ESS Target Water Cooling, Purification and Radiolysis Gas Handling

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Abstract. The goal for the ESS facility is to construct an accelerator with the ability to deliver a 5 MW proton beam on the tungsten target. Most of the power is deposited as heat in the fluids and structures in and around the target. To be able to run the facility the nuclear heating from the spallation process need to be cooled in a safe and reliable way. The tungsten target in itself is helium cooled, but this system is in turn water cooled and there are several other water cooling systems, e.g. for moderators, reflectors and structural components. In this paper the water cooling systems are described and what challenges and requirements the systems needs to deal with.

1. Introduction

Unlike fission, spallation is an endothermic nuclear reaction that converts kinetic energy into mass. Of the 5 MW of beam power incident on target, about 89% gets deposited as sensible heat that must be removed, 9% is converted to mass in the liberation of neutrons (56 neutrons per proton incident on target), and about 2% of this power is carried off by neutrinos.

From the above calculations, the cooling needs are roughly 4450 kW where 3000 kW will be deposit in the tungsten blocks in the target wheel and cooled by the helium cooling system. The remaining heat will be deposited in the components within the monolith structure (i.e. moderators, reflectors, plugs) and in the shielding blocks surrounding the target wheel.

The water used to cool the components and the shielding blocks will be highly activated due to the spallation process in the water and the intense neutron radiation. Due to the neutron/proton radiation there will also be a decomposition of the water molecules and eventually there will be hydrogen gas in the system. If this is not handled within the systems it could lead to an uncontrolled hydrogen combustion or detonation.

2. Primary Water Cooling

The primary water cooling systems are divided into three main loops (Thermal Moderator, Reflector and Shielding & Plugs) according to table 1. For the moderator and reflector loops the maximum pressure in the components are set to 5 bar. For the Shielding & Plugs no such requirement exists but the pump will be able give a pressure of around 7 bar(g).

| System name | Cooled component          | Cooling demands, (kW) | Flow (kg/s) | Inlet temperature (°C) | Outlet temperature (°C) |
|-------------|---------------------------|-----------------------|-------------|------------------------|-------------------------|
| Thermal Water | Thermal water moderators | 172                   | 2.4         | 20                     | 37.1                    |
All primary loops are designed in a similar way, fig 1, where the main components are the pump, control valves, delay tank, Gas Liquid Separation (GLS) tank and a heat exchanger. The delay tank is designed for a 90s delay mainly to let the short-lived isotope $^{16}$N decay, $t_{1/2}=7.1$s. The GLS tank is designed for a retention time of 300s to allow for de-gassing of the generated gases formed in the spallation process.

A partial flow from each cooling loop will also be directed through the water purification system consisting of ion-exchange columns.

Within the monolith, the circulating water will be activated due the intense proton and neutron radiation. The main radioactive isotopes in the water systems are the short-lived isotope $^{16}$N, $^3$H and $^7$Be. All primary water cooling loops will be placed in rooms non-accessible during operation and for approximately 4 h after beam shut-down. The very high energy gammas from $^{16}$N decay (6.1 MeV and 7.1 MeV) also requires extra shielding around the outgoing pipes and the delay tanks (5-15 cm Pb). The shielding is needed to protect electronics close to the pipes as well as to be to keep low dose level in adjacent rooms.
3. Intermediate Water Cooling

The intermediate water cooling systems cool the primary cooling systems and delivers heated water to the Central Utility Building (CUB) where the heat is re-used for district heating or other applications.

There are three intermediate systems cooling different primary systems. One of these, the Target Intermediate Cooling system, then consists of three independent loops. Two of the loops cool the helium in the target primary cooling loop from about 230°C down to maximum 60°C which is a limit for the helium circulator. The third loop will cool the helium after the circulator to a temperature of maximum 40°C at full power before it enters the target wheel.

The primary requirement is to make the systems stable and robust and the second requirement is sustainability meaning returning the water at as high temperature as possible to the CUB.

| System name                | Cooled system                  | Cooling demands, (kW) | Flow (kg/s) | Inlet temperature (°C) | Outlet temperature (°C) |
|----------------------------|--------------------------------|-----------------------|-------------|------------------------|-------------------------|
| Target Intermediate Cooling| Target Helium Cooling          | 1500                  | 11.2        | 50                     | 85                      |
|                            |                                | 1600                  | 7.0         | 25                     | 85                      |
|                            |                                | 400                   | 3.8         | 25                     | 55                      |
| 15 °C intermediate Cooling | Thermal & pre-moderators +     | 388                   | 3.2         | 8                      | 40                      |
|                            | Reflectors                      |                       |             |                        |                         |
| 30 °C Intermediate Cooling | Shielding & Plugs              | 944                   | 12.4        | 25                     | 45                      |

Table 2 Intermediate water cooling (best estimate)

4. Water Purification

Ion exchange systems are used for the water purification of the primary cooling systems since those systems are affected by radiolysis process, which generates aggressive compounds that can cause corrosion and that lead to the transport of activated products through the system. Corrosion products have to be removed in a controlled and continuous way in order to keep their concentration as low as practically possible. High concentration of these products will cause a higher activation and radiation levels in the system, and an increased risk for hot spots, due to precipitation of corrosion impurities in valves, pumps and piping systems. This is an obstacle for efficient and safe maintenance of the systems and will lead to increased access times and more complicated maintenance of equipment.

Based on these measurements performed at LANSCE [1], [2], a conservative value of 1 μm/y corrosion rate in the water-cooled austenitic steel at the ESS target station is chosen for the design basis. For the other material present in the systems an extensive literature study and comparison with other facilities lead to the following figures:

- Steel, 316 L: 1 μm/y
- Aluminium: 10 μm/y
- Beryllium: 25 μm/y

Each primary water cooling loop will have two ion-exchange columns, but only one in operation. When resin in one of the column is full the other one will be put in operation. This means it will be in operation for one year and then stored for another year before replacing the ion exchange resin in the column. It is not planned to be operated for longer times, as there might be problems with emptying the column if the operation and storage time are increased to several years.

5. Radiolysis Gas Handling
While the water in all three primary water cooling systems is exposed to radiation during operation, radiolysis and spallation gases are formed in the circulating water systems and must be taken care of. The most dominant reaction is the decomposition of water (radiolysis), although formation of other gases does exist (spallation of water and corrosion products). However, water does not decompose into hydrogen and oxygen directly, but rather into hydrogen, hydrogen peroxide, hydrogen radicals and assorted oxygen compounds. The consequence of this is that the recombination of the formed radiolysis products to water is not a simple, stoichiometric problem. Due to this there will be a build-up of radiolysis and spallation gases in the circulating gas phase, where hydrogen and oxygen, besides the carrier gas, will be the dominating gases. If not treated or vented, the radiolysis and spallation gases will eventually increase the pressure in the circulating gas loop with unpredictable consequences. Also, the concentrations of hydrogen and oxygen may move into the flammability region, which may lead to uncontrolled hydrogen combustion or detonation. A Radiolysis Gas Treatment System is therefore implemented. Such a system should be designed to:

- recombine the hydrogen formed
- keep the concentration of hydrogen below the lower flammability level
- keep the non recombinable gases contained until decay allows release to the atmosphere

With the above requirements, a Radiolysis Gas Treatment System has been designed utilizing a commercial recombiner catalyst for recombining hydrogen and oxygen to water and at the same time ensure a residence time allowing sufficient decay of active non-recombinable spallation gases before release to the atmosphere. Figure 2 below shows a flow diagram indicating the basic design. The system consists mainly of a fan circulating a carrier gas through the Moderator, Reflector and Shielding & Plugs GLS tanks and then through the recombiner catalyst. The condensed water will be returned to the primary cooling loops making a closed loop of the systems.

![Diagram of Radiolysis Gas Treatment System](image)

**Figure 2** Radiolysis Gas Treatment System.

**References**

[1] R. S. Lillard et al, Corrosion Measurements on APT Prototypic Materials in the LANSCE High-Power Proton Beam and Applicability to Other Systems, LA-UR-02-2853, May 2012.

[2] R.S. Lillard et al, Journal of Nuclear Materials react-text: 55 278(s 2–3):277–289 April 2000