mode (for component handling and access); and TS conditioning mode (for circuit reconditioning and system preparation to restart).
3. Studies mode is associated either with TS decay, maintenance and condition modes (when the tuning beam dump is being used by the accelerator) or with TS calibration mode (for system requalification) or with TS ramping-up and nominal power modes.
4. Restart mode is associated with TS ramping-up mode and TS nominal power mode.

However, enabling-class TS systems have their own specific modes for maintenance, qualification and operation. The three enabling-class modes are requalification, operation and preventive maintenance. The modes for the beam class TS systems are illustrated in Table 3.6. The operational modes of the two classes of TS systems will be different from, but not independent of each other, as systems in the two classes interact with and are constrained by each other. The ways in which the operational modes of the two classes constrain each other can be depicted by a compatibility matrix.
Table 3.6: ESS operational modes and associated accelerator, target station and instrument modes.

### Target station systems design assumptions

The target station systems are designed on the basis of a set of assumptions about operation and maintenance conditions, which is presented in Table 3.7, and assumes the reference beam trip rate that is shown in Figure 3.5. The design loads in normal situations for each beam-class TS system can be derived from the appropriate columns of Table 3.7, integrating across operational modes. Pressure loads, static and dynamic loads, thermal loads and fatigue loads are derived from proton beam power. The fatigue cycles are derived from the number of occurrences a year and from proton beam trips, creep analysis duration and irradiation damages duration of occurrence, as shown in Figure 3.6. The enabling-class TS systems are designed taking into account the irradiation characteristics of the beam-class systems, for example, the irradiation time for radioactive inventories, or replacement frequencies from irradiation damages and loads. Enabling-class designs also are informed by the mode compatibility matrix, which imposes constraints on the number and duration of periods available annually to perform necessary TS system maintenance.

<table>
<thead>
<tr>
<th>ESS mode</th>
<th>Accelerator mode</th>
<th>Target mode</th>
<th>Instrument mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maintenance</strong></td>
<td>Decay</td>
<td>Decay</td>
<td>Several</td>
</tr>
<tr>
<td></td>
<td>Access</td>
<td>Maintenance Conditioning</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Powering</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Studies</strong></td>
<td>Insertable dump</td>
<td>Decay</td>
<td>Several</td>
</tr>
<tr>
<td></td>
<td>Tune-up dump</td>
<td>Maintenance Conditioning</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beam on-target</td>
<td>Calibration</td>
<td>Several</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ramping-up</td>
<td>Nominal power</td>
</tr>
<tr>
<td><strong>Restart</strong></td>
<td>Insertable dump</td>
<td>Ramping-up</td>
<td>Several</td>
</tr>
<tr>
<td></td>
<td>Tune-up dump</td>
<td>Nominal power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beam on-target</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Production</strong></td>
<td>Beam on-target</td>
<td>Nominal power</td>
<td>Several</td>
</tr>
</tbody>
</table>

Table 3.7: Operation and maintenance conditions assumed for the design of target station systems. The reference beam trip rate is shown in Figure 3.5.
CHAPTER 3. TARGET STATION

3.1.5 Target station control system

Monitoring and control of the target station systems is performed through the integrated control system (ICS) and a consistent set of three safety systems. The target control system is a part of the ICS, which is a non-safety class system that provides normal controls, regulation functions, settings archiving and data logging functions for the target station.

The first safety system, the machine protection system (MPS), protects equipment against damage due to beam losses and malfunctioning equipment components. The MPS is classified as non-safety; however, the MPS contributes to overall safety by triggering alarms and actions (e.g. performing an emergency shutdown of the machine and beams) when safety classified functions operated by target station systems are detected operating outside permitted ranges. The MPS will then act as a preventative system before the target safety system operates. MPS will be a very fast, reliable and fail-safe system, based on hardware and software described in Sections 5.2.2 and 5.2.3.

The second safety system is the target safety system (TSS), which is subject to the highest relia-
bility demands in ESS safety operation, as illustrated in Figure 5.4. The TSS guarantees that the target station operates within the design domain. If an abnormal situation occurs, the TSS triggers and controls mitigation functions in both internal and external associated target station systems. The main external trigger signal is to shutdown the proton beam. From an operational point of view, TSS is also a back up for MPS for the target station. However, in that case, there is no guarantee the systems will be kept in the normal operation domain, so the restart of the facility is not optimised. The TSS is essentially dedicated to the nuclear safety functions of protecting workers and the public from exposure to unsafe levels of radiation, and preventing the release of radioactive material beyond permissible limits. The TSS will be installed based on hardware or a highly reliable software system. Figure 3.7 illustrates control hierarchy for these first three control systems.

The third safety system is the personnel protection system (PPS), which is largely dedicated to the nuclear safety function of protecting personnel against irradiation when the transfer of contamination is not an issue. The PPS also protects operators from non-radiological hazards, but these functions are not addressed in this chapter. The PPS stops the proton beam when openings are made in the shielding barrier, by monitoring the doors and locks, and by assuring they are closed during operational states. PPS manages the entrance and egress from radiation-controlled areas according to a pre-defined classification. The target station PPS branch is a part of the global PPS system for ESS, as discussed in Section 5.2.4.

**Target station system operating domains, associated actions and mechanical design criteria**

The evolution of parameter measurements during operation will be continuously monitored by the control system, which will assure that target station systems operate within their design values. In normal situations, the values of operating parameters will be kept within their normal operating range by the non safety classified control system, ICS. A value evolving outside this normal operating range will trigger the MPS to take precautionary measures to prevent an incidental situation. As long as it is possible to rely on MPS to take protective actions, the target station will avoid a situation in which safety concerns might delay restart of the facility. Should MPS fail to act, TSS will take independent action, for example, by shutting down the accelerator, when its operating parameters cross specified thresholds. Crossing a
first threshold will trigger S_Alarm1 and S_Action1, and crossing a second threshold will trigger S_Alarm2 and S_Action2. The TSS serves as a failsafe mechanism to keep the systems within the design domain in both incidental and accidental situations. For that reason, triggering TSS actions could lead to delays in restarting the plant. The principles illustrating the relative threshold values for an ICS, MPS and TSS operating parameter are depicted in Figure 3.7.

Target safety system principles

The role of the target safety system is to bring the target station into a safe state in case of an abnormal event from a nuclear safety point of view, in order to reduce the risk of harm to people, equipment and environment. This will be accomplished through the emergency shutdown of the proton beam and actions on the target internal isolation barriers. Potential abnormal events are listed in the risk analysis report for the target station [302]. ESS risk analysis documents define a top event as an undesired event that poses a risk to people or to the environment. An initiating event is defined as any event or circumstance that heralds the occurrence of a top event. A top event may have one or many initiating events, and an initiating event may have the potential to trigger a top event on its own or in combination with other initiating events. The consequence is defined as the impact of a top event on people or the environment. Although TSS risk analysis focuses on abnormal events, ESS will also conduct risk analysis for the other operating modes of the target station, such as maintenance. In addition to the risk analysis, functional analysis is underway to detail activity flow in different operational modes for each target system, defining instrumentation; regulation process under normal conditions; and alarms, interlock and activities to be undertaken following an initiating event in order to move the target station to a safe state in a controlled way. An important issue in design and implementation of the TSS is licensing. ESS is a non-nuclear facility. However, many parts of TSS have to be licensed by the Swedish radiation safety authority (SSM), as discussed in Chapters 10 and 11. Standard guidelines will be used for both software and hardware implementation. International Electrotechnical Commission (IEC) standards potentially applicable to TSS development are listed in Table 3.8.

<table>
<thead>
<tr>
<th>Safety standard</th>
<th>NPP related</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 61226</td>
<td>Yes</td>
<td>Instrumentation and control systems important to safety: This standard is used to assign the instrument and control functions of a nuclear power plant to one of three categories.</td>
</tr>
<tr>
<td>IEC 61513</td>
<td>Yes</td>
<td>Instrumentation and control important to safety: This standard provides requirements and recommendations for the instrumentation and control of systems important to the safety of nuclear power plants.</td>
</tr>
<tr>
<td>IEC 61511</td>
<td>No</td>
<td>Functional safety: Safety instrumented systems for the process industry sector.</td>
</tr>
<tr>
<td>IEC 60880</td>
<td>Yes</td>
<td>Instrumentation and control systems important to safety: This standard serves as a reference for IEC 61513, which deals with the system aspects of high integrity computer-based I&amp;C used in safety systems of nuclear power plants.</td>
</tr>
<tr>
<td>IEC 60709</td>
<td>Yes</td>
<td>Instrumentation and control systems important to safety: Separation. This standard defines the technical requirements to be met for I&amp;C systems and their cables, in order to achieve adequate physical separation between redundant sections of a system and between one system and another system.</td>
</tr>
<tr>
<td>IEC 60987</td>
<td>Yes</td>
<td>Instrumentation and control systems important to safety: Hardware design requirements for computer-based systems.</td>
</tr>
<tr>
<td>IEC 61500</td>
<td>Yes</td>
<td>Instrumentation and control systems important to safety: Data communication in systems performing category A functions.</td>
</tr>
</tbody>
</table>

Table 3.8: International Electrotechnical Commission (IEC) standards potentially applicable for target safety system development. NPP stands for nuclear power plant.
3.1. GENERAL DESCRIPTION

Target safety system functions

For each operating mode, TSS will have different functions and actions that may be either external to the target, such as emergency shutdown of the proton beam and machine, or internal, such as static and dynamic confinements of affected TS systems. As fatigue for mechanical systems components can be a parameter relevant for nuclear safety analysis, another TSS function will be to monitor and trace the cyclic load history when required.

Target safety system architecture

The TSS design uses highly reliable programmable logic controller (PLC) systems designed and qualified to be used as plant safety systems. In order to achieve the high reliability required, the TSS will have two, separated, redundant, safety-qualified PLCs as shown in Figure 3.8 to meet the ESS risk probability goal of $10^{-6}$. Each safety-qualified PLC will have fault-tolerant processors and will include diagnostics designed to detect failures and ensure failsafe operation of the I/O and communication networks. The TSS design will include capabilities to facilitate periodic testing in order to certify that its components are functional and continue to maintain the design value of the probability of failure on demand. Several networking methods are under study to achieve the required millisecond shutdown response time required for some design basis accidents. The TSS PLCs will be located outside areas classified as explosive. The safety-related devices that are in areas classified as explosive will be designed and installed to meet industry standards that ensure they will not initiate a hydrogen gas explosion.

The TSS triggers proton beam shutdown to ensure design basis accidents do not harm workers or the public. The safety integrity level of the TSS will be determined using the guidance in the standard IEC 61508 and the hazard analysis risk determinations. In accordance with this standard, the TSS will have instruments, networks, cabling, and final actuator elements separated from non-safety equipment and between redundant channels, to prevent propagation of failures in non-safety systems from affecting the TSS safety functions. The two redundant final actuator elements will de-energise contactors that will shut down the proton beam by de-energising either the ion source or the low energy beam transport (LEBT) chopper.

![Figure 3.8: Illustration of TSS interfaces to external systems, e.g. ICS and PPS.](image)
3.1.6 Global simulation of target station system

Global simulations will be performed for the target station, consisting of mechanical and fluid analyses. Both types of analysis will be performed at the end of the design process, after the mechanical and fluid systems have been fully defined.

The target station has a number of different fluid systems under different operating conditions defined, for example, by temperature and pressure. The physical parameters of these systems are subject to strong transient effects due to dynamic operations such as the shutting down and starting up of the pumps or the beam trips. These transient effects have an impact on operating conditions which must be understood to ensure safe operation. Furthermore, in case of accidents, it is important to understand the behaviour of these systems in order to react appropriately. Since target station fluid systems are all embedded within ESS’s global fluid systems, and since fluid systems interact with beam control systems, it is of importance to simulate this behaviour in a global setting. The purpose of this global simulation is to link control, different operating modes (normal, tuning and abnormal) and different loop parameters together, including cryogenic systems, ensuring the compliance of target systems with safety, operational and control requirements, even during transient situations. The global mechanical analysis will cover the impact of an earthquake on the monolith and an aeroplane crash on the target station building. As this kind of analysis is quite standard, the mechanical analysis will not be discussed further in this section.

Methodology

The global simulation of TS fluid systems, will be undertaken in the following steps. After having benchmarked the chosen software to ensure its suitability, the different operational modes and scenarios will be defined in the first step of the analysis. These modes will exhibit different behaviours, placing different loads on the systems. The next step is then to build independent models for each system and subsystem, following which, the independent models are implemented and connected to the global target station model. Before starting the simulation, all necessary transient situations have to be defined and qualified. After

Figure 3.9: The model of the target helium loop.
calculations, they can be analysed and updated in the way that satisfies control and safety requirements.

While each system can be modelled independently of the others, potential connections have to be prepared, so that the connections among system models can be made later. Hence, it is important to prepare all piping and instrumentation diagrams (P&ID) in a detailed way and to clearly define the interfaces to other systems such as the control systems. This means that all P&IDs must contain all components (heat exchangers, filters, valves, etc.), and that the control of these components and the loops must be defined during this phase as well. A checklist will provide the most flexible and efficient way to build the global model of the ESS target station. As an example, the gaseous cooling system for the target cooling is composed of a primary helium circuit and intermediate nitrogen circuit, as discussed in Section 3.4. At the subsystem level, either the He-loop or the N$_2$-loop can be analysed separately. Figure 3.9 shows the helium loop model prepared for simulation and analysis. This model has free connections to other systems, so that it can be implemented in a more global model. When all the subsystems have been prepared, which includes cryogenic, moderator, target and control systems, they can be connected to the global system. For example, the full target loop is shown in Figure 3.10.

The global model will encompass the component system models, the ways that they are controlled and the different interfaces between the systems. Several operating modes have been defined in Section 3.1.4. The various modes are subject to different beam powers, changing the general behaviour of the facility. In order to design all the system correctly and ensure the reliability of the systems in all those cases, the different operating modes have to be clearly defined.

Prior to analysis, transient effects must be sorted into two different categories, one corresponding to normal operation and the other corresponding to incidental and accidental scenarios. The accidental scenarios are defined in close collaboration with the ESS safety division and can be found in the risk analysis report [302]. Transient effects that have to be analysed as part of normal operation are those associated with the start up or shut down of the facility or its components, and the beam trips. Transient effects that have to be analysed as part of incidental and accidental events are those associated with undesirable occurrences such as the leakage of a loop, obstruction of a loop, heat exchanger leakage, retarded rotation of the target wheel, or failure of sensors in the control system.

Dymola [303] has been chosen for the simulation tool. This is a modelling and 1-D simulation tool for dynamic multi-field systems. Models created with this software can combine fluid, mechanical, thermodynamic and control systems. All these fields can interact with each other, allowing a better simulation of the facility. Other software tools are available for this type of simulation analysis, including Cathare (CEA) and Relap5 (Idaho National Laboratory). However, Dymola suits ESS needs better. First, it is based on the Modelica language [304], which is an open source language. This makes it extremely flexible and means that there exist a large number of model libraries that can be shared or bought. EDF, Air Liquide and Linde, for example, use Modelica libraries to simulate the behaviour of products and equipment. This also makes it easier to develop specific model libraries that will fit ESS needs. Second, Dymola is a Dassault product that can be embedded in the ESS Enovia system. This facilitates the exchange of data and model archiving. Finally, Dymola is a multi-engineering tool, so that the TS global model will be able to combine

![model_diagram](image-url)
control, thermodynamic and fluidic effects, which will make the dynamic behaviour more realistic.

ESS will undertake a benchmark study to validate Dymola results. For this purpose, it has been pro-
posed to operate the low pressure helium loop of HELOKA at the Karlsruher Institut für Technologie (KIT)
under conditions similar to those at ESS, and to compare Dymola simulation results with experimental
results for HELOKA [305-307]. Discussion with Swedish licensing authorities will be more informative
after ESS has the results of this benchmark study.

3.1.7 Material properties

As is the case for existing spallation targets such as SNS, SINQ, and ISIS, the lifetime of the ESS target will
be limited by materials performance in normal operating conditions. The behaviour of materials during
normal and abnormal conditions sets requirements on other target station systems such as safety and
filtering systems. Due to its special design based on a helium gas-cooled rotating solid tungsten target,
the materials issues encountered in the ESS target will differ from those of the liquid metal targets at
SNS, J-PARC and MEGAPIE and the water-cooled solid targets at SINQ and ISIS. This section discusses
materials issues related to the helium gas-cooled rotating solid tungsten target design, based on target
operating conditions and previous experience at other spallation targets and published materials data
obtained in the spallation, fusion and fission materials communities. The main focus is on those materials
exposed to high fluxes of protons and spallation neutrons, which are used for the target wheel, the proton
beam window, and the moderator-reflector system. Some materials data are provided here for guidance,
with the knowledge that the detailed design of components will draw materials data from the body of
knowledge currently available and the recognition that, as with all spallation sources built and operated
date, component lifetimes will increase with operating experience.

Pure tungsten has been selected as the target material, beryllium as the reflector material, austenitic
stainless steel (SS) 316L(N) as the structural material for the target shroud and reflector container, and
aluminium-alloy Al-6061-T6 as the material for the proton beam window and moderator canister. Accord-
ing to the latest calculations, the operation temperature range is 25°C to 600°C for the tungsten, 25°C to
150°C for beryllium, 25°C to 300°C for SS 316L(N), and 20 K to 293 K for Al-6061. Detailed information
about the distribution of irradiation dose, temperature and thermal mechanical stress, etc. can be found
in other sections of this report. This section describes relevant information for these materials in the ESS
temperature range. The nominal chemical compositions of the materials are given in Table 3.9. As a
general rule, the concentration of an alloying element may vary by up to 10% around its nominal value.
Some of the data in Table 3.9 have been applied to neutronic calculations [308].

In thermo-mechanical and flow dynamics calculations, physical properties, such as thermal conductivity,
thermal expansion and specific heat, and mechanical parameters such as Young’s modulus and the Poisson
ratio are often used. These properties are usually temperature dependent. In the relevant temperature
ranges mentioned above, the numerical value of each of these properties can be expressed by the polynomial
\[ A + BT + CT^2 + DT^3 \]
where \( T \) is the absolute temperature and \( A, B, C \) and \( D \) are coefficients that depend

<table>
<thead>
<tr>
<th>Material</th>
<th>Al</th>
<th>C</th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Mn</th>
<th>Mo</th>
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<th>Si</th>
<th>Ta</th>
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</thead>
<tbody>
<tr>
<td>Beryllium</td>
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<td>.04</td>
<td>.06</td>
<td>.01</td>
<td>.03</td>
<td></td>
<td></td>
<td></td>
<td>.6</td>
<td>.075</td>
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<td>Al-6061</td>
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</tr>
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</tr>
</tbody>
</table>

Table 3.9: The nominal chemical compositions of the target materials, measured in percentage weight
(except for tungsten*, where the unit is parts per million). In addition to the listed components, SS316L
and SS316LN contain 0.03% cobalt, 0.02% phosphorous, and 0.01% sulphur, while SS316LN also contains
0.07% nitrogen, beryllium includes 0.64% beryllium oxide, and tungsten includes 5 parts per million of
oxygen. The values given for tungsten correspond to PLANSEE’s pure tungsten product, and the values
given for beryllium correspond to Brush Wellman’s Be S-65 product.
3.1. GENERAL DESCRIPTION

Table 3.10: Physical and mechanical properties of Al-6061, SS316L(N), and tungsten [309]. The four coefficients $A, B, C$ and $D$ describe a cubic fit: $A + BT + CT^2 + DT^3$, where $T$ is the absolute temperature. The thermal expansion is the mean coefficient rather than the instantaneous value.

Properties of structural materials

SS 316L(N) is one of the most widely used structural materials in existing spallation neutron sources and in nuclear installations. It is normally used in the solution-annealed condition, denoted by the letter “N” in parentheses, and its properties are extensively studied. Table 3.11 presents the typical tensile data for non-irradiated SA316L(N) [310]. Based on its tensile properties, design stress can be considered to be 150 MPa to 125 MPa in the temperature range of 300 K to 500 K [311].

Austenitic steels are one of the main classes of materials irradiated in the SINQ target irradiation program (STIP). Several kinds of austenitic steels from Europe, Japan and the USA have been irradiated to a maximum dose of about 20 dpa and a sample of the specimens have been tested [312]. After irradiation at temperatures below 350°C, the yield stress (YS) and the ultimate tensile strength (UTS) increase, while the uniform elongation or strain to necking (STN) and total elongation (TE) decrease with irradiation dose. After irradiation, the difference between YS and UTS is much smaller than that before irradiation at zero dpa. This implies that the steels lose their work hardening capability after irradiation due to irradiation-induced hardening. Although the STN drops significantly to very low level, TE remains generally at about 8%, indicating that the steels still have relatively good ductility at 10 dpa to 20 dpa. The tensile data of the STIP specimens and the experience of SINQ targets indicate that SA 316L(N)

<table>
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<tr>
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<tbody>
<tr>
<td>Al-6061</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>300 K – 400 K</td>
<td>$A$</td>
<td>116.4</td>
<td>19.96</td>
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<td>78.01</td>
</tr>
<tr>
<td></td>
<td>$B$</td>
<td>0.2865</td>
<td>$6.133 \times 10^{-3}$</td>
<td>5.761</td>
<td>$-2.801 \times 10^{-2}$</td>
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<tr>
<td></td>
<td>$C$</td>
<td>$-4.938 \times 10^{-4}$</td>
<td>$1.230 \times 10^{-5}$</td>
<td>$-0.01488$</td>
<td>$1.758 \times 10^{-5}$</td>
</tr>
<tr>
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<td>$D$</td>
<td>$3.282 \times 10^{-7}$</td>
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<td>$1.310 \times 10^{-5}$</td>
<td>$-8.030 \times 10^{-8}$</td>
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<tr>
<td>SS316L</td>
<td>$A$</td>
<td>10.145</td>
<td>14.287</td>
<td>185.7</td>
<td>217.6</td>
</tr>
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<td>300 K – 600 K</td>
<td>$B$</td>
<td>$1.253 \times 10^{-2}$</td>
<td>$-1.120 \times 10^{-3}$</td>
<td>1.332</td>
<td>$-6.899 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$C$</td>
<td>$2.1927 \times 10^{-6}$</td>
<td>$2.021 \times 10^{-5}$</td>
<td>$-1.642 \times 10^{-3}$</td>
<td>$-9.414 \times 10^{-6}$</td>
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<tr>
<td></td>
<td>$D$</td>
<td>$-1.636 \times 10^{-8}$</td>
<td>$7.28 \times 10^{-7}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>$A$</td>
<td>247.3</td>
<td>4.049</td>
<td>120.8</td>
<td>417.2</td>
</tr>
<tr>
<td>300 K – 900 K</td>
<td>$B$</td>
<td>$-3.164 \times 10^{-1}$</td>
<td>$1.9 \times 10^{-3}$</td>
<td>0.048</td>
<td>$-3.767 \times 10^{-2}$</td>
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<tr>
<td></td>
<td>$C$</td>
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<td>$D$</td>
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<td>$7.319 \times 10^{-10}$</td>
<td>$1.697 \times 10^{-8}$</td>
<td>$-2.604 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Table 3.11: The tensile properties of non-irradiated SA316L [310].
can certainly withstand 10 dpa in the above-mentioned conditions, which corresponds to approximately 8 years of lifetime for the target vessel as can be deduced from Table 3.15. If the thermal stress in the shroud is found to be too high to use SA 316L(N), annealed inconel 718 can be considered as an alternative. Annealed inconel 718 has been used at the proton beam window of SNS and LANSCE. Some results obtained from specimens irradiated in STIP show excellent ductility after irradiation up to about 18 dpa [313]. Martensitic steels are less desirable because of the relatively low operation temperature of the shroud. The ductile-to-brittle transition temperature (DBTT) may increase rapidly to the operation temperature at above 10 dpa. Aluminium alloys are widely used in existing spallation neutron sources. All cold moderator tanks are made of Al-alloys. For instance, Al-6061 is used for the moderator tanks at SNS, LANSCE and J-PARC, while AlMg3 is used for those at SINQ. AlMg3 is also used as the proton beam window material at J-PARC and the target container material at SINQ.

The properties of Al-6061-T6 are reviewed in detail in an article published by LANL [309]. Irradiation in the fission neutron spectrum at 423 K and below can introduce significant hardening and embrittlement effects [314]. However, the reduction of ductility saturates at high irradiation doses and TE maintains at above 8% at a dose of $3 \times 10^{27}$ neutrons/m$^2$ (approximately equivalent to 400 dpa). Al-6061-T6 is currently used as the material for the moderator canister at SNS. Exchange of the moderator tank is planned for 2015. By then, the material will have received a dose of about 21 dpa in the peak position [315]. Extrapolating from SNS and J-PARC experience to ESS conditions indicates a moderator lifetime of slightly more than a year.

AlMg3 has been used in SINQ since 1997 as the material for the target container and the moderator tank. In the proton beam window position of the target container, the material receives both high-energy proton and spallation neutron irradiation. The maximum irradiation temperature is about 330 K. The proton beam window of the SINQ Target-3 was investigated. The tensile test results indicate strong irradiation hardening and embrittlement effects [316]. At the maximum dose of 3.6 dpa, the TE decreased from 22% in non-irradiated condition to about 8%. It is expected that the ductility of AlMg3 will further decrease with increasing irradiation dose. Nevertheless, in SINQ, no problems have been encountered with the target containers since the first one operated in 1997. In the last target, the proton beam window of the AlMg3 container received a dose of about 8 dpa and 2000 appm He. The post-irradiation examination will be conducted on the proton beam window to demonstrate whether it can be exposed to higher irradiation dose in such a severe irradiation environment. The present moderators in SINQ have been used since 2000. This also indicates that AlMg3 has a good resistance to neutron irradiation.

It can be seen that both Al-alloys have good track records in applications in spallation sources. There is much more neutron irradiation information available for Al-6061-T6 than there is proton irradiation. Nevertheless, the excellent experiences obtained from SINQ, operating at 1 MW continuous proton beam, demonstrate that AlMg3 performs well in both proton beam window and moderator tank applications. As the ESS moderator will be subject to higher energy deposition, it is worth considering applying zircaloy for some parts of the moderator tanks, for example, for the exterior envelope, since its use may reduce the moderator heat load at equivalent mechanical resistance.

**Properties of non-structural materials**

In the ESS baseline design, the target wheel is composed of bare pure tungsten slabs in various sizes. There are two requirements from the material point of view, which the tungsten slabs must satisfy. First, although tungsten will not play a structural role due to its brittleness, it must retain structural integrity over the lifetime of the target to avoid blocking the cooling channels. Second, the radioactive inventory should be retained in the slabs as much as possible to minimise contamination of the helium cooling loop.

The mechanical properties of tungsten depend strongly on production procedures. Normally, the sintered tungsten has a few per cent of porosity with isotropic grain structure and grain size between 50 and 200 $\mu$m. Pores of sizes up to a few $\mu$m are closed and located mostly at grain boundaries. Sintered tungsten is very brittle and has low ductility and high DBTT. Hot deformation is therefore required at about 1000°C. However, hot deformation is usually applicable only to thin ($\sim 20$ mm) plates or rods. Hot-deformed tungsten exhibits a texture grain structure with grain sizes of a few $\mu$m in diameter and a few tens of $\mu$m length, and grain sizes increase with distance to the outer surface of a plate or rod. As for direct comparisons, dpa remains the most often quoted unit, another unit to express radiation damage in Al-alloys such as neutron fluence or silicon production might be desirable in the future.
3.1. GENERAL DESCRIPTION

usual, a hot-deformed tungsten plate or rod has higher fracture resistance in transverse direction. Irradiation data of tungsten are very limited, particularly in the spallation irradiation case. Compression tests conducted on small tungsten rods irradiated at LANSCE to a maximum dose of 23 dpa at 270°C show that irradiation induced hardening and embrittlement effects increase with irradiation dose [317]. Testing at 475°C exhibits further increased brittleness than that observed from testing at room temperature.

Concerning water-cooled targets, online operation and post-irradiation examinations of the irradiated LANSCE tungsten target showed high water corrosion rates which increase with irradiation dose [318]. Early experience at the first generation (MK-0) tungsten target of LANSCE also revealed severe cracking caused by a steep temperature gradient under beam [319]. All these observations led to the adoption of various cladding or canning techniques with materials such as tantalum and stainless steel 304L in the LANSCE and ISIS targets.

Unlike the situation with a water-cooled tungsten target, coolant flow-induced corrosion damage is not expected with the helium-cooled tungsten target at ESS. However, since the pulsed proton beam will induce cycling stress as high as 300 MPa in tungsten slabs, care must be taken to maintain the mechanical integrity of the tungsten slabs. To avoid cracking, the tungsten slabs must be designed to have the lowest possible thermal stress during full beam power operation. It is also important to pay careful attention to the surface treatment of the slabs, in order to reduce the risk of having micro-cracks on the surface. Transmutation of tungsten to osmium and rhenium in large enough quantities could also contribute to increased embrittlement, but this is not expected to be a significant problem at ESS.

Neutron irradiation experiments demonstrate that pure tungsten may undergo swelling at a rate of 0.2% per dpa at temperatures above 600°C [320]. Although there is no experimental data, the swelling effect is expected to be less pronounced in the ESS target, because the temperature is lower, and furthermore, the helium produced by spallation reactions can form stable clusters around vacancies, which significantly suppresses void formation.

Another important issue posed by using bare tungsten as the target material is tungsten dust production. In high purity helium atmosphere, the tungsten dust will come from the tungsten grains detached from the surface of tungsten slabs. The pure tungsten grain sizes are large enough that the cyclonic filters can remove them with high efficiency, as discussed in Section 3.4.1. If oxygen incidentally infiltrates the helium loop, the tungsten will be oxidised at high temperatures and tungsten oxide dust will be produced. W-Ni-Cu and W-Ni-Fe alloys exposed briefly in He+5%O2 gas showed significant oxidation above 600°C [321]. A more significant level of oxidation was observed from pure tungsten exposed to air in the same temperature range [322], with oxidation beginning take place at 550°C. The size of oxide particles varies from 0.1 to about 400 µm in the testing temperature range of 550°C to 800°C [322]. Handling this issue is difficult, because the size of the volatile oxide particle is unknown. To collect tungsten oxide dust, various filters will be installed in the helium loop. However, the cyclonic filters that work well for filtering pure tungsten dust would be significantly less efficient if the oxides should turn out to be in the sub-micron range. Therefore, impurity level of the helium cooling gas must be kept as low as possible during operation.

It is difficult to make an accurate assessment of dust production in a helium-cooled tungsten spallation target, due to the lack of direct measurements under representative environments. For safety and licensing and for maintainability of the helium loop components, a good understanding of this issue is needed. In order to get necessary information to support the target design, a number of experiments on bare tungsten in both non-irradiated and irradiated conditions will be planned and the issues discussed here will be investigated. Tungsten samples clad, canned or coated with various techniques and materials will be studied as well. Irradiation of various kinds of samples will be performed in the next STIP irradiation campaign in the temperature range relevant to ESS.

Reflector materials also will not have structural functions. At present, beryllium is commonly used for nuclear applications as a neutron multiplier and reflector material. Though it is very suitable for these purposes, some aspects, such as tritium inventory and the structural integrity of beryllium blocks should be investigated with account taken of the differences between spallation and fission reactor environments.

Neutron irradiation leads to complex changes in the micro-structure of beryllium, which may lead to swelling resulting from the formation of He bubbles. There are two important pathways for gas production. One is the (n, 2n) reaction in which the 9Be is reduced to 4He, which then splits into two 4He atoms. The second is the (n, α) reaction in which the 9Be absorbs a neutron and then splits to form a 4He and a 6Li. The 6He then reacts with a thermal neutron to produce 4He and 3He. Therefore, a large amount of helium and tritium may be produced in the beryllium reflector, as indicated
by the neutronic calculation results presented in Table 3.14. Nevertheless, since the operation temperature of the reflector is low, the swelling rate also is expected to be low. Fusion materials studies concluded that for an irradiation temperature below about 400°C, swelling of beryllium containing 1,500 appm of helium is less than about 1% [323]. Neutron irradiation at low temperatures will induce embrittlement as well. However, as the stress level in the reflector should not be high, the embrittlement may not cause serious failure in the integrity of the reflector during the design lifetime of more than one year.

3.2 Neutronic design

3.2.1 Target and moderator concepts

The main goal of the neutronic study of the ESS target station is to define the parameters of the target moderator-reflector configuration for a neutron source with excellent neutronic performance. Another objective is to provide data essential to the engineering design, such as heat deposition, gas production and radiation damage. This work is done using advanced Monte Carlo simulation codes. The determination of the absolute neutronic performance is important, in order to compare the expected performance with existing facilities and validate the choice to enter into construction. In order to achieve this goal, validated codes must be used, and uncertainties must be estimated from the different sources, coming for instance from the libraries and models used. The most important figure of merit is the source brightness, defined as the neutron flux per unit of solid angle, per neutron wavelength, in units of \( \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{˚A}^{-1} \). This quantity is independent of the distance from the surface of the moderator, and is therefore an indication of the performance of the facility.

The chosen spallation material for neutron production is tungsten, which is known to be among those materials yielding the highest numbers of neutrons per incoming proton [324]. In terms of neutrons leaking from the surface of a target per incoming proton, tungsten gives an excellent performance. Its choice for the target material is not, however, driven primarily by neutronic issues, but rather by arguments related to cooling and safety, which are discussed in other parts of this chapter. Similarly, the rotating target concept described in Section 3.3 was chosen because it makes it possible to cool at full beam power. The neutronic design helped in this case in determining the thickness of the target, which was chosen after a neutronic optimisation that also took into account the proton beam profile and the presence of moderators and reflectors.

For the moderators, the design philosophy is determined by the constraint of the start date of 2019 for neutron production at ESS. New design concepts typically require a decade or more to go from the first tests to production. Therefore, it is wise to rely for the start-up on the best existing state-of-the-art technologies, to provide the best possible neutron source from the beginning. At the same time, development of innovative concepts, such as directional moderators, will be pursued. This strategy is justified by the expected lifetime of the moderators (on the order of one year) due to radiation damage. Thus, there will be opportunity in the future to install moderators exploiting new concepts that are currently under study, or, perhaps, that have not yet even been conceived of.

The choice of the type of moderator is also related to the proton pulse structure of the ESS accelerator, 2.857 ms pulse length at 14 Hz. Since the pulse is remarkably long, compared to a short pulse facility, a coupled moderator is proposed. Neutron pulses are shaped by choppers, eliminating the need for the decoupled or poisoned moderators used at short pulse facilities such as SNS, J-PARC, and ISIS. The best choice for a long-pulse source is a coupled moderator of relatively large volume. Volume moderators, of cylindrical shape, filled with supercritical para-hydrogen have been shown to provide the highest peak flux [325, 326]. Also, the high energy of the protons forces the use of a wing-type moderator, in order to reduce the flux of fast neutrons and the associated radiation background in the experimental lines. The choice of moderator is also related to the power of the facility. At ESS power levels, the only sensible choice for a cold moderator is supercritical H₂.

The cross sections for ortho- and para-hydrogen differ significantly in the low-energy region: the neutron scattering cross section in pure para-H₂ drops significantly below about 15 meV of neutron energy, while the cross section for ortho-H₂ increases [324]. This implies that the moderator of pure para-H₂ becomes almost transparent for low-energy neutrons, thus favouring neutron extraction from the moderator, while at the same time the number of collisions and thus the probability of neutron capture, is reduced. Another concept that has been shown to work at the research reactor HZB in Berlin, and that is of great interest for
the ESS user community, is bispectral neutron extraction [327]. This option provides the opportunity to offer both full thermal and cold neutron spectra in the same beam line and enhances the dynamic range of the instruments. The challenge is to design a moderator with high performance for both cold and thermal neutrons. Calculations have been performed using MCNPX [328] and PHITS [329] codes. Details about the codes and options (models and libraries) used are given below.

### 3.2.2 Description of the model

Figure 3.11 shows the global MCNPX model of the target station monolith. Two horizontal cuts are shown corresponding to the centre of the top moderator and to the centre of the target. Figure 3.12 shows details of the proton interaction zone in the target and of the moderators. Two supercritical, cylindrical \( \text{H}_2 \) moderators are placed above and below the tungsten target. On the side of the cold moderators, extensions filled with ambient light water are placed for moderation of neutrons to thermal temperatures. A beryllium reflector that maximises the neutron flux surrounds both moderator and premoderator. Materials definitions according to the chemical compositions listed in Section 3.1.7 were used. Details of the neutronic calculations leading to this design choice are reported below. The presence of ortho-hydrogen considerably reduces neutron brightness, so catalytic converters will be considered for use in the cryogenics systems, in order to guarantee the highest possible concentration of para-hydrogen.

### 3.2.3 Neutronic codes and nuclear data

Neutronic design studies were performed using MCNPX and PHITS, with MCNPX used as the primary simulation option due to its long history of validation and benchmarking as well as due to a number of features not available in PHITS (e.g. next event estimators and ability to mix models and libraries freely). Auxiliary codes used for visualisation and data processing include MORITZ, MCAM and MC-CAD [330–333]. The quality of the neutronic design strongly depends on the quality of the nuclear interaction models and nuclear data libraries used. In order to assess the influence of models and libraries on the neutronics of the target-moderator-reflector system, two integral parameters were analysed: 1) cold brightness (brightness of the moderator surface integrated over the 0-5 meV energy range), and 2) moderator heat load or total heat deposited in the cryogenic part of the moderator suite due to prompt nuclear interactions. The first parameter reflects neutronic performance, while the second reflects engineering constraints and limits.

---

**Figure 3.11:** MCNPX model of the target station monolith. Left: Horizontal cut through the top moderator. Right: Horizontal cut through the proton beam line and target.
Several intra-nuclear cascade (INC) models (Bertini, Isabel, INCL4) and evaporation/fission models (Dresner, ABLA), as well as the self-contained package CEM03, were employed for simulation of high-energy physics in MCNPX. The results are shown in Figure 3.13 (top left). Apart from the INCL4 INC model, the models returned values within $\pm 5\%$ of each other for neutronic performance and heat deposition. The intermediate energy region (above a few eV) is especially important for the neutronics of moderators and reflectors. Three neutron libraries, ENDF/B-VII.0 (US), JENDL-4.0 (Japan), and JEFF3.1 (Europe), were tested on system components, with the results shown in Figure 3.13 (top right). The differences in neutronic performance was again found to be within $\pm 5\%$. Neutron scattering kernels are used for detailed simulation of neutron transport at thermal energies and below. Figure 3.13 (bottom left) shows that the use of scattering kernels at ambient temperatures is not crucial: the difference between free gas treatment and $S(\alpha,\beta)$ formalism is within $5\%$ for non-cryogenic parts. Scattering kernels are, however, absolutely necessary for cryogenic parts, for example, liquid hydrogen. The difference in neutronic performance and heat deposition due to the difference in para-hydrogen scattering kernels is illustrated in Figure 3.13 (bottom right).

The analysis shows that uncertainties associated with nuclear interaction models and nuclear data libraries are expected to be about 15%. While almost any combination of models and libraries studied would suffice (with the notable exception of the outdated MCNPX INCL4 INC model), the default MCNPX Bertini-Dresner model coupled with ENDF/B-VII.0-based neutron libraries and scattering kernels (whenever available) are recommended to simplify inter-comparison of neutronic results. The default MCNPX nuclear interaction model is generally accepted by the spallation source community for calculating most quantities of interest, such as neutronic performance and nuclear heating [334]. In addition, it requires less computing time than other models and is therefore preferred for optimisation studies.

### 3.2.4 Optimisation of the beam-target interface

Optimisations of the neutronic design were performed by choosing integral values of the cold or thermal neutron brightness as the figure of merit:

$$FoM = \int_0^\infty dt \int_0^{E_c} \Phi(t, E)dE$$

(3.1)
where $\Phi(t, E)$ is the neutron brightness as a function of time and energy, $E_c = 5 \text{ meV}$ for the cold neutrons and $E_c = 0.5 \text{ eV}$ for thermal neutrons. The results of these optimisations are summarised below. For more details, the reader is referred to the paper by Batkov et al. [335].

A sensitivity analysis of this figure of merit as a function of the height of spallation material was performed for different beam profile configurations. The optimal value for the target thickness was found at 8 cm. The shape and footprint of the proton beam affect important target station parameters such as material damage and cooling, which in turn contribute to defining the engineering constraints that limit possible beam profile configurations. Monte Carlo simulations were performed using PHITS 2.30 [329]

![Figure 3.13: Cold brightness and moderator heat load obtained under different simulation conditions.](image)

Figure 3.13: Cold brightness and moderator heat load obtained under different simulation conditions. Top left: With different nuclear interaction models. Top right: With different neutron libraries. Bottom left: With and without scattering kernels. Bottom right: With different para-hydrogen scattering kernels.

<table>
<thead>
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<th>Uniform</th>
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<td>3.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Proton beam height</td>
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</tr>
<tr>
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<td>10.8 ± 0.2</td>
<td>10.7 ± 0.2</td>
</tr>
<tr>
<td>Maximum heat load density</td>
<td>kW/cm³</td>
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<tr>
<td>Cold neutron brightness</td>
<td>%</td>
<td>96</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3.12: Beam profile optimisation results. The baseline beam profile gives 96% of the maximum theoretical performance achieved in the limit of a zero emittance beam.
Figure 3.14: Neutronic performance and moderator heat load as a function of proton peak current density, for parabolic, uniform and baseline beam distributions. Top: Average neutronic performance. Middle: Average moderator heat load. Bottom: Average maximal heat load density in the target wheel.

peak cold brightness is a factor of 75 larger that at ILL at 4 Å, a factor of 61 larger at 6 Å, and a factor...
3.2. NEUTRONIC DESIGN

and MCNPX 2.7 [328] codes with the JAM [336] and Bertini [337] models, respectively, and coupled with ENDF/B-VII data libraries [338]. The beam divergence between the proton beam window and target was not taken into account in this work. Two proton beam profile distributions were studied, a parabolic and a uniform distribution. In each distribution, the overall width and height of the beam footprint varied between 0.01 cm and 25 cm, and between 0.01 cm and 10 cm, respectively, thus spanning the phase-space of realistic beam profiles.

For MCNPX, the figure of merit was calculated by a standard sample biasing technique of scoring neutron flux at a point detector behind an ideal collimator, followed by a solid angle correction. A surface-crossing tally was used for the figure of merit in PHITS. The results of the optimisation are summarised in Table 3.12. From a theoretical point of view, a zero emittance proton beam would provide the best neutronic performance, at the cost of a huge peak current density. However, the baseline double parabolic profile configuration [339] gives only 4% lower performance than the neutronically optimal beam. This result holds true despite the use of a double parabolic beam profile with a peak current density of 47 µA/cm² in the simulations, slightly different from the peak current density of 52 µA/cm² that has been derived from the beam dynamics calculations described in Section 4.7.

Figure 3.14 shows how average values of neutronic performance and heat load depend on the peak current density of the proton beam. All of these figures support the conclusion that, for a given peak current density, there is no significant difference between the parabolic and uniform beam profiles. The main results of this optimisation study are: 1) the baseline beam parameters give 96% of the maximum neutronic performance achieved with a pencil-like beam; and 2) there is no significant difference in the neutronic performance and engineering parameters studied between parabolic and uniform beam profiles, as long as the peak current density is the same [335].

3.2.5 Neutronic design of the target-moderator-reflector system

The geometrical configuration of the bispectral moderator is shown in Figure 3.15. This model was used as a reference in a parametric optimisation process, during which each of the system parameters was varied in a sequential way, until the optimal configuration shown in Figure 3.12 was reached. Figure 3.16 (right) indicates that the optimal diameter is around 18 cm for a conventional pure para-hydrogen moderator, although the loss in neutronic performance is not dramatic when a smaller moderator is used. ESS has chosen a diameter of 16 cm in order to reduce the heat load on the moderator, and thus, the cryogenic system requirements of the facility. Another parameter related to neutronic performance and the design of moderators is the dimension of the premoderator. In particular, a thicker water layer between the target

Figure 3.15: MCNPX model of the target and surrounding moderator and reflector. The cold moderator is shown in red, the thermal moderator for bispectral beam extraction and the premoderator are in yellow, and the beryllium reflector is in orange. Left: Longitudinal view. Right: Top moderator showing the thermal extensions for bispectral extraction.
and the moderator can reduce heat deposition in the moderator, while at the same time improving its neutronic performance. Figure 3.16 (left) shows that thick ambient water premoderators placed between moderator and target can substantially decrease the heat load on moderators without compromising their neutronic performance.

The thermal moderator extensions provide thermal neutrons for bispectral extraction. The bispectral moderators are positioned so as to optimise the flow of neutrons from the target to the cold moderators, which implies that the thermal moderators will not receive optimal neutron flow from the target. Nevertheless, as shown below, their neutronic performance is excellent. The thermal moderator extensions affect the brightness of the cold moderator, because their presence makes it necessary to reduce the amount of

Figure 3.16: Sensitivity studies of the bottom premoderator and moderator dimensions. Left: Premoderator thickness. Right: Moderator diameter. Variation of these parameters strongly influences the heat load on the cryogenic moderator, dictating the choice of the optimal dimensions.

The thermal moderator extensions provide thermal neutrons for bispectral extraction. The bispectral moderators are positioned so as to optimise the flow of neutrons from the target to the cold moderators, which implies that the thermal moderators will not receive optimal neutron flow from the target. Nevertheless, as shown below, their neutronic performance is excellent. The thermal moderator extensions affect the brightness of the cold moderator, because their presence makes it necessary to reduce the amount of

Figure 3.17: ESS absolute peak brightness [339] compared to ILL yellow book data [340]. “ESS bispectral” is the weighted sum of “ESS cold” and “ESS thermal” using calculated weight factors corresponding to a typical bispectral beam extraction neutron guide configuration [341]. The ILL spectra are accurate to within about a factor of 2: slightly too high for thermal neutrons and too low for cold neutrons.
3.2. NEUTRONIC DESIGN

Figure 3.18: Neutron pulse shapes at 2 Å, 4 Å and 6 Å out of the moderator, with the same parameters as in Figure 3.17.

reflector surrounding the cold moderator. This effect was studied, comparing the calculated flux from an isolated cold moderator with the flux from a cold moderator with thermal extensions on the side. The addition of thermal extensions was found to result in a 15% reduction in cold neutron brightness. Earlier studies carried out by J-PARC and SNS show that beryllium is the optimum reflector material to maximise cold brightness in a coupled moderator. Based on previous experience, ESS has selected a composite reflector, with an inner reflector made of beryllium and an outer reflector made of steel. The main nuclear properties of beryllium when it is used as a reflector material are that it introduces a significant moderation, has a very low threshold for the \( (n, xn) \) reactions and does not have an important capture cross section. The diameter of the inner reflector in the baseline design is 60 cm.

Cold and thermal brightness

Figure 3.17 shows the spectral brightness of the ESS moderators. The absolute brightness was calculated at a distance of 10 m from the moderators, using collimators to view only the moderator surfaces. The peak cold brightness is a factor of 75 larger that at ILL at 4 Å, a factor of 61 larger at 6 Å, and a factor of 65 larger at 10 Å [340]. The thermal neutron brightness is at the same level as that called for in the 2003 design [334]. In summary, the proposed configuration for the cold moderator with thermal extensions allows the production of thermal neutrons in conditions that are similar to those for the long pulse moderator of 2003, while the production of cold neutrons is significantly increased. Further optimisation of the design of the thermal moderator is expected to increase thermal neutron brightness. The peak of the thermal spectrum is about 2.5 times higher than the cold peak. It is interesting to compare this relationship with the situation at the HZB reactor, which has bispectral extraction. At HZB, the cold moderator is a liquid \( H_2 \) bottle, while the thermal neutrons are extracted from the beryllium reflector surrounding the core. The ratio of thermal to cold is about five; one can expect that with an optimised cold moderator like the one for ESS, this ratio would drop by about a factor of 2, consistent with the present results.

In summary, Figure 3.18 shows the time distribution of the neutron pulse for wavelengths of 2, 4 and 6 Å. The calculations take into account the presence of a beryllium reflector, for which neutron flux almost reaches a saturation value after about 1 ms, although the value does increase slightly over time thereafter.

3.2.6 Support to beam extraction

Neutron beam extraction and beam delivery are inseparable. Their task is to make possible an efficient transfer of neutrons by matching the phase space distribution at the sample to the phase space distribution at a position close to the moderator surface, while rejecting as many neutrons as possible from outside
the desired phase space volume. This requires high quality reflective optics, and careful design of the geometry of the optical system and the shielding. The beam extraction layout and its engineering design concepts are described in Section 3.3.9. This section discusses aspects of the layout related to openings in the reflector for optimal beam extraction, and to the use of shutters.

**Viewing angles from the moderators**

The amount of reflector around the moderator affects its neutronic performance; any reduction in the amount of beryllium will negatively affect neutronic performance. In the ESS baseline configuration, the reflector material around each moderator has two 60 degree openings which allow for the extraction of neutrons to the guides and instruments. The brightness of the moderator is a function of the total angular size of its openings. Figure 3.19 shows the brightness calculated from the moderator surface for different angular values of the openings. The brightness decreases with increasing angular values, and the effect is only slightly dependent of the number of openings; that is, the brightness calculated with one opening of 120 degrees is nearly the same as that calculated with two openings of 60 degrees each. The brightness can be increased by reducing the beam extraction angular range, in a way similar to common practice in reactors (i.e., with openings of 10 degrees to 15 degrees per moderator). This opens the opportunity for an innovative ESS beam extraction layout. Instead of fixed beamline positions uniformly covering about 240 degrees, as is the current practice at pulsed spallation sources, a flexible grid will be used of possible beamline positions every 5 degrees, which would be able to accommodate changing instrumentation over the lifetime of the facility. This will make it possible to group beamlines depending on instrumental needs, with minimal angular spread. By using this approach, it will be possible, for instance, to reach a brightness of 15% to 20% above baseline with 22 operational beamlines. This approach would create the option to close one opening in the beryllium reflector in the moderator plug, when the corresponding beam ports were not being used for a period of time.

**Experience from PSI on shutter design**

The layout of the shutters is discussed in Section 3.3.9. In general, two different solutions are available for closing the primary neutron beam ports at neutron sources. The first approach uses a so-called high energy shutter system, in which a strong shutter (more than 1.5 m thick) is incorporated into the biological shielding. Such a system allows access at any time to all components of the beam line. The second concept is based on a “light” shutter solution. In this approach, the light shutter is positioned at the end of the biological shielding where it provides shielding from secondary radiation (mainly activation) when the neutron source is switched off. Such a light shutter system is installed on various beamlines at the spallation source SINQ. Three days after the SINQ shutdown in 2012, gamma and neutron measurements were performed to check the radiation levels with closed and opened light shutter. The measured dose...
3.2. NEUTRONIC DESIGN

Figure 3.20: Neutron and gamma dose rate measurement configuration at SINQ. Measurements were performed three days after the shutdown.

Rates were 0.5 $\mu$Sv hr$^{-1}$ with a closed shutter and 450 $\mu$Sv hr$^{-1}$ with an open shutter. The light shutter itself is a 30 cm thick steel block positioned about 6 m away from the SINQ target. Figure 3.20 shows the measurement setup employed at one of the SINQ beamlines.

In addition, ESS has also performed simulations to analyse the shielding behaviour of a light shutter during normal neutron production. As a first step, simulations assumed the use of a simple, 0.5 m thick steel block as a shutter. Using the ESS spectrum as input, this shutter was able to reduce the neutron dose rate by a factor of 500. Optimisation of the system with further simulations increased this by a factor of two, without any loss of gamma shielding ability. The optimised solution was found to be a layered block of borated epoxy and tungsten.

3.2.7 Neutronic support to engineering design

Within the framework of neutronics to engineering activities, detailed assessment of heat deposition, gas production, and radiation damage throughout the target station monolith was performed. Selected findings are presented here. The results are normalised to the baseline time average beam current of 2 mA and peak current density of 47 $\mu$A cm$^{-2}$. Divergence of the beam was not taken into account since the proton beam profile at the accelerator-to-target interface has not been fixed yet.

The prompt heat deposited in various parts of the target station monolith is summarised in Table 3.13. The peak heat deposition in the PBW is an average over the central part of the structure. Total production

<table>
<thead>
<tr>
<th>Component</th>
<th>Materials</th>
<th>Total [kW]</th>
<th>Peak value [W cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>Tungsten, stainless steel, helium</td>
<td>2800</td>
<td>3100</td>
</tr>
<tr>
<td>Target vessel</td>
<td>Stainless steel</td>
<td>62</td>
<td>940</td>
</tr>
<tr>
<td>Target shaft</td>
<td>Stainless steel</td>
<td>53</td>
<td>11</td>
</tr>
<tr>
<td>Cold moderators</td>
<td>Para-hydrogen, aluminium</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Water moderators</td>
<td>Water, aluminium</td>
<td>51</td>
<td>29</td>
</tr>
<tr>
<td>Inner reflector</td>
<td>Beryllium, aluminium</td>
<td>300</td>
<td>21</td>
</tr>
<tr>
<td>Outer reflector</td>
<td>Stainless steel</td>
<td>840</td>
<td>18</td>
</tr>
<tr>
<td>Proton beam window plug</td>
<td>Aluminium, stainless steel, helium</td>
<td>2.9</td>
<td>34</td>
</tr>
<tr>
<td>Neutron beam extraction</td>
<td>Stainless steel</td>
<td>7.5</td>
<td>0.014</td>
</tr>
<tr>
<td>Shielding &amp; monolith structure</td>
<td>Iron, helium</td>
<td>290</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Table 3.13: Prompt heat deposition in various parts of the target station monolith.
### Component Gas production [litres/GW-day]

<table>
<thead>
<tr>
<th>Component</th>
<th>$^1\text{H}$</th>
<th>$^2\text{H}$</th>
<th>$^3\text{H}$</th>
<th>$^4\text{He}$</th>
<th>$^4\text{He} + \text{He}$ total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>82</td>
<td>18</td>
<td>8.6</td>
<td>1.7</td>
<td>17</td>
</tr>
<tr>
<td>Target vessel</td>
<td>3.4</td>
<td>0.39</td>
<td>0.069</td>
<td>0.061</td>
<td>0.70</td>
</tr>
<tr>
<td>Target shaft</td>
<td>2.6</td>
<td>0.33</td>
<td>0.054</td>
<td>0.053</td>
<td>0.53</td>
</tr>
<tr>
<td>Cold moderators</td>
<td>0.57</td>
<td>28</td>
<td>0.0058</td>
<td>0.00048</td>
<td>0.094</td>
</tr>
<tr>
<td>Water moderators</td>
<td>1.9</td>
<td>23</td>
<td>0.044</td>
<td>0.0068</td>
<td>1.0</td>
</tr>
<tr>
<td>Inner reflector</td>
<td>5.6</td>
<td>1.6</td>
<td>2.8</td>
<td>0.31</td>
<td>120</td>
</tr>
<tr>
<td>Outer reflector</td>
<td>29</td>
<td>3.4</td>
<td>0.48</td>
<td>0.42</td>
<td>6.1</td>
</tr>
<tr>
<td>Proton beam window plug</td>
<td>0.079</td>
<td>0.012</td>
<td>0.0047</td>
<td>0.0049</td>
<td>0.021</td>
</tr>
<tr>
<td>Neutron beam extraction</td>
<td>0.048</td>
<td>0.0052</td>
<td>0.00069</td>
<td>0.00052</td>
<td>0.010</td>
</tr>
<tr>
<td>Shielding &amp; monolith structure</td>
<td>7.7</td>
<td>1.1</td>
<td>0.16</td>
<td>0.15</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 3.14: Total gas production in various parts of the target station monolith.

<table>
<thead>
<tr>
<th>Component</th>
<th>Stainless steel, iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>0.58</td>
</tr>
<tr>
<td>Target vessel</td>
<td>1.2</td>
</tr>
<tr>
<td>Target shaft</td>
<td>0.081</td>
</tr>
<tr>
<td>Cold moderators</td>
<td></td>
</tr>
<tr>
<td>Water moderators</td>
<td></td>
</tr>
<tr>
<td>Inner reflector</td>
<td></td>
</tr>
<tr>
<td>Outer reflector</td>
<td></td>
</tr>
<tr>
<td>Proton beam window plug</td>
<td></td>
</tr>
<tr>
<td>Neutron beam extraction</td>
<td></td>
</tr>
<tr>
<td>Shielding &amp; monolith structure</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.15: Peak values of the number of displacements per atom (dpa) per GW-day in various parts of the target station monolith.

The production of light gases (hydrogen and helium) within the target station monolith is shown in Table 3.14. The values are normalised to 1 GW-day of proton beam energy, which is equivalent to 200 days of operation at 5 MW power, and then converted to litres (1 mol = 22.4 litres) for convenience. Note that part of the hydrogen produced will be bound within various compounds. Only production data are given; depletion due to intra-hydrogen and intra-helium transitions is not taken into account. Radiation-induced damage of the main structural materials (stainless steel and aluminium), as well as of tungsten, is given in Table 3.15, again normalised to 1 GW-day of proton beam energy. These data, as well as gas production in steel and tungsten, were evaluated on the basis of cross sections provided by KIT [342].

### 3.2.8 Development of optimisation tools

Besides the main task of the neutronic design of the target-moderator-reflector system, as described above, some effort is being devoted to development of tools based on the available transport codes, which will be important for future work in the construction phase, in particular for cross-functional activities with instrument design experts. On the one hand, considerable effort has been dedicated to the coupling of the Monte Carlo transport code MCNPX with the ray-tracing code McStas, mainly for use in applications to beam extraction, but also with an eye to future work on advanced moderators. On the other hand, a more elaborated figure of merit could be beneficial, for instance, a more detailed specification of the range of wavelengths that instruments may need, and of the ratio of thermal to cold neutrons required by the experiments. Recent progress in these areas is reported below.
Interfacing MCNPX and McStas for simulations of neutron transport

Simulations of the target-moderator-reflector system at spallation sources are conventionally carried out using MCNPX [328], whereas simulations of neutron transport from the moderator and the instrument response are performed by neutron ray tracing codes such as McStas [343, 344]. The coupling between the two simulation suites typically consists of providing analytical fits of MCNPX neutron spectra to McStas. This method is generally successful but has limitations, for example, it does not allow for re-entry of neutrons into the MCNPX regime. These shortcomings can be resolved by interfacing MCNPX and McStas by direct or indirect coupling [345]. Some of the coupling options ESS has implemented are briefly described below.

At present, the tally option is the default approach. It is based on fitting MCNPX neutron distributions such as those at the moderator surface, making it possible to model neutron states on a statistical basis. In short, a detailed MCNPX simulation of a target, reflector and moderator system at a given neutron facility is performed and the resulting neutron fluxes and spectra at the moderator surface are approximated by simple distributions. McStas then “draws” random neutron states from these distributions. One challenge posed by using this approach is correctly describing the correlations between the parameters constituting a neutron state. For example, non-trivial phase space correlations could exist, such as those between the neutron location and momentum at the moderator surface. Quantifying correlations is thus an important part of employing this method. The tally method has the advantage that the time consuming MCNPX simulation step is decoupled from McStas and therefore only needs to be carried out once. This makes subsequent McStas simulations faster and therefore this method is very useful for applications such as instrument design.

A second option is to use the MCNPX source surface write/read (SSW/SSR) feature that permits a user to stop a simulation at a given surface, and restart it later. A new interpreter has been developed, allowing McStas to run based on SSW/SSR file input, and to produce a SSW/SSR output once the McStas simulation is complete [345]. The main advantage of this approach is that MCNPX runs can be based on the SSW/SSR input files. In this way, one can first do a MCNPX simulation, for example, of thermal neutron moderation. Once the neutrons enter the beam extraction region, the neutron states are handed to the SSW/SSR interface, and based on this input, a McStas simulation is carried out, for example, a simulation involving mirrors and coherent scattering (which is not possible in MCNPX). The scattered and/or the non-scattered neutrons can then be handed back to MCNPX using the same interface. One example application of the SSW/SSR interface is shown in Figure 3.21, where the cold neutrons emitted from the moderator side surface are shown.

![Figure 3.21: Map of cold neutrons emitted from the surface of the moderator at different angles and longitudinal positions.](image-url)
The supermirror option is the third possibility. This option is based on modifying the MCNPX source code \[346,347\]. In this case, however, the idea is not to launch a McStas simulation from within MCNPX, but rather to extend MCNPX with functionality inspired by McStas. The most important shortcoming of using MCNPX for cold neutron applications is the lack of coherent scattering. Coherent scattering can be described as a neutron wave interacting with a lattice, while MCNPX only addresses scattering on single particles. The process gives rise to wavelength-dependent reflection and can for present purposes be well approximated by the following expression:

\[
R = \begin{cases} 
R_0 \times \left(1 - \tanh \frac{(Q-m)Q_c}{W}\right) \times \left(1 - \alpha(Q - Q_c)\right)/2 & \text{for } Q > Q_c, \\
R_0 & \text{otherwise} 
\end{cases}
\]  

(3.2)

where \(Q\) is the scattering vector, \(Q_c\) is the critical scattering vector, \(R_0\) is the low angle reflectivity constant, \(W\) is the width of supermirror cut-off, \(\alpha\) is the reflectivity slope, and \(m\) is the \(m\)-value of the material.

In order to validate the recently developed software, an experiment was performed at the BOA beamline at PSI to demonstrate how the MCNPX-McStas interface can be used to analyse an experimental setup. Other activities planned for the future include ‘cradle-to-grave’ simulations of BOA, starting with an energetic proton bunch reaching the target and concluding with cold neutrons giving signals on simulated detectors in the instrumental hall. It is foreseen that this cradle-to-grave setup will be useful for such purposes as redesigning or re-optimising the moderator shape, since it will provide the means to see the effects of alternative geometries directly on neutron distributions at the sample position, without relying on questionable assumptions such as fits taking into account only parts of the neutron phase space.

**Extension of the figure of merit**

The figure of merit has been extended, based on a survey of the broad user community that was conducted among neutron instrument scientists and beam users at the Paul Scherrer Institut. A number of figures of merit that emphasise different interests can be optimised simultaneously [348].

The moderator performance is expressed numerically by a set of quantities, representing the shape of the neutron flux spectrum extracted from the surface of the moderator. Such a numerical representation is critical when a programming automation of the optimisation process is used, in order to derive at each optimisation step the value for the figure of merit. Figure 3.22 shows a theoretical bispectral spectrum that is composed of two separate Maxwellian distributions. The first Maxwellian distribution, \(\Phi_{th}\), simulates the thermal neutron spectrum, and the second, \(\Phi_c\), simulates the cold one. Each of these distributions is characterised by the position of its peak, \(\lambda_{th}^p\) and \(\lambda_c^p\), by the value of the neutron flux at the peak, \(\Phi(\lambda_{th}^p)\) and \(\Phi(\lambda_c^p)\), by the position of the crossing point between thermal and cold peaks, \(\lambda_x\), and by the value of the neutron flux at the crossing point, \(\Phi(\lambda_x)\).

![Graphical description of the bispectral spectrum.](image)

**Figure 3.22**: Graphical description of the bispectral spectrum.
3.3. MONOLITH AND PLUGS

In the optimisation process, the positions and peak values of thermal \( \Phi(\lambda_{th}^p) \) and cold \( \Phi(\lambda_{c}^p) \) fluxes are extracted from the neutron spectrum estimated by a point detector tally with a solid viewing angle limited to the side surface of the moderator of 12 cm × 24 cm. The integral neutron fluxes \( \Phi_{th}^I \) and \( \Phi_{c}^I \) of the thermal \([\lambda_{th}^p, \lambda_{th}^{max}]\) and cold \([\lambda_{c}^p, \lambda_{c}^{max}]\) parts of the spectrum are compared to optimisation requirements. The optimisation framework follows the procedure described in a 2010 article discussing the design of a solid rotating target [349], although new expressions for the figure of merit are implemented, which allow both thermal and cold neutron fluxes to be simultaneously maximised. In particular:

1. Thermal performance of the moderator can be evaluated by maximising neutron flux in the thermal part of the spectrum by setting the figure of merit to be:
   \[
   FoM_1 = \Phi(\lambda_{th}^p).
   \]

2. Similarly, cold performance of the moderator can be studied by maximising the cold neutron flux:
   \[
   FoM_2 = \Phi(\lambda_{c}^p).
   \]

3. Bispectral performance of the moderator can be optimised by establishing some ratio between the peak values of thermal and cold neutron flux, for example by requiring these values to be equal and maximal simultaneously:
   \[
   FoM_3 = \min(\Phi(\lambda_{th}^p), \Phi(\lambda_{c}^p)).
   \]

4. Assuming effective ranges of the measurements as required by the instruments, integral values of thermal and cold neutron flux can also be maximised while keeping them equal with the following figure of merit:
   \[
   FoM_4 = \min(\Phi_{th}^I, \Phi_{c}^I).
   \]

In this last expression the thermal neutron flux is given by

\[
\Phi_{th} = \int_{1.4 A}^{\lambda_x} \Phi(\lambda) \, d\lambda
\]

where

\[
\Phi(\lambda_x) = \min_{\lambda \in [\lambda_{th}^p, \lambda_{c}^p]} \Phi(\lambda)
\]

while the cold neutron flux is

\[
\Phi_{c} = \int_{4.1 A}^{6 A} \Phi(\lambda) \, d\lambda
\]

This approach has been used successfully for the optimisation of bispectral extraction on the basis of a box-shaped moderator model, similar to that of the 2003 design [348]. In such a model, the bispectral moderator contains two separated moderating materials, liquid cold 100% para-H\(_2\) at 20 K and room temperature H\(_2\)O, side-by-side in the common 12 cm × 12 cm × 24 cm moderator volume. Target geometry, bottom moderator, and reflector are assumed to be the same as in the previous sections. The model can be used with up to 30 parameters. The important ones are the relative offset of the moderator centre on \((y, z)\) and the position of the hydrogen/water separator with respect to the middle of the moderator box [348].

3.3 Monolith and plugs

3.3.1 Monolith

The design of the monolith is based on the general design, dimensions and handling philosophies of the target station baseline design [339]. The main purpose of the monolith is to provide sufficient shielding to reduce neutron background in the experimental hall and to allow personnel access close to the monolith wall. Besides the shielding function, the monolith needs to be designed to allow neutron extraction to the instruments and handling of components located inside the monolith. Shielding of high-energy neutrons requires high-density material. Early studies showed that steel is the most cost effective shielding material for the target shielding monolith [350]. Calculations indicate that more than 7 m of steel shielding will
be necessary in the proton beam forward direction [300]. Nevertheless, for simplicity and the requirement for the instruments to allow a first chopper position as close to 6 m from the moderator as possible, it was decided to design the monolith fixed structure with a constant radius of 6 m. The neutron beam line shielding outside of the monolith boundary will provide the additional necessary shielding. Figure 3.23 shows the general layout of the monolith.

The monolith can be subdivided into different areas with respect to design, choice of material, power deposition and manufacturing tolerances. The handling of components internal to the monolith, during exchange or maintenance, is described in Section 3.5. Minimising the costs of material and manufacturing is important in light of the very large volumes in question, especially of the bulk steel shielding. Access to components should be facilitated in accordance with their expected lifetime and reliability. Alignment of critical components must be achievable in a robust manner.

These design objectives are met through the following key features. Access to all components and shielding blocks that potentially can fail will be assured by design. The design facilitates exchange for components with limited lifetimes. On the other hand, for parts of the monolith that are unlikely to fail, the design may require longer maintenance periods for exchange or repair, in return for a simpler and more cost effective design. Water cooled shielding blocks that do not need to be moved for regular handling procedures will have redundant cooling channels where justified. A potential leaking channel can then be shut off and repair can be postponed to a suitable long maintenance period. A drain pipe connected to the lowest point of the monolith is installed for drainage of eventual spills and potential condensate. A base plate, manufactured with high accuracy, will allow installation of neutron beam guide inserts with a minimum of alignment features. It also offers the possibility to optimise the monolith with respect to choice of shielding type within different sections in order to reduce costs.

While the primary function of the monolith is to provide adequate shielding, it contains eight key components of the target station, which are described below, and shown in Figure 3.23. The rotating target system with long shaft is located near the central part of the monolith, while the drive, seal and bearing units are positioned on top of the monolith, reaching into the connection cells while still being part of the monolith helium system. The moderator-reflector (MR) plug, consisting of cold and thermal moderators as well as the inner and outer reflector, constitutes the central part of the monolith. It is attached to a backpack-shielding block, which allows the plug to be handled. The proton beam window (PBW), located upstream of the proton beam relative to the target, separates the high vacuum of the accelerator from the helium at atmospheric pressure inside the monolith. A separate helium valve plug will make the removal and exchange of the proton beam window possible, while preserving most of the helium atmosphere of the monolith. A proton beam diagnostic plug will house several diagnostic devices.
to monitor the proton beam footprints on the PBW and on the target as well as at the location of the diagnostic plug. Potentially, a target diagnostic plug will be introduced for online monitoring of the rotating target downstream of the proton beam, as well.

The monolith shielding design provides for 48 possible beam port positions arranged in four beam extraction sectors of 60 degrees each, with 5 degree angular separation between neighbouring beamline positions. Any of these positions may either be closed by a shielding block or opened as a beamline by replacing the shielding block by a neutron beam guide insert (NBGI). The large flexibility offered by the 5-degree grid of possible beam line positions will allow for optimally positioning the open beamlines during the whole lifetime of the facility. For the suite of 22 instruments funded within the ESS construction phase, this implies using 5 degrees of separation for as many instruments as feasible in order to maximise neutron flux for all instruments by minimising the volume of reflector removed for beam extraction purposes and placing instruments that need more lateral space at 10 or 15 degrees from the neighbouring open beamlines. Light shutters and associated drive units will be integrated into the monolith [339]. The shutters will open and close the neutron beam ports to block gamma radiation from the target and the moderator-reflector plug, allowing human access to beamline components outside the monolith when beam is off.

Liner

The liner system confines the helium atmosphere, at a slight under-pressure, inside the monolith. Figure 3.24 shows its general layout. It represents one of the safety-relevant barriers of the ESS target station confinement barrier system, as discussed in Section 3.1.2, requiring the best possible helium tightness. On the other hand, some components inside the monolith need regular and frequent handling. The liner system consists of a base plate, including a cup-like structure supporting the inner lower cooled shielding; the cylindrical wall of the monolith; and the top plate, including covers for frequent and scheduled access as well as a cover to access water-cooled shielding blocks that are designed for the lifetime of the facility but still need to be accessible in case of unexpected damage. The base plate consists of several segments to facilitate manufacturing and transportation to the site. These segments will be placed on the lower shielding, levelled and grouted in place. Finally, the gaps between the segments will be welded together to create a tight seal. This seal weld is not intended to transfer loads.

While the lower part of the liner system is a fully welded structure, the covers on the top plate are either welded for higher helium tightness for the less frequently accessed components, or equipped with

Figure 3.24: The general layout of the liner system (left) and generic double seal design with monitored interstitial gap for removable covers (right).
a double seal with monitored interstitial space to access the more frequently exchangeable components, as shown in Figure 3.24. In addition to the liner system, the confinement barrier will be completed by a fast-acting valve in the proton beamline outside the monolith, as well as by neutron beam windows allowing the neutrons to leave the confinement barrier towards the instruments. All liner components will be manufactured from stainless steel and will be welded together on site. Special care will be taken to monitor the weld quality. The total volume of the liner system will be 543 m$^3$ most of which is filled with shielding and components. The gaps between components making up the free volume will amount to about 34 m$^3$. This void volume may be increased if found necessary to cope with a target or moderator shell rupture and the consequent pressure build-up in the atmosphere within the monolith.

The target drive, seal and bearing system extends over the top plate, and is covered by a housing which is a part of the liner confinement barrier. In order to allow gas evacuation of the monolith before opening any lid or cover for handling components, the liner system will be designed for vacuum. This is accomplished by ribs on the covers as well as resting points on the top of the shielding to allow the top plate to touch inner shielding blocks during evacuated conditions.

Monolith shielding blocks and internal structure

The monolith shielding will be composed of the lower permanent shielding, the base plate, neutron beamline shielding block segments, lower semi-permanent shielding, water-cooled inner shielding blocks, removable shielding blocks and passive (helium-cooled) shielding blocks. The lower permanent shielding will consist of low tolerance and low quality steel embedded in high-density grout, ensuring low cost. Cast blocks made from pre-irradiated material can potentially be used for this shielding [351].

The base plate will consist of 13 parts: 12 segments and one cup-like centre piece. Each segment will be machined to tolerances up to ±0.25 mm in the workshop. All segments will be assembled on site, levelled and adjusted using a laser tracker. Bolts will be used to adjust the height of each segment individually. After all segments are in place and adjusted, the space underneath will be filled with low shrink grout. The segments will be bolted together. The gap between adjacent segments will be welded to achieve a helium tight layer. The hole in the centre of the base plate (diameter 4 m) will be closed with a cup-like, thick-walled vessel to carry the centre shielding blocks that need active water-cooled shielding. The lower permanent shielding will be far enough from the spallation centre not to require active cooling.

The neutron beamline shielding blocks will be placed directly on top of the levelled smooth surface of the base plate. The neutron beam line shielding blocks themselves will be manufactured to high tolerances and thus form the geometric basis for the guide-insert alignment. Despite tight tolerances required to avoid radiation streaming, the surfaces will be stepped as much as is geometrically possible. Due to seismic requirements, these blocks will most likely be bolted to the base plate. Due to the high number of neutron beam lines in combination with the spatial requirements of the large rotating target, limited space is available for supporting the structural loads of the shielding. The major load is supported through the outer shielding ring with radius larger than 2.7 m. In the area of the neutron beamlines, the small wedges between the openings for the inserts will be used to support the loads. Figure 3.25 illustrates the sequence of the shielding assembly.

Two approaches are used for the inner water-cooled shielding. The blocks that will not be removed during regular handling will be equipped with redundant water cooling channels. For the remaining blocks, only a single channel is foreseen. Cooling channels inside the shielding blocks consist of grooves inside the single layers of each block. Depending on the specific heat load, the layers are thinner in areas with high heat load and larger in areas in which the specific heat load is lower. Figure 3.25 shows as an example the water-cooled block underneath the MR plug. The inlet water supply will be at a pressure of about 1.0 MPa with a temperature of 20°C to 30°C. The maximum global block temperature is about 50°C, with some allowance for very local regions of slightly higher temperature.

3.3.2 Target design requirements and configuration

The target wheel will consist of 33 sectors, to ensure mechanical integrity of the target vessel while resulting in minimal loss of neutronic performance. Proton beam pulses will be synchronised with the target rotation speed. The number of sectors has been chosen in order to have an arc length for each sector large enough to accommodate the beam footprint, given the 2.5 m diameter of the wheel. The odd number of sectors also will eliminate direct line-of-sight via the helium cooling channels in the event that a desynchronised
proton pulse hits the target in between two sectors. Channels on the side, and gaps above and below the tungsten blocks have been designed to provide adequate cooling through helium flow. The gaps above and below the tungsten blocks also will prevent direct contact between the tungsten slabs and the steel vessel, which would lead to excessive heating of the steel at the points of contact.

Several factors have been taken into account in the arrangement of the spallation material. The proton beam will deposit most of its heat in the region near the outer rim of the target, mainly in the first 10 cm, while the coolant (helium) will be brought through the shaft from the back of the target. As previously discussed, the beam and the target will be synchronised, so straight channels will be used to move the coolant towards the outer rim of the target where the spallation material is located. The structural material will be kept at temperatures below 500°C, in order to avoid significant creep behaviour. The maximum temperature of the spallation material will be kept as low as possible, and the surfaces of the tungsten slabs will not exceed 500°C to avoid oxidation of the tungsten in the event that air infiltrates the target vessel. The beam entrance window (BEW) will be as thin as possible to minimise proton loss at the point of beam entry into the target material. Therefore, the BEW also will require substantial cooling so that its local maximum temperature can be kept low enough during beam operation.

The tungsten slabs will be arranged in three groups. The first group of tungsten slabs will be located at the outermost radial part of the target wheel, where the highest heat load is expected. It will consist of six slightly curved slabs, which will cover the area facing the two moderators. The tungsten slabs in this group will be between 12 and 14 mm thick, and will be separated from one another by 2.5 mm wide cooling channels. The second group of tungsten slabs will be located just interior to those of the first group. It will consist of four slabs, which will form the transition area between the outer rim portion of the target wheel with highest heat load, and the inner rim portion with negligible heat load. The tungsten slabs in
CHAPTER 3. TARGET STATION

Figure 3.26: Spallation material arrangement. The helium flow follows a serpentine pattern through the tungsten slabs, guided by the channel separation walls. Blue arrows indicate direction of helium flow.

this second group will have rectangular cross sections with thicknesses between 14 and 32 mm. The third group of tungsten slabs will be located at the innermost radial part of the target wheel. It will consist of three thick slabs with rectangular cross sections. These three groups inside each of the 33 sectors will be cooled in series, using helium flow entering the target wheel, with mass flux of 3 kg s\(^{-1}\) total (or 91 g s\(^{-1}\) per sector) and inlet temperature of 25\(^{\circ}\)C. The global arrangement of the tungsten slabs in one of the 33 target wheel sectors is shown in Figure 3.26. In the so-called “S-channel” arrangement, the coolant will flow in a serpentine pattern through the tungsten slabs, as shown in more detail in the figure.

As described in the following sections, the target material and flow configuration presented here ensures that the front part of the target, which will be exposed to the highest load, will be properly cooled by the cold helium flow, which will enter the target wheel area from the shaft. As a consequence, the peak temperature of the tungsten slabs will be kept below 500\(^{\circ}\)C. Temperatures in the BEW will be held below 200\(^{\circ}\)C during normal operation. The thermo-mechanical analyses presented in this section are based on the parabolic proton beam profile with peak current density of 64 \(\mu\)A cm\(^{-2}\) unless otherwise specified [339]. This peak current density value is conservative, compared to the value of 52 \(\mu\)A cm\(^{-2}\) that is derived from beam dynamics calculations in Section 4.7, for the beam footprint shown in Figure 4.86.
3.3. MONOLITH AND PLUGS

3.3.3 Analysis of spallation material arrangement and behaviour

Thermal-hydraulic simulations were carried out with ANSYS-CFX V14.0 [352]. The estimated Reynolds number is about \(2.2 \times 10^5\) using the shaft inlet hydraulic diameter as the reference length, and it is about \(1.0 \times 10^4\) using the equivalent hydraulic diameters of the narrow channels between tungsten slabs. Under these conditions, the turbulent model \(k-\omega\) SST was selected for these simulations, based on previous validation work done for similar applications [353].

Steady state flow analysis

For the steady state flow analysis, the simulation domain was one target wheel sector with flow inlet and outlet sections. For the steady state simulations, the target wheel was treated as stationary. The effects of rotation were not taken into account for this analysis, as the angular speed of rotation, 25 rpm, is small compared to the beam pulse length of 2 ms. The time-averaged volumetric heat deposition obtained from particle transport simulations was used for steady state thermo-mechanical simulations [354]. The periodic boundary condition was applied on both sidewalls of the sector under consideration.

Tables 3.16 and 3.17 list the simulated temperatures and amounts of heat generation resulting from the beam interaction. The total heat generation over the whole target wheel is about 2.45 MW. The highest heat density is located in the second tungsten slab. These values correspond to the beam footprint defined in the baseline target design [339]. The simulated pressures and area-averaged temperatures at the inlet and outlet of the helium flow are \(P_{in} = 374\) kPa, \(P_{out} = 316\) kPa, \(T_{in} = 25.1^\circ\)C and \(T_{out} = 181.1^\circ\)C, respectively. The fluid temperature rises 156°C with a pressure drop of 58 kPa. The maximum temperatures in the beam entrance window and vessel are 175°C and 221°C, respectively. The maximum temperature of tungsten, 462°C, is observed in tungsten slab number 9 in Figure 3.26, a temperature that is below the critical temperature of 500°C.

Figure 3.27 shows the streamlines of the coolant flow, where the flow between the tungsten slabs shows an S-shape. Also shown in Figure 3.27 is the temperature distribution of the wall surfaces. The hot regions correspond to the local flow recirculation between the tungsten slabs and vessel. The holes on the separation walls help to break up the flow circulations. Without these holes, the temperature of the hot regions would increase by about 20°C. Figure 3.28 shows the calculated temperature field along the cut-planes in tungsten and the heat flux at the interface between the tungsten and helium flow, while Figure 3.29 shows the calculated velocity and pressure fields in helium flow. A low temperature zone is observed in Figure 3.28, at the inlet-side of the first tungsten group. This region is cooled by the cold fluid coming directly from the sector inlet. The highest temperature is observed in the second tungsten

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<th>(T_{\text{maximum}}) [(^\circ)C]</th>
<th>(P_{\text{nuclear}}) [kW]</th>
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Table 3.16: Simulated temperature \(T\), heat generated by nuclear interaction \(P_{\text{nuclear}}\), and power density \(P_{\text{density}}\) in target components, assuming an inlet pressure of 374 kPa and a mass flow rate of 3 kg/s.

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Table 3.17: Simulated temperature \(T\), heat generated by nuclear interaction \(P_{\text{nuclear}}\), and power density \(P_{\text{density}}\) in different tungsten blocks, assuming an inlet pressure of 374 kPa and a mass flow rate 3 kg/s.
CHAPTER 3. TARGET STATION

Figure 3.27: Calculated helium flow and temperature distributions in the target vessel and the beam entrance window. Left: Helium velocity streamlines. Right: Temperature.

Figure 3.28: The calculated temperature field along the cut-planes in tungsten and the heat flux at the interface between the tungsten and helium flow.

Figure 3.29: The calculated velocity and pressure fields in helium flow.

group, where the coolant flow rate between the tungsten slabs is relatively low, as shown in Figure 3.29. This behaviour arises from the fact that more fluid is drawn into the top and bottom channels as the channel gaps between the vessel and the tungsten blocks enlarge from 1.5 mm to 6.5 mm wide in the second tungsten group. The highest heat flux region is observed on the middle of the channel sidewalls between tungsten slab 2 and 3, as shown in Figure 3.28 (right). The heat flux on the top and bottom walls of the tungsten slabs is much smaller.

Transient flow analysis

For the transient flow analysis simulations, only the transient beam pulses were considered, not taking the effects of wheel rotation into account. The beam frequency used was 14 Hz with a pulse duration of 2.86 ms and a waiting period of 68.57 ms. Decay heat was assumed to be generated during the waiting period, the intensity of which was assumed to be 0.5% of the active value, based on neutronic calculations by the International Fusion Materials Irradiation Facility, IFMIF, in Japan. With an angular speed of rotation of 25.45 rpm, a given sector will be hit by the beam every 2.358 seconds.
In the simulation, the steady-state results were used as the initial state. Figure 3.30 shows the transient temperatures over time at chosen locations. After 4 or 5 cycles, the temperature stabilises. The temperatures in the centre of tungsten slabs 1 and 2 are close to each other, while the temperatures at the corners of tungsten slab 2 are much lower. The temperature decreases exponentially during the waiting period and it increases rapidly when the beam is activated. The amplitude of temperature oscillation is about 110°C at the centre of tungsten slab 2, and about 60°C at the centre of tungsten slab 7. Compared to the steady state results, the maximum temperature in tungsten slab 2 is higher by about 50°C. The flow parameters at the channel outlet oscillate after the beginning of the beam pulse. The amplitude of the oscillation is about 10°C for the fluid temperature, 20 m/s for the velocity and 1 kPa for the pressure. The oscillations in pressure are due to fast transient change in gas density, which is caused by powerful pulsed heating.

The three panels in Figure 3.31 show the temperature on the top of the vessel, in the tungsten (central cut-view) and on the BEW at the front surface reconstructed in four sectors, respectively. The beam axis is along the centre line of the first sector from the bottom. The target wheel is assumed to rotate clockwise. The temperatures are calculated at the point in time 14.145 s after an active beam pulse. Therefore, the solid temperature of the first sector from the bottom is the highest, while the temperature of the second
sector is the lowest. The peak temperature of the vessel shows less than 1°C variation during one cycle. The peak temperatures of the tungsten and the BEW change by about 110°C and 20°C during one cycle, as previously shown and in agreement with Figure 3.30.

**Afterheat analysis**

Afterheat (or decay heat) is the residual power in the irradiated tungsten due to the decay of radioactive species, about 47 kW [56]. The results presented below were calculated on the basis of this residual power estimate combined with the heat profile of the proton beam deposition shown in Figure 3.32. Heat is transferred between the target and the surrounding shielding, which is actively cooled by water during operation, since about 30% of the 5 MW beam power is deposited there [55]. The target and this shielding are not in direct thermal contact. Therefore, the heat transfer mechanisms that transport the power from the tungsten towards the shielding are: 1) heat conduction though the helium that fills the gap between the target and the shielding, 2) the free convection due to the helium surrounding the target, and 3) the thermal radiation from the vessel surface towards the shielding block surface. The radiation mechanism is ensured to function at all times, while the convection and conduction within the helium are not.

To be conservative, only the radiative heat transfer was taken into account in the first stage of analysis. In the second stage, the heat conduction effect of helium was added for thermal analysis. Finally, the effect

![Diagram](image)

Figure 3.32: Top: The geometry of heat transfer between the target and the surrounding shielding. Bottom: The power density profile of the proton beam heat deposition.
3.3. MONOLITH AND PLUGS

of free convection was also taken into account. The overall thermal analysis showed that heat conduction through the helium between the target and the monolith played a significant role. The size of these helium gaps determined the temperature gradient between the target and the monolith. When the decay heat from the target was balanced solely by radiative heat transfer, a maximum temperature of 550°C was reached in the tungsten, assuming conservative values for the surface emissivity of the target material. A full thermal analysis, including all three types of heat transfer mechanisms, yielded a maximum temperature of 480°C [356]. If the helium were to be replaced by air, the conductive heat transfer would be lower and therefore the maximum temperature would be higher.

Afterheat will not bring the tungsten to a temperature at which oxygen ingress can start an oxidation reaction. Passive cooling due to heat transfer between the target and the monolith will evacuate the heat inside the target at a sufficient rate. The monolith will not suffer from afterheat due to its huge thermal inertia. Instead, the monolith will act as a heat sink for the target afterheat. The maximum temperature of the tungsten could be reduced by increasing the emissivity through surface treatment, such as sand blasting. The benefits of such a surface treatment have to be balanced against possible effects on the mechanical performance of the vessel, especially with respect to fatigue limits.

Mechanical behaviour of the tungsten

The mechanical behaviour of the tungsten was also analysed. In steady state, the calculated maximum value of von Mises stress is 225 MPa. Before and after pulses, the maximum stress levels reach 218 MPa and 340 MPa respectively, as shown in Figure 3.33, leading to a stress range during operation of roughly

![Figure 3.33: Von Mises stress distribution in tungsten, with only half of the tungsten volume shown, cut along the vertical plane. Left: Just before the proton pulse. Right: Just after the proton pulse.](image)

![Figure 3.34: Tungsten and molybdenum sheet material in stress-relieved and recrystallised condition [357]. The tungsten and molybdenum sheets are 1 mm and 2 mm thick, respectively. Left: Typical 0.2% yield strength. Right: Ultimate tensile strength.](image)
CHAPTER 3. TARGET STATION

Figure 3.35: The maximum principal stress distribution in a vertically sliced tungsten plate. This shows that effective options exist to reduce stress levels, if this is found to be necessary.

120 MPa (0.03% of strain). The calculated maximum stresses are below the yield stress limits shown in Figure 3.34. Furthermore, the maximum stress level in tungsten slabs could be further relaxed by taking measures such as machining a nut in the plates, resulting in a greater margin of safety. Figure 3.35 illustrates an option to relax maximum stress levels in tungsten. The stress configuration shows the effect of vertically slicing the tungsten slab. This solution would require further elaboration on the holder arrangement, but shows a dramatic reduction in the maximum stress level. The vertically sliced tungsten slab option is not intended as recommendations for a new design, but rather as an example to show that effective options exist to solve the problem if stress levels in the tungsten slabs are found to be excessive at a future date.

3.3.4 Target vessel and beam entrance window

Thickness optimisation of the target vessel

The baseline target design calls for 33 target sectors, each made up of slabs of tungsten, the spallation material, held in place between two structural holder beams. The 33 beams delimit the target sectors and are connected to a massive central hub that makes the transition to the shaft, as shown in Figure 3.36. The 33 sectors of spallation material and structural beams are contained between top and bottom ring-shaped lids welded to the periphery of the central hub, with a rim composed of the beam entrance windows and their frames. The target wheel rotates around a vertical axis. The shrouds and rim form the gas-tight target vessel, which, together with the structural beams to which it is welded, forms the target’s pressure container.

Figure 3.36: The 33 target sectors, separated by 33 structural beams.
In order to determine the optimal thicknesses for the walls of the structural beams and target vessel, a SHELL model in ANSYS Workbench was used to perform the thickness optimisations for one target sector. The material of the pressure container will be 316L(N) annealed austenitic stainless steel with controlled nitrogen content. As the primary loading on the container is the pressure, only this physical boundary condition was taken into account. The mechanical gravitational load from the weight of the spallation and structural materials was treated as negligible for the first pass analysis. Figure 3.37 shows the cross section of one sector, with emphasis on the pressure-loaded parts and the mechanical connections between the structural beams, vessel and tungsten slabs.

Mechanical analysis was performed for different wall thicknesses. Five mm was found to be optimal for the vessel thickness, and 6 mm was found to be optimal for the thickness of the walls of the supporting beams. Figure 3.38 shows the results of the mechanical calculations (total von Mises stress distribution and the total deformation) for the optimal thicknesses. As the next step in the design, a solid finite element (FE) model was developed for one sector including more construction details. For the meshing of the model, solid 90 and solid 186-187 element types in ANSYS were applied while performing the thermal and structural calculations, respectively. In this FE model, besides the primary loading (internal pressure), temperature loading was included as a secondary load on the vessel. Only pure thermal conductance was taken into account to obtain the temperature distribution in the solid parts. However, the full range of mechanical loads were included in the FE simulations, including the weights of the tungsten and structural material, the inertial forces of the tungsten slabs due to wheel rotation, temperature field of the vessel from CFD calculations, and inner pressure.
Steady state structural results

The target vessel was designed for a relative pressure of 0.26 MPa, with internal pressure of 0.36 MPa and environmental pressure in the target monolith of 0.1 MPa. The vessel will be welded onto the structural beams by a welding island, as illustrated in Figure 3.39, which shows the design with one welding island. (ESS has also studied solutions with two welding islands: a final decision on the number of welding islands has not yet been made.) Von Mises stresses and total deformation of the target vessel were simulated, taking into account both pressure and thermal loading. In all cases, the welding islands were modelled as a bonded linear contact between the edge of the vessel and the top and bottom of the holder beams. The results of the mechanical calculations presented in Figure 3.40 were assessed according to the rules.
3.3. MONOLITH AND PLUGS

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<td>T</td>
</tr>
<tr>
<td>Margin %</td>
<td></td>
<td>80.3</td>
<td>199</td>
<td>80</td>
<td>105</td>
<td>67</td>
<td>49</td>
<td>35</td>
<td>25</td>
<td>61</td>
<td>83</td>
<td>83</td>
</tr>
</tbody>
</table>

Table 3.18: Target vessel stresses calculated for various paths, compared with acceptance criteria contained in RCC-MR 2007. $P_m$ is the primary membrane stress, $Q_m$ is the secondary membrane stress. $P_b$ is the primary bending stress, $Q$ and $F$ are respectively the secondary stress and the peak stress, $S_m$ is the allowable stress, $P_{mb} = P_m + P_b$, $Q_{mb} = Q_m + Q_b$ and $PQ_{mb} = P_{mb} + Q_{mb}$.
Fatigue analysis of the beam entrance window

The beam entrance window has the optimised shape of a rectangular concave wall with a minimum thickness of 2 mm in the beam path, and a maximum thickness of 5 mm at the outer corners. This maintains structural integrity under a pressure of about 0.3 MPa and under the thermal load from the proton beam, while minimising the neutronic penalty. In order to ensure the reliability of the target wheel, it is important to assess potential fatigue damages during the design phase. As the beam entrance window is exposed directly to the incoming proton beam and must contain inventories from the target material and helium coolant volume without leaking, the fatigue reliability of the BEW has a primary importance for robust target wheel design. ESS is using the methodology proposed by RCC-MRx draft (2010) [359] for its BEW fatigue analysis. This methodology is based on the accumulation of damage, similar to Miner’s rule. Material data provided by the design standard are based on neutron irradiation. Hence, calculations must include sufficient margin to ensure reliable results, considering that target materials are exposed to a high power proton beam. Proton beam footprint profile parameters are defined in two technical reports [339,360]. The cycling history over the lifetime of the target must be defined, in order to carry out the fatigue analysis. All cycles are divided into sub-cycles of definite strain ranges, for each of which an individual usage factor (IUF) is calculated. The IUF is defined by the number of cycles experienced during one lifetime, divided by the allowable number of cycles. The cumulative fatigue usage factor (CUF) – the sum of all the IUFs – must be less than one in order not to have a fatigue failure during the lifetime of the BEW. An internal document defines a set of 8 possible events in the target cycle [361]. Table 3.19 summarises the IUFs and the CUF for the beam entrance window, based on the frequency of each type of event. The baseline design provides sufficient margins for 5 years of target lifetime, even with proton irradiation [362].

<table>
<thead>
<tr>
<th>Stress load</th>
<th>Number of occurrences</th>
<th>IUF per occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[10^3]</td>
<td>[10^{-3}]</td>
</tr>
<tr>
<td>Mass itself</td>
<td>0.001</td>
<td>10^{-16}</td>
</tr>
<tr>
<td>Pressure and rotation speed</td>
<td>0.175</td>
<td>5 × 10^{-6}</td>
</tr>
<tr>
<td>Average thermal load</td>
<td>9.0</td>
<td>0.015</td>
</tr>
<tr>
<td>Proton beam pulse</td>
<td>43,600</td>
<td>0.636</td>
</tr>
<tr>
<td>Beam trips from 2.4 s to 10 s</td>
<td>39.1</td>
<td>0.046</td>
</tr>
<tr>
<td>Beam trips from 10 s to 30 s</td>
<td>31.2</td>
<td>0.006</td>
</tr>
<tr>
<td>Beam trips from 30 s to 60 s</td>
<td>26.0</td>
<td>0.004</td>
</tr>
<tr>
<td>Beam trips from 60 s to 100 s</td>
<td>21.7</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Cumulative usage factor</strong></td>
<td>–</td>
<td>0.687</td>
</tr>
</tbody>
</table>

Table 3.19: Individual Usage Factors (IUFs) and the cumulative usage factor – the sum of all IUFs – for the beam entrance window for a set of 8 possible events [361], showing sufficient margins over the design target lifetime of 5 years. The accumulation of beam pulses is more than 10 times more damaging than the accumulation of beam trips.

3.3.5 Target shaft, seal, bearing and drive

The spallation material will be placed in a rotating target wheel, which will be connected to a long vertical shaft reaching out through the top plate of the monolith, where the driving and bearing system will be located, as shown in Figure 3.42. The target container, the outer wall of the shaft and all pipes of the cooling circuit will be part of the first barrier of the system that will prevent the escape of highly activated particles from the cooling loop. The spallation zone will be enclosed by the shielding blocks of the monolith, forming part of the necessary biological shielding and reducing the radiation to levels allowing the use of radiation-sensitive devices and materials. To avoid radiation streaming through the shaft, a helical inset will be used which, just by virtue of its geometry, will attain a shielding effect of 50% compared to the bulk monolith. Using a high-density material for this inset could increase the shielding efficiency even further, should this be found necessary to avoid or reduce activation of components in the service area above the monolith.
The driving and bearing system on top of the monolith will be the interface between the stationary and rotating parts of the target system, including the stationary and rotating parts of the first barrier between the contaminated cooling circuit and the helium atmosphere in the monolith. Therefore, adequate sealing of the first barrier and leakage monitoring are vital for this system. The accessible box on top of the monolith will enclose the whole bearing and driving unit and will be part of the monolith helium system and thus part of the second barrier for the cooling helium.

**Target shaft**

The concept of driving a rotating target from a long shaft was initially considered in the design study for the low to medium power spallation source for the Basque Country [363]. This design used water as the cooling medium. The concept was worked out in more detail in the design study for the second target station for SNS [349]. The long shaft has the advantage that all system-relevant components are located at a significant distance ($\approx 5$ m) from the spallation zone and thus from the high radiation area. The target shaft forms the interface between the spallation zone and the functional system groups, as shown in Figure 3.43.

The envelope of the ESS target shaft will consist of two tubes, with dimensions (outer diameter, inner diameter, and length) of $600 \text{ mm} \times 540 \text{ mm} \times 1900 \text{ mm}$ and $700 \text{ mm} \times 640 \text{ mm} \times 2390 \text{ mm}$, which will be welded together using a connecting piece at the interface. The resulting offset in the outer contour of the shaft will serve, together with the fitting contour of the monolith, as a step to reduce radiation streaming in the unavoidable gap between the shaft and the surrounding shielding blocks. The driving torque will be transferred by the outer envelope of the target shaft from the driving unit to the target wheel. The outer envelope of the shaft also will provide mechanical stiffness to the whole arrangement. Within the shaft there will be two concentrically arranged pipes for separating the inlet and outlet flow. These pipes will be centred relative to the outer envelope of the shaft by three circumferentially distributed spacers. The gap between the outer and inner pipes will serve as the helium inlet for target cooling and will have a
cross section of 77,000 mm$^2$ in the upper part and 75,400 mm$^2$ in the lower part of the shaft, respectively. The central pipe including the helical insert will be used for the helium return flow. Due to the presence of the helical insert, the return flow will also acquire an angular momentum, which may serve the purpose of separating large contaminated particles from the flow, thus preventing them from leaving the shielded area of the target station. Further calculations and experiments will be needed to validate this separation feature. The smallest cross section of the outlet is 54,000 mm$^2$ in the present design.

The target shaft will be welded to the container of the target vessel. Therefore the shaft and the target wheel will be handled as a single unit during installation and dismantling. The total mass of this unit will be about 17,200 kg while the total moment of inertia will be about 5,730 kg/m$^2$.

**Seal**

An interface is needed between the helium inlet and outlet to the rotating target shaft and the stationary helium loop. For this interface, a sealing is necessary which is suitable for helium, resists wear and has a lifetime of at least 5 years in an area of modest radiation. Moreover, the sealing must sustain the role of the first safety barrier for the target-cooling medium. The most promising solution for this sealing is a double labyrinth seal together with an additional pressurised seal gas which guarantees that leakage always flows from non-contaminated to contaminated volumes. Figure 3.44 shows the planned configuration. The red lines indicate rotating parts of the target wheel and the blue lines stationary parts. The red areas indicate contaminated helium within the first barrier and the green areas indicate monitored and clean helium.

The coolant will be fed into the target through the inlet with a pressure of 0.36 MPa and will leave the target shaft with a pressure of about 0.30 MPa. A small amount of the helium flow, the bypass flow, will pass a labyrinth seal directly to the outlet, as shown in Figure 3.44. To prevent contaminated helium from getting into the helium atmosphere of the monolith, a seal gas will be used at a pressure of 0.38 MPa. The non-contaminated seal gas (He$_b$) will pass a labyrinth seal and will enter the contaminated helium coolant loop (He$_c$). The pressurised seal gas will also pass another labyrinth seal and will enter the helium.
3.3. MONOLITH AND PLUGS

Figure 3.44: The sealing concept for the target wheel’s bearing and drive unit: The red lines indicate rotating parts and the blue lines stationary parts. The red areas indicate contaminated helium within barrier 1 and the green areas indicate monitored clean helium.

atmosphere of the monolith (He\(_a\)). The total amount of seal gas needed to compensate for the leakage through these labyrinth seals was calculated to be about 10 g/s, which have to be released continuously from the helium atmosphere of the monolith and from the cooling helium storage tank. (Section 3.4.4 gives more details.) The calculated value of 10 g/s consists of a \(\approx 3\) g/s flow towards the cooling loop and a \(\approx 7\) g/s flow towards the monolith. The values were calculated using an analytical, semi-empirical method backed up by computational fluid dynamics (CFD) calculations [364].

For safety reasons, the barrier system will have a back-up seal, as shown in Figures 3.44 and 3.45. During normal operation this seal will be opened by applying low inward pressure. If the target wheel rotation stopped, whether during normal shutdown or in the event of a failure (e.g. due to loss of electrical power), the seal would be vented and would close itself due to spring pressure. The static seal concept is shown in Figure 3.45. The contact surfaces are polished to minimise leakage through the closed seal. The static seal is necessary avoid evacuation of the whole monolith chamber through the labyrinth seals (and vice versa) when the helium loop and the target are evacuated. It remains to be evaluated to what extent organic material can be used at this position to improve tightness of the static seal.

Bearing and drive system

The drive, the seal and the bearing units are illustrated in Figure 3.46. The design of the bearing and drive system [365] was driven by a number of requirements. Easy access to all components is necessary so that inspections can take place without opening barrier 1 or rearranging the components outside of barrier
1 and within barrier 2. The second barrier should cover the whole bearing and drive unit and the flanges of the cooling loop in order to monitor possible leakage of barrier 1 seals in this area. It should be possible to easily exchange the bearings and drives. Redundancy in the drive system is essential to avoid long shutdown periods if a drive unit fails. Separable connection between the target shaft and the bearing and drive unit is also necessary, so that the bearing and drive unit can be reused after exchange of the target wheel and shaft. The connection to the monolith must be robust, in order to guarantee stable support of the target wheel. Sensors must be integrated into the drive system to make it possible to monitor the system’s behaviour. Finally, fully developed technology with a track record of robustness should be used whenever possible.
ESS has selected a torque motor \([366,367]\) with a maximum torque of 2,500 Nm and a power of 8 kW for the drive unit for the target wheel. The torque motor will drive the shaft directly without requiring gears or belt to transmit torque to the shaft. This choice took into account the total 17,200 kg mass of the target and shaft unit, and a ramp-up time of 20 seconds until the nominal rotational speed of 25.5 rpm is reached. Depending on the reaction time available to readjust the target velocity after detecting a desynchronisation between the target rotation and the proton beam pulses, the necessary power and moment might even be higher. In this case drive units of the design selected for ESS providing torques up to 10,250 Nm are available in 1,250 Nm increments. Sufficient cooling with water will be provided to implement this approach. Although the motor does not feature gears, lubricant or other sliding parts, investigations about operation in helium atmosphere are still necessary.

### 3.3.6 Target monitoring instrumentation

Successful operation of the target to produce neutron beams for the research instruments will require real-time monitoring of a number of system parameters, as well as data archiving for subsequent analysis. Table 3.20 presents a summary of the parameters and locations which will be monitored during operation of the target wheel. Details of each parameter, and monitoring approaches are discussed below.

<table>
<thead>
<tr>
<th>Location</th>
<th>System</th>
<th>Monitored parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium cell</td>
<td>Helium circuit</td>
<td>Radioactive release, pressure, temperature, tungsten dust, oxygen and other gas content</td>
</tr>
<tr>
<td>Target rear plug</td>
<td>Target vessel</td>
<td>Temperature, velocity, displacement, vibration and gamma spectra</td>
</tr>
<tr>
<td>Drive unit</td>
<td>Target rotating seal &amp; bearing</td>
<td>Vibration, rotation velocity and helium leaks</td>
</tr>
</tbody>
</table>

Table 3.20: Summary of the target parameters monitored during operation.

**Target vessel temperature**

Through the spallation processes in the tungsten target material, considerable heat will be generated, which will expose the steel target vessel to thermal stress. Unlike the tungsten, the steel target vessel and structural beams, will function as the first safety barrier between the target wheel and the outside environment, as explained in Section 3.1.2. For this reason, its temperature will be monitored to ensure that the wheel is cooled sufficiently to function properly and to prevent structural failure in the vessel. The target vessel is rather large and it will be difficult to monitor its whole surface using thermocouples. ESS will use an alternative approach, integrating an optical path into the monolith to monitor the target vessel via an infrared camera placed at a distance from the harsh irradiation area, as illustrated in Figure 3.47. This will give accurate measurements of first safety barrier temperature. Each section of the wheel will be monitored once every full rotation. The optical path for target wheel monitoring will be placed in the beam instrumentation plug shown in Figure 4.117, located between the PBW plug and the MR plug. This makes the replacement of aging monitoring components easier, without requiring a complicated remote handling process such as target exchange.

**Target vessel vibration and displacement**

The optical path will also be used to track structure vibration with a laser Doppler vibrometer (LDV). A three-dimensional scanning laser vibrometer is a unique tool which makes it possible to accurately determine the operational deflection shapes and eigenmodes of the target across a wide range of frequencies. Measurement data are reliable as they reflect the actual vibration characteristics of the real object in comparison to accelerometers directly placed on the structure. Nevertheless, it is mandatory to also have at least two accelerometers on the target to properly calibrate the LDV. These sensors will be placed close to the harsh irradiation area, which will severely limit their lifetimes. In comparison, the LDV and the infrared camera will be well protected.
CHAPTER 3. TARGET STATION

Figure 3.47: An optical path through the monolith to monitor target vessel temperatures and vibrations, using an infrared camera and a laser Doppler vibrometer placed away from the harsh irradiation area.

Tungsten material temperature

The thermal and mechanical failure of a tungsten block within the target wheel can be diagnosed by monitoring the temperature of each target block. Any mechanical change in the tungsten block causes a change in the heat exchange mechanism between the tungsten and the helium coolant, which leads to an anomalous temperature change in the target material. However, as there are a large number of target blocks inside the target vessel in constant revolution, it is technically difficult to monitor tungsten temperatures directly. Therefore, thermal sensors that are placed on strategically chosen measuring points on the target vessel will indirectly monitor the tungsten temperature. Extrapolation from the monitored temperature data on the target vessel will provide thermal information about the tungsten blocks inside the target wheel, using a methodology presented in a technical report [368].

Small leak detection

J-PARC has developed a system based on mass spectrometry of the helium in its target vessel interstices [369] to detect spallation products in the helium gap which indicate if the mercury vessel is corrupted somewhere. A similar approach will be used to monitor vessel integrity at ESS through analysis of the helium flowing around the target within the target vessel. Small tubes will be inserted at strategic points to sample the helium in order to detect spallation products from the tungsten. CFD analysis will be used to determine the appropriate placement of these tubes.

Target wheel assembly balance

The target wheel loaded with tungsten must be balanced in order to reduce vibration and ready it for operation. After achieving required balance accuracy, vibration will be monitored at different locations in the top of the shaft and wheel vessel to provide baseline information about the vibrational characteristics of the undamaged target before operation begins. During operation, the target will deform due to its own weight, rotation acceleration and proton beam load. The thermal load from the proton beam stopping in the target will extend the radius of the target and cause a displacement of the target material by 2 mm, compared to its beam-off state. This thermal deformation changes the balance and vibrational behaviour of the wheel, and these changes must be monitored during operation. The target wheel can become unbalanced during operation if the target material is displaced due to local mechanical failure of the wheel structure. For reliable operation of the target station, this anomalous dynamic mechanism must be diagnosed in real time by an appropriate monitoring system for the assessment of failure locations and the degree of material displacements. Once the target has cooled off after proton beam shutdown, the balance of the target must be checked in more detail. Slow rotation could compromise the accuracy of this measurement. Therefore, details of the mechanical balance of the target wheel must be checked by
rotating the target at a much higher angular speed than the nominal one. This testing technology has been extensively used in the turbo machinery industry, for instance, where the rotation velocity is much higher. Such tests will be conducted at ESS after every short shut down.

### 3.3.7 Moderators and reflector system

#### Requirements

One of the key challenges for the engineering design of the moderators and reflector (MR) system is the heat load produced by the 5 MW proton beam power. It will be roughly five times higher than that of the most powerful spallation sources worldwide, SNS and J-PARC. From this 5 MW beam power, approximately 1.2 MW will be deposited in the (cold) hydrogen and water moderators as well as in the reflector [339]. A large engineering effort needs to be put into the design of the moderator vessels and the H\(_2\) circuit because of the heat load (approximately 8.3 kW) deposited in each of the H\(_2\) moderators. Although the heat load is relatively small compared to the total deposited, it is the fact that it occurs in the cryogenic (20 K) H\(_2\) that significantly increases the challenge. For the other components (the water moderators consisting of pre- and thermal parts and the reflector) water will be used for moderation and cooling. Figure 3.48 shows temperature distributions in the liquid hydrogen (LH\(_2\)) moderators, calculated and derived by CFD simulation. The basic dimensions of the major components were obtained by neutronic calculations [339]. The engineering design takes into account all applicable loads, stresses and temperatures and conforms to applicable design rules, standards and regulations. Cost and manufacturing issues were also considered. The engineering outcome is iterated with the neutronic performance (using the more realistic engineering geometry), for purposes of optimisation.

#### Cold moderator

For the cold moderator, liquid hydrogen (LH\(_2\)) at approximately 20 K and 1.5 MPa is used as the moderating medium. The structural material for the moderator vessel is required to be tolerant to radiation damage, as transparent as possible for neutrons at all energies, and suitable for cryogenic temperatures. Operational experience and assessments at other neutron sources led to the selection of Al-6061-T6, a high strength aluminium alloy also used at SNS and J-PARC [370]. Specific heat load in the aluminium is about three times higher than in the LH\(_2\) itself and because of this, efforts have to be made to minimise the wall thickness. Local overheating in the LH\(_2\) and high temperature gradients across the vessel’s walls are to be avoided. Coupled fluid dynamics and structural mechanics calculations led to a wall thickness of 3 mm, as shown in Figure 3.49. Even with an optimised flow pattern providing efficient cooling of the wall, as shown in Figure 3.48, the 3 mm vessel wall thickness is about the maximum permissible to handle the thermal stresses induced by the temperature gradient, at least in the highest heat load region close to the target. The operating pressure of 1.5 MPa, in contrast, requires a greater wall thickness for simple box geometry to stay within the allowable stress limits. This tension led to a more complex design using a cone-like
structure in the centre of the moderator to route the flow while also connecting the top and bottom flat surfaces to reduce deformation and stress. Figure 3.50 shows a cross section through the moderator that shows the centre cone-shaped inner duct.

Compared to the concentric inlet-outlet arrangement used for cold moderators at other sources, a swirl flow pattern was identified as a solution to enhance wall cooling and avoid stagnation zones. The vessel features a tangential LH$_2$ inlet close to the bottom (facing towards the target). This leads to a highly turbulent spiral flow pattern that routes some of the flow along the cylindrical vessel wall and up to the top where it enters the inner duct (connecting the top and bottom surfaces) through holes and leaves the vessel. The remainder of the flow enters the inner duct at the bottom and flows up through the centre. Thus, this duct acts both as a flow guide and as a stiffener.

Despite this optimisation, stresses in the vessel wall are still significant, and a thorough material investigation is necessary. Testing was performed for welded and un-welded assemblies at both room temperature (RT) and 77 K. Figure 3.51 shows some of the test results. Further testing will include the
3.3. MONOLITH AND PLUGS

The water moderator assembly shown in Figure 3.52 is made up of two parts. The first part is a water premoderator that surrounds the liquid hydrogen cold moderator. The second part consists of extended wings, which constitute the thermal moderator, which makes possible bispectral neutron beam extraction from the moderator assembly. The assembly also makes up part of an insulating vacuum layer for the cold moderator. The total heat load to each water moderator assembly is calculated to be 24.2 kW [339].

Compared to the cold moderator, heat removal for the water moderator assembly is of less concern because higher temperature differences can be allowed in the water. Due to the thermal wings, the design of the water moderator assembly is rather complex and includes two independent water flow paths. Figure 3.52 shows the design of the two parts forming the water moderator assembly. For the final assembly, the cold LH₂ moderator vessel will be positioned inside the premoderator (Figure 3.52, left) and then the thermal part of the moderator is added (Figure 3.52, right). The water moderator assembly will be welded together, thus forming the insulation vacuum for the cryogenic vessel.

This system does not feature a separate helium blanket as is usually seen in other cryogenic LH₂ installations. The main reason for this is that the vessel wall between the vacuum layer and the helium blanket would lack sufficient cooling and would overheat at the ESS power level. To assure detection of small water leaks into the insulating vacuum (and the associated risk that oxygen might freeze out on the cold surfaces), it is proposed to saturate the water with helium gas. In case of leakage, helium gas would enter the insulation vacuum (it would not freeze because its liquefaction temperature is lower than room temperature to 77 K) to simulate thermal stress ageing.

Water moderator assembly

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Figure 3.51: Measured tensile strengths and yield strengths for Al-6061-T6 samples at 77 K and 293 K. Two samples were tested; one was an unwelded simple solid, while the other was composed of two Al-6061-T6 halves that were welded together in the middle. Tensile and yield strengths are labelled as Rm and Rp0.2 for the unwelded sample, and Rm-S and Rp0.2-S for the welded sample.

![Figure 3.51: Measured tensile strengths and yield strengths for Al-6061-T6 samples at 77 K and 293 K. Two samples were tested; one was an unwelded simple solid, while the other was composed of two Al-6061-T6 halves that were welded together in the middle. Tensile and yield strengths are labelled as Rm and Rp0.2 for the unwelded sample, and Rm-S and Rp0.2-S for the welded sample.](image-url)
CHAPTER 3. TARGET STATION

Figure 3.52: The parts of the water moderator. Left: The premoderator, highlighted in solid green. Right: The thermal moderator.

than the temperature of LH$_2$ operation) and be detected by monitoring instrumentation in the insulation vacuum system. Final proof of this concept will have to be shown by experiment. Figure 3.53 shows fluid dynamics simulation results for the water-aluminium boundary layer for the two parts of the water moderator assembly. Although the temperatures shown are already acceptable, further optimisation will be performed. Due to the low pressure drop and reasonable temperature rise per water moderator part (pre- and thermal moderators) both can be operated in series, reducing the necessary amount of piping from the MR plug to the top of the monolith.

Reflector

The reflector is composed of inner and outer parts. The inner reflector, which extends to a diameter of 0.6 m and a height of 0.9 m, will be made from beryllium. The outer reflector will most likely be made from steel and will feature a diameter of 1.3 m and height of 1.5 m. The frequent exchange of shielding blocks outside the outer reflector is not expected during the lifetime of the facility.

The inner reflector is housed inside an aluminium vessel. The beryllium will be introduced in slices

Figure 3.53: Computational fluid dynamics results for the water temperature field in the two parts of the water moderator. Left: The premoderator. Right: The thermal moderator.
3.3. MONOLITH AND PLUGS

Figure 3.54: Computational fluid dynamics results for the temperature field in the inner reflector. Left: In the beryllium. Right: In the water-cooling channels.

with grooves machined in them for the cooling water flow. Since the total heat load to the inner reflector of 350 kW is not homogeneously spread, as shown in Figure 3.54, the slices are dimensioned to deal with the heat load profile. The water-routing grooves for each slice are connected by vertically drilled holes. Since the beryllium is housed in an aluminium vessel, the contact area between slices does not need to be hermetically tight. A small bypass flow can be tolerated and actually is helpful for cooling the vessel itself. Figure 3.54 shows the temperatures in the beryllium of the inner reflector and in the water-cooling channels. The rather complex routing of the flow results in a pressure drop of 0.75 MPa [371]. This leads to a water-cooling loop operating at at least 1.0 MPa. The maximum temperature in the cooling water is 85°C for a 30°C inlet temperature and the maximum beryllium temperature will be in the range of 150°C. From a neutronic point of view, this seems to be acceptable. The ratio between beryllium and water averaged over the whole inner reflector is about 96.5%, with higher peak water content close to the target.

Moderator-reflector plug and moderator plug

Figure 3.55 shows the assembled MR plug including the inner and outer reflector, the two moderator plugs and the backpack block designed for handling and routing piping with appropriate stepping to avoid radiation streaming. The assemble sequence is as follows; first the inner reflector will be attached to the water piping and lowered into the centre of the outer reflector and then a cover block will be fitted on top to complete the outer reflector, then the backpack block will be bolted to the outer reflector. After this the two moderator plugs (each containing a cold moderator, a water moderator assembly, their associated piping and back-filling material, mainly beryllium) will be horizontally inserted into their openings. Finally, some in-fill blocks (shown in dark brown in Figure 3.55) will be attached to the backpack block filling in some cutouts in the shielding necessary to assemble the piping.

The lifetime of the moderator plug will be limited by radiation damage to structures close to the target to a little over one year at full power. It is expected that this lifetime can be extended after gaining operational experience with the system. The remaining components of the MR plug will have longer lifetimes. Thus, it will be possible to reuse the longer lifetime components of the MR plug by removing the whole plug as one unit from the monolith and transporting it to the active cells. The plug will be replaced by a spare unit. During the operation time of the spare unit the horizontal moderator plugs will be removed from the remaining MR plug and replaced by new units. Figure 3.56 show cut views of the
Figure 3.55: Left: The moderator plug. Right: The moderator-reflector plug, including the inner and outer reflectors. Also shown is the backpack block that handles and routes piping, with steps to avoid radiation streaming.

Figure 3.56: Cut views through the moderator plug. Left: Through the target plane. Right: Through the instrument plane, where the cut blue surface represents the horizontal moderator plug. The outer reflector is shown in grey, the inner reflector orange and the steel backpack block is shown in dark red.
target and instrument planes of the moderator plug. The mass of the assembled MR plug will be about 24 tons. It will be transported to and from the active cells using a dedicated handling cask. The MR plug will be handled in a two-axis movement. First, the plug will be moved horizontally from the operating position close to the target to a position further upstream, in order to get clear of the target wheel and allow vertical movement into the shielded handling cask. While the lifting process is facilitated by the tools inside the handling cask, a special machine will be used to allow horizontal movement with the required accuracy both with respect to the operating position and with respect to the position to start vertical handling.

The horizontal handling machine will be a separate tool that can be stored in the high bay area until needed. For operation, it will be lowered on the rails mounted on top of the monolith by the high bay crane. The rails are equipped with limit stops for both positions (“operation” and “ready for vertical handling”). These limit stops will be adjusted during initial installation using a dummy PR plug equipped with end switches to sense the accurate positions at target elevation. This will allow the relevant positions to be duplicated for operation and vertical handling on the target level to the limit stops on the rails. This duplication procedure can be repeated even after the facility has been activated if made necessary by significant geometric changes due to monolith settling, seismic events, or the necessity to disassemble the rails or if modifications are made that change the plug’s centre of gravity. The handling machine will be equipped with a bridge for horizontal movement carrying a lifting device that can be attached to the plug. For attachment, there will be two self-aligning bolts and a threaded centre bolt available. The centre bolt will carry the load of the plug. The lifting device will only need to lift the plug by a couple of millimetres to allow horizontal movement without friction and to avoid touching the target wheel. The lifting device is not intended to lift the plug to a higher position. The drive system for horizontal movement will be designed to allow only very low speeds to avoid any dynamic response of the plug hanging underneath. Figure 3.57 illustrates the vertical handling tool for the MR plug.

Figure 3.57: Vertical handling tool for the moderator-reflector plug.
3.3.8 Proton beam window

Requirements and configuration

The proton beam window (PBW) module will consist of the window itself – a rectangular curtain of hollow pipes machined from a solid block of aluminium – welded into an aluminium frame, which, in turn, will be mounted between two steel flanges. The PBW will separate the high vacuum of the accelerator beam tube from the helium atmosphere in the monolith. As this window will be stationary, it will be subjected to much higher radiation damage than the beam entrance windows of the rotating target wheel. In addition to the radiation damage issue, the need to provide cooling for 5 MW beam power and up to $85 \mu A/cm^2$ beam current density at the PBW is a major design driver. Aluminium is a good material for the window because of its low density and consequent low specific heat deposition, which enable it able to withstand high accumulated proton beam intensity, and to generate relatively little heat as the proton beam penetrates the window. In addition, aluminium’s high stress tolerance will make it possible to circulate the helium coolant through the window at high pressure.

Using aluminium for the PBW, as has been done in other facilities such as SINQ/PSI, leads to an expected window lifetime on the order of one half to one year at full power. Given this comparatively short lifetime, the PBW is designed so that it can be easily replaced. It is thus designed as a module that can be exchanged from the top of the monolith, in a fashion similar to the design at SNS and J-PARC.

Therefore, a fast-acting valve in the proton beam tube upstream of the window will serve as the safety-relevant boundary of the second barrier. The PBW is designed to withstand the differential pressure of 0.1 MPa between the monolith helium atmosphere and the accelerator vacuum as well as the pressure of the helium coolant circulating through the window.

Water is used for PBW cooling at other facilities, including SNS, J-PARC ISIS and SINQ. ESS’s baseline design calls for the use of helium gas for this purpose, just as it relies on helium gas as the coolant for the target. Using helium gas to cool the PBW will mitigate the effects of a PBW break on the accelerator beam tube, and will also avoid the tritium production that would occur with water-cooling. The PBW is located about 4.5 m upstream of the centre of the monolith. The proton beam will be more focused at the PBW than at the target. Therefore, the profile at the target entrance window was used for the PBW design, but with an appropriately scaled higher peak current density. This scaling results in a conservative calculated value corresponding to more than 5 MW proton beam power. At a later stage, this conservatism can be reduced by using a more realistic definition of the beam profile at the PBW.

A special coating will be used on the downstream (helium) side of the window, in order for the integrated control system (ICS) to monitor the proton beam profile. Luminescence from this coating will be viewed from the proton beam diagnostic plug, which will be located half way between the PBW and the target. Since this coating will produce an additional heat load on the window, it has to be as thin as possible. The most recent calculations do not include the effect of the additional heat load from the coating, but this will be taken into account as the PBW design is refined.

Window design

The window will be composed of a series of pipes through which the helium coolant will flow continuously. These pipes will form a “curtain,” rather like a panpipe. Their diameter will be small enough to enable them to withstand cooling medium circulating under high pressure with relatively low stresses. The diameter will also be small enough to make the pipes stiff enough to withstand the bending load from the 0.1 MPa differential in pressure between the monolith atmosphere and the accelerator vacuum over the window height. Internal pressure loads from the monolith atmosphere under accident conditions will be further investigated before the design is finalised. The window will be manufactured from a solid block of aluminium by high-speed milling and computer controlled drilling of the holes. The general feasibility of manufacture has been demonstrated by the machining of a sample window section. This window will be welded into a larger aluminium frame that will provide mechanical support and will be equipped with channels to guide the flow of the cooling medium into the window, as shown in Figure 3.58.

The panpipe section of the window will be 70 mm in height and 192 mm in width. This is enough to allow a beam of 60 mm $\times$ 160 mm with $\pm$6 mm variation of the real proton beam from the nominal axis.
3.3. MONOLITH AND PLUGS

The pipes feature an outer diameter of 6 mm and a wall thickness of 0.3 mm and are placed with a centre-to-centre distance of 6 mm. The intersection between the pan pipe section of the window and its much larger frame is flexible in the vertical direction to compensate for thermal expansion in the longitudinal direction. Moreover, this flexible clamping compensates for the tilting effect at the end of the pipe section that is a consequence of the window deflection caused by the pressure difference over the window.

As Al-6061-T6 has been chosen for the window material, the maximum temperature is limited to approximately 100°C, because at temperatures above 130°C the material will lose its tempered state and consequently its strength [372]. Preliminary analytical calculations using formulae for pipe flows have shown that for an inlet temperature of 20°C, a helium mass flow rate of 0.1 kg/s is needed to achieve this design criterion. In order to further reduce thermal stresses, a mass flow rate of 0.2 kg/s was selected for the reference design calculation. For this mass flow rate, detailed CFD flow simulations and FEM thermo-mechanical calculations were performed for a parabolic and time-averaged heat deposition profile with a peak value of 0.5 kW/cm³ and footprint dimensions of 160 mm × 60 mm. The maximum temperature for the time-averaged heat deposition is approximately 65°C, which will occur in the centre of the beam footprint. Considering a temperature increment in the centre of the PBW of about 15°C during one pulse, the maximum temperature for the pulsed operation will vary between approximately 73°C at the end of one pulse and 56°C prior to the next pulse. The maximum temperature of 73°C will give leeway to increase the helium inlet temperature at a later stage of the project without exceeding the temperature limit for the chosen aluminium alloy.

Relevant stresses emerge in the flexible intersection between the panpipe section of the window and its massive frame and thus outside the beam penetration zone. The maximum local stress is about 83 MPa and emerges at the end of the cylindrical part of the central cooling channel. Relevant bending and membrane stresses of about 67 MPa are expected at the flexible intersection that has to compensate for the thermal expansion of the PBW. Dynamic amplification due to the pulsed operation can be neglected in this case, because the pulse length is much longer than the period time of relevant eigenmodes. Nevertheless, the pulsed operation has a significant impact on fatigue. One can expect stress amplitude of about 10 MPa for the flexible intersection during pulsed operation and resulting temperature oscillations. These are postulated to occur about 3 × 10⁸ times during the lifetime of the window. In addition to these stress cycles during normal operation, cyclic stresses due to beam trips have to be considered. Beam trips of more than 0.5 s will lead to a complete cool-down of the PBW and consequently to stress cycles that might – depending on the expected number of beam trips – require additional measures to reduce fatigue damage. One remedy is to further increase the helium mass flow rate. However, fatigue evaluations show that the PBW structure can withstand more than 2.9 × 10⁴ postulated trips in a year.
Proton beam window plug

The PBW frame is mounted between two stainless steel flanges forming a PBW module, as shown in Figure 3.59. These flanges are actively water-cooled and carry the inflatable metal seals. The module can be exchanged as one unit from the top of the monolith. For installation and alignment purposes the module is equipped with guides that engage into grooves in the proton beam window duct structure. These grooves define the exact position of the PBW module. The module can be adjusted after initial assembly of the monolith.

The general sealing technology is similar to that used at the neutron sources at SNS and J-PARC. The inflatable seals are double seals with an interstitial space that can be monitored and evacuated for leak detection and better sealing quality. The PBW duct will be operated in a rough vacuum so that requirements on the seals are reduced. The first seal (viewed from the monolith helium atmosphere) seals the helium against the rough vacuum, while the second seal seals the rough vacuum against the high quality vacuum of the proton beam tube. The counterpart for the inflatable seals is a polished metal sealing surface. In order not to damage this surface, the inflatable seals will be retracted by evacuating the seals. In any case, should the surfaces be scratched it is possible to exchange the beam tube section containing these seals, as shown in Figure 3.59. This is done horizontally, after extracting the first 2 or 3 meters of beam tube upstream of the monolith. All necessary piping, helium-cooling, water-cooling and vacuum lines, will be routed from the module to the top of the monolith. Flexible hoses can be used to cope with tolerances as well as thermal expansion of the piping. The routing of the piping has been designed so that the shielding blocks above the PBW module can be retracted without touching the piping.

The handling sequence is as follows; first the cooling helium loop will be emptied, flushed and refilled with an inert gas or dry air. Then cooling water circuits will be emptied, flushed and dried. After this, both the vacuum valve in the proton beam tube towards the accelerator and the helium valve downstream of the PBW will be closed. After venting the PBW duct with air or an inert gas, the upper cover (in the connection cell) can be removed in order to enable hands-on disconnection of the pipe elbows right underneath the cover. Now the shielding blocks above the PBW module can be removed. Depending on the accumulated activation, the lower one may be removed using a shielded flask due to activation on its lower end. After this, the PBW module itself can be removed into a shielded flask. The piping can be cut down at the module with a hydraulic remote pipe cutter. This allows independent pipe removal, thus relaxing size requirements on the flask. After a remote inspection of the sealing surfaces, the new PBW module can be lowered into position guided by the pre-aligned groove in the duct structure. The remaining work will be done in reverse order.

Figure 3.59: The proton beam window module and plug. Left: Inflatable seals. Right: Plug sealing system.
3.3.9 Beam ports and beam extraction system

The target monolith structure must have at least 22 openings for neutron beam guide inserts NBGI, in order to accommodate the full suite of 22 neutron instruments.

The current design of the beam extraction system includes 48 possible beamline positions in four fan-shaped beam extraction sectors, as shown in Figure 3.60. Each beam extraction sector is 60 degrees wide and has 12 possible positions with 5 degrees of angular separation, each of which can be opened for a beamline. For shorter instruments that need more than 5 degrees of angular space to the neighbouring instrumented beamlines, 10 degrees or even 15 degrees of separation can be achieved by keeping the neighbouring beamline positions closed. Current estimates suggest that about 40% of the instruments will need more than 5 degrees of beam separation from their neighbours, which implies that a maximum of about 36 open beam lines can be placed on the 5 degree grid of the 48 possible beam port positions. This design offers high flexibility to optimise beamline distributions to instrument suites that will vary over the lifetime of the facility. For example, with the 22 instruments slated to be built during the ESS construction phase divided into 40% short instruments that require 10 degrees of angular separation from neighbouring beam lines, and 60% longer instruments that require only 5 degrees of separation, the neutron flux gain for the whole facility will amount to 13% compared to a conventional uniform distribution, as discussed in Section 3.2.6. Implementing this flexibility involves marginal additional costs during the initial construction phase because, as shown in Figure 3.61, it implies the use of a larger number of smaller, removable shielding blocks compared to a smaller number of larger shielding blocks installed permanently for the lifetime of the facility. Opening additional beam ports at positions initially not prepared during the construction of the monolith would be prohibitively complex and expensive.

The beam ports will be arranged in two layers. The centre axes of the ports in the top layer will be directed towards the top moderator assembly, which will be situated 180 mm above the proton beamline.
Figure 3.61: Two ways to shield closed beamline positions. Left: With removable shielding blocks. Right: With permanent shielding blocks.

The centre axes of the ports in the bottom layer will be directed towards the bottom moderator assembly, which will be situated 180 mm below the proton beamline. It will be possible for the neutron beam guides inserted into the ports to view both parts of the moderator assembly (thermal and cold), thus allowing bispectral extraction, in those cases where the dimensions of the guide permit this flexibility. The approximate separation of 170 mm at 2 m from the centre of the monolith (where the beam guide inserts originate) between neighbouring beamline axes with a 5 degree separation, allows good visibility of both types of moderator. Moving further out from the centre, adequate space becomes available to accommodate the installation of ballistic or elliptical guides.

All the beamline inserts will be identical in outer shape. The baseline design preliminarily calls for each insert to be equipped with a 500 mm thick light shutter which, when closed, will provide adequate shielding to allow access to beamline components outside the monolith after the proton beam is shut down. Unlike full heavy shutters, these light shutters are not able to block high-energy neutrons while the beam is on target. The final combination of no shutter, light shutter and heavy shutter solutions will be consolidated at the beginning of the construction phase.

Neutron beam guide inserts and shutters

A neutron beam guide insert NBGI will consist of a solid block of steel that is stepped on the outside to avoid streaming of radiation through the gap between the insert and the opening in the monolith-shielding block. Due to the narrow angular separation of adjacent beamlines, there is limited space for stepping. The design takes this tight spacing into account by setting strict manufacturing tolerances for the blocks at the beamline level as well as the inserts themselves. The resulting small gaps allow minimal stepping to be effective in reducing streaming and thus unwanted background radiation. The insert will be loaded and unloaded horizontally using a rail system, which will be built into the high precision-machined monolith shielding blocks. Figure 3.62 shows a neutron beam port with a shielded handling cask in place.

Due to the 5 degree separation between beam port sites, the width of the insert at the upstream end will be as low as 170 mm. The insert outer geometry will widen to 210 mm as soon as geometrically possible. The front section of the insert will be 270 mm high and the height will increase in steps to 400 mm. The helium inside the guide insert will be part of the monolith’s helium atmosphere. Since the neutron beamline inside the monolith will feature a light shutter, alignment between the upstream guide element and the guide segment that travels with the shutter gate has to be guaranteed. The resting points
for the shutter gate in the open position will be so-called “highly repeatable” kinematic mounts, that is, kinematic mounts that make it possible to repeatedly precisely position a moving component on the mount. The shutter will be made an integral part of the guide insert, with the shutter gate’s open-position resting points attached directly to the insert. Thus, it will be possible to align the guides inside the insert, as well as the gate, to the outer surface of the insert and to each other in the open position. In order to assure failsafe operation, the shutter gate is designed to be closed in the down position.

The drive system for the shutter gate will be mounted on the top of the monolith, outside the helium atmosphere. Metal bellows will separate the drive system from the pull rod that reaches down to the shutter gate. The pull rod will be engaged in the gate and will pull it towards the kinematic joints. Springs in the drive system will allow the rod to securely press the gate to the kinematic joints while not allowing the whole insert to be lifted. Thus, access will be provided to mechanical components such as drives and motors for repair without interfering with the monolith helium or creating a need for remote handling. Water cooling connections for the guide insert will be provided from the downstream side before mounting the neutron beam window.

Handling of the insert will be performed by a shielded horizontal handling cask, as shown in Figure 3.62. In order to remove and reinstall a guide insert, the first 6 m of neutron beamline outside the monolith for the relevant instrument, and perhaps for the two neighbouring instruments as well, will have to be removed. Outside of the monolith, every beamline will be equipped with kinematic mounts to allow the flask to be positioned exactly in front of the beam port. The handling cask will feature a double door to minimise the potential for spreading contamination from the monolith into the experimental hall. Nevertheless, removal and reinstallation of the neutron beam window will open the experimental hall to the monolith atmosphere for a brief period of time.

Neutron beam windows

The neutron beam windows will separate the monolith atmosphere from the experimental hall. Thus, they will be part of the monolith liner confinement barrier. In order to minimise their effect on the neutron spectrum, the windows will be made of aluminium and have been designed to be as thin as possible. To provide a margin of safety, a double wall window design with monitored interstitial space has been adopted, as shown in Figure 3.63. The inner window (on the monolith side) is designed to withstand evacuation of the monolith and thus a 0.1 MPa pressure differential. The outer window (on the instrument side) will be only about 0.5 mm thick and so will require careful monitoring for even small pressure differentials. The frames of adjacent beamline windows will abut each other leaving very little space between window flanges.
3.3.10 Irradiation ports

The main goal of ESS is to generate thermal and cold neutron spectra that will be used by the neutron-scattering research instruments. In addition, fast neutron spectra (possibly mixed with proton spectra) can be extracted from the monolith, in order to irradiate samples and components. The primary goal is to irradiate components or materials as part of ESS’s own program of target station R&D. Other applications could also be investigated, however, such as irradiation of materials for fusion research or tests of microchips.

Two possible irradiation concepts are of interest, either placing samples close to the target, moderator and reflector, or placing samples in the path of fast neutrons extracted through irradiation ports. In turn, three different possibilities for irradiation ports have been considered. One is a high energy beam transport (HEBT) port located in the proton beam horizontal plane, in a backward direction at an angle of about 160 degrees with respect to the proton beam axis, in order to disturb neither the neutron guides nor target handling, as shown on the left of Figure 3.64. Another possibility is a forward fast neutron port, located in the forward zone close to the proton beam axis, starting at the target wheel opposite the proton footprint, and continuing through an opening in the monolith shielding, as shown on the right of Figure 3.64. Again, this arrangement would not disturb the neutron guides or target handling. A third possibility is a fast neutron basement port leading from the target wedge on which the protons impinge, but on the opposite side from the proton footprint. A possible path, taking into account monolith design constraints, travels downwards in the monolith, below the wheel shaft, as also shown in Figure 3.64.

Samples could be placed inside the target, or in the moderator plug close to the neutron production zone, to be irradiated for short time (in which case a system for inserting and removing the samples would be needed), or for a longer term (one or more years), in which case samples would be inserted and removed during operations on the MR plug. The design of removable irradiated components (such as a target, PMR plugs, PBW plug, and shielding) would include the ability to retrieve samples after their dismantling or during their maintenance phase in the hot cells, in order to monitor irradiation damage. This would provide important information for improving the design and lifetime of regularly replaced target subsystems, over the 45 year lifetime of the facility.

The MCNPX input file for the target station was modified to include possible fast neutron ports. Neutron fluxes and radiation damage parameters were calculated for some representative locations: in the
3.3. MONOLITH AND PLUGS

Figure 3.64: Three potential locations for fast neutron ports. Left: High energy beam transport port. Right: Forward port and basement port.

Figure 3.65: MCNPX model layout describing locations P1 to P7, from the HEBT port closest to the reflector and the proton beam, to the reflector plug.

forward irradiation port close to the wheel, and in the HEBT port close to the reflector and close to the proton beam (positions P1 and P2 in Figure 3.65), inside the target in a location representative of the sector edge and in the wheel body close to the tungsten sector (positions P3 and P4), in the space between target and moderator at the moderator radial centre (position P5), at the beginning of the HEBT port, close to the wheel (position P6), and in the position where the reflector plug is set (position P7). Calculated fast neutron spectra above 1 MeV are plotted in Figure 3.66. The maximum neutron flux is reached at the moderator centre. Interesting positions for flux magnitude in the energy region of fusion applications (10 to 20 MeV) are P1, P3 and P6. Figure 3.66 shows the mapping of the neutron flux integrated between 10
CHAPTER 3. TARGET STATION

3.3. MONOLITH AND PLUGS

Figure 3.66: Calculated neutron behaviour in the target-moderator-reflector assembly. Top: Neutron spectra at the reference locations P1 to P7. Bottom: Integrated neutron flux between 10 MeV and 20 MeV.

and 20 MeV in the TMR region. The effects of radiation damage have been addressed by calculation of the displacement per atom (dpa) over the course of an operational year of 5000 hours, and the hydrogen and helium gas production rates measured in atomic parts per million (appm) per dpa. These calculations relied on cross sections for iron reported in recent KIT evaluations [342]. The calculations were performed in the positions listed above. The results are reported in Table 3.21. For comparison, the estimated parameters of radiation damage in the planned DEMO fusion reactor are also presented [373].
### 3.3. MONOLITH AND PLUGS

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Table 3.21: Radiation damage and gas production in the target-moderator-reflector assembly, at the positions shown in Figure 3.65, and in the DEMO fusion reactor first wall [373].

#### 3.3.11 Tune-up dump

The tune-up dump will stop the proton beam during accelerator tuning. It will be located in the basement of the target station in the A2T area of the target building. By design, it will be a passive device, which will last for the life span of the facility, although it will operate only during periods of accelerator tuning. The baseline design calls for a graphite core embedded in aluminium cladding, cooled by water circulating through several channels. Alternative metallic materials could replace the graphite if necessary.

Figure 3.67 shows that the tune-up dump will be separated from the accelerator proton beam tube by a window. The current design of the dump’s enclosure tank includes a cylindrical graphite core 2 m in length and 0.3 m in diameter, with 0.05 m thick aluminium cladding. Four cooling channels are drilled along the aluminium cladding, each 0.02 m in diameter. Together, the channels make possible a total mass flow rate for the water of 2 kg/s. The tune-up dump window consists of two thin (3 mm thick) aluminium layers cooled by a water film in between. The tune-up dump is designed to require minimal handling and maintenance during its lifespan. Regular handling is necessary will be conducted from outside the dump window. The tube between the dump and the window, shown in Figure 3.67, passes through a concrete wall. Maintenance will thus be conducted manually or semi-remotely from the other side of the wall, out of the direct line-of-sight of the activated graphite, with limited dose rates. As mentioned above, the tune-up dump will be located in the basement of the target station in the A2T area, straight ahead from the accelerator proton beam tube. The high bay overhead crane will cover this area. If the dump...
CHAPTER 3. TARGET STATION

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Table 3.22: Beam modes and parameters for the A2T tune-up dump.

should have to be accessed for handling, the accelerator components and tube, as well as the shielding required for the accelerator above the dump will have to be removed. The dump could then be lifted to the high bay.

A shutter system will be placed between the tune-up dump and the accelerator, upstream from the dump window. The shutter will be closed when the dump is not in use in order to limit dose rates in the HEBT area, allowing for operation or maintenance of the accelerator components. The dump will be in its own vacuum environment, separated from the accelerator vacuum by the dump window. The environment around the dump will consist of low-pressure helium. The emission of activated volatile compounds and failure of the cooling channels will be monitored. Any graphite dust produced during dump operation will be removed from the dump environment.

Eight beam modes have been defined for the tune-up process, as shown in Table 3.22, which also includes thermal simulation results [374]. These beam modes present a Gaussian beam profile. The cooling scheme for the dump has been analysed for each of these modes and no feasibility issues have been detected. All cooling tubes will be joined in a manifold that will serve as the interface with the cooling system handled by the target systems. The maximum temperature of the graphite during transients will be low enough to guarantee its stability. The graphite core is the only part of the tune-up dump that will be subject to thermal stresses, but it is not a structural material for the dump. Thus, the graphite could break down without compromising the integrity of the dump. Because of the low thermal expansion coefficient of graphite, the aluminium will not be deformed by thermal stresses. Average operating temperatures are low enough to guarantee safe operation even when thermal contact between aluminium and graphite is not perfect.

3.4 Fluid systems

The target station fluid circuits are of two distinct types, the closed circuits and the open circuits. The closed systems include the water, helium, nitrogen and cryogenic liquid hydrogen circuits. The open circuits are the ventilation and the confinement air systems.

Closed circuits

The closed circuits are dedicated to power removal from the active zones of the target station or, for the helium flowing within the monolith, to avoiding accumulation of radioactive products and corrosion inside the large, irradiated containment vessel. They are staged in primary circuits that directly carry the heat away from the spallation zone, and in intermediate circuits. The intermediate circuits exchange the heat taken from the primary circuits with external circuits flowing outside the target station areas, and with conventional facilities located in non-monitored areas. A notable characteristic of these external circuits is that these are not individually controlled online, from a radiological point of view. The closed fluid circuits are organised so that all the primary circuits running through the activating fluxes of primary and secondary particles and gammas are confined within controlled areas, which are not accessible during power operation modes. These primary fluid circuits are slightly activated by protons and neutrons, or
contaminated by corrosion products, or by outgassing from their activated containment parts, in normal situations. However, these primary circuits are physically separated from the non-monitored areas by intermediate fluid circuits, and heat is transferred from the primary to the intermediate circuits via heat exchangers. Consequently, any transfer of contamination from these circuits will be contained within the target station areas where it can be detected online or during periodic tests. This general layout principle guarantees that no transfer of radioactive contaminant outside the target station area can occur either in normal operating circumstances, or in case of incidents or accidents. It would require at least a double failure for unplanned radioactive releases to occur. The water circuits are organised so that the different functions, such as removing energy, draining circuits, filling circuits, or filtering fluids, are separated as much as possible from one another, for reasons of safety and operational convenience. All the liquid circuits will drain to designated activated water storage facilities and will be collected inside the target station building during maintenance. All the potentially contaminated circuits will also be ventilated via the radioactive gaseous effluents and confinement system (RGEC), which will make it possible to route them through a decay tank and purification subsystem if necessary. Additional information about fluid system interfaces can be found in Chapter 7.

Open systems

The radioactive gaseous effluents and confinement system will be an open-air circuit. It will take air from different target station building volumes and extract it to the exhaust stack. Since the entrance of air will be managed by the target station building’s heating, ventilation and air conditioning (HVAC) system, there will be no air conditioning function in the RGEC system, as discussed in Chapter 7. The RGEC system will connect to a number of circuits ventilating different portions and individual rooms in the target station. The RGEC functions are required both during the power operation and the maintenance periods of the target station. The RGEC system contributes to the functioning of the confinement barriers, assuring dynamic confinement when the intrinsic barrier tightness is not sufficient, especially during target station maintenance periods. It also enhances confinement performance to limit the radiological impact of released contamination during abnormal situations. The RGEC system is composed of sub-branches serving various parts of the target station, including the active cells (transfer zones in and out of the cells in the processing, handling and storage zones); the connection cells in direct communication with the monolith atmosphere during maintenance; and the internal neutron guide extraction zone (located within the additional shielding surrounding the neutron beam windows in the experimental hall, which are open during neutron guide insert exchange). The RGEC also serves areas with subject to much lower levels of contamination than the active cells, including the target station high bay, the utility rooms hosting the primary fluid circuits including the target station basement where the radioactive fluid storage tanks are located and the target station A2T zone.

3.4.1 Gaseous cooling circuits

There are four independent gaseous cooling systems in the target station. These are the target cooling system, the proton beam window cooling system, the monolith atmosphere system and the intermediate gas cooling systems. Each cooling system is based on system-specific purification and filter-handling concepts, and are therefore treated separately below.

Target cooling system

The target will be cooled by circulating helium gas. The coolant temperature at the inlet to the target must be as low as possible and as close as possible to the installation temperature. This will reduce the operating temperature level of the target and also will minimise target displacement due to thermal elongation of the shaft during the ramp-up period from zero-proton current to operating temperature. The design must allow online purification of the coolant, and must be able to handle the potential of dust contamination, mainly from the tungsten spallation material. Based on these considerations, an O-shaped cooling system configuration has been selected, as shown in Figure 3.68.

A helium compressor will drive the helium around the O-shaped circuit at a flow rate of 3 kg/s, which is the rate necessary to cool the target below the critical temperature, as discussed in Section 3.3.2. Given the rated compression ratio of 1.5, the helium from the compressor will be heated to about 70°C, and will
then be cooled to 20°C by a heat exchanger. The cold helium flow will go directly to the target system through the rotary feedthrough. In the target, the helium will be heated to about 220°C. The leak rate from the target cooling helium circuit is conservatively estimated to be less than 0.1% per day, based on the operating experiences of the HELOKA test loop at KIT [375].

In order to prevent dust contamination of the helium circuit by tungsten or other (active) solid particles, a mechanical filtering system will be installed downstream of the target. To ensure stable operating conditions for the compressor, a second cooler will be installed between the filter and the compressor, in order to cool the hot helium flow from the target to 20°C. A purification system connected on a bypass to the compressor will make it possible to purify the helium online. This system will cope with volatile and gaseous components that need to be removed from the coolant stream. The bypass itself will also be dimensioned to control the helium flow rate through the target.

The helium circuit will deliver a relatively high volumetric flow of approximately 6.4 m³/s at a relatively low pressure of 0.3 to 0.4 MPa. The goal of the relatively low pressure is to relax constraints on the design of the target vessel and, especially, of the beam entrance windows (BEW) along the rim of the target shroud. The structure exposed to the proton flux will receive a volumetric power deposition from beam stopping and scattering. The associated thermal stresses, combined with mechanical stresses due to the filling pressure of the cooling flow, determine the required design thickness of the BEWs and the shroud. As a thicker target shroud results in reduced neutronic performance of the target system, it is important to make the BEWs and the shroud as thin as possible, which is facilitated by the low filling pressure. The top and bottom covers of the target wheel, which are most subject to the pressure load, are flat and therefore difficult to reinforce against internal pressure. This is also an important issue for the optimisation of the target, and especially for the neutronic performance of the system. The high flow rates at low pressure induce high velocity. It is therefore important to carefully assess the pressure drop along the circuit. Figure 3.68 illustrates the global layout of the circuit and the placement of each component. Table 3.23 summarises the circuit’s essential parameters.

A multi-stage compressor will be used for circulating helium for target cooling. The commercially available helium compressors that meet the target cooling circuit requirements described above are typically
### 3.4. FLUID SYSTEMS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump head, or total head loss</td>
<td>MPa</td>
<td>0.1</td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>MPa</td>
<td>0.3</td>
</tr>
<tr>
<td>Design pressure (relative)</td>
<td>MPa</td>
<td>0.35</td>
</tr>
<tr>
<td>Helium mass flow rate</td>
<td>kg s(^{-1})</td>
<td>3</td>
</tr>
<tr>
<td>Pumping power</td>
<td>kW</td>
<td>800</td>
</tr>
<tr>
<td>Bulk temperature at target inlet</td>
<td>°C</td>
<td>20</td>
</tr>
<tr>
<td>Bulk temperature at target outlet</td>
<td>°C</td>
<td>220</td>
</tr>
<tr>
<td>Pipe diameter</td>
<td>mm</td>
<td>250 – 300</td>
</tr>
<tr>
<td>Pipe total length</td>
<td>m</td>
<td>185</td>
</tr>
<tr>
<td>Cyclone filter volume</td>
<td>m(^3)</td>
<td>3.2</td>
</tr>
<tr>
<td>Total volume of the circuit</td>
<td>m(^3)</td>
<td>15 – 23</td>
</tr>
</tbody>
</table>

Table 3.23: Key parameters of the target cooling system helium circuit.

About 4 m × 8 m large, with a required electrical power rating of approximately 800 kW. This power rating implies that the helium temperature at the outlet of the compressor will rise to about 70°C. The operating pressures at the inlet and at the outlet are 0.3 MPa and 0.4 MPa respectively, for commercially available helium compressor technical specifications [376,377].

An important aspect of compressor performance is the leak rate. The compressor will have two rotating seals. A dedicated inflow of clean and controlled helium will leak towards the atmosphere, creating a negative pressure across the sealing and preventing helium from the target cooling circuit from leaking. The leak rate – the required helium supply – is estimated to be about 2 Nm\(^3\)/hr, where “Nm\(^3\)” is a normal cubic metre of gas at a temperature and pressure of 0°C and 0.1 MPa. Figure 3.69 presents the principle of a sealing solution. The enclosure has a pressure of helium slightly higher than the pressure inside the core of the pump. That will insure that the helium can only flow from this enclosure towards the helium circuit. Some helium will leak though the last seal towards the atmosphere, but this will be the controlled helium fed by the supply directed to the enclosure. This concept will also be considered for the rotary feedthrough, which will provide the helium from the fixed part of the circuit to the rotating target shaft.

Two kinds of dust filters are under consideration for use in the helium circuit. For small particles, standard filters could be used. They would be placed on the bypass circuit, for instance in the purification

![Diagram](image_url)
circuit, as shown in Figure 3.68. The use of cyclonic filters in the main helium stream is also under consideration. Such filtering systems are widely used in industry, even in harsh environments. The high density of tungsten makes it suitable for this type of filter.

The goal of the filtering system is to capture and remove from the helium stream any tungsten particles that may have been flushed away from the target. A hurricane, or cyclonic, system would be the simplest, most robust and cost effective technical solution. The efficiency of the global filtering system is enhanced by adding a mechanical recirculator to the simple hurricane system. The efficiency is further enhanced by adding an electrostatic recirculator. The purpose of the recirculator is to reintroduce the fine non-captured particles into the cyclone after these have been driven to the outer walls of the recirculator by centrifugal forces. The mechanical recirculator decreases emissions 40% to 60% more than does the simple hurricane filter, and the electrostatic recirculation system reduces particle emissions even further. In the electrostatic approach, a DC high voltage is applied to the concentrator, allowing the recirculation of very fine particles, which are more resistant to centrifugal forces, to the cyclone collector. After having been separated in the recirculator and concentrated in the recirculation flow, electrically charged particles are attracted by the cyclone walls, while agglomerating with larger particles entering the system, both facilitating capture. A hurricane system equipped with an electrostatic recirculator is illustrated on the left of Figure 3.70.

A preliminary analysis has been made of the filtration efficiency of commercially available cyclonic systems, assuming a conservative particle size distribution (PSD) over grain sizes between 0.01 µm and 100 µm, and for a particulate emission density of 0.27 µg/(Nm)³ [378]. The result are summarised on the right of Figure 3.70, which shows the particle size dependent filtration efficiencies for three configurations. The simulated overall efficiencies range from 94.2% to 97.6%, agreeing well with measured efficiencies between 92.9% and 98.9% [378]. The measured pressure drop in the cyclonic system is 1.3 kPa, negligible compared to the overall pressure drop in the helium circuit. The filtration efficiency of ESS cyclonic systems will be close to 100% under normal operational conditions, considering that the grain size of the tungsten target material is expected to be approximately 10 µm [379]. Some additional issues remain to be analysed, especially regarding the handling of the container. These should not be difficult to deal with, but some key parameters must be better determined before the maintenance routine can be fully specified. Finally, the chosen configuration was assessed for its ability to deal with the formation of tungsten trioxide (WO₃) dust, which would occur in the event of air ingress if the tungsten temperature were to rise above 500°C. The analysis relied on earlier estimates of the tungsten trioxide erosion rate and particle size.
3.4. FLUID SYSTEMS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten trioxide (WO$_3$) erosion flux</td>
<td>kg m$^{-2}$ s$^{-1}$</td>
<td>5 × 10$^{-5}$</td>
</tr>
<tr>
<td>Total surface area potentially eroded</td>
<td>m$^2$</td>
<td>17.5</td>
</tr>
<tr>
<td>Tungsten trioxide erosion rate</td>
<td>kg/s</td>
<td>8.7 × 10$^{-4}$</td>
</tr>
<tr>
<td>Average WO$_3$ concentration in the flowing helium</td>
<td>kg/m$^3$</td>
<td>8.2 × 10$^{-5}$</td>
</tr>
<tr>
<td>Expected WO$_3$ emission density</td>
<td>µg/(Nm)$^3$</td>
<td>1.76</td>
</tr>
<tr>
<td>Expected total filtration efficiency for the nominal PSD</td>
<td>%</td>
<td>95.41 – 97.47</td>
</tr>
</tbody>
</table>

Table 3.24: Expected filtration efficiency for tungsten trioxide dust in the event of air ingress [379].

distribution [322, 380]. The parameters used for the analysis and the expected filtration efficiency for the nominal PSD are summarised in Table 3.24.

The target cooling circuit is a closed circuit which will require pressure control. Since the coolant is gas, any change in the mean temperature of the system will have an impact on the pressure. Particularly during start-up, the helium temperature on the return line will increase by about 160°C, while the temperature in the rest of the circuit will remain unchanged. In order to maintain the pressure level, a fraction of helium will have to be removed from the system, since the volume of the circuit is constant. In addition, during operation, there will be helium inserted into the system through the rotating seals at the helium pump and the target shaft. Assuming that the pipes and filter volume is 23 m$^3$, the total amount of helium that will have to be removed will be about 9 m$^3$. This can be accomplished by putting the surplus of helium in an intermediate buffer, and then compressing it for storage.

Due to the fact that the compressor is a centrifugal machine, there is no separation of volumes in the circuit, and the connecting point of the pressure control system (PCS) can be located anywhere along the circuit. However, it is desirable to put it downstream of the machine for the stability of the compressor. Another source of pressure increase comes from the positive leakage that occurs at the labyrinth. The helium constantly put into the system has to be removed. This can be achieved with the same system, as described above. To reduce the loss of helium and simplify inventory tracking, circuit helium storage could be used as helium supply for the rotating seals. In order to do that, it is necessary to purify the gas from the buffer first, as discussed in Section 3.4.4.

In order to study the dynamic behaviour of the whole target cooling system, a thermal-hydraulic model has been built using the RELAP5-3D system code [381]. This code has been developed for the best-estimate transient simulation of light water reactor coolant systems, during postulated accidents. It includes libraries for helium properties, which allow the simulation of this gas as a working fluid. The model is built up, starting from modelling one sector, then setting up the target wheel model by connecting 33 sectors in parallel and, finally, generating the model of the whole helium circuit. For one sector, the model gives a total temperature rise of the helium of 150 K and a pressure drop of 46 kPa. These results are comparable to the CFD results presented in Section 3.3.3. The RELAP model gives lower values than the maximum temperature level from the CFD analysis, due to its coarser meshing. Using shaft design data, the flow to the wheel is modelled as an annulus flow and the return flow is modelled as a pipe flow. The pipe diameter corresponding to the equivalent hydraulic diameter of the spiral is modelled as a branch flow for each sector. The target wheel is modelled using 33 sector models installed in parallel. The model also takes the heat transfer between the inlet and outlet flow in the shaft region into account. The model is calibrated in such a way that the flow is equally distributed for the 33 sectors for the cold run at 20°C.

In a transient simulation, the pulsed operation is started at 50 s from the cold stage. For this simulation, a perfect synchronisation between the wheel and the beam is assumed. Between the pulses, in each sector, the decay heat is simulated for 47 kW of power, as discussed in Section 3.3.2. Figure 3.71 shows the simulation results. The temperature increase of the target wheel is 150°C and the total pressure drop is 51.6 kPa. The total pressure drop of the target including the shaft is estimated at 60.7 kPa. In a similar way as for one sector, the time constant of the target is calculated to be 44 s.

Proton beam window cooling system

The proton beam window (PBW) is cooled by helium at a mass flow rate of 0.2 kg/s, as described in Section 3.3.8. This cooling is provided by a closed cooling circuit, in which the helium takes heat in the PBW and gives it to the intermediate water-cooling circuit for gas described in Section 3.4.2, via a heat
In order to study the dynamic behaviour of the whole target cooling system, a thermal-hydraulic model has been built ... outlet manifolds.

The pulse temperature in PBW material is about 100 °C, but time spent in the window is short and the

risks and remedies for nitrogen ingress in the main target circuit have been extensively investigated [382].

coolant circuit, even in the event of a heat exchanger failure, this intermediate circuit uses nitrogen. The

the latter from contamination in the former. In order to ensure that no water can enter the primary target

system. This system takes heat from the primary target cooling system, and gives it to the conventional

in Section 3.4.3, the only intermediate cooling system working with gas is the intermediate target cooling

In addition to the cryogenic refrigeration systems, which may be viewed as intermediate but are described

exchanger. The system works as follows. A blower blows the helium through a filter and a heat exchanger

which cools the helium to room temperature before it is led into the PBW. The filter takes care of traces

of lubricants from the blower. The flow rate and pressure are controlled either by speed control or bypass.

In the PBW, the helium is heated, mainly by the thin window walls and the inlet and outlet manifolds.

The pulse temperature in PBW material is about 100°C, but time spent in the window is short and the

area is small. Therefore, the bulk temperature increase in the helium in the cooling system is lower by an

order of magnitude than the pulse temperature. After the PBW, the helium passes through another filter
to remove dust from the window and protect the following components. After this, it enters the blower
again.

There are also a number of side connections to the circuit. In order to stabilise the pressure in the

circuit, there is a small accumulator tank connected to the circuit after the blower. Before and after the

blower, there are connections to the gas purification system, as discussed in Section 3.4.4. The pressure

level is maintained via a connection to the helium purification and storage system, which is also used to

fill and refill the system after outages.

Monolith atmosphere system

The helium inside the monolith will have to be circulated in order to avoid pockets of stagnant hot or

possibly contaminated helium. The best way to ensure movement of the helium, at least in the vicinity of

the target where hot spots might occur, is under evaluation. One source of helium injection into the

monolith atmosphere will be the barrier gas used for the rotating seal for the target shaft. Direct injection

or extraction of helium in the vicinity of the hot components, the target and the moderator-reflector system
close to the target could also be beneficial. Further calculations may show that cooling the upstream end

of the guide insert can be done by moving helium only, avoiding the need for a water-cooled insert.

Intermediate gas cooling systems

In addition to the cryogenic refrigeration systems, which may be viewed as intermediate but are described

in Section 3.4.3, the only intermediate cooling system working with gas is the intermediate target cooling

system. This system takes heat from the primary target cooling system, and gives it to the conventional

facilities cooling system via heat exchangers between the systems. The purpose is to protect and isolate

the latter from contamination in the former. In order to ensure that no water can enter the primary target

coolant circuit, even in the event of a heat exchanger failure, this intermediate circuit uses nitrogen. The

risks and remedies for nitrogen ingress in the main target circuit have been extensively investigated [382].
Measures will be taken to protect against this eventuality, such as the placement of rupture discs in the primary helium circuit.

The flow rate in the intermediate target cooling system is about 60 kg/s. The system works as follows. A compressor presses the nitrogen through a filter at 1 MPa. The filter takes care of traces of lubricants from the compressor. The flow rate and pressure are controlled either by speed control or bypass. After the filter, the flow passes a heat exchanger where the nitrogen compressor heat is transferred to the conventional facilities cooling system. Then the nitrogen flow is divided into two parallel paths. The first path goes to the heat exchanger before the primary target-cooling compressor and takes out the heat from the target. This means that the available temperature difference on the primary helium side of this heat exchanger is about 200°C. The second path goes to the heat exchanger after the primary target-cooling compressor. This means that the available temperature difference on the primary helium side of this heat exchanger is about 50°C. After cooling the two target cooling system heat exchangers in parallel, the nitrogen flows are united again, before entering another heat exchanger in the nitrogen system. Here, the heat from the primary target cooling system is removed, and the nitrogen is cooled to room temperature before it enters the compressor again.

There are also a number of side connections to the circuit. In order to stabilise the pressure in the circuit, there is a small accumulator tank connected to the circuit after the pump. This connection is also used to evacuate the system and lower the pressure if needed. The pressure is maintained via a connection to the nitrogen supply system, which is also used to fill and refill the system after outages.

3.4.2 Water cooling systems

Water moderator cooling

All parts of each of the two water moderator assemblies above and below the target (discussed in Section 3.3.7) are connected to one closed water circuit, which is cooled via the intermediate water system that is, in turn, cooled with water from conventional facilities. Within the closed circuit, the cooling water from the water moderators first passes a delay tank to allow decay of short-lived isotopes, thus reducing radiation exposure of the components downstream. After the delay tank, the water goes into a tank for gas and liquid separation, where gaseous radiolysis products are either recombined in the gas separator or sent to the cover gas system. Water from the gas and liquid separation tank goes through a heat exchanger and a pump, before re-entering the water moderators. Downstream of the pump, a small bypass flow is directed to the water purification system, consisting of filters and ion exchangers. Purified water is returned to the system to the suction side of the pump. The system can be drained to a storage tank for maintenance. The water moderators will operate at close to room temperature, i.e. at about 20°C. The temperature rise in the water is expected to be approximately 10°C [371]. A heat load of about 25 kW has been estimated for each of the water moderators, making 50 kW in total [339,371]. The operating pressure for structural integrity is set to 1.1 MPa [371]. This power, pressure and temperature will require an approximate flow rate of 0.9 kg s\(^{-1}\) per water moderator assembly.

Reflector cooling

The basic configuration of the inner (beryllium) reflector is analogous to that of the moderator described above, although the heat deposition and thus required mass flow rate are different. This cooling circuit will also operate at about room temperature. The heat load to the inner beryllium reflector is calculated to be 350 kW [339]. Due to the higher heat load, the temperature increase will be about 60°C [371]. This power and temperature difference results in a required flow rate of roughly 2 kg/s. The operating pressure is set to 1.1 MPa [371]. The outer reflector will be cooled by the shielding, plugs and component cooling system, which is described in the following section.

Shielding, plugs and component cooling

This system contains circuits for all parts within the monolith that require water-cooling, except the moderators and the inner (beryllium) reflectors. It also contains circuits for the tune-up beam dump and the fixed proton collimator in the A2T part of the high energy beam transport (HEBT), as discussed in Sections 3.1.2 and 4.7. The radiation exposure of the water system will be lower than the exposure of the water circuits serving the moderators and inner reflector, although it will still be significant. Hence,
requirements on the gas and liquid separator tank, delay tank and filters are a little more relaxed. This circuit’s basic design will be similar to that of the other water-cooling circuits described above. The system will operate at approximately room temperature with an outlet temperature set to be lower than 35°C, and the operating pressure will be 1.1 MPa.

All components within the monolith with operational cooling requirements have active cooling systems. The shielding cooling circuits are thus designed to provide cooling to all shielding blocks in the monolith that have been identified as needing active cooling. The current basis for design is that all areas with a specific heat load higher than 1 kW/m³ will need water-cooling. The total power deposited in the inner (cooled) shielding is calculated to be 290 kW [339], leading to a required flow rate of 14 kg/s in the region. The outer reflector cooling circuit power is calculated to be 780 kW [339], giving a required flow rate of 46 kg/s. The cooling powers required for the proton beam window plug and the proton beam diagnostics plug have not yet been estimated, but will probably be small compared to requirements for shielding and reflector cooling. The cooling power for the tune-up dump is limited to a maximum of 50 kW in total [339], giving a required flow rate of about 0.6 kg/s. Similarly, the collimator cooling requirement is estimated to be 35 kW, yielding a circulation requirement of 0.4 kg/s.

In total, the cooling requirement and water flow rates for this system are 1.2 MW and a little over 50 kg/s. The system is designed with redundancy to take at least 1.6 MW, in order to ensure removal of the full beam power, minus target, moderator and inner reflector cooling.

Intermediate water cooling systems

There are two intermediate cooling systems working with water, separating the primary systems from direct exchange with the conventional facilities. The intermediate water system for water serves as an intermediate for all the primary water systems, which include those of moderators, (inner) reflectors, and shielding systems. The intermediate water system for gas serves as an intermediate for all the primary gas systems, which include those of monolith flush and atmosphere, proton beam window and gas purification systems. Though the total power transferred in the system for the water is several times larger, because these systems receive more heat, the two intermediate systems are similar. They operate as follows. A pump generates a flow through a heat exchanger, where the intermediate water is cooled by water from the conventional facilities cooling system. Then the water flow is divided in parallel paths for each primary system to be cooled. The flow rate in each path may be controlled depending on the cooling needs in the primary systems. After the parallel paths, the flows are united again and go into a combined accumulator and gas separation tank. After this tank, the water is led back to the suction side of the pump. There are also side connections to water purification (for the unlikely event of contamination), to conventional facilities sewage and to water refill.

3.4.3 Moderator liquid hydrogen cooling circuit

The hydrogen circuit supplies supercritical liquid hydrogen (LH₂) at a flow rate of approximately 0.8 kg/s and a cooling capacity of about 20 kW at 20 K. The cryogenic system required to achieve this can be subdivided into three main sections, as illustrated in Figure 3.72. The first section represents the medium supply. Besides hydrogen, helium and liquid nitrogen are supplied from storage tanks kept separate from the main circuit components. Helium is used for the cooling of hydrogen, as discussed in Section 6.1.3, as a blanket gas and as a purge gas for safety reasons. Liquid nitrogen can be used for pre-cooling and in a gaseous form, as a blanket gas. Nitrogen will also be used to dilute the hydrogen inventory to well below the flammable limit in the case of a vent release through the stack.

The second section contains the main components of the hydrogen circuit as shown in Figure 3.72, which includes the circulators, the hydrogen-to-helium heat exchanger, the accumulator, a hydrogen heater and the ortho-to-para converter. It is necessary to avoid leakage of hydrogen to the outside and ingress of air (thus oxygen) towards the cold surfaces of the liquid hydrogen circuit, so the main components of the circuit are housed in a double-walled vacuum vessel with an interstitial helium blanket layer. Leaks and air ingress can be detected by the use of appropriate instrumentation to monitor off-gas in the exhaust of the vacuum pump and the hydrogen concentration in the blanket gas. The components in this vacuum vessel are connected via transfer lines and an appropriate coupling system to the cryogenic moderator vessels. The vessels and the in-monolith piping represent the third section of the system.
Figure 3.72: Liquid hydrogen cryogenic system flow diagram, showing three main sections: medium storage and supply, the hydrogen circuit, and vessels and in-monolith piping. Courtesy of Y. Beßler.
The main hydrogen circuit consists of pump, heat exchanger, accumulator, heater and ortho-to-para converter. With current technology and commercially available equipment, achieving the necessary mass flow rate will be a challenge for the circulation system. Discussions with potential pump manufacturers led to the conclusion that it is possible to manufacture a suitable pump, although there is currently no such pump readily available on the market. Nevertheless, it was decided to plan the circuit with two pumps both capable of the full mass flow, running at 50% of the rated power during normal operation. If one pump fails, the system will be able to operate for a limited time using the remaining pump. This technique also avoids having a “warm” redundant pump. The main source of heat into the cryogenic H\textsubscript{2} system will be from neutronic heating inside the moderator vessel. This heat load scales directly with the proton beam power. In order to continue operation during beam trips and short shut downs, a heater will provide heat to substitute for the neutronic heat load to the circuit. In addition, an accumulator will dampen the remaining volumetric changes.

Since the moderator dimensions are optimised for pure para-hydrogen, an ortho-to-para converter will be installed in the circuit. At 20 K, the natural equilibrium of hydrogen is very close to 100% para-hydrogen (at T = 300 K the natural para concentration is 25%). As the temperature of the hydrogen is reduced, a natural conversion takes place, but it is a very slow process and thus the ortho-to-para catalytic converter will be used to markedly reduce the required time of conversion. It is proposed to operate the converter in a bypass line as the heat load and irradiation could potentially reconvert para to ortho hydrogen and this will allow for flexibility in terms of the amount of fluid passed through during operation.

The hydrogen circuit in the current design has an inventory of about 280 litres of liquid hydrogen. This leads to a need for 265 m\textsuperscript{3} of gaseous hydrogen (at 300 K and 1 MPa) for each filling.

3.4.4 Active fluids purification and storage systems

Water purification and storage systems

The target water systems will all be connected to the water purification and storage systems. These systems will serve as a base point for supply and storage of activated and non-activated water. Tanks in the storage system will be available to hold system water of all types, depending on contamination levels. The active water tank will be shielded and large enough to simultaneously contain the water of all possibly contaminated water systems. The pure water tank will contain deionised water from the conventional facilities water supply, or purified and conditioned water from the water systems. It will serve as a buffer tank for water supply and also as a control tank before release into the conventional facilities sewage system. The tanks will be kept within the controlled areas. Filters and ion exchanger columns in the water purification systems will remove contaminants, either by continuous circulation of the water or by passage between the active and pure water tanks. It will also be possible to add traces of hydrogen in the water purification and storage systems, in order to remove oxygen from the circuits and thus decrease oxidation.

Gas purification and storage systems

The target helium systems, with the exception of the hydrogen cryo-system, will all be connected to the gas purification and storage systems. These systems will serve as a base point with supply and storage of activated as well as non-activated gas. They will be shielded and located in dedicated rooms in the utilities block. It will be possible to remove filters and other contaminated components in casks via the high bay above. The connection of the target cooling helium circuit and the monolith atmosphere circuit, due to the injection in the rotating seals, imposes special demands on the purification system. The closed balance of these systems is described below in normal operation, excluding all ancillaries for purposes of clarity. More details can be found in a technical report [383].

A simplified sketch of the connections of these systems, including the purification system, is shown in Figure 3.73. Several planned connections, such as the connection to the helium supply and exhaust, have been left out of the figure, because these circuits will work together as a closed volume in normal operation. The target circuit contains cyclone filters (C), heat exchangers (HX1 and HX2) and a circulator (CT). The target circuit mass flow rate is denoted $\dot{m}_T$. Low and high pressure tanks (TP1 and TP2) for the target circuit pressure control system (PCS) and the purification compressor (CP) are shown. The purification mass flow rate ($\dot{m}_P$) must be at least as large as the sum of the target injection mass flow rates ($\dot{m}_{ST}+\dot{m}_C$), in order not to raise the target circuit pressure. Purified flow in excess of the injected flow
is led back into the target circuit via a valve (VP). The monolith pressure control contains the monolith compressor (CM) and the low pressure monolith circuit tank (TM1). The valve VM connects back to the monolith to allow circulation, analogous to VP for target circuit purification. The monolith atmosphere mass flow rate is denoted $\dot{m}_M$.

Figure 3.73 shows the three seals in the rotary feedthrough, and indicates their leakage mass flow rates. (The three-seal concept for the bearing and drive unit is also shown in Figure 3.44, and is discussed in Section 3.3.5.) The by-pass leakage flow rate out of the top seal into the target circuit is denoted $\dot{m}_B$, while the leakage out of the bottom seal into the monolith is $\dot{m}_{SM}$, and $\dot{m}_{ST}$ is the leakage from the middle seal into the target circuit. The total seal flow rate is thus $\dot{m}_S = \dot{m}_{SM} + \dot{m}_{ST}$. The seal buffer tank, TS, is used to control the seal pressure and thus ensure the seal flow rate. There is also a lower seal flow, $\dot{m}_C$, into the smaller seals of the circulator (CT). The maximum seal flow of pure helium into the monolith is $\dot{m}_{SM} = 7$ g/s. Helium will be removed from the monolith atmosphere at the same rate in order to maintain the pressure cascade. At zero recirculation (with valve VM closed) this is also the flow rate in the monolith atmosphere circuit $\dot{m}_M$. There also will be a continuous injection of purified helium into the target circuit via the rotating seals. The maximum injection rate in the target wheel seal is $\dot{m}_{ST} = 3$ g/s.

The rotational seals in the cooling circulator will be of a multi-level type used in chemical industry, as shown in Figure 3.69 and discussed in Section 3.4.1. Purified helium is injected as a buffer gas between the first and second circulator labyrinth seals, with a maximum injection rate of 0.1 g/s. Some of this goes inward through the first seal into the target circuit. The rest goes outward through the second seal and is collected at lower pressure between the second and the third circulator seals. The purified helium collected between the second and the third seals is led back and re-injected. Due to the low pressure between the second and third seals, the leakage of purified helium outward through the third seal will be very low, comparable to diffusion in narrow gaps and within the leak rate of 0.1% per day. As already been noted in Section 3.4.1, this is a conservative estimate based on operating experiences at comparable facilities. Optionally, an additional level with a fourth seal and an additional separation gas could be added. It will be possible to temporarily operate both the target and circulator seal flows using fresh helium from storage tanks if the purification system is not available. The compressors in the purification circuit and

![Figure 3.73: Simplified flow chart of helium in the target, monolith and purification systems, showing only the basic components and connections for helium balance in user mode operation.](image-url)
monolith atmosphere circuit (CP and CM) will be smaller and of a different type, which does not require a seal injection flow.

The target helium purification system will contain several subsystems. Before the first purification step, there will be a tank that ensures that the flow through the purification steps is continuous and controlled. Then there will be a mechanical filter. The first step of the purification will be oxidation at elevated temperature with copper oxide (Ox). Here, all oxidisable substances will be oxidised, with special focus on binding hydrogen, including isotopes such as tritium, in water. The oxide carrier may be re-generated by disconnecting the helium flow and injecting oxygen. In a second step, after the oxidation, the flow will be cooled and the water will be captured in molecular sieves (MS). The third step of the purification, low temperature adsorption in charcoal (CC), will remove substances with boiling points down to that of nitrogen and also will capture any remaining iodine. This will include noble gases from argon and up, and also oxygen and nitrogen, among other substances. The cooling in this last step will be accomplished by liquid nitrogen or a cryogenic refrigeration system. After the last step, there will be another tank to ensure a controlled flow. Purification systems working with these principles (Ox+MS+CC) and capacity (3 g/s), have been investigated and verified by measurements [384–386].

After purification, the gas is led to the seal injection tank (TS) and to the target system via opening VP shown in Figure 3.73. It may also be led to used gas storage or to the stack, although this option is not shown in the figure. Different purification steps may be used depending on the gas to be purified. All the different connections – used, for example, to lead all helium through the purification system during maintenance, including the PBW cooling helium – are not shown in Figure 3.73. In normal operation, the purification system will be continuously available, to keep the levels of contamination low, particularly in the primary target cooling system. It is however also possible to operate for a limited time using the storage tanks. Helium storage that is used, for example, for maintenance purposes, is also not shown in Figure 3.73. There will be a compressor after the purification chain, which may fill either of two used gas tanks. The used helium tank will be large enough to contain all helium used in the target systems, that is, the target cooling, monolith and PBW systems. There also will be a buffer for helium supply. Just as for helium, there will be tanks for the nitrogen in the intermediate target cooling system. As the intermediate system will not be contaminated in normal operation, there will be no continuous purification system – only filters. The used nitrogen tank will be able to contain all nitrogen used. It also will serve as a buffer for all nitrogen in the intermediate target cooling system.

Gases from the gas and liquid separation tanks in the water systems will be led to a system in which water vapour will be condensed in a heat exchanger connected to the intermediate water system for gas. The condensed water will return to the water purification and storage system. The gases may go via delay tanks and monitoring to the stack, or may be led to the storage systems.

3.5 Handling and logistics

3.5.1 Active cells

The active cells facility is designed to maintain, process, package and store used radioactive components from the target station operation. It is located in the target station building, downstream of the monolith relative to the proton beam direction. The active cells are bordered on the top by the high bay floor, and on the bottom by the ground concrete slab. The layout of the active cells facility is shown in a 3D view in Figure 3.74, and in a side view along the vertical cut in Figure 3.75. The important dimensions of the facility are summarised in Table 3.25.

The active cells facility will consist of five main areas, the process cell, the maintenance cell, the storage cell, the transfer area and the technical galleries. These areas have different functions related to the treatment, storage and shipment of radioactive components. On each side of the active cells, the technical galleries will be located on two levels in order to provide access to the full height of the active cells. From these areas, workers will be able to control and perform remote handling operations in the maintenance cell and the process cell. They will be able to make use of through-wall master-slave manipulators, as well as of a power manipulator and in-cell crane. The galleries will contain enough lead glass windows to facilitate operations as well as monitors and control boards for in-cell cameras and equipment. The technical galleries also will be equipped with wall penetrations through which the cells will be supplied with the electricity and compressed air needed by the active cells’ equipment.
3.5. HANDLING AND LOGISTICS

Figure 3.74: The active cells system layout.

Figure 3.75: The flow of active cell logistics, and a side view of the system of active cells along a vertical cut, including (from left to right) the transport hall, transfer area, maintenance cell, storage cell and process cell.
CHAPTER 3. TARGET STATION

<table>
<thead>
<tr>
<th></th>
<th>Length (external) [m]</th>
<th>Width (internal) [m]</th>
<th>Height (external) [m]</th>
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</thead>
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<td>16</td>
</tr>
<tr>
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<tr>
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<td>25</td>
<td>8</td>
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</tr>
<tr>
<td>Storage pits</td>
<td>25</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Transfer area</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.25: Dimensions of active cells.

Confinement

The active cells facility is designed to prevent unintended escape of radioactivity through its confinement barriers. This will be achieved by good confinement design and proper management of contaminated wastes and components, and will be under constant and ongoing measurement, monitoring and control.

The confinement design concept can be divided into two categories, static confinement and dynamic confinement. Static confinement will be achieved by the structural elements delimiting the active cells, including walls, stainless steel liner, HEPA filters, and lead glass windows. In order to satisfy the general safety objectives' dose limits for ESS radiation workers laid out in Table 11.3, the walls of the active cells will be made of heavy concrete and will be 1.45 m thick [387], which will make it possible for a person to work in the technical galleries for as many as 2000 h/year without exceeding dose limits. Dynamic confinement prevents the escape of contamination through the openings of the structural elements that provide static confinement. This is achieved by the ventilation system that determines air circulation rates and pressure levels. A pressure cascade will be established so that pressure in the active cells is approximately 230 Pa below the reference pressure. The process cell and the maintenance cell will have individual ventilation systems. When the intra-bay door between these two cells is open, contamination in the maintenance cell will be avoided by forcing external air to flow from the maintenance cell toward the process cell. The dynamic confinement design complies with all relevant international standards. [388–390].

Access protocol

Permitted levels of access will vary across different areas of the active cells facility, depending on contamination and operational status. All the areas around the active cells will be classified as controlled areas because of potential contamination risk during an incident scenario.

For the technical galleries and the transfer area, no contamination is expected under normal working conditions and unlimited access will be permitted to ESS personnel. As mentioned above, shielding will be sufficient to allow any individual to work in these areas up to 2000 hours per year. Even under incident conditions, contamination in these areas will be low. In general, access to the high bay will also be unlimited for personnel. However, radiation and contamination risks in the high bay area will be higher than those in the technical galleries and transport hall during the transport and docking of casks containing irradiated material from the monolith to the active cells. Therefore, human access to the high bay will be limited during critical operations.

Human access to the maintenance cell will be permitted only if all of the following conditions have been satisfied: no waste or baskets containing irradiated components are located in the cell, all the storage pit lids are closed, the intra-bay shielded door is closed, no shipment cask containing irradiated waste is docked to the maintenance cell, and the contamination level in the cell is below an established threshold. If the contamination level is above the threshold, the maintenance cell must be decontaminated, and remote handling equipment will be required for this purpose. Since the waste and components will have been transferred to sealed baskets before entering the maintenance cell and no cutting operations will take place in this cell, the level of contamination in the maintenance cell will be low. Nevertheless, human access to the maintenance cell will be permitted only with protective equipment since it will be difficult to ensure that the maintenance cell is completely sealed off from the process cell and airborne contamination may occur in the process cell.

In general, human access will not be permitted to the process cell during normal working conditions.
3.5. HANDLING AND LOGISTICS

However, some exceptional maintenance operations may require human access. In this case, the process cell will be emptied of contaminated components and decontaminated with slave manipulators before personnel with protective equipment are allowed access via the airlock connecting the process cell and the technical galleries. Due to the cutting operations that will take place in the process cell, and the chips that they will produce, the contamination level is expected to be high, but decontamination using robust procedures will be possible. To facilitate decontamination, liquid coolant will not be used during cutting operations. The decontamination of the process cell will be quite time consuming, so human access will be restricted to a limited set of circumstances in which operations cannot be performed by remote handling.

Component logistics

Most of the irradiated materials will consist of radioactive and/or contaminated components and waste transferred from the monolith to the active cells facility. The major features of the logistics for radioactive materials transport are described here. Shielding blocks that are removed to permit access to the target monolith will be stored in specified areas in the high bay during monolith component maintenance operations. Many components of the target station will require regular exchange and maintenance. To facilitate these activities, these components have, in most cases, been housed within plugs that can be removed or exchanged as a single module with minimal disturbance to surrounding systems. After shut down, the monolith will be conditioned to permit opening and relevant shielding will be removed, opening access to the plug requiring exchange or maintenance.

The handling cask for the plug will be stationed on the floor valve installed on top of the monolith, as shown in Figure 3.76 and discussed in Section 3.5.2. The component will be lifted from the monolith into the handling cask via a lifting unit that is built into the cask and that will be equipped with a dedicated handling grip for each irradiated component. The high bay crane will be used for heavy lifting operations. It will move the handling cask holding the component and will dock it to the active cells facility. The floor valves will be opened and the component will be delivered either to the process cell or to the maintenance cell pit for intermediate storage before process cell operations. The schematics of the flow of components, and of the waste generated during components maintenance and processing inside the active cells facility are illustrated in Figure 3.75. The component will be processed (cut or dismantled) in the process cell and the waste will be placed in baskets. The baskets will be decontaminated and transferred with the crane to a dedicated storage pit beneath the maintenance cell. When the activity of the waste has been reduced to an acceptable level, it will be inserted via the maintenance cell into a waiting shipment cask docked in the transfer area. The shipment cask will be moved to the transport hall and prepared for shipment off-site.

Process cell

The process cell is where all the processing operations of inserted components will occur. This includes activities such as cutting, refurbishing and packing. This cell will have the highest contamination levels of all the active cells during normal operations, due to dust and particles arising from processing operations. The process cell has three floor valves that connect it to the high bay. These valves will allow the entrance of radioactive waste coming from the monolith. The cell will also have a shielded door that will allow human access from the technical gallery via the airlock located below the maintenance cell. This will occur only in exceptional circumstances. One lateral intra-bay shielded door and one upper shielded door separate the process cell from the maintenance cell. The functions provided by the process cell will be determined by the particular radioactive components being processed. The main components, which have been the focus of attention in the design of the process cell, are the target, the MR plug and the PBW plug. Schematics of the main components of the process cell are given in Figure 3.77, and processing of the main radioactive components is described below.

The target will be introduced into the process cell from its handling cask through a floor valve. It will then be placed in a handling basket previously fixed on a translating worktable located on the process cell floor. A lifting system fixed on the process cell wall will clamp and hold the target steady, and a gripping system also fixed on the process cell wall will secure the shaft. A band saw will cut the shaft from the wheel, and the wheel will remain in the handling basket. The handling basket containing the wheel will be moved backward with the worktable translation and transferred with the crane into a containment basket. A lid will be mechanically fixed onto the containment basket and then welded to it in order to ensure a good sealing. After decontamination, the containment basket will be stored in a dedicated storage pit.
The same procedures are used to cut the shaft into smaller pieces.

The MR plug will be lowered through a floor valve from its handling cask to a turning table located on the process cell floor. A mechanical structure attached on the turning table will ensure that the centre of the moderator is aligned with the centre of the turning table. A moderator assembly exchange device that can turn around the turning table will be used to extract the moderator assembly from the side of the moderator and reflector plug. The power manipulator and/or the through-wall master-slave manipulators will perform the necessary bolting and unbolting operations. Once the moderator assembly is extracted from the MR plug, it will be transferred to the shear cutting device with the in-cell crane. Once the pipes are cut, the pieces of pipes and the moderator assembly will be placed into baskets, the lids of the baskets will be attached and sealed by welding, the baskets will be decontaminated and transferred to the dedicated storage pits in the maintenance cell. In order to reduce waste, the steel reflector and the beryllium reflector of the moderator and reflector plug will be refurbishable. Unlike the MR plug, the PBW plug will be lowered through a floor valve straight to the turning table equipped with the shear-cutting device. After cutting, the pieces of pipes and the PBW itself will be placed into baskets, which will be transferred to the dedicated storage pits in the maintenance cell after being welded shut and decontaminated.
A large number of operations on highly radioactive components will be performed in the process cell. Established procedures will identify all critical scenarios and define operational procedure for each incident case ahead of time, in order to avoid critical situations such as failure of equipment during operation. These will include robust procedures for the overhead crane and power manipulator. Should an equipment failure occur in the process cell, it will be handled either by through-wall master-slave manipulators or by the power manipulator. If remote handling is unable to perform maintenance of the equipment, the equipment will, after decontamination, be transferred to the maintenance cell.

**Process cell equipment**

The major equipment operating in the process cell is listed below. For reference, all the equipment will have a radioactive resistance between 1 MGray and 10 MGray. The schematics of the equipment are illustrated in Figure 3.77. The in-cell overhead crane has a lifting capacity of 25 tonnes. It will reach both the process cell and the maintenance cell. The engineering design of the crane will be robust enough to ensure a safe operation in the anticipated hazardous environment. It will be possible to change the grip of the crane remotely to facilitate different lifting operations in the cells.

A *power manipulator* will run on its own bridge in the process cell. It will be the main handling tool for the operations performed in the process cell. It will take part in the decontamination of the process cell, when needed. In case of the need for hands-on maintenance, it will be possible to lift the power manipulator with the overhead crane and to transfer it to the maintenance cell where the power manipulator will rest on a special support. A *shear-cutting device* will be used to cut steel pipes. The dimension of the shear-cutting device is defined, for example, by the size of the pipe diameters, the pipe thicknesses, the movements of the robot and so forth. An electrical motor-driven device is preferable provided that the required strength of the shearing tool can be achieved. A *cold cutting device* will be used for larger cutting operations like separating the shaft from the wheel. The system foreseen is a circular saw or a band saw. The details of the cutting device will be determined by the thickness, the configuration of the internal channels of the

![Figure 3.77: Process cell equipment, including a power manipulator, a shear-cutting device to cut steel pipe, a cold-cutting device, several turntables, and other equipment.](image-url)
CHAPTER 3. TARGET STATION

shaft and the flexibility of the available technology. The sawing tool will be turned up to 90 degrees so that it will be possible to use it to cut other components, if necessary. The saw is designed so that it will be possible to change the blade by remote handling. Several turntables will be used to position and orientate the components as needed. Various jaws and grippers will be fixed on the turning tables, depending on the intended usage.

Other cell equipment includes (but is not limited to) welding machines, lead glass windows with master slave manipulators, HEPA filters, stainless steel liner, floor valves, intra-bay door, lights, translating worktables, target lifting system, target gripper, moderator assembly exchange device, decontamination tools such as brushes, air blower, and vacuum cleaning.

Maintenance cell

The maintenance cell will be connected to the process cell via an intra-bay shielded door. In addition, access for components will be provided via floor valves from the high bay and access for humans via an airlock. The cell will be used for hands-on maintenance on active cells equipment and decontamination operations on tools. The airlock functions as a safety barrier between humans and potentially contaminated areas. In the floor of the maintenance cell there will be access to: 35 pits of 1.2 m diameter used to store standard size baskets, one pit of 3 m diameter to store the baskets to contain the target wheel, one pit of 3 m diameter to temporarily store the entire irradiated target before its transfer to the process cell for cutting operations and one pit of 2 m diameter to store the entire MR plug, (refurbished or irradiated). The pits will be used to store all the waste temporarily before off-site shipment. The pits will be covered with lids that ensure their sealing towards the maintenance cell. The lids also will provide the necessary shielding against irradiation when humans enter the maintenance cell. On the floor of the maintenance cell, the transfer docking port will be located. It will allow the transfer of a basket from a storage pit to a shipment cask docked to the maintenance cell from the transfer area side. Consequently, human access will be possible only if the storage pits lids are closed and if no baskets containing radioactive waste are located on the floor of the maintenance cell. There will be two floor valves of different diameters on its ceiling, connecting the maintenance cell with the high bay. The cell is shown in Figure 3.78.

The maintenance of active cells equipment makes it necessary that the maintenance cell environment is safe for human access, especially in regard to contamination and radiation. Human access requires (for
example) that the intra-bay shielding door is closed, that the pressure cascade is within its thresholds, and that no wastebasket is located in the area. The maintenance cell will also be used as the logistical hub for insertion and extraction of wastebaskets in the storage pits and shipment casks docked to the docking port in the maintenance cell floor. It also serves to control the dose rate on the wastebasket surface and eventually to decontaminate it before its introduction into the shipment cask. The contamination level in the maintenance cell will be low because no cutting operations will be performed there. The lids of the storage pits will ensure a sealing between the pit and the maintenance cell. Regular hands-on decontamination of the maintenance cell will ensure an acceptable contamination level. If needed, decontamination by remote handling will be possible by installing slave manipulators in crossings in the maintenance cell walls. Some maintenance operations on maintenance cell equipment such as the intra-bay shielding door will require that the maintenance cell be emptied of radioactive components, in which case the process cell might have to be decontaminated.

The main equipment of the maintenance cell will be an overhead crane, the intra-bay shielding doors, the storage pit lids, the docking port to the transfer area and some general items like lead glass windows, through wall slave-master manipulators, airlock doors, stainless steel liner, lights, decontamination tools, and dose rate measurement equipment. The overhead crane will be able to reach both the maintenance cell and the process cell. The maintenance and process cell cranes provide backup for each other if one crane fails.

**Transfer area**

The transfer area will be used for docking the shipment cask to the floor of the maintenance cell, in order to transfer the wastebaskets from a storage pit to a shipment cask. The main function of the transfer area will be to provide an area for the safe handling of the wastebaskets when they are introduced into an off-site shipment cask. The shipment cask will be transferred beneath the transfer docking port on a special carriage. The lifting system of the carriage will lift the shipment cask and dock it to the docking port. A tight connection between the cask and the transfer docking port will be secured. The wastebasket will be taken from a storage pit and introduced in the shipment cask via the maintenance cell. Once the waste has been transferred into the shipment cask, the lid will be placed back on top of the cask. Human access to the transfer area will ensure that the cask has been decontaminated to a level within regulations for off-site shipment. The shipment cask will then be transferred to the transport hall for further handling before shipment. The major equipment of the transfer area will be the special carriage used for shipment cask transport from the transfer area to the transport hall. The design of this system depends on the various container sizes to be docked and the shielded door design between the transfer area and the transport hall.

**3.5.2 Casks and associated handling devices**

**General description**

Handling casks will be used to transfer irradiated components between the monolith and the active cells. The main components that will be transported by casks are the target, PBW plug, MR plug and the NBGI inserts. There also will be smaller and lighter handling casks for the transfer of some low irradiation level components such as shielding blocks or equipment going through maintenance. These lighter-handling casks will not be described in this report, since the development of these casks will be realised later in the project. The functions to be provided by the main handling casks are 1) lifting and transporting active components from one place to another, 2) limiting the contamination to the surroundings during transport operations, 3) protecting workers and public against radiation and 4) containing waste to provide protection in accordance with the standards developed in the GSO [391]. The high bay crane will transport the casks in the high bay area. The weight of the cask and its built-in component is thus one important criterion for the high bay crane design and rating. For safety reasons, the handling casks will only be lifted a minimal required height above the floor. This is to minimise the impact of a dropping accident and to minimise the radiation exposure to workers through the bottom plate of the casks, as is also discussed in Section 11.4. Furthermore, the hook of the high bay crane will be designed to minimise dropping risks. The dimensions of the various internal handling casks will be adapted to the size of the component they handle and the need for shielding. As the space on the top of the monolith is limited for the positioning of the casks, their design must take these space limitations into account. A summary of the main dimensions and data for the handling casks is given in Table 3.26.
There will also be several general purpose handling casks that will be used for moving slightly con-
taminated items such as shielding blocks or other equipment from the primary cooling loops. When the
shielding is lifted, it will be stored in dedicated areas in the high bay. These handling casks will also
provide the functions of shielding, transport and confinement. The design of these casks is less challeng-
ing than the design of the four main casks listed in Table 3.26, and their lower weight does not represent
a binding constraint for the high bay crane capacity, so details have been left for a later stage. Unlike
the four main handling casks, these lower weight casks will not be equipped with built-in internal lifting
devices. All lifting operations will be done using overhead cranes. When the handling casks are empty,
they will be stored on the high bay floor in a designated location or used for training in the mock up area.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Target casks</th>
<th>MR cask</th>
<th>PBW cask</th>
<th>NBGI cask</th>
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<td>Max length (including floor valve)</td>
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<td>4</td>
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</tr>
<tr>
<td>Max width (including floor valve)</td>
<td>m</td>
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<td>2</td>
</tr>
<tr>
<td>Max radiation 1 m from cask surface</td>
<td>$\mu$Sv/h</td>
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<td>25</td>
</tr>
<tr>
<td>Max weight (including moved component)</td>
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<td>95</td>
<td>95</td>
<td>95</td>
</tr>
</tbody>
</table>

Table 3.26: Main parameters for the internal handling casks used for the target, moderator-reflector (MR),
proton beam window (PBW), and neutron beam guide insert (NBGI).

### Handling casks engineering concept description

The handling casks will have a mechanical structure composed of cylindrical metal rings that will ensure
the mechanical integrity and the integration of the different pieces of internal equipment. On the upper
part of the mechanical structure, there will be two handling ears located on each side of the metal cylinder.
These will allow the high bay crane equipped with a connection attachment to grab the cask and lift it. The
structures also will contain the shielding that is required to fulfil dose limits in the high bay. A lifting
unit will be installed on the top of the casks. It will be capable of lifting the plug to be extracted or
introduced. This lifting unit must ensure that the item cannot fall during the lifting operation and the
transfer of the cask to the active cells. Therefore, the lifting unit will be equipped with a gripper allowing
a safe remote extraction and introduction of plugs to and from the monolith and the active cells. The
top of the handling casks must ensure enough shielding to permit a worker to safely perform maintenance
operations on the lifting unit. A ladder will allow human access to the top of the casks. It will also be
possible to remove the top of the casks for exceptional maintenance or decontamination operations.

The bottom of the casks will be equipped with a floor valve consisting of a fixed mechanical frame
welded to the down part of the casks. This mechanical structure will fixates two sliding lids guided in the
mechanical frame. The drive units moving the two lids will be fixed on the external side of the handling
casks, in order to facilitate access during maintenance. In case of failure, it will be possible for a worker
to manually move the lids using a turning rod. The bottom part of the casks will be equipped with an
alignment structure for correct positioning over the monolith and the active cells. The transfer of a plug
into a handling cask will not be possible unless the floor valve is fully open and locked in the open position.
During transport, the floor valve will be properly closed. A mechanical device inside the handling casks will
be used for the alignment of a plug, in order to reduce the risk of movement of the plug during transport.
A camera system installed inside the casks will ensure a sufficient view of the operations. In case of a
camera failure, it will be possible for a worker to change the camera from the external side of the casks.

### Confinement

Handling cask confinement will be ensured by the cylindrical mechanical steel structure, the top of the cask
and the floor valve on the bottom of the cask. The top opening on the top of the cask will allow the chain
or wire of the internal lifting unit to grab the component. Due to the clearance between the sliding lids and
the frame of the floor valve, the cask will not be airtight. This will not pose a safety hazard for four
reasons. First, the plugs are dried in the monolith before movement. Second, the pipe connections can be
sealed before lifting. Third, dust is not expected on the exterior of the plugs. And fourth, the movement of
the casks is slow, which keeps the airflow inside the cask stable. To ensure acceptable radiation dosages for the workers in the high bay, metal shielding of the casks is necessary. This metal could be either steel and lead, depending on weight optimisation. The metal shielding surrounding the cask mechanical structure with the floor valve and the top of the casks provides irradiation protection for the workers. The floor valve may be thinner than the shielding around the casks as no worker is expected to be under the casks during transport. The top of the casks will be designed to protect a worker against irradiation during intervention on the top of the cask, even in the presence of waste. The cask confinement requirements will ensure that all operations performed with the cask respect the GSO [391].

**Target handling**

Once the monolith has been opened and the drive unit of the target has been removed, the shielding blocks around the target can be removed. Before extracting the most irradiated shielding blocks just surrounding the wheel, a floor valve will be installed on the top of the monolith above the target. An alignment structure between the monolith and the floor valve will ensure the correct positioning of the floor valve. The aim of this floor valve is to limit the exchange of air in the monolith and the radiation exposure of personnel when the upper shielding blocks are removed. After the shielding blocks above the wheel have been removed, the cask used for target replacement will be placed on the previously installed floor valve, using the high bay crane. Both the cask floor valve and the floor valve installed on the top of the monolith will be opened and the target will be lifted with the internal lifting unit into the handling cask, as shown in Figure 3.76. Both floor valves will be closed and the cask will be lifted with the high bay crane and transferred to the top of the active cells. There, it will be docked to an appropriate floor valve installed on top of the active cells. Once the target cask has been installed on the active cells floor valve, both floor valves will be opened and the target will be lowered into the active cells.

**Proton beam window handling**

In order to increase the flexibility of the active cells, floor valves of identical size will be used for both the PBW plug and the MR plug. The handling casks used for these components will be of different sizes, however, and so it will be necessary to install an intermediate steel spacer on the active cells floor valve. This will ensure shielding during transfer operations on top of the active cells. Alignment pins will ensure a correct positioning of both the spacer and the cask on the active cell floor valve. Once the lid on the monolith covering the PBW plug has been opened and the pipes have been disconnected, the shielding blocks above the PBW plug will be removed. A floor valve will be installed on top of the pit and the PBW plug cask will be placed and aligned above the plug on the top of the monolith floor valve. The floor valves, one on the monolith and one on the cask, will be opened, and the PBW plug will be lifted remotely with the high bay crane and transferred to the top of the active cells where it will be installed on the appropriate floor valve previously equipped with the spacer. Once the PBW cask has been installed on the spacer, the floor valves will be opened. Then, the PBW plug will be lowered into the active cells.

**Moderator and reflector plug handling**

The handling procedures for the MR plug cask are similar to those for the PBW plug, except that the steel shielding spacer will not be needed for docking the MR plug cask on the floor valve above the active cells.

**Neutron beam guide insert handling**

Since the NBGI is handled in the experimental halls, its handling procedures have a major interface with experimental hall operations and equipment. The cask will be docked on the side of the monolith, requiring the removal of neighbouring beamlines. The second barrier will be opened and a valve and distance plate will be installed in front of the NBGI. The cask will be connected and the NBGI will be extracted horizontally into it. The cask will be moved to the high bay and tilted, in order to protrude the used NBGI into the active cells. The design of the NBGI handling cask will be compatible with the floor valve design on top of the active cells.
3.6 Fallback and comparative target technologies

In line with decisions taken by the ESS Steering Committee, two additional target concepts that are not the baseline choice have been explored in order to provide a complete and robust technical underpinning for the target design. The water-cooled rotating tungsten target is a back-up option to the baseline concept, developed in order to reduce the technical risk associated with the target station. The water-cooled target concept provides a type of insurance against the possibility that serious unexpected problems may emerge with the baseline option. However, preliminary studies at ESS and other projects show that existing water-cooled spallation target technologies for a proton beam power less than 1 MW cannot simply be rescaled to work with the 5 MW ESS proton beam. Therefore, considerable R&D effort would be needed to realise reliable 5 MW technologies for a water-cooled rotating solid target. The lead-bismuth-eutectic (LBE) target uses liquid metal both as target material and coolant. It was studied as a comparative option for assessing broad environmental implications of different target designs. In the context of that comparison, the baseline option emerged as particularly advantageous.

3.6.1 Water cooled rotating tungsten target

Introduction

Considerable effort has been devoted to the study of a water-cooled rotating tungsten target option, with a focus on identifying solutions to potential problems and critical issues. Some technical designs and materials that might provide solutions to identified problems remained outside the scope of this work. These potential solutions might be worthy of study at a later stage.

The scope of the study presented in this section focuses on examining the basic questions of feasibility for a reference configuration that was identified as a favourable candidate from the point of view of environmental safety. The accidental overheating of the target is a particularly important issue with water cooling, since as temperatures increase beyond 500°C, many metals start to exothermically interact with water vapour in a reaction producing H2 gas. This becomes a serious safety hazard above 700°C. The after-heat due to radioactive decay at the ESS power level is sufficient for the target to reach such temperatures if active cooling is lost, for example because of a power failure. This mechanism led to the reactor accident in Fukushima, which was made possible by serious safety system flaws. It is a key design goal for ESS to guarantee the highest level of safety for the inhabitants living in the facility’s vicinity and for the environment. None of the established water-cooled solid spallation target technologies can be safely used at the ESS power level without substantial additional R&D effort. For this design report, the focus is on demonstrating the feasibility of the chosen target configuration with satisfactory safety margins. For this purpose, the technology does not have to be an optimal concept from all points of view. As the ESS goes into construction, other candidate water-cooled target design concepts will also be investigated in order to develop the best possible design concept for a water-cooled spallation target with 5 MW power.

The target configuration considered for feasibility analysis is described as follows. The spallation volume consists of tungsten rods that are each 10 mm in diameter and 80 mm in length. For protection against corrosion in water, each tungsten rod is canned by a zircaloy tube that is 0.5 mm thick. Tantalum, the conventional cladding material, would substantially enhance the after-heat and would thus aggravate the safety hazard of overheating. The development of canning technology could also open the way for the use of other materials for corrosion protection, such as stainless steel, which react less violently than tantalum or zircaloy with water vapour at elevated temperatures. The canned tungsten rod bundles are vertically placed in a vessel made of stainless steel, and the diameter of the horizontally rotating target wheel is 2.5 m, as in the baseline helium-cooled target option. This cannelloni-shaped water-cooled target has an average density approximately 60% of that of solid tungsten. Heavy water is considered as cooling fluid, in order to avoid a 10% loss in slow neutron yield that light water coolant would imply. The spallation volume is cooled by single-phase cross flow with adequate pressure preload, in order to avoid boiling. The target wheel is sectored as for the helium-cooled option, in order to have enough strength to sustain the pressure preload. The distance between the outside of the vessel and the nearest moderator surface is assumed to be 15 mm.

In this section, cases are identified requiring in-depth experimental, numerical and theoretical studies and tests to reach conclusive answers. The results described in this section contribute to providing a basis for the further assessment of water-cooled target approaches for ESS-class pulsed spallation sources.
3.6. FALLBACK AND COMPARATIVE TARGET TECHNOLOGIES

Transient water cooling

In order to evaluate the feasibility a tungsten target water-cooling system, some initial thermal analyses have been performed based on a rod cross flow configuration. The cross flow configuration has been chosen, because with required flow speeds for axial flow, the mass flow rate becomes unmanageable. Details of the calculations presented in this section can be found in a more extensive report [392].

The heat load in the rods was evaluated using the MCNPX code, using the reference proton beam and studying the rod with the highest heat deposition. The mean free path of protons at 2.5 GeV is much longer than the diameter of the rod, so a constant heat distribution in the radial direction was studied. The parabolic profile of the heat deposition in the axial direction was reproduced by means of 8 axial sectors with constant heat deposition. The maximum value in the centre of the rods was 4.1 kW cm$^{-3}$ for tungsten, 1.85 kW cm$^{-3}$ for zircaloy and 0.4 kW cm$^{-3}$ for the water [393]. In order to take a conservative approach in the calculations, 5 kW/cm$^3$ was used for tungsten and 2 kW/cm$^3$ for zircaloy. The thermal-hydraulic calculations were made for 10 mm diameter tungsten rods canned in 0.5 mm thick zircaloy tubes in a triangular pattern with 1 mm pinch between the tubes, as shown in Figure 3.79. This implies the 61% tungsten and 14% zircaloy volumetric filling ratio. The volume fraction of the tungsten can be increased somewhat by larger rod diameter, thinner canning and smaller tube pinch. The rods are placed vertically between the radii 0.85 m and 1.25 m in the wheel. To fill this concentric area, while removing radial sectors for the cooling water inlet and outlet, requires about 14,000 rods.

For a cross-flow cooling scheme, handbook correlations can provide preliminary approximations of the heat transfer coefficient to be expected [394]. With a bulk water velocity of 1 m s$^{-1}$ between the tubes, the overall heat transfer coefficient is about 10 kW m$^{-2}$ °C$^{-1}$. The heat transfer coefficient is expected to be higher for the cross-flow configuration than for the axial flow. However, it will also be more fluctuating and unevenly distributed around and among the tubes [395]. This has to be investigated further by detailed numerical analysis for the chosen configurations and compared to experiments. The applicability of the handbook correlations for this comparatively low-pinched configuration (compared to usual heat exchangers) should also be assessed. With tangential flow in 33 sectors of the wheel, the total mass flow rate is 290 kg/s, and the overall temperature increase is less than 3°C. By optimisation and more detailed design, for example, by directing higher mass flow to the most heated areas, the mass flow could be decreased and this temperature increased.

A change in the heat transfer coefficient will affect the average temperature of the surface quite strongly, but will have less of an effect on the tungsten temperature increase during the pulse. As a first estimate, the adiabatic temperature increase in the tungsten is about 140°C. The temperature at the outer surface of the canning will determine the limit to boiling. Between the pulses, the rod temperature will not fall quite as low as the water entrance temperature. For initial estimates, it is assumed that the rod temperature has only reached 30°C when the next pulse arrives. Such calculations lead to a peak temperature of 170°C, which is the sum of above mentioned 140°C and 30°C. The water saturation pressure at that temperature is 0.8 MPa, which means that this pressure plus some margin is required to avoid boiling.

The assumption that the heat is deposited instantaneously, which is used in the initial estimate made above is quite conservative. In reality, there is cooling during the pulse, so the surface temperature will not
In required pressure. Also, the heat transfer at the surface is controlled by the heat transfer coefficient, which will be further investigated. In order to capture the transient heat transfer, the applicability of the modelling tools will also be assessed, because the standard CFD tools for simulations assume stable conditions in both flow and heat transfer.

Pressure fluctuations

Figure 3.80: Temperatures in the water-cooled target as a function of time for one pulse cycle: $T_{WCentre}$, and $T_{WRo}$ at the tungsten centre and outer edge, and $T_{ZRi}$, $T_{ZMid}$ and $T_{ZRo}$ at the inner, middle and outer surfaces of the zirconium can.

Figure 3.80: Temperatures in the water-cooled target as a function of time for one pulse cycle: $T_{WCentre}$ and $T_{WRo}$ at the tungsten centre and outer edge, and $T_{ZRi}$, $T_{ZMid}$ and $T_{ZRo}$ at the inner, middle and outer surfaces of the zirconium can.

Pressure fluctuations have also been studied. With microsecond proton pulses, severe thermal shocks will be created in water. For example, an instantaneous temperature rise of 1°C in water at 50°C will cause an instantaneous pressure rise of nearly 1 MPa when all the beam-deposited energy is instantaneously converted into heat. With slower heating over 2.8 ms at ESS, this effect should be reduced substantially, provided that the pressure wave created by the thermal expansion of the rods and the water can freely propagate over 2.8 ms into the cold water across the whole wheel. In this case, values of below 0.1 MPa can be expected. However, if the sectorisation partially or totally prevents this dissipation, higher pressures will arise. Whether or not this occurs depends on the mechanical layout of the wheel.
A further pressure rise in the water will be caused by the quasi-static thermal volume expansion of the rods and, to a lesser extent, of the water [396]. Assuming, for the sake of argument, an average volume increase in the most significant part of the target of 20 cm $\times$ 20 cm $\times$ 6 cm, an excess volume of about 2 cm$^3$ will have to be accommodated to avoid a build up of pressure. This again may be absorbed by the total volume of water contained in the wheel, 50 to 100 litres, to arrive at a pressure rise of less than 0.1 MPa. Also, small temporary expansions of the covers of the vessel will mitigate this effect, although undesired vibrations of the vessel may be induced. A more precise assessment of the above dynamic effects, including the dynamic coupling between the cannelloni and the vessel through the water, should be done, based on a more detailed geometry.

**Experimental verification**

As stated above, the complex water-cooling regime requires experimental verification and benchmarking of the numerical codes. It is of particular importance to investigate the thermal response of the cannelloni during the beam heating over a period of 2.8 ms, and shortly thereafter over a period of about 100 ms, as demonstrated by the studies, presented above. Various approaches to such experiments are at present under investigation at Forschungszentrum-Jülich and ESS-Bilbao. One approach is continuous heating at maximum temperatures. Electrical heating by a DC current of a bundle of cannelloni up to the maximum temperature could be used, with temporary peak temperature of about 200°C. A realistic geometry of the cannelloni and water flow, including adequate pressure pre-load must be provided and a power of about 4.5 kW per cannelloni is required. Such an experiment will provide average heat transfer coefficients at different water flows, pre-loads, heat fluxes and onset of boiling and will thus serve to benchmark the codes applicable for continuous heating regimes. Another approach involves mechanically induced heat pulses. A bundle of cannelloni, pre-heated to about 200°C is driven rapidly into a stream of cold water and the decrease of temperature is measured. The length of time over which the water flow is disturbed will have to be verified, so that the time span of interest, substantially shorter than 100 ms, can be investigated.

An experiment could also be performed with electrically induced heat pulses. In this type of experiment, a bundle of cannelloni or even only its cans, are heated by an electrical pulse over 2.8 ms up to about 200°C, while placed in a realistic geometry and flow of cold water. Since the prime issue is the surface temperature of the cannelloni and its interface with the cooling water, empty pipes with suitable electrical resistivity may be selected to study short term behaviour, when the heat flux from the filling of the cannelloni is not yet relevant. At longer times of around 100 ms, when the heat input from the cannelloni filling starts to matter, this missing heat can be provided by continuing the electrical pulse in an adequate way.

There is also a need for fatigue tests of the cannelloni. In these tests, each cannelloni is submitted to cyclic thermal loads. Temperature rises over 2.8 ms are different in the zircaloy can and the inside tungsten. The interface and, in particular, the thermal contact between the mating materials is of prime importance for the evacuation of heat. About 4 million cycles are accumulated in each cannelloni over 100 days of continuous operation. Cannelloni with adequate pressure at the tungsten-zircaloy interface should be thermally cycled between room temperature and about 200°C. With cycle times for heating up and cooling down of about 10 s (which is not trivial to achieve), 1.7 million cycles will be accumulated over 200 days. Although only thermal cycles with uniform temperature over the cross section of the cannelloni are tested, and the temporary temperature difference between the zircaloy and the tungsten is ignored, the approach should provide insight into the long term thermal behaviour of the cannelloni. Some resilience tests to very high temperatures of around 500°C, which may occur during incidents due to the after heat if no active cooling is available, should also be planned for.

**Layout and operation**

About 14,000 cannelloni must be manufactured to equip one wheel. The tungsten rods are press fitted into the zircaloy pipes under sufficiently high pressure between the mating parts to ensure good thermal contact. A radial pressure preload between the canning and the rod of 7.2 MPa results from accepting a circumferential stress of 72 MPa in the canning due to the press fitting in the reference configuration. Thus, in the event that pressure buildup occurs due to gas production inside the cannelloni, thermal contact will not be lost unless this pressure is exceeded. To achieve the required preload during manufacture in a reliable and reproducible way, the tungsten-rods and the zircaloy-tubes must be fabricated to micron precision. Assembly procedures, procedures for the closing of the cannelloni and final acceptance criteria
must be specified carefully. The global structure of the wheel is made entirely of stainless steel, as shown in Figure 3.81. A separate support holds each cannelloni in place, as shown in Figure 3.79. Perforations in the support provide for good transparency for the passage of water, as discussed above. This holding structure is linked to the global structure of the wheel. Further engineering is required to ensure that the strength of this support is adequate to support at least 45 kg, the weight of each significant part of each target sector, and also to optimise water passage vertically.

Figure 3.81 shows how the wheel is enclosed at the top and bottom by slightly undulated stainless steel sheaths. This shape combines high-pressure resistance with minimum wall thickness. A thickness of 2 mm and wave amplitude of 5 mm resists up to 1 MPa, when a membrane stress of 500 MPa is accepted. This can readily be optimised further by slightly increasing the thickness and/or the wave amplitude. Since the average increase of the water temperature after crossing a target sector is small, no major deformations due to temperature variations around the wheel are expected. With the proposed layout of the wheel, and maintaining a safety distance between the vessel and the adjacent moderator of 15 mm, the distance between the centre of the spallation material and the moderator is 64 mm.

Figure 3.82 shows that the beam entrance window forms an integral part of the wheel, which is thus a monolithic structure, entirely welded together without assembled joints or flanges. The BEW also has a semi-spherical shape. At a thickness of 2 mm and sufficient bulge, pressure resistance to 1 MPa can readily be achieved. The temperature rise in the BEW per pulse is about 30°C to 40°C. Due to the high ratio of cooling surface to mass, a convection coefficient well below 10 kW m⁻² °C⁻¹ is sufficient to ensure adequate cooling. This is much smaller than the convection coefficient required for cooling the cannelloni. As the BEW is among the most critical items in the wheel, it merits detailed studies, including investigations of thermal stresses, dynamic effects and vibrations induced in it via pressure bumps in the cooling water.

**Operation**

During operation, all standard controls have to be provided and interlocked. These include proper rotation of the wheel, locked to the linac timing; operation of the water cooling system; and the rotating seal and pressure pre-load in the water as well as the measurement of beam position and shape. Safe filling procedures must be devised for the whole circuit and for the wheel which contains more than 2 m³ of water, in particular. Similarly, scenarios for purging, venting, dry-out and storage of the activated heavy water have to be provided. Shut-off valves will be required to isolate the wheel from the circuit for purposes such as maintenance of the rotating seals or exchange of the wheel. Fast emergency shut-off valves in running circuits must be avoided, since water hammer would aggravate dangerous situations.

During planned shut downs or minor incidental stops, a small water flow should be maintained to evacuate the afterheat safely and to avoid increasing the temperature above the operational level. If the wheel has to be drained, auxiliary gas cooling will be required to avoid temperature rises of several hundred degrees. For intermittent test of the integrity of the wheel, He-leak tests, involving evacuation of the wheel, and pressure tests will be carried out, provided, of course, that the afterheat can be tolerated during such interventions. In principle, it is feasible to instrument the outside of the vessel with temperature sensors and to guide the radiation hard cables to the top of the shaft and transfer the signal through rotating electrical contacts. Such sensors may not be very sensitive to excessive, accidental temperatures inside the wheel, since they are masked by the cooling water.

It is desirable to measure the footprint of the beam on the beam entrance window, as is done for
3.6. FALLBACK AND COMPARATIVE TARGET TECHNOLOGIES

Figure 3.82: The beam entrance window before the tungsten rods in the water-cooled target wheel.

the proton beam window. In general, pulse-by-pulse measurement of the beam profile is of particular
importance to protect the wheel from over-focused beams, which might perforate both the PBW and the
BEW. The consequences of such an accident, in particular in terms of down time, are more severe when
a large amount of water is lost and the wheel has to be removed, than they would be if only a PBW had
to be exchanged. The pulse-by-pulse reproducibility of the footprint and the precision of its measurement
will define the safety margin required for a reasonably continuous operation without an excessive rate of
interlocks.

SINQ is among the spallation sources most relevant to ESS’s water-cooled back-up target design. Its
target is cooled with heavy water, using a similar geometry to that foreseen for ESS’s water cooling [397].
However, at SINQ the spallation material consists of lead-filled zircaloy tubes. The total energy deposited
in the water may be used as a measure for possible corrosion of the target by the water. The SINQ target
is routinely changed after it has absorbed an energy of 9,000 MWh, at which point there is no sign of
degradation on the actual target. In particular, no adverse corrosion effects have been detected. To put
this into perspective for ESS, each of the 33 target sectors on its wheel will have absorbed only 3600 MWh
over 5 years (200 days per year of operation). However, the material of the wheel at the exit of the water
near the shaft, where all the 33 circuits are merged, is in touch with water that has accumulated higher
dose levels. Long-term experience at PSI over some 15 years has shown that no detrimental effects appear
on stationary components of the cooling circuit that are not regularly exchanged, such as piping. However,
the unprecedented high energy of close to 17 J/g at ESS, combined with the pulse deposited directly in
the water will have to be looked into carefully. Temporary very high ionisation and hydrolysis, involving
threshold effects, could be present in the water path immediately downstream of the target. The substances
and ions might quickly recombine and decay, and thus not be detectable in parts of the water circuit that
are further downstream. As yet, no examples of beam-induced energy densities in water comparable to
those at ESS have been found. The literature search will continue and advice in radio-chemistry will be
sought.

Globally, the technology of heavy water cooling circuits operated in radiation environments is well
established, as demonstrated by long term experience at SINQ and other facilities [398]. In ESS’s water-
cooled target design, the water ducts are made of stainless steel with safety qualified welding and as few
flanged connections as possible. They will be designed for a pressure of about 0.7 MPa, taking into account
a pressure preload of 0.5 MPa, to prevent cavitation in the pumps, and pressure drop across the whole
circuit. Rotating water seals are available from industry, although they would have to be adapted to the
specific needs of ESS, including high water flow and radiation resistance. Cleanliness of the water, low
electrical conductivity, proper handling and disposal of radioactive isotopes, $^3$H, $^{17}$N, $^7$Be and radiolysis
gas, are important issues that are readily addressed by using delay tanks and resin filters in bypass and
recombination stations. Experience from ISIS, LENS and SNS will also be relevant for ESS [399, 400].
Some contamination by deposition of Be-7 along the inside of the pipes has to be expected. If required,
local hot spots can readily be shielded. Small quantities of water escaping through incidental leaks, or
recuperated continuously from the rotating seals, can be detected by tracking increases in radiation level
due to tritium, as is the practice at SINQ. It remains to be determined, however, if the emerging signal can
still be detected against the overall tritium background produced during normal operation over prolonged
periods, or by previous incidents. This background might be important in the immediate vicinity of the
wheel and the top of the rotating shaft.
Fundamental safety issues

Management of the afterheat after prolonged operation is a crucial safety issue for the water-cooled target. The afterheat – or decay heat – is the residual power in the irradiated tungsten due to the decay of radioactive species. If the water-cooled target has a tungsten volume fraction similar to that of the baseline helium-cooled target, a residual power of 47 kW in the water-cooled target’s tungsten volume can be assumed [355]. The afterheat decays to about 30 kW after some hours. This heat is dissipated throughout the bulk of the spallation material, uniformly distributed around the wheel over a significant depth of about 20 cm.

The first of a number of afterheat issues is the case in which the flow of water ceases after the beam stops, so that stagnant water remains in the wheel. The pressure preload must be released. Devising a system of cooling via natural convection is difficult in this case, since the migration of heated water through the wheel to the top of the shaft and the return from there of cold water, via a buffer water reservoir or a heat exchanger, would be difficult to make compatible with safety regulations. However, if the stagnant water remains in the target, after some minutes, its temperature will have reached 100°C and it will have evaporated within about half an hour. The phase during which the remaining water boils needs additional study, mainly through experimental tests supported by numerical simulations focusing on the migration of vapour bubbles through the bundle of cannelloni in the radial direction towards the centre of the wheel and into the shaft. The wheel is initially filled with about 1 m³ of cold water at nearly 0.1 MPa. As it boils, the vapour must be collected close to the top of the shaft, and the tritium carried in the water and vapour at or above 100°C must be contained. After the boiling phase, the wheel will still be filled with water vapour. The temperature will continue to rise and then will stabilise when sufficient removal of heat by radiation sets in. Temperatures well above 400°C are to be expected.

High temperatures can also be reached in the event of a sudden, massive water leak, such as would be caused by a breach of the BEW. In this case, 1 to 2 m³ of water, pressurised to 1 MPa, would be lost from the wheel. Such a catastrophic scenario could be initiated by continuous beam during an undetected loss of rotation and/or cooling. To prevent such accidents, reliable systems must ensure that the beam is stopped within one or two pulses, or 100 ms, after the wheel stops. Tritium and other isotopes released at elevated temperatures of about 400°C must also be handled safely. In the event of a large breach in the target wheel vessel, the liquid water would be released. In this case, the target vessel would be filled with a mixture of water vapour, helium and possibly also air – a loss-of-coolant accident. The cause for concern is the possible exposure of the tungsten to the high temperature vapour and air due to thermomechanical failure of the zircaloy canning tube. A hazardous steam-tungsten interaction is known to begin at a threshold temperature of approximately 600°C. Zircaloy also reacts with oxygen at high temperature, creating hydrogen and zirconium oxides, and is likely to fail due to its crystalline structure. It is therefore important to remove the decay heat and to keep the target temperature below the critical limit of 500°C.

The decay heat in the target wheel volume is balanced by three heat transfer mechanisms: heat conduction though the helium (or air, in case of air ingress) which fills the gap between the target and the shielding; free convection due to the helium (or air) surrounding the target wheel; and thermal radiation from the target vessel towards the shielding block surface. Conservative estimation of the tungsten temperature in the water-cooled target was carried out under the assumption that the decay heat is balanced solely by radiative heat transfer, ignoring the other two heat transfer mechanisms. In order to get a qualitative understanding of the thermal behaviour of the target due to decay heat, it was also assumed that the decay heat is uniformly distributed in the tungsten volume. The temperature of the inner surface of the shielding block was uniformly set to be 100°C, for simplicity. It was also assumed that the surface of the vessel is blackened to have a surface emissivity of 0.7 and that the slightly oxidised surface of the zircaloy cladding has a surface emissivity of 0.4. Given that the radiative heat transfer at the first 50 cm of the outer diameter region of the target wheel dominates, an estimate based on grey body Stefan-Boltzmann law shows that the temperatures at the tungsten surface approach 600°C. This indicates that further engineering efforts are required to keep the tungsten temperature below the critical value of 500°C during a loss-of-coolant accident. However, heat removal by outside gas conduction and convection provides some safety margin. This is an area that will be studied in more detail as the geometrical design is further elaborated.

A number of spallation facilities that rely on water cooling have added a second safety vessel tailored closely to the dimensions of the wheel. However, this would be difficult at ESS, in view of the size of the wheel and the weight of the water or volume of the vapour to be recuperated. A second safety vessel
would suffer from radiation damage and beam induced heating from narrowly focused beams in the same way as would the wheel itself. If this second vessel is not rotating, but remains stationary, an additional PBW must be provided, although the second PBW does not provide additional safety. Therefore, the ESS water-cooled reference design does not call for a second safety vessel. Instead, means must be found to recuperate as much as possible of the water, or in the worst case, the vapour, spilt around the wheel, in a well-tailored sump. Means to dry out the area surrounding of the wheel should also be provided, to recuperate any remaining humidity.

Neutronic performance

The water-cooled cannelloni target is based on the idea of placing spallation material rods canned in zircaloy tubes. Compared to the helium-cooled target option based on a tungsten slab structure, this concept reduces the density of the spallation area. This increases the mean free path of protons, allowing them to interact with oxygen and hydrogen/deuterium. These effects will induce a reduction in neutron yield and a less concentrated source. This neutronic under-performance can be partially compensated for in terms of total system performance, for instance, by optimisation of the premoderator thickness. Analysis shows that a cannelloni target cooled with heavy water can reach 80% of the helium target performance for a single coupled cylindrical para-hydrogen moderator and 1.5 ms of pulse length [401]. On the other hand, this configuration has advantages from a thermal point of view, since it reduces the distance from the spallation material to the cooling media, reducing the thermal gradient inside the target, compared to the helium-cooled option.

Based on these considerations, a new model of the heavy water cannelloni target with the bispectral moderator has been developed for use in its neutronic evaluation, as illustrated in Figure 3.83. This model includes a matrix of 10 mm tungsten rods canned by a 0.5 mm thick layer of zircaloy, cooled by heavy water. Note that the target vessel is made of 7 mm thick aluminium alloy 6061 in this model [402]. The relative position between target and moderator and the thickness of the premoderator have been optimised in order to obtain a preliminary evaluation of the relative performance of this option. The relative position between target and moderator is related to target density. Since the cannelloni target has a much lower average density than the helium-cooled tungsten slab target, the positioning has to be reviewed. Also, the water inside the target produces a significant moderation of the neutron spectrum, so the premoderator can be reduced to 1 cm in thickness.

Figure 3.83: Geometrical model for a cannelloni target [393]. The target shown is made of aluminium and lead, but similar principles apply for stainless steel and tungsten.
The new cannelloni configuration reduces the heat load on the moderator by about 10%, mainly due to the lower neutron flux. The improvement for the premoderator is significantly larger, reducing the heat load from about 17 kW to about 11 kW due to the difference in total volume. Thus the backup solution is completely compatible with the cryogenic loops designed for the baseline proposal, and no additional capacity needs to be provided. To summarise, the preliminary neutronic study shows that the cannelloni-type water-cooled tungsten target has manageable disadvantages in neutron performance compared to the helium target option, but that it does not require much modification of the moderator-reflector assembly geometries to achieve the optimum configuration.

Summary

At present, the most powerful spallation sources are SNS, operating at 1 MW average beam power and 60 Hz with microsecond pulse duration, and SINQ, operating at 0.9 MW in DC mode. Extrapolating from these facilities to a water-cooled wheel at ESS is not straightforward. For example, the energy per pulse is about 20 times higher at ESS than at SNS. A water-cooled option has been proposed for ESS, inspired by SINQ, with tungsten rods, contained in zircaloy cans (cannelloni) and cooled by a transverse (cross) flow of heavy water with a velocity of about 1 m/s. Canning in stainless steel may also be an option. As 33 target units are contained in the wheel, so that each unit is hit every 2.4 s, the removal of the average power from each target sector is straightforward. However, understanding the detailed pulsed evolution of the temperature in time and space in and immediately around each cannelloni is much more complex. Different components (tungsten, zircaloy and water) are heated differently by the beam pulse, within a rise time of 2.8 ms.

The thermal interplay among these components over very short time spans measured in milliseconds, the convergence among these different temperatures over 100 ms, and, finally, the decaying average temperature of the whole cannelloni over many seconds is complex and difficult to assess reliably using existing simulation codes. Estimates indicate that temporary peak temperatures well above 100°C on the outer surface of the most loaded cannelloni will be reached. Including phase changes of water with boiling will make the investigation more complex. Thus, at this stage it is assumed that boiling is prevented by pressure pre-loading the water circuit to a value between 0.7 MPa and 1.0 MPa. Possibilities for experimental verification of the thermal regime, most importantly between the time spans of zero to some 100 ms are being investigated. Also, the more global thermal cycling of the cannelloni under fatigue, and in particular the thermal contact between the tungsten rod and the can, must be determined.

The dynamic interplay caused by the pulsed beam between the spallation material and the vessel, coupled to each other by the water, is another phenomenon requiring further investigation. The overall pressure resistance of the vessel up to about 1 MPa does not seem to be a problem and should be amenable to engineering solutions. Such pressure resistance may be required anyway by safety rules for water circuits in which a complex heat source of about 3 MW, contained inside a water volume of about 100 l, is connected at a distance of 6 m to an overhead voluminous water supply of 1 to 2 m³. The cooling plant and in particular its pumps, heat exchangers, filters and ion exchangers are well established technologies, applied in many facilities around the world. While the lifetime of the wheel is expected to be above 5 years, a number of aspects remain to be studied, such as the effects of radiation damage in the wheel and gas production inside the cannelloni. The production and control of tritium during regular operation and its containment in accidental scenarios also must be investigated in more detail.

Responses to incidents and severe accidents require further investigation and elaboration. For small, incidental stops, for example, loss of water flow, active interlocks are required to stop the beam and to provide means to evacuate the afterheat. For the severe event of a loss-of-cooling accident, water or vapour will be spilt from the wheel into its surrounding area. A second target vessel will not be provided for reasons detailed above, so means to collect the spilt water and to dry out the flooded area should be provided.

3.6.2 Liquid lead bismuth eutectic target

The objective of developing the design of the MEgawatt TArget: Lead bIsmuth Cooled (META:LIC) has been to make available a target solution for comparison with ESS's baseline target design. In this context, the effort to design and validate META:LIC was comparatively limited and priorities have been directed mainly to the target design. However, the decision to develop a liquid lead bismuth eutectic
(LBE) target design is justified by the fact that Europe has developed a remarkable base of experience with LBE technology, and that experience has been very well documented in technical reports, handbooks and scientific papers. In particular, this experience has been gained in the frame of the development of accelerator driven reactor systems that couple a sub-critical reactor core (cooled with liquid lead or LBE) with a liquid LBE high power spallation target and proton accelerator.

The accelerator driven system (ADS) demonstration road map included the design, construction, commissioning, operation, post-operation analysis and decommissioning of the liquid LBE spallation target MEGAPIE (Megawatt Pilot Target Experiment). MEGAPIE has been successfully operated at the Paul Scherrer Institute in Switzerland since 2006, demonstrating the feasibility of liquid LBE high power spallation targets. Moreover, the selection of liquid metal as a prominent comparative solution is also motivated by the relevant operational experience gained in the USA and Japan on the liquid mercury spallation targets at SNS and J-PARC, respectively. This experience is especially important when considering the ancillary systems for liquid metal targets, which are complex.

A more detailed technical report on META:LIC is under preparation as a separate document. In addition to the description of the META:LIC design, below, further elements (e.g. ancillary systems, licensing procedures) considered relevant to operate a liquid metal target have been added. However, due to the limited resources available, the description of these elements is based on the MEGAPIE experience. Their further development would require a more detailed analysis and adaptation to META:LIC’s circumstances. The baseline monolith layout conceived specifically for the rotating helium-cooled tungsten target cannot accommodate META:LIC. With relatively minor changes it is possible to adapt existing monolith designs from SNS and J-PARC to ESS. The META:LIC design is conceived as an evolutionary design in which both window and windowless configurations are feasible. This evolutionary design allows the operation of the window configuration both at lower beam power (e.g. the beam power expected during commissioning of the facility) and at full beam power, but with relatively short lifetime. The windowless configuration is potentially capable of power upgrades beyond 5 MW and has a longer lifetime than the window configuration. Both configurations are addressed below.

The META:LIC concept

Figure 3.84 shows the layout of the META:LIC target, which is the same for both the window and the windowless configuration, consisting of three separately replaceable modules. These modules are the target (window/windowless), the pump and the heat exchanger. The heat exchanger and pump modules are submerged in the pool and the target module is attached to the pool. In order to replace individual modules, the whole system is moved on a trolley into the hot cells, where the container can be opened. One of the attractive properties of META:LIC is that the pressure is below ambient pressure within the beam interaction region, which prevents major leakage in case of a leak or break of the window. Figure 3.84 also shows schematically the placement of two moderators that can operate at distinct temperatures for cold and ultra-cold neutrons. Not shown in this figure is a container that safely encloses the whole system, which is described in a later paragraph of this section.

Figure 3.84: The LBE target system consists of the target module, two moderators and a pool with submerged pump and heat exchanger modules. The proton beam arrives from the left along the beampipe and interacts either with structural material (window) or directly with LBE (windowless).
Neutronics and nuclear data assessment

Displacement damage in the side, top and bottom steel walls of META:LIC has been calculated with the parabolic proton beam profile defined for the helium-cooled rotating target. Following 5,000 h at full beam power, the accumulated induced radiation damage amounts to about 15 to 19 dpa in the side and bottom walls. For the window configuration, the window itself is subjected to damage levels up to 50 dpa per 5000 h at the location where the proton beam hits the top steel wall. Under these conditions, helium and hydrogen production are 50,000 appm and 10,000 appm, respectively. These data clearly show that the beam would need to be reconsidered for META:LIC to reduce the peak proton current density. Nuclear heating, neutron and proton flux distributions were calculated using the parabolic proton beam profile. The maximum power density in the LBE amounts to about 2 kW/cm$^3$. The maximum values of the proton and neutron flux densities are about 3 × 10$^{14}$ cm$^{-2}$s$^{-1}$ and 3 × 10$^{15}$ cm$^{-2}$s$^{-1}$, respectively. Figure 3.85 compares the neutron spectral brightness for the baseline helium-cooled target and for META:LIC. The moderator-reflector system and the proton beam parameters optimised for the baseline helium-cooled target have been used for neutronic calculations. The relative positions of the target module and the moderators have been varied to find the position with maximal cold neutron flux, with kinetic energy below 5 meV [403]. Earlier comparisons with a common Gaussian beam profile showed that the neutronic performance was roughly similar between LBE and tungsten [404].

![Figure 3.85: Comparison of neutronic performance of the baseline helium-cooled target (RoTHeTa) and the META:LIC target with a cold H$_2$ moderator.](image)

**Figure 3.85:** Comparison of neutronic performance of the baseline helium-cooled target (RoTHeTa) and the META:LIC target with a cold H$_2$ moderator.

Window target

The preliminary engineering design of META:LIC has been optimised in both configurations (window and windowless), given the calculated neutronic and heat deposition performance. The window target consists of a proton beam guide with a safety window, an inflow channel leading to a nozzle producing a uniform block velocity profile, a U-bend with an expansion chamber, and an outflow duct. The flow is pumped upwards, then directed into an inclined channel (at a 3 degree angle) and then accelerated by a nozzle into another channel, which is inclined relative to the horizontal plane by a 15 degree angle. This leads to an extremely stable block velocity profile that does not suffer instabilities. The proton beam enters the liquid metal through a solid wall, which is approximately 2 mm thick. The small inclination angle of 15 degrees allows for almost coaxial beam and flow, as in many earlier target designs (e.g. MYRRHA-target, MEGAPIE, EURISOL) in which the coolant is heated quite uniformly, so that a minimal coolant flow rate can be established. On the other hand, due to the inclination, the flow component perpendicular to the beam transports the fluid across the beam in a short time. This is advantageous for pulsed beams, as successive beam pulses interact with fluid that was not subjected to the beam previously.

The target module is installed at a geodesic height above the LBE level in the pool. Therefore when the pumps are not operating, the target module completely drains. A reservoir above the target level could
be provided to remove stored heat in the walls in case of a pump failure. The pressure inside the target module (determined by gravitational pressure and small losses) at the highest elevation is chosen to be slightly above the vapour pressure of LBE. This implies that the pressure at any location within the target is below ambient pressure. The target module is attached to the pool by a plug to allow replacement of the target module structure (excluding LBE inventory). As shown by dedicated investigations, the pulsed nature of the proton beam results in water hammer phenomena in the window target module. Indeed, the energy deposition due to a proton pulse leads to a temperature rise in the material within a short timescale. Due to the inertia of the surrounding LBE, the thermal expansion of the target material in the spallation zone is suppressed. This will result in an initial pressure rise and a shock wave, which potentially leads to high stresses on the container material. The risk of cavitation damage occurs when the pressure wave is reflected, leading to negative pressures.

While for a short pulse target, the time scale of the pulse is too short to allow the target material to expand at all during the pulse and the whole thermal expansion has to be compensated for by a compression of the target material, the time scale for the long pulse target is such that the target material can respond by appreciably expanding during the pulse. In this case, the maximum pressure is no longer proportional to the total energy per pulse, but rather to the sudden change in the heating rate at the beginning and the end of one pulse \[405\]. Preliminary calculations of pressure development for the META:LIC window configuration have shown that at the container material, peak pressures up to 1 MPa can be reached in normal operating conditions, and the pressure wave will reflect between facing walls. Compared to a short pulse target with sub-microsecond pulses where pressures up to 370 MPa could be expected with these boundary conditions, the pressures calculated here are relatively small. Therefore the risk of cavitation is reduced significantly for long pulse targets such as the ESS target with a 2.86 ms pulse length.

More critical are sudden events like beam trips. Starting with normal operation conditions, the pressures in the window region will significantly decrease due to the inertia of the liquid metal flow and the missing thermal expansion when the beam is suddenly cut-off. Once the flow field conforms to the beam-off conditions, the pressure will increase during the first pulses when the beam starts again. There is insufficient stress relaxation during the first pulses following a beam trip and deformations, so that stresses will be accumulated for several pulses. Countermeasures have been considered, to prevent cavitation issues in the META:LIC target. Two methods have been identified to counteract the water hammer effect and impact of non-steady state conditions such as start-up transients or beam trip. The first is to modify the shape of the pulse at the beginning and end, and the second method is a modification to the design including dedicated expansion volumes.

The maximum pressure in the liquid metal can be reduced if a ramped proton current, and hence a ramped heat deposition, can be provided at the beginning and the end of the pulse. Figure 3.86 shows the influence of the steepness of the ramp on maximum pressure, which can be reduced by a factor of two by having a rise time of about 50 \(\mu\)s. The reduction factor is about 7.5 for a rise time of 200 \(\mu\)s, resulting in

\[
\begin{align*}
\text{Heat deposition} \\
\text{Maximal pressure [bar]} \\
\end{align*}
\]

Figure 3.86: Heat deposition and maximum pressure for a ramped proton beam pulse. Left: Heat deposition versus time. Right: Maximum pressure in the target as a function of the ramp time \(t_{\text{ramp}}\).
The second method to prevent cavitation and high stress on the container material in transient conditions is to adapt the design of the target. In the current design, an expansion volume and a spoiler enforcing flow detachment have been integrated in the U-bend region, as shown in Figure 3.87. This modification leads to two internal free surfaces, one in the outflow channel and the other in the expansion volume. Free surfaces effectively decouple the flow in the beam interaction zone from the flow in the outflow duct. Thus, the establishment of a flow which is capable of accepting the beam can be detected by measurement of the filling level of the inflow channel, where simple and robust technology exists for radiation environments. The introduction of the free surface will also be beneficial for reducing the stress on the target in transient conditions.

Figure 3.87 shows schematically how the integrated free surfaces achieved by the described design modifications interact with transients due to unsteady events (e.g. in the case of a sudden beam trip). Starting with steady-state operation conditions, the fluid pressure in the window region will decrease due to the inertia of the liquid metal flow and the absence of thermal expansion when the beam is suddenly cut off. This sudden change in volume will be compensated for by deformations of the container in the window region and probably cavitation bubbles within the fluid. Once the flow field conforms to the beam-off conditions, the pressure will increase during the first pulses when the beam starts again and the sudden thermal expansion is again compensated for by deformations of the container in the window region. Figure 3.87 depicts the approximate locations of the expansion chamber and the spoiler. Thermal expanded volumes – or cavitation bubbles – are indicated for a time scale corresponding to three successive pulses. The thermal expansion zone is transported downstream with the bulk velocity to the free surface in the expansion volume chamber zone, within 2 or 3 beam pulses. The thermal expansion zone is mitigated when it reaches the free surface. Wall stresses due to the compensation for a missing thermal expansion during a beam trip or during start-up transients after a beam trip, reach saturation after 2 or 3 beam pulses.

Windowless target

The windowless target module mainly differs from the window target module by the fact that the window is removed and a free surface flow is established. Moreover, the water hammer phenomena counter measures (expansion volume and spoiler) are not needed, as high pressure and cavitation zones are neutralised at the free surface. Therefore, the LBE flow is guided back towards the pool by a simple U-bend. The free surface closely follows the shape of the window target module. The geometric dimensions of the windowless target module are nearly identical to those of the window target module. Since it can be assumed that the window is the lifetime limiting structure, removing the window means that the target module lifetime can be extended. The windowless option also provides for proton beam power upgrades [403].
Thermo-hydraulic analysis

The thermo-hydraulics analysis has focused on the calculation of temperature distributions, the feasibility of the expansion volumes within the window target module and the stability of the free surface in the windowless target configuration. The temperature distribution has been calculated with the commercially available program package Star-CCM+ \[403\]. The computed mean temperature distribution in the fluid and in the target structure are shown in Figure 3.88 for the windowless option. All computed temperatures are within the temperature range that is allowed for the proposed structural material. Thermal stresses are yet to be computed, but are expected to be acceptable for the calculated temperature cycling.

The investigation of the feasibility of the expansion volume proposed for the target with a window, to mitigate cavitation effects, has been conducted with three-dimensional isothermal and transient CFD simulations using the open source CFD tool OpenFOAM Version 2.1 \[403\]. For both simulations an inflow velocity of 1.5 m/s in the x-direction and vanishing pressure at the outlet has been assumed. Figure 3.89 shows the resulting velocity magnitude distribution of the LBE phase in the interval from \( t = 1.5 \) s to \( t = 3 \) s, confirming that the internal free surfaces form at the desired locations. The computed flow velocities of LBE range between 1 and 4 m/s. The material limits related to these velocities are discussed below, but it can already be anticipated that it is crucial that the corrosion limit of the proposed structure material (T91) at the critical locations, that is, at thin walls, should not be exceeded. Less can be said about erosion limits, since these seem to be dependent on the formation of vortices or similar phenomena. Figure 3.89 also shows that non-wetted walls are subject to splashing, so that these structures can be cooled from the inside alone. Splashing can be enhanced by design, if necessary.

![Figure 3.88: Mean temperature distribution in the windowless target option. Left: In the LBE. Right: In the target.](image)

![Figure 3.89: Velocity distribution of LBE at two times. Left: At \( t = 1.5 \) s. Right: At \( t = 3 \) s.](image)
CHAPTER 3. TARGET STATION

Figure 3.90: Development of the free surface flow in the windowless target, for an iso-surface of volume-of-fluid of 0.5. Some longitudinal standing waves are visible near the sidewalls, originating from the corners at the outlet, but they do not propagate towards the beam centre-line.

The free surface flow condition of the windowless target module has been investigated with an unsteady formulation of the volume-of-fluid. Figure 3.90 shows that these simulations demonstrate the advantageous development of a relatively smooth free surface. Even though some longitudinal standing waves are visible near the sidewalls, originating from the corners at the outlet, they do not propagate towards the beam centre-line [403].

Target module validation

An experimental campaign is foreseen to validate the META: LIC design [403]. The experiment will be focused on thermo-hydrodynamics of the liquid metal flow and will be conducted on a mock-up of the META: LIC target at the LBE loop at the Institute of Physics of the University of Latvia (IPUL). The mock-up is shown in Figure 3.91. The LBE loop at IPUL has a total length of 10 m and contains 1,100 kg of LBE. The loop is equipped with an electromagnetic cylindrical induction permanent magnets pump, which could provide a liquid metal flow rate up to 12.0 l/s at a discharge pressure of 0.4 MPa (compared with a flow rate of up to 30 l/s for the ESS LBE target). Two flow meters of the induction and conduction types, as well as a Venturi tube are installed on the loop.

Figure 3.91: Mock-up of the META: LIC target body.
3.6. FALLBACK AND COMPARATIVE TARGET TECHNOLOGIES

Structural materials

The structural steels discussed for use in liquid metal targets are the nickel-containing austenitic steel 316L and the nickel-free ferritic/martensitic steel T91. Several corrosion tests and mechanical tests in LBE on both steels have been performed and good summary papers can be found [406,407]. The corrosion resistance of the two classes of steels at higher temperatures depends on the oxygen concentration in the LBE. Indeed, an oxidation mechanism on the steels occurs if the oxygen potential in the LBE is high enough. The oxide that forms on the steel surfaces apparently protects the steels against further corrosive attacks. On the other hand, some observers have suggested that too thick an oxide scale might crack and chip off, opening paths for LBE penetration. Above 500°C, the austenitic steel is susceptible to dissolution attack even at sufficient oxygen potential. In general, austenitic steel does not suffer degraded mechanical properties when exposed to LBE, unlike ferritic/martensitic steels. However, if the steel surface is protected either by an oxide scale or by an artificial iron/aluminium coating, the impact of LBE on the mechanical performance of the steel might be mitigated. One thermo-mechanical load not yet addressed is high-cycle fatigue. Temperature fluctuations like those expected for the LBE-cooled ESS target need to be addressed in specific experiments.

Two different erosion mechanisms are anticipated, causing different types of defects. The first mechanism has been attributed to the flow velocity and the resistance of the oxide layer. In particular, the oxide layer that forms on the steel surface has multiple layers. The outer one is formed by magnetite, while the inner one is a spinel oxide. It has been shown that increasing the flow velocity above 1.4 m/s causes the magnetite layer to disappear due to erosion phenomena. However, the spinel layer resists up to 2 to 3 m/s. Tests at higher LBE velocity have not been performed. The second type of erosion, which is apparently more severe, is due to the formation of vortices in the liquid metal flow. It has been observed that in flow conditions where vortices are generated, the liquid metal attack can be very deep. A thorough understanding of the flow conditions within the LBE loop is therefore mandatory. Note that the block profile of the velocity in the vicinity of the window is very stable and nearly laminar, so that corrosion issues concern other structures like the U-bend.

Irradiation phenomena should also be taken into account for the materials assessment. Indeed, in the proton-neutron irradiation environment, in addition to irradiation hardening, embrittlement due mainly to helium is often observed, which might limit the target lifetime. Investigation of the combined effects of corrosion and irradiation is an ongoing work that is currently being targeted in experiments performed in Bor 60 (LEXURII) and the PIE of MEGAPIE. These experiments will give some initial indications of the possible effects of the combined loads.

Instrumentation

Efforts have been made to assess and evaluate a further qualification route of existing measurement techniques for liquid metal flows, with particular view towards the application to a possible liquid metal target at ESS and its test experiments. The relevant measurement techniques are 1) contact-less flow-metering for the determination of integral flow rates, 2) ultrasound Doppler velocimetry (UDV) for the determination of velocity profiles and 3) contact-less inductive flow tomography (CIFT) for monitoring the three-dimensional velocity distribution in the target.

The contact-less flow meters developed at HZDR are a phase-shift sensor and a rotating single-magnet flow meter. A phase-shift sensor might well be applied for determining the total flow rate at a supposed liquid metal target in environments with low neutron fluxes. In its application, the necessary calibration and a temperature drift have to be taken into account. In contrast to that, the signal of the rotating single-magnet is largely independent of temperature fluctuations of the fluid. However, due to inertia, the time resolution of this sensor is rather limited. The UDV technique is not suited to the harsh environment of an ESS target, but it may well be applied at a lead-bismuth test target in order to identify flow variations due to heat fluxes. Contact-less inductive flow tomography is a promising technique for inferring the flow structure in the ESS target. The CIFT method is based on the fact that a flow under the influence of an externally applied magnetic field induces electrical currents which in turn deform the applied magnetic field [408,409]. The measurable magnetic field deformation outside the volume of the fluid carries information about the current flow state and can be used, by means of solving an inverse problem, for the reconstruction of the flow structure. In order to apply CIFT to ESS conditions, two problems have to be solved in advance: First, given the extreme neutron fluxes in the immediate vicinity of the liquid metal target, the Hall and
Fluxgate sensors used up until now must be replaced by more robust magnetic field sensors. Second, the CIFT inversion technique that has been used mainly on closed flows, or on flow with minor throughput, has to be adapted to flows with a dominant throughput and relatively low sideways or backward directed flow. Given the resulting very small induced fields, the increase in robustness and immunity to external interference is also an important issue. Further R&D activities would be required to investigate the feasibility of the CIFT technique for META:LIC. At present, the focus is on the adaptation of the CIFT method to the IPUL test loop. There is an on-going study to find a coil/sensor configuration that allows, with minimal instrumental effort, reliable identification of flow instabilities and backward directed flow components in the target. It is plausible that relatively simple pick-up coils would be much less sensitive to the expected radiation damage than Hall sensors or Fluxgate sensors. For this reason, a pick-up coil with 192,000 turns was developed and tested at the Mini-LIMMCAST facility which had been previously equipped with Fluxgate sensors. In order to reduce noise sensitivity, a gradiometric version of the pick-up coil was also designed and tested [403, 410].

**MEGAPIE experience with different sensors**

Temperature sensors proved to be very reliable for MEGAPIE, both inside the target and for the ancillary systems, with both thermocouples and platinum-based resistive sensors [411]. The thermocouple-based leak detector proved to be the most sensitive diagnostics for proper beam centring. Some problems were encountered with heated thermocouples, which were employed in level sensors. The reproducibility and thus the reliability of level determination of the liquid metal in the expansion volume of the MEGAPIE target was compromised, most probably due to LBE and oxides sticking to the sensors during operations. In the cover gas system, purportedly radiation-resistant pressure gauges showed strong radiation-induced drift in two sensors close to the target, resulting finally in the complete failure of one of the gauges.

Reliable pressure measurement is essential inside any new liquid metal target. Pressure gauges should be installed at suitable positions inside the target, to make it possible to gain experience with respect to long term performance in relevant conditions; continuous cross calibration with some external reference measuring the water flow through the target would allow the calibration of these devices. In combination with direct temperature measurements, true flow rates and thermal balances could be established on-line. This would certainly benefit safe operation. This applies to the primary spallation loop as well as to any intermediate cooling loop. One or more electromagnetic flow meters might be included as redundant and diverse devices for determining flow rates. Leak detection inside a liquid metal target should without doubt be based on temperature sensing employing thermocouples. The positive MEGAPIE experience with such devices is amply justifies this conclusion. A decision about whether to include stripe-type leak detectors could only be made after careful investigation into the properties of possible insulator materials. In MEGAPIE, the ZrO${}_2$ turned out to respond very sensitively to changes in the gas composition in the insulation gas volume. In addition, strong and varying temperature and irradiation effects have been observed. Finally, for long-term operation, levels of oxygen in the liquid metal and their effects on materials corrosion should also be controlled and monitored.

**Trolley design, interface to monolith and safety concept**

The conceptual target station enclosure system pictured in Figure 3.92 provides three physical barriers for LBE while the beam is on. The first barrier represents the META:LIC target module itself. The target module is double-walled, except for the window. The gap between the walls is filled with a cover gas and monitored for contamination. The double-walled proton beam guide and the proton beam entrance window complete the enclosure of the target module. To address the possibility of a leak in the window, the proton beam guide is monitored for contamination and equipped with cold traps for LBE vapour. As the pressure inside the target module is approximately equal to the ambient pressure, there is a negligible differential pressure drop at the proton beam window. An inert inner liner represents the second barrier. It encloses the target module excluding the trolleys and the proton beam entrance window. The pressure inside the inner liner is slightly above the adjacent atmosphere’s to prevent the diffusion of oxygen into the atmosphere, which would lead to the formation of explosive gases in the event of a leak in the hydrogen moderator system. The outer liner, which surrounds the hot cells, represents the third barrier for LBE. The pressure inside the outer liner is lower than inside the inner liner. The three physical barriers for the LBE are partially disrupted during maintenance operations when the beam is shut off.
Ancillary systems

Special attention has to be paid to issues of safety and containment in ancillary systems, in addition to safety and containment measures for the target itself. MEGAPIE’s experiences are relevant here. At MEGAPIE, the heat removal system and cover-gas system proved to be more expensive than the target and posed significant challenges. MEGAPIE featured an intermediate cooling loop with heat transfer oil as medium, in order to bridge the large temperature difference between the liquid metal on one side and the final heat sink provided by water-cooling under normal pressure on the other side. A big temperature step might also be bridged by other means, such as an intermediate liquid metal loop or a thermosyphon. The MEGAPIE fill (and drain) system worked well, although preheating inside the target would need to be improved compared to MEGAPIE.

In the absence of oil, fire is not a concern in the target, and thus it seems possible to guarantee that a dedicated cold area inside the target stays cold all the time. This would then be the perfect location to install a gas absorber. A cover gas system could be installed, for example to take gas samples or to handle gases that are produced by accident. However, in principle one should consider the option to trap and enclose volatile spallation products inside the target. A cover gas system with an intermediate gas system would have the advantage of being able to handle gases inside the target by trapping and/or gettering them, at least for out-gassing sources, or for tiny leaks. For large leaks, measures similar to those taken at MEGAPIE would be unavoidable.

Licensing issues: radioactivity and accidents

One of the major safety concerns for liquid metal targets is the release of volatile radionuclides, because release of these substances is enhanced by the higher mobility of isotopes within liquid metal compared to a solid target. Furthermore, substantial amounts of highly volatile mercury and highly radiotoxic polonium are produced in LBE. Nevertheless, the success of MEGAPIE at PSI has demonstrated that a 1 MW LBE spallation target can be licensed and safely operated. In particular, PSI had to convincingly demonstrate that the consequences of a very severe accident (as defined by the Swiss Federal Office of Public Health) could be dealt with, and that exposure to the public could be kept below 1 mSv. For ESS, the higher irradiation doses and longer operation times associated with an LBE target would be likely to result in more stringent licensing requirements. However, the ESS facility would be designed in such a way that certain accident scenarios that were relevant for MEGAPIE will not be an issue. For example, it is difficult to imagine scenarios that would result in a complete spill of the liquid metal at ESS. Once accident scenarios for ESS are established, experiences from MEGAPIE can help to identify the most important issues and solve them. There is also a large community developing ADS (MYRRHA) and other LBE-based reactor systems that can supply a wealth of information and will address relevant questions by new research.

Naturally, for reliable safety assessments of a spallation target, the radionuclide inventory has to be known with reasonable accuracy. Calculations have been made for an ESS facility with an LBE-target
CHAPTER 3. TARGET STATION

geometrically similar to the 2003 design [412, 413]. Similar radionuclide production has been assumed for the current design. For gaseous elements such as hydrogen and the noble gases, instantaneous release from the liquid metal is assumed as a worst case for accidents and for systems for handling the cover gas in routine operation. Oxygen and nitrogen easily form a variety of chemical compounds such as oxides, nitrides, nitrites, and nitrates. Since they only form relatively short-lived radionuclides, and are not produced in large quantities, they are not taken into account into the current design. For elements that have a significant vapour pressure at typical operating temperatures for LBE, recommended functions for conservative estimations of effective vapour pressure and thermodynamic activity coefficients in dilute LBE solutions have been derived for Pb, Bi, Po, Hg, Cd, Tl, and I [414]. Processes for the formation of volatile chemical compounds of various impurities will be investigated within the ongoing R&D program in support of the MYRRHA design. Little experimental data is available on the evaporation kinetics of volatiles from LBE, and it is limited to polonium and mercury [413]. Other physical phenomena that can lead to entrainment of radioactivity into the gas phase are sputtering caused by radioactive decay and aerosol formation [413, 414].

Radionuclide volatilisation in an LBE-based target has been studied. Estimates of the maximum gas phase activities that can occur in the cover gas under equilibrium conditions, that is, for a closed system, have been evaluated omitting the possible formation of volatile compounds among the present impurities. Table 3.27 shows activity and release data for the most important volatile elements at shutdown of the facility after 40 years of operation [414]. Masses of lead and bismuth are given based on the amount of target material present at the start of irradiation. Though a measurable “burn-up” of the material will occur during the four decades of operation, these changes are small compared to the uncertainties introduced by experimental error, simplifications and conservative assumptions, and may safely be ignored. Mercury is the dominating contribution to cover gas activity due to its high volatility and the absence of chemical interactions that could lead to its retention. With respect to the volume, hydrogen isotopes make up the dominating contribution, with helium ranking second at approximately 10% of the gas volume. The contribution of the remaining noble gases and the volatile elements to the gas volume is negligible.

<table>
<thead>
<tr>
<th>Element</th>
<th>Liquid phase</th>
<th>Gas phase</th>
<th>Release fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hg</td>
<td>2.99</td>
<td>7.54</td>
<td>1.2 \times 10^9</td>
</tr>
<tr>
<td>Cd</td>
<td>0.11</td>
<td>0.20</td>
<td>1.9 \times 10^4</td>
</tr>
<tr>
<td>Cs</td>
<td>0.01</td>
<td>0.28</td>
<td>406.</td>
</tr>
<tr>
<td>I</td>
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<td>0.24</td>
<td>2.47</td>
</tr>
<tr>
<td>Po</td>
<td>0.03</td>
<td>3.97</td>
<td>0.01</td>
</tr>
<tr>
<td>Tl</td>
<td>1.68</td>
<td>18.30</td>
<td>0.02</td>
</tr>
<tr>
<td>Bi</td>
<td>5.5 \times 10^3</td>
<td>23.90</td>
<td>4.41</td>
</tr>
<tr>
<td>Pb</td>
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<td>25.90</td>
<td>0.81</td>
</tr>
<tr>
<td>Rb</td>
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<td>0.62</td>
<td></td>
</tr>
<tr>
<td>Br</td>
<td>0.02</td>
<td>0.57</td>
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Table 3.27: Activity and release data for volatile elements in an LBE-based target after 40 years of operation, sorted by activity in the gas phase. The masses of lead and bismuth listed are the amounts of target material initially present. Mercury is the dominating contribution to cover gas activity due to its high volatility and the absence of chemical interactions that could lead to its retention.

A gas purification system that safely removes both Hg isotopes and Po and other radioactive substances from the cover gas is mandatory. Here, one can build upon the experience gained in the safe operation of such systems with liquid mercury spallation sources at SNS and J-PARC. The off-gas system of SNS consists of a decay tank, two absorbers for binding mercury on a special gold-on-alumina substrate, a copper oxide reactor for converting the hydrogen (tritium) isotopes to water, and two molecular sieves for the absorption of the produced water. Finally, the gas flows over a liquid nitrogen-cooled charcoal absorber to remove the heavier noble gases and residual activity.

In summary, only a small fraction of the volatile nuclear reaction products will escape to the gas phase. Compared to MEGAPIE predictions, the total activity of volatiles in the cover gas phase of an LBE-based
ESS will be orders of magnitude higher, resulting from both the longer and more intense irradiation and the much larger gas volume. Overall, the gas phase activities for the volatile elements predicted here seem to pose no serious safety concerns. Nevertheless, the gas phase has to be purified to reduce its radioactivity to allow for safe maintenance procedures and for routine handling of off-gas.

**Radiotoxicity**

The radiological hazard of the most dangerous radionuclides was evaluated for MEGAPIE licensing, based on the dose that they generate for the public living near the PSI site in certain accident scenarios. Inhalation, ingestion and direct radiation were considered, to estimate the accumulated dose resulting from each radionuclide. The results of these calculations showed that mercury and polonium isotopes, and iodine isotopes resulting from xenon decay, pose the greatest hazards. Doses caused directly by noble gas release are rather low and mainly caused by direct radiation. Ingestion was found to be the main pathway, indicating that the committed dose can effectively be reduced by administrative methods such as restrictions on the consumption of contaminated agricultural products. During operation, a spallation target facility may be regarded as a closed system having a controlled emission rate of volatile radioactivity. The critical condition is an uncontrolled release due to damage of the target structure, either caused by internal failure or external action.

Two reference accident scenarios were defined for licensing the MEGAPIE target, that differ in their consequences with respect to the containment of radioactivity released from the target [415]. The first is an internal failure in which the target window fails, resulting in a complete spill of the liquid metal, leaving behind a thin layer of LBE sticking to the still hot walls of the target. The second is a failure caused by external events such as an earthquake. Here, in addition to target container damage and a liquid metal spill, ancillary systems such as the off-gas systems are at least temporarily compromised, leading to an unfiltered emission of radioactivity. The inventory used within the MEGAPIE licensing procedure was calculated for an irradiation of 200 days with a proton current of 1.4 mA at 575 MeV [416]. It was assumed that approximately 88 litres of LBE with a mean temperature of 300°C flows out of the target. As a starting point to estimate the release from a pool of LBE, the model of a pool with a $4 m^2$ surface area and a depth of 22 mm was introduced [417]. Estimates showed that the activity released from the pool due to mercury and polonium is three orders of magnitude lower than that that released from the thin film of LBE, which remains on the wetted surfaces of the walls of the target. Using the values for evaporated and sputtered activities, the environmental radiological impact and hence the contributed effective dose to the local population was estimated. It was proven to the licensing authorities that even under severe accident scenarios, the population living in the environment of the facility would not be exposed to doses higher than 1 mSv.

The inventory of volatile elements due to LBE is distributed over three source terms: the gas phase of the expansion volume, the spilt LBE below the target, and the LBE surface film adhering to the inner surfaces of the target. Physicochemical and kinetics data about the relevant elements are needed for the assessment of these three source terms. The amount of volatile nuclear reaction products in LBE at the end of irradiation was calculated, for MEGAPIE, to be 64.1 g, of which 43.6 g are radionuclides. To a good approximation, the activities of the single elements are about one order of magnitude lower than that expected for an LBE-based ESS at the end of its irradiation. The noble gases, hydrogen and mercury are the prominent elements in the cover gas phase. Generally, the gas phase inventory of ESS would be higher than at MEGAPIE because of the longer irradiation times and five times higher power, but also because of higher operating temperatures and possibly gas volumes of up to 1000 times larger. Furthermore, a larger amount of liquid metal in ESS may lead to up to a factor of 10 higher dilution and thus lower equilibrium gas phase concentrations. The last three factors, however, greatly depend on details of the design of the system. Among the volatile elements, only the most hazardous mercury and polonium were considered in the assessment of the MEGAPIE reference accident case. The gas phase activity due to these two elements in the cover gas of ESS is predicted to be 1000 times higher than in MEGAPIE.

**Summary of the LBE comparative study**

The META:LIC target design is an evolutionary design based on existing experience of operating liquid metal targets including SNS, J-PARC and MEGAPIE. Cavitation is a major concern of liquid metal targets subjected to pulsed proton beams. This issue has been addressed for META:LIC and potentially reliable
solutions have been designed. The ESS adoption of a 2.86 ms long pulse substantially reduces container material pressures compared to short pulse targets running with proton beam pulses in the microsecond range. Moreover, the issue of major leakage from the target has also been addressed through design measures such as keeping the target pressure below 1 MPa. A distinctive feature of META:LIC is that analytical flow analysis is possible, enabling the nozzle design to be frozen at an early stage, but retaining the flexibility for adjusting the design when and where needed. Finally, a preliminary overview of needed ancillary systems and instrumentation has been drafted on the basis of the MEGAPIE experience as well as needed data and approaches to prepare the safety and licensing for META:LIC.
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