Post-irradiation examinations of Target-11 of the Swiss spallation neutron source

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The eleventh target (Target-11) of the Swiss spallation neutron source (SINQ) was in operation in 2015 and 2016. It was shut-down due to an incident in June 2016, during which the pressure drop in the cooling water loop increased significantly, and meanwhile, the activity of the cooling water also increased tremendously. The evidence indicated a serious failure of the target. As this is the first severe failure since SINQ was in operation in 1997, some post-irradiation examinations (PIE) were performed to analyze the failure mechanisms.

KEYWORDS: SINQ target, PIE (post-irradiation examinations)

1. Introduction

SINQ has been very successfully operated since 1997 [1-3]. The first incident of SINQ happened in Target-11 which was in operation in 2015 and 2016. It was shut-down due to an incident in June 2016, during which the pressure drop in the cooling water loop increased significantly, and meanwhile, the activity of the cooling water also increased tremendously. The evidence indicated a serious failure of the target. To understand the failure mechanisms, it is necessary to conduct detailed post-irradiation examinations on the broken parts of the target.

The target was opened in a hot-cell (ATEC) next to the SINQ target station in June 2017. After removing the AlMg3 safety container, it was observed that lead (Pb) was melt and leak out from the bottom of the target-block. The tubes in the first row of the target were broken. During extracting some target rods for PIE, it was found that the rods in the high proton and neutron flux zone (the central region of the lower part) could not be pulled out. This implies that the core of the target was broken and the Pb was melt and froze the rods in this part. Finally, five rods or tubes were removed from the target for PIE which include hardness measurement, metallography (with etching for viewing hydrides), Electron Probe Microanalysis (EPMA), and ring compression test. However, the ring compression test has not been done yet.

2. Experimental results

2.1 Broken rods
Figure 1 illustrates the position of these five rods removed for PIE and also shows, as an example, the appearance and a neutron radiography picture of Rod P1-3. The original length of Rod P1-3 was about 11 cm, while this piece is just about 4.5 cm. This implies that the middle part, about 2 cm, was melted. The neutron radiography picture indicates a large empty space in the tube. It means that a part of the Pb was lost.

The rods were cut in a hot-cell using a diamond disc cutter and ring specimens from the tubes were obtained for different examinations.

Fig. 1. Left: a sketch showing the position of the 5 rods removed from Target-11 for PIE; Right: the appearance and neutron radiography picture of Rod P1-3. The outer and inner diameters of the Zircaloy tube are 10.75 and 9.25 mm, respectively.

2.2 EPMA analyses

EPMA analyses were performed on the specimens extracted from the position nearby the fracture surface of three rods: P0-5, P1-3 and P19-4. The estimated irradiation doses of the three EPMA specimens are 25, 18 and 9.5 dpa, respectively. Microstructure in different places on the cross section of the tubes was observed. A common feature observed in the three specimens is the formation of hydrides. In the specimen of P0-5 which was originally an empty tube filled with cooling water during operation, the hydride structure looks similar on the whole cross section. For specimens of P1-3 and P19-4, the appearance of hydrides is not homogeneous over the whole cross section of the tube. Figure 2 presents two micrographs taken from the inner surface layer of the specimens. The black lines are considered as hydrides, which are up to about 20 µm in length. It can be seen that the hydrides in the specimen of P19-4 are much thicker than those in the specimen of P1-3. During normal operation time, the temperature at outer surface of the cladding tubes is below 100 °C and at the inner surface is below 200 °C. The temperature in P1-3 should be slightly higher than that in P19-4, because the proton flux in the position of P1-3 is much higher. The same is for the irradiation dose. The pronounced hydride structure in the specimen of P19-4 is most probably due to the temperature history during the incident period. However, there is no precise information.
available. Since the picture of the P19-4 specimen was taken in an area about 4 mm away from a region which showed melting on both outer and inner surface layers [4], it can be concluded that the temperature in this area was also very high during this short period.

![Micrographs showing hydride structure in the inner surface layers of specimens taken from Rod P1-3 and Rod P19-4.](image)

**Fig. 2.** Micrographs showing hydride structure in the inner surface layers of specimens taken from Rod P1-3 and Rod P19-4.

### 2.4 Hardness measurement

After EPMA analyses, hardness measurement was conducted on the same specimens. The hardness of reference unirradiated material was also measured, but with another machine. Irradiation induced increase of hardness is plotted in Fig. 3. For comparison reasons, some STIP data are also presented. It can be seen that the STIP specimens show much stronger hardening effect. The reason should be the high temperature experienced by Target 11 specimens.

![Hardness measured from the EPMA specimens. STIP data are used for comparison.](image)

**Fig. 3.** Hardness measured from the EPMA specimens. STIP data are used for comparison.

### 3. Discussion and Conclusion

The aim of the PIE is to understand the failure mechanisms of SINQ Target 11. Although the preliminary results are interesting, they should be used with caution, because the status of the material of the cladding tubes was greatly changed after the incident, particularly for the part in the damaged zone. The STIP specimens irradiated to doses >10 dpa demonstrate strong hardening and embrittlement effects, which implies that attention should be paid to the operation of SINQ targets in the future, even though the previous targets were irradiated to much higher doses without failure. It should be noted that the operation mode of the present target has been changed to reduce the effect
of beam trips, which can certainly improve the safety of operation.

References
[1] G.S. Bauer, Y. Dai, W. Wagner, SINQ layout, operation, applications and R&D to high power, J. Phys. IV France 12 (2002) Pr8-3.
[2] Werner Wagner, Yong Dai, Heike Glasbrenner, Mirco Grosse, Eberhard Lehmann, Status of SINQ, the only MW spallation neutron source—highlighting target development and industrial applications, Nuclear Instruments and Methods in Physics Research A 562 (2006) 541–547.
[3] Y. Dai and G.S. Bauer, Status of the first SINQ Irradiation Experiment, STIP-I, Journal of Nuclear Materials 296 (2001) 43-53.
[4] Y. Dai, V. Boutellier, R. Grabherr, A. Urech, A. J. Wissting, J. Bertsch, M. Pouchon, PSI Technical Report, TM-46-17-06, 2017.