Operation experience with the SINQ heavy water cooling system

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Abstract. PSI is looking back to 15 years operation experience with the SINQ heavy water cooling systems, three independent circuits for the SINQ target, the double-walled safety shroud and the surrounding moderator tank containing about 4 m^3 D_2O. All three circuits, together containing about 9.5 m^3 of D_2O, are exposed to proton, neutron and gamma radiation and thereby get activated/contaminated which requires an appropriate coolant management. A set of sensors, filters, bypass lines and outlets for sample taking are installed. Regular water radiochemistry analysis is made to control the quality and to detect possible hazardous contaminants. These measures are mandatory to allow controlled operation and maintenance, and they proved to be very appropriate not only for normal operation conditions. One possible abnormal incident is a failure of the target canning, causing spallation products to be leaking into the water. SINQ experienced this incident twice and was well able to manage it. This paper describes the characteristics in layout of the SINQ D_2O cooling system and addresses the

1. Introduction

The Swiss spallation neutron source SINQ, operated at the Paul Scherrer Institut, is driven by PSI's 590 MeV proton accelerator at a beam power of 0.9 MW, as such being among the most powerful (CW) spallation sources worldwide. The core element of such a facility is the neutron production target. The routinely operated SINQ solid target consists of an array of Zircaloy-II (Zr) canned lead rods (so-called lead 'cannelloni'), the entire array contained in a double walled aluminum shroud. The target is inserted from top into a central tube connected to the accelerator beamline, surrounded by a moderator tank containing about 4 m3 D2O. Target, safety shroud and moderator tank are actively cooled by three independent cooling loops, all three using heavy water as cooling fluid. A fourth, light water loop is installed to cool a reflector shell surrounding the large D2O moderator tank.
By the incoming proton beam and the neutrons released, a variety of radioactive isotopes is produced, by the spallation reaction itself, and by neutron capture/activation. These reactions not only make the structures and materials surrounding the reaction zone highly radioactive, but also cause an activation of the cooling water with partly volatile nuclides. This requires special management of the cooling loops and the associated gas volumes, ensuring safe enclosure and staggered containment structures to prevent uncontrolled release of radioactivity to the environment. For details on staggered barriers and

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enclosures of SINQ, which cannot be seen independent from the cooling systems, we refer to Thomsen at al. [1].
The present paper presents the PSI-SINQ cooling system characteristics including the system monitoring and surveillance. It further reports on meanwhile 15 years of operation experience, including in particular the management of abnormal incidents which occurred.

2. The SINQ cooling system layout

Figure 1 shows schematically the layout of the SINQ cooling and moderation systems: The target, target enclosure (safety shroud) and moderator tank heavy water cooling loops. The piping passes into the cooling plant room, a compartment adjacent to the target head enclosure chamber. Both compartments have barrier/containment function, are held at reduced atmospheric pressure and are connected to the controlled exhaust system. Furthermore, walls and floors of both rooms are painted with a special paint (Debratan®) impenetrable for tritium-contaminated water, a precaution for the case of a heavy water leak. Note that the D2O is contaminated with Tritium, in the target cooling loop at a level of 25’000 MBq/litre, see Figure 3. In Figure 1 the H2O reflector surrounding the moderator tank is indicated as well, and also the cold D2 moderator system, which is not subject of the present paper.

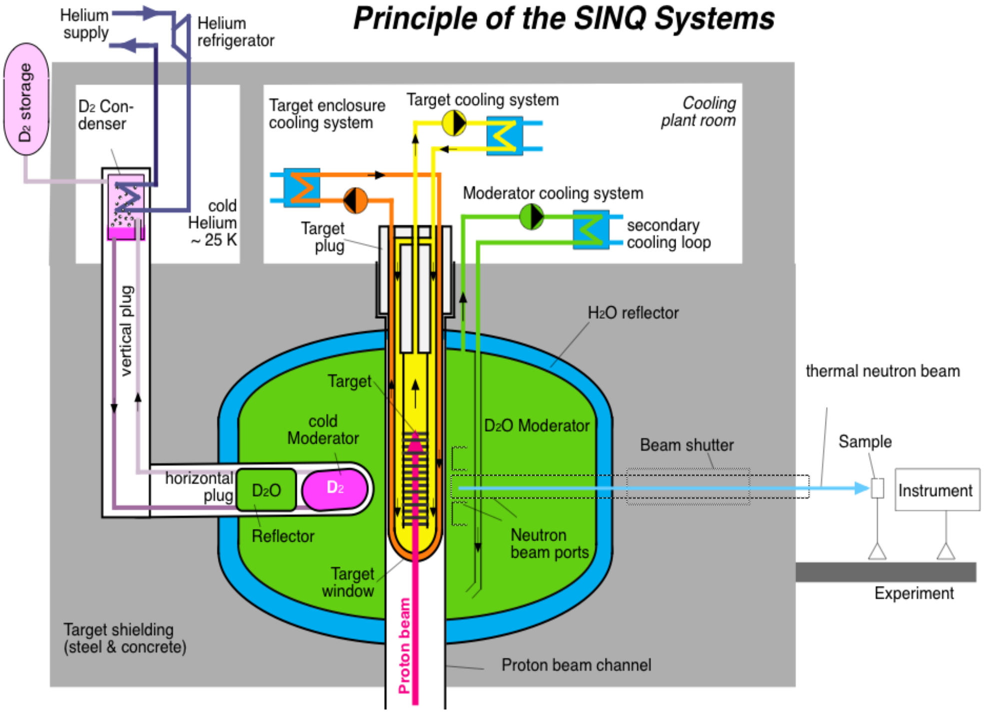

Figure 1: Schematic layout of the SINQ cooling and moderation systems

The historical photo of Figure 2, taken in 1996, gives a glance at the installations in the cooling plant, showing the installations of only one of the three heavy water cooling loops, the target cooling loop. The largest components are the pumps, heat exchanger, expansion tank and shielded filter. A delay tank, not shown in the figure, is part of the system, installed close to the exit of the target cooling behind a shielding wall. It serves for the decay of short-living radioisotopes produced in the water before entering the cooling plant room. Here, the leading isotope is 16N with a half-life of 10s and high specific activity, which is significantly reduced in the 120s delay line.

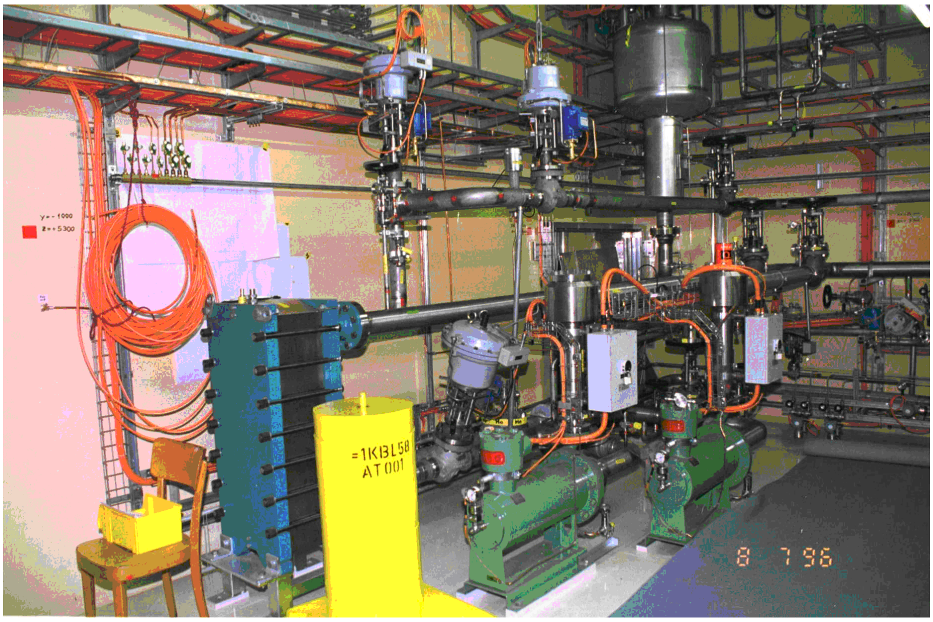

Figure 2: The installations of the target D2O cooling loop in the cooling plant room

3. System monitoring and surveillance

A variety of sensors serving the cooling process control are installed along the loops, obeying the request on redundancy and diversity whenever possible: leakage sensors, level sensors in the expansion volumes, flow rate sensors, and sensors for pressure and temperature control. Others serve for surveillance of possible hazardous or radiological relevant incidents: D2 and O2 sensors monitoring radiolysis products in the He-filled expansion volume, electrical conductivity measurements of the (highly de-ionized) water, and on-line γ-dose rate monitoring in the cooling plant room. Water samples can be drawn for remote analysis of the inventory of radioisotopes whenever required.

4. Radioactive inventory

In the cooling water (D2O) two isotopes dominate the radioactive inventory during normal operation conditions: Tritium and 7Be (see Figure 3). The tritium inventory is in saturation at a level slightly above 25 GBq/litre. The 7Be inventory continuously increases during target operation and after the start of the annual shutdown rapidly decreases due to active filtering. Other isotopes, in particular spallation products from the target material, under normal operation conditions are below the detection limits. This situation holds only as long as the canning of the target material does not sustain any damage. Two incidents where the SINQ lead ‘cannelloni’ target was damaged by irregular beam steering are described in the following chapter.

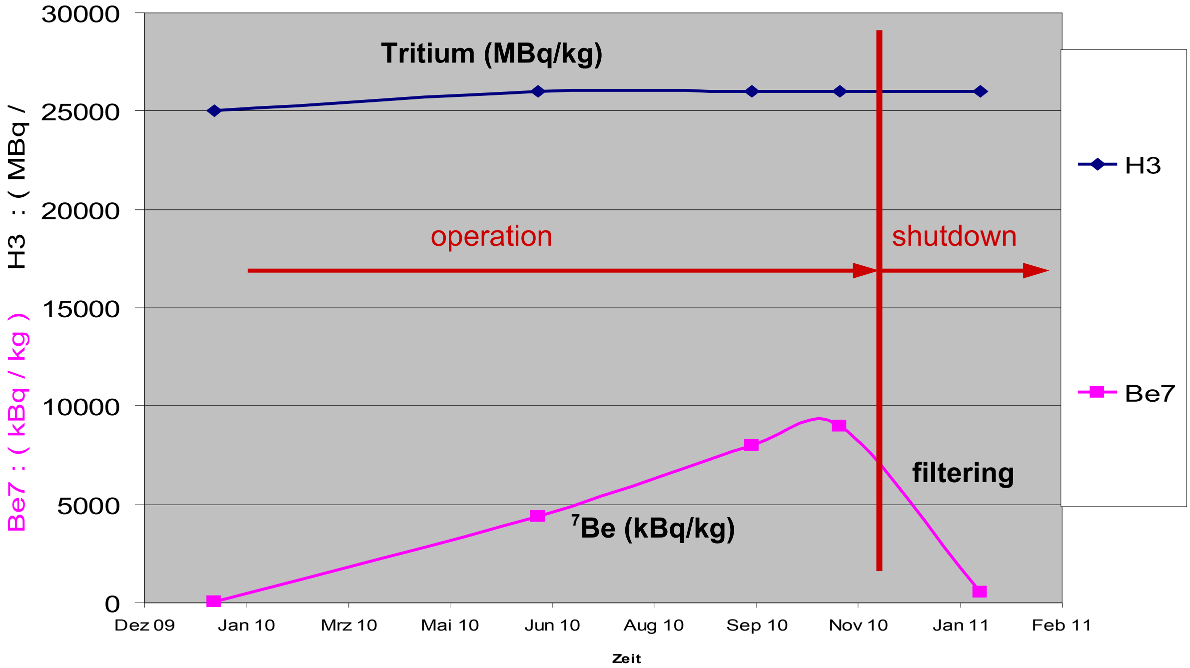

Figure 3: Tritium and 7Be inventory of the target cooling loop, measured in 5 water samples taken over the year 2010 (the curves serve as guide for the eye)

5. Incidental release of spallation products into the cooling water

One incident of that kind occurred in the operation period 2004/2005: At this time, the former target of type MARK 3, a square-shaped array of steel-canned lead rods, was operated, with the special feature that the three peripheral rows and 4 rods near the centre were replaced by Zircaloy-canned test rods (Figure 4, left: the rods with the flat covers). During the course of irradiation an unintended beam focusing happened, caused by an incorrect setting of quadrupol magnets in front of the target. This beam excursion was recognized only after 8 hours of operation, and it had caused an internal temperature rise in the central target rods up to 800 °C. The beam visualisation system VIMOS [2] was installed at that time, but still in the test phase. It observed and recorded the beam focussing but was not set 'sharp' to trigger a beam interrupt. After this incident, the on-line monitoring of the cooling circuit cover gas detected an increased radiation level stemming from 137Xe, which gave strong indication that a target rod was leaking and spallation products from lead had leaked into the cooling circuit. Evidence was obtained by the analysis of a water sample taken afterwards, showing 252 kBq/l of 137Xe and between 20 and 40 kBq/l of 195Au, 184Re, 185Os, 203Hg.
The investigation of the target found two of the steel-canned rods burst in the center, see figure 4, right. The lead, locally molten by the focussed beam, was partly spilled into the cooling water. Neutron tomography investigations at the SINQ neutron radiography station NEUTRA [3] allowed insight into the tubes and the filling (Figure 5). These images were obtained by a special Dy-based conversion technique [4] to overcome the all-outshining radiation background from the highly radioactive target tubes. Figure 5 (top) shows an undamaged steel-clad rod, position 01-4 (4th rod in row 01), holding a thermocouple inside, bent downwards after irradiation (the figure is flipped upside down). At the bottom the figure shows the burst rod 08-4, also holding a thermocouple (entering from right). The lead filling is partly emptied at the left side. Probably, the thermocouple was pinning the

filling at the right side. The neighboring rods canned in Zr, remarkably, did not show any indication of damage: Neither visible inspection nor neutron radiography nor metallographic inspection gave any evidence of damage or failure. For more details see [5]. Since this time, all follow-up lead ‘cannelloni’ targets were canned in Zircaloy tubes.

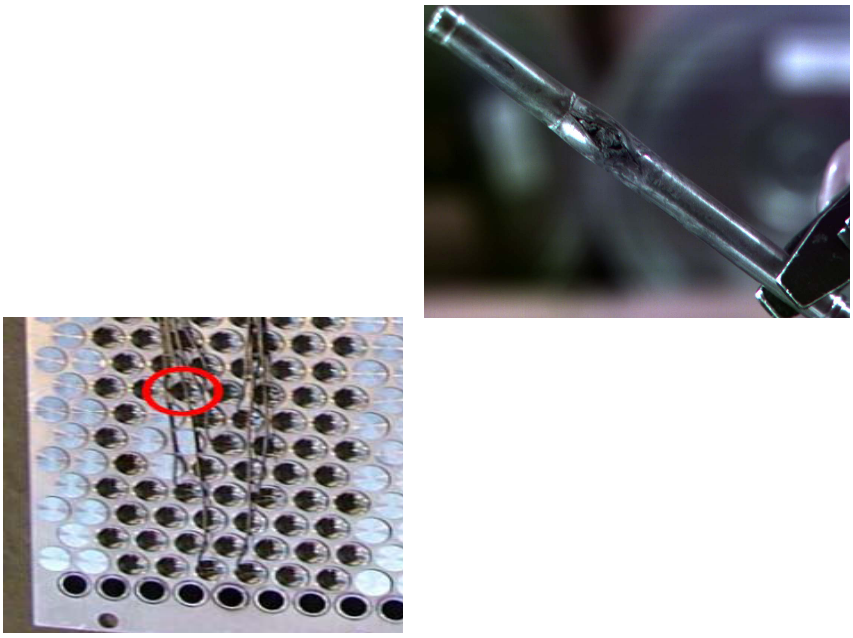

Figure 4: Left: Target 5 with Zircaloy-canned test rods in 3 peripheral rows and 4 rods near the centre (flat covers), all others canned in steel (SS316L). Right: The burst steel-canned rod from position 08-4 (4th rod in row 8, encircled in left), neighboured to the Zr rod 07-4 which did not show any damage

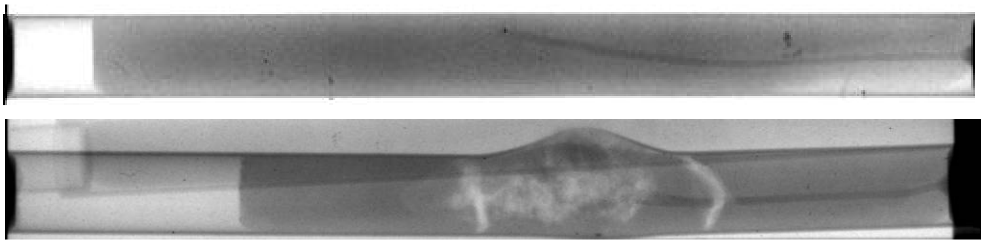

Figure 5: Neutron radiography images: Top: The undamaged steel-clad rod 01-4. Bottom: the burst rod 08-4. The lead filling is partly emptied (left).

A similar, but obviously less severe incident occurred in June 2010. At this time, the square-shaped target MARK 3 (Figure 4) was replaced by a new, compact Zr-canned lead ‘cannelloni target, circular in shape and surrounded by an Al-canned lead blanket/reflector [6]. VIMOS detected an abnormal deflection of the proton beam out-of-centre, and initiated a beam interrupt. This happened twice in sequence. The deflected beam was hitting the edge of the collimator and most likely also the Al-canned lead blanket. A water sample taken after that incident found a considerable increase in the radioisotopes 24Na (stemming from Al) and 88Y (stemming from Zr). Water samples taken later in Sept. and Nov. 2010 found increasing amounts of spallation products from lead: most of all 137Xe, and also 195Au, 184Re and others. This clearly indicated a (probably small) leak in the canning, either the Zr-canning of the target rods or the Al-canning of the blanket. By filtering, these spallation products could efficiently be removed from the cooling water, as a sample taken in Jan. 2011 has

proven. The dismantling and investigation of the target planned for early summer 2012 is expected to give detailed information about the cause and location of the failure.
The lesson learnt by these incidents: A megawatt class beam is a powerful tool; there is always a chance for an unintended miss-steering or unintended focussing of the beam, and even a very robust target and/or structural materials around the target can suffer damage.

6. Heat exchanger failure in the D2O moderator system

Inside the cooling plant room, the three D2O cooling circuits are connected to a heat exchanger each, formerly re-cooled by the general H2O cooling circuit of PSI WEST, the so-called ‘Kreis 6’, an about 400 litre water containing loop which serves commonly re-cooling the accelerator and many other facility of the PSI west area. In June 2007, the heat exchanger connecting the large D2O moderator cooling system to ‘Kreis 6’ showed a leak. This leak, besides spilling a few litres of water into the cooling plant room, had two major, unpleasant consequences: At the one hand, about 200 litre of D2O infiltrated into ‘Kreis 6’, contaminating this loop with 6 GBq tritium and 55 MBq 7Be, at the other hand, visa versa a similar amount of H2O having infiltrated the heavy water moderator volume reduced the neutron flux for the users by about 30%. Figure xxxx shows the neutron flux monitored at the SANS I and POLDI instrument in the period after the leak had occurred. This happened at night and was not detected before the next morning, where immediate mitigating measures were initiated. The remedial actions which followed were:

- Repair of the heat exchanger, an action delayed by about 6 weeks when waiting for the replacement part.
- Modest and controlled draining of the tritium-contaminated ‘Kreis 6’, along with consecutive replenishment with new de-ionised light water.
- Installation of a new intermediate D_2O loop between the three primary D_2O loops and ‘Kreis 6’, filled with fresh, uncontaminated D_2O to prevent the unpleasant consequences (see above) another intermediate leak could cause.
- Recovering the reduced neutron flux for the users.

For the latter a possible action would have been the refinery or complete exchange of the about 5.7 m3 of D2O in the moderation system, an extremely tedious or expensive undertaking. PSI has chosen a different procedure: exchanging the infiltrated D2O moderator coolant by the ‘clean’ D2O coolant of the target and safety shroud cooling circuits. Some H2O (about 3%) in the latter ones has essentially no or only little influence on the extracted neutron flux, due to the very limited water volume inside the target and safety shroud combined with the fact that the neutron spectrum inside the target is much harder than outside and therefore less effected by the presence of H2O. The exchange action needed only 600 l fresh D2O to be replenished into the 5.7 m3 containing moderator system. After the exchange the neutron flux was found fully recovered.

7. Summary

During 15 years operation experience with the SINQ heavy water cooling systems, it was shown that such systems can be safely and reliably operated. Radiological issues and hazards could well be handled and controlled. Chemical activity like corrosion is not an issue in the prevailing ultra-clean conditions of SINQ. Even abnormal incidents like failure of the target canning, spilling spallation products into the water, or heat exchanger failure in the D2O moderator system with very unpleasant immediate consequences could be managed and the consequences successfully mitigated.

8. Acknowledgements

Safe and reliable operation of a facility like SINQ is not possible without the engaged support of the operational crew and the technical support of other PSI divisions. As well, the support of the SU group (Radiological Safety and Surveillance) is mandatory for a safe operation without intolerable hazards to PSI workers or to the public. Sincere thanks are given to all these people involved.

9. References

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