The dismantling of the MEGAPIE target

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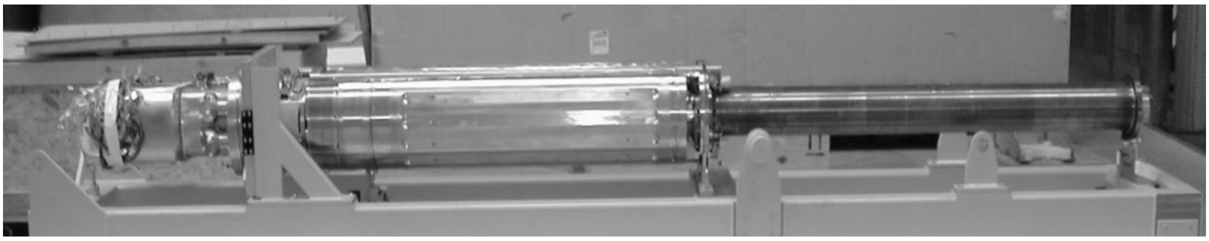
Abstract

The MEGAPIE target was the first liquid metal target ever operated in the Megawatt regime, at a power level of 0.8 MW. The LBE target has successfully been irradiated in a period from August until December 2006 in the Swiss spallation neutron source SINQ. During this time the spallation target received an integrated beam charge of 2.8 Ah of 575 MeV protons. After operation the target was stored in the target storage facility of SINQ, waiting for its dismantling and the post-irradiation examination (PIE). After 2006 several campaigns were conducted by the Paul Scherrer Institut (PSI) and the central Würenlingen interim storage facility (ZWILAG) in the hot cells of ZWILAG to test the dismantling of MEGAPIE. In these tests the feasibility of the conditioning of the target and the extraction of target sample pieces for the PIE was proven. In July 2009 the dismantling of the MEGAPIE target started. The target was successfully cut into 21 pieces. Nine of these target pieces and the so-called leak detector will be shipped to the Hot Laboratory (HL) of PSI in 2011 to serve as base material for structural materials and LBE samples for the PIE. The remaining parts of the MEGAPIE target were conditioned in ZWILAG for radioactive waste disposal. Currently it is foreseen that the PIE sample preparation will start in the first half of 2011. In this paper the status of the MEGAPIE project is reported, with a special focus on the successful dismantling of the target in ZWILAG. In addition some details about the PIE sample preparation phase of MEGAPIE will be given.

Introduction

The Megawatt Pilot Experiment (MEGAPIE) project [1] is an international collaboration of nine institutes/institutions: CEA, CNRS, DOE, ENEA, KIT, JAEA, KAERI, SCK Mol and PSI. The main goals of the project are to design, fabricate, operate, dismantle, investigate and dispose a liquid metal lead-bismuth eutectic (LBE) target. After the feasibility study and the design of the target at CNRS MEGAPIE was fabricated at ATEA, France, in 2005 (Figure 1). It then was delivered to the Paul Scherrer Institut (PSI), Switzerland, for final assembly, testing and subsequent operation. The MEGAPIE target was a small slim structure, length 5.35 m, diameter maximum 0.404 m. The total weight of the target structure was 1.5 tonnes and after filling it contained 89 litres of LBE [2]. The ancillary systems ([2] and references therein) were designed and built by various institutes; the cover gas system (CGS) as well as the LBE filling system was developed at ENEA Brasimone, the heat removal system (HRS) was designed by CEA, the EMP pumps were developed and built at IPUL and the insulation gas system (IGS) was provided by PSI. After extensive pre-operation tests in 2005 (without beam) the LBE target and its ancillary systems were installed in the Swiss spallation neutron source SINQ at PSI [3], in 2006. The SINQ facility receives its protons from the world's most powerful DC proton accelerator, currently delivering a current of 2.2 mA of 590 MeV protons. The target is hit by protons vertically from below. SINQ has been in operation since 1997. Over these years of operation a steady improvement programme for the target system as well as the accelerated proton current was pursued [4]. On 14 August 2006 the first liquid metal target, operated in the MW range (0.8 MW) – MEGAPIE – was put into operation [5]. The LBE target received an integrated current of 2.8 Ah of 575 MeV protons and operated successfully until 21 December 2006; an 80% increased neutron flux, compared to the solid target operated in 2004/2005, was observed. In the shutdown following the MEGAPIE operation the ancillary systems of MEGAPIE were disintegrated. The target was put into the target storage facility of SINQ, waiting for its dismantling and the extensive post-irradiation examination (PIE). As no suitable, sufficiently large hot cell existed at PSI, it was decided to transport MEGAPIE to the hot cell of the central Würenlingen interim storage facility (ZWILAG) for dismantling; for a detailed description of the concept see Refs. [6,7]. In 2007 and 2008 several campaigns were conducted in the hot cell of ZWILAG to test the different devices and machinery for the dismantling of MEGAPIE, as well as to train the involved personnel [8]. In 2009 the target was successfully dismantled into 21 pieces using a band saw. Ten of the cut target pieces will be used to produce PIE samples, while the remaining target cuts were directly prepared for disposal. The target sample pieces are currently stored in a transport container (TC3) in ZWILAG. The TC3 will be shipped back to PSI in 2011 and the PIE sample preparations in the Hot Laboratory will start subsequently. In a first step PIE samples from the solidified LBE will be taken to investigate the distribution of radioisotopes as well as to validate theoretical predictions of the radionuclide inventory in the LBE. Thereafter, the LBE will be molten in a special oven, so that structural materials of the MEGAPIE target can be accessed and PIE samples can be produced. Samples will be cut from various structures, such as the proton beam window, the liquid metal target container, the flow guide tube and many more to investigate the behaviour of the materials under irradiation and direct contact to a liquid metal. All in all approximately 750 PIE samples (LBE and structural material) will be produced. Currently tests for the PIE sample preparation are ongoing. A part of these PIE samples will be retrieved by the international partners of the MEGAPIE project at PSI for further investigation.

Figure 1: The MEGAPIE target as delivered from ATEA



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In this paper the status of the MEGAPIE project is presented, with the main focus on the dismantling of the target. In the following sections the transport of the MEGAPIE target from PSI to ZWILAG and the dismantling of the target will be explained. Subsequently an overview on the planned operations in the Hot Laboratory (HL) at PSI will be given.

The transport of the MEGAPIE target to ZWILAG and its dismantling

Directly following the operation of the MEGAPIE in SINQ the target was first cooled down from its operation temperature of 250°C minimum until the LBE solidified (melting temperature 125°C). Then MEGAPIE was transferred from the irradiation position in the SINQ target block into the target storage facility of SINQ. The transfer was done remotely with the SINQ target exchange flask. The LBE target was stored without any active cooling as the induced afterheat in the target was calculated to be low (80 W). In 2007 and 2008 the dismantling processes of the MEGAPIE target were cold tested in several campaigns; tools and machinery needed for the dismantling were extensively tested and the personnel was trained.

On 6 July 2009 the dismantling phase of the MEGAPIE project started. The dismantling phase consists of four major milestones: the transport of the target from PSI to ZWILAG, the cutting of the target into 21 pieces, followed by the conditioning of the “unneeded” parts (12 pieces) and the transport of the target sample pieces to the Hot Laboratory (HL) at PSI. The dismantling phase will be followed by the PIE sample preparation, disposal of the residual radioactive material and the investigation of the PIE samples.

The basic principle of the dismantling process was to cut the target into a total of 21 pieces. Some of those pieces were prepared for disposal, while the rest serves as base material for the samples preparation for the PIE of the world’s first LBE target operated in the MW regime.

The first milestone of the dismantling phase of the MEGAPIE target was the transport of the solidified MEGAPIE target from PSI to the adjacent ZWILAG facility. The target was pulled out from its parking position in the target storage facility of SINQ into the target exchange flask. The exchange flask, now containing the irradiated target, was lifted onto a cube-like structure made from concrete (shielding) blocks. In the centre of this “concrete cube” a special transport container (TC1), manufactured for the transport of MEGAPIE from PSI to ZWILAG, had been positioned. The target was lowered from the exchange flask into the TC1 (vertically standing in the “concrete cube”). The aim of the “concrete cube” around the TC1 was to prevent tilting of the TC1 in case of an earthquake and to reduce the dose rate to personnel. Primary and secondary lids of the container were closed and checked for tightness. To load the TC1 onto the transport vehicle, one side of the “concrete cube” was removed. The transport container weighing ~40 tonnes was lifted from its parking position onto a transport vehicle; there the TC1 was brought into a horizontal position for the transport to ZWILAG. A series of dose rate measurements was performed on the surface of the TC1; the measured dose rates were of the order of 1 μSv/h. After that the transport to ZWILAG started, which took about 2 hours (distance roughly 2-3 km), see Figure 1 for transport path; no problems were encountered.

The transport of the MEGAPIE target from PSI to ZWILAG fell under the regulations of the ADR (European agreement concerning the international carriage of dangerous goods by road), as a public road had to be used. However, the factory premises of ZWILAG and PSI are adjoint/close to each other. The transport container TC1 for MEGAPIE was built to obey to the rules of ADR. According to the ADR certified containers have to be drop-tested and have to withstand a fire over a certain time span. For such tests several similar containers must have been built. In accordance with the Swiss authorities PSI decided that only theoretical predictions of the damage due to a drop of the container and a fire would be made (instead of real tests). As the maximum lift height of the TC1 was 2.5 meters, the layout was done for this height rather than the requested 8 meters from the ADR. Several additional safety measures were taken for the transport of the TC1: the transport took place at night (only little personnel at the institute), the road (partly public) was blocked for the time of the transport, fire fighters guarded the transport vehicle which drove with a maximum speed of 5 km/h.

For the PIE investigation it was necessary to cut the target into smaller pieces that can be handled in the hot cells of PSI's HL. The cutting of the MEGAPIE target was done remotely in the hot cell of ZWILAG (Figure 2) with a band saw, which had been extensively tested in the years prior to the dismantling. During the test phase, procedures were optimised with respect to engineering and radioprotection aspects, e.g. optimisation of cutting parameters, identification of suitable saw bands, minimisation of the spread of contamination. To avoid the production of contaminated liquids the cutting process was done without lubrication and cooling of the saw band. Within several campaigns in the hot cell of ZWILAG the handling of the saw, the handling of cut pieces (packing, cleaning, etc.), the exchange of the saw band and other devices were extensively tested. All processes and handling procedures were documented on a step-by-step basis in so-called Q-plans (quality assurance plans), which served as a guideline during the "hot" dismantling.

Figure 2: Transport path from SINQ to ZWILAG (left); transport vehicle with TC1 at the entrance of the ZWILAG area (right)

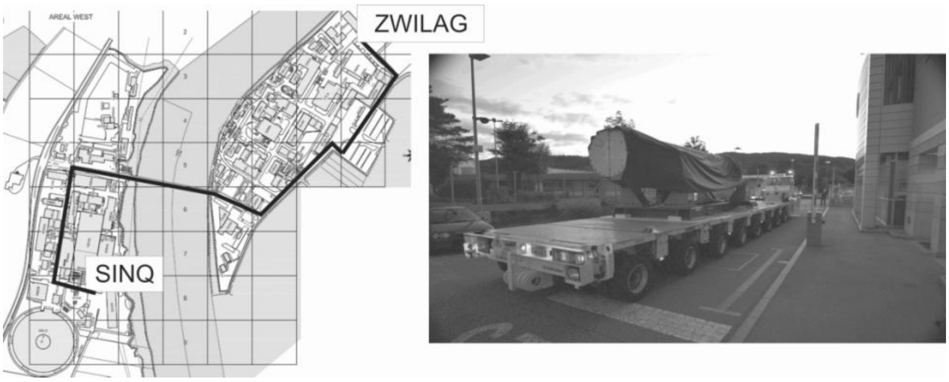
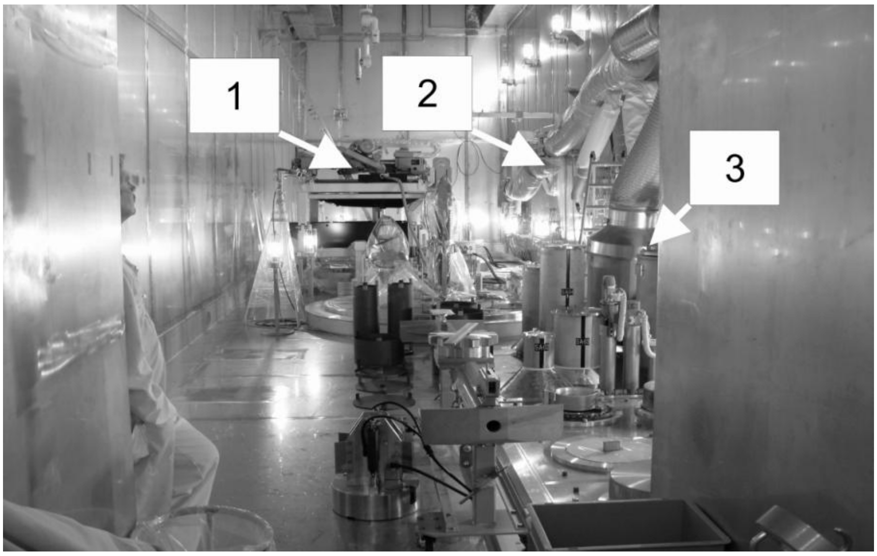


Figure 3: The hot cell of ZWILAG before the start of the dismantling

1 – band saw, 2 – suction system, 3 – hot cell filter



One of the main problems during the cutting of the MEGAPIE target was the production of airborne particles. Such particles would immediately have led to a "widely spread" contamination of the hot cell of ZWILAG. To minimise the production of such particles, the velocity of the saw blade was limited to a maximum speed of 17 m/min; the feed of the blade was 5 mm/min. These

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slow velocities decreased the probability of heating and melting the LBE during sawing and therefore, the production of potential contamination products. Special focus was put on the Po-isotopes produced during irradiation. Temperatures during the cutting process were kept as low as possible to prevent high releases of these alpha-emitters; above 600°C the release of Po from LBE grows rapidly [9]. Nevertheless, local melting of the LBE was still possible, due to the heating of the blade in structural materials (mainly steels) and subsequent contact of the hot blade with LBE. A quantification of the produced airborne (Po-)activity was not possible, because tests with activated materials could not be done. However, measurements during cutting of inactive LBE revealed a concentration of at most 170 $\mu g/m^3$ of aerosols in the direct vicinity of the blade. The low sawing velocities minimised the production of aerosols. Nevertheless, an additional suction system that could swing into position roughly 50 cm from the blade was installed, so that produced aerosols were directly transferred to the filtering system instead of spreading in the whole hot cell.

On 9 July the TC1, docked to the hot cell of ZWILAG from below, was opened and the MEGAPIE target was pulled into the hot cell using the crane. A slight colour change of the aluminium lower target enclosure (LTE) in the region of the peak neutron flux was observed; such discolouration is also found on the aluminium safety shrouds of solid targets operated in SINQ. Before the cutting of the target could start the LTE was unscrewed and the remaining target was pulled out of the LTE. A dark deposit on the lower end of lower liquid metal container (LLMC) as well as loose flaky smut on the leak detector (LD) was found (see Figure 5). The LD, positioned below the beam entrance window (BEW), was cut from the target with a gripper. Moreover, thermocouples fixed on the LLMC were removed and the target was prepared for the first cut. The cutting scheme of the target is shown in Figure 4. The target was cut from the bottom upwards (in SINQ the target is installed vertically with the proton beam coming from below).

The first six cuts were done on the LLMC, which mainly consists of a T91 shroud ($\varnothing_o$ = 180 mm) filled with LBE (Figure 5 upper right). Inside the T91 shroud the flow guide tube (FGT) was installed, which guided the LBE flow downwards in an outer annulus, reversed the flow direction at the BEW and guided the liquid metal up inside an inner cylinder. After those cuts the LTE was re-screwed to the remains of the target and the aluminium LTE (double-walled structure) was sawed into five pieces. In the first (lowest) pieces of the aluminium LTE (also called safety hull) a gleaming piece of material was found (Figure 5 lower right). The composition of the material could not be analysed up to now, because only equipment for the dismantling had been put in the hot cell of ZWILAG due to space constraints. However, the object will be shipped to and analysed in the HL of PSI together with the target sample pieces. Finally the upper part of the MEGAPIE target was cut. This part of the target ($\varnothing_o$ = 404 mm) contained a 12 pin heat exchanger (HRS), two electromagnetic pumps, the expansion tank of the cover gas system

Figure 4: Cutting plan of the MEGAPIE target

The target was cut hanging on the crane; the arrows indicate the proton beam direction as well as the direction of cutting (from the lower to the upper part of the target

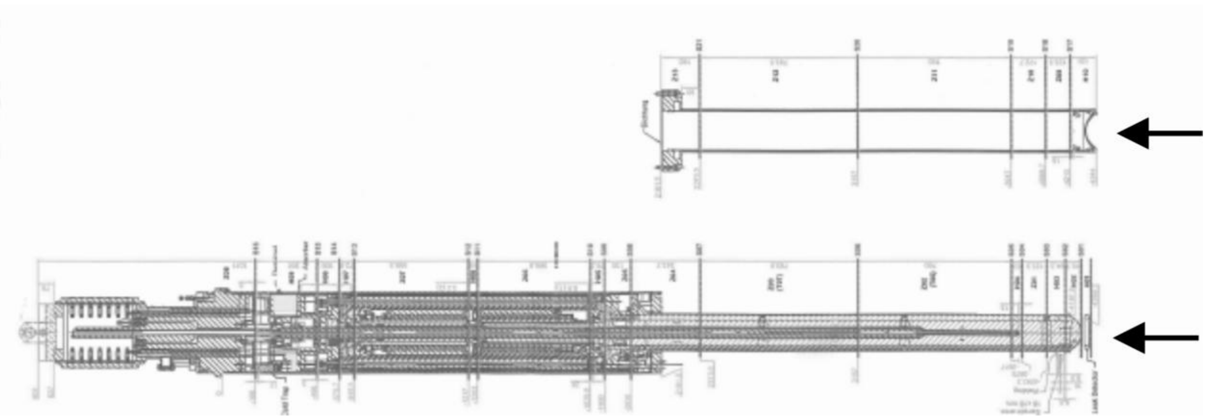
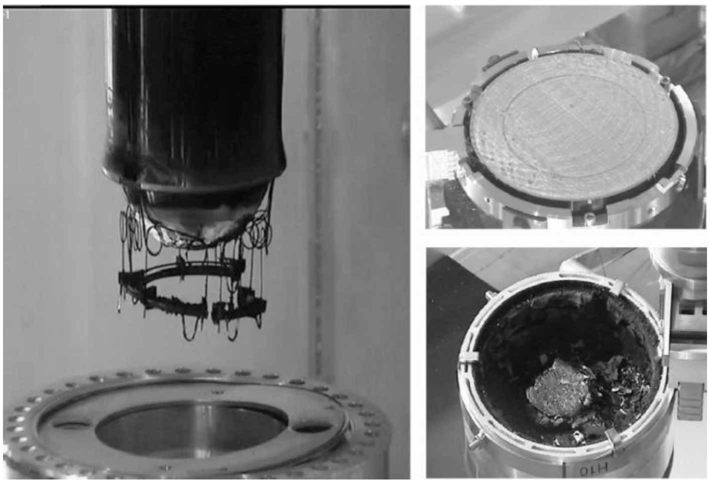


Figure 5: Beam entrance window (BEW) and leak detector (LD) after unscrewing the aluminium LTE (left); target piece (BEW) after cutting (upper right); gleaming material in the lowest part of the LTE (lower right)



(CGS) with a cold trap and getter foils, steel shielding and the so-called target head with feed throughs of heaters, thermocouples, etc. The degradation of the saw band increased significantly in the upper part because of the higher amount of steel compared to the LLMC. As a consequence the saw blade had to be exchanged two times.

In order to exchange the saw blade, the whole saw had to be cleaned remotely (with a special vacuum cleaner). Then the saw was lifted into a separate compartment of the hot cell. There, after radioprotection measurements of the contamination, two workers entered the hot cell compartment and exchanged the saw blade manually. The duration of the manual exchange of saw band was roughly 35 minutes; the dose rate to personnel was less than 5 μSv. The whole exchange procedure of one saw band took one week.

Overall 20 cuts on the target were done using the band saw; additionally the LD was cut using a gripper. Nine of the produced pieces, called target sample pieces, as well as parts of the LD will be transported from ZWILAG to the HL of PSI to serve as base material for PIE sample preparation and investigation. The remaining 12 target pieces as well as the collected flakes from the cutting were stacked into four specially manufactured cylindrical stainless steel containers (primary containers). Partly the primary containers were equipped with additional lead shielding to minimise dose rates. These containers were then closed with a lid which was remotely welded to seal them. The primary containers then were placed in a standard concrete waste container of PSI, which had been reinforced by a special steel insert for shielding purposes. This waste package is called TC2. After filling the TC2 with the primary containers, it was undocked from the hot cell. In a special compartment outside the hot cell area concrete was poured into the gaps and the TC2 was sealed with special mortar and a lid. Currently this waste container is temporarily placed in ZWILAG's storage facility for medium active waste and will be transported to the Swiss Federal Interim Storage facility (BZL) at PSI at a later stage.

The nine target sample pieces and the LD of the MEGAPIE target were stacked in a standard waste barrel (Figure 6, left). This barrel was remotely lifted into a transport container (TC3) (Figure 6, right), docked to the hot cell of ZWILAG. Currently the TC3 is situated at ZWILAG as well. It will be brought to the HL of PSI at the beginning of 2011, so that the PIE sample preparation from the target sample pieces can start. The TC3 was checked for tightness and dose rates on its exterior (3 cm from its surface) were measured. Those ranged from 10 μSv/h to 1.5 mSv/h on top of the lid. In a distance of 1 meter from the containers side wall dose rates of 10 μSv/h were measured (measurements performed on 24/09/2009).

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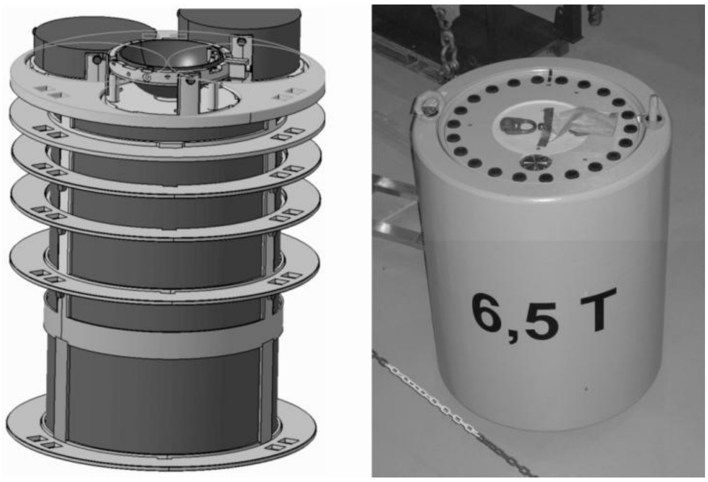
Figure 6: Drawing of the nine stacked target pieces (left); the TC3 transport container (right)



After the cutting and the packing of the target samples and target waste pieces was finished, the hot cell of ZWILAG was investigated for contamination. For this purpose, whip tests (up to three at one position) had been placed at dedicated positions in the hot cell of ZWILAG prior to the start of the dismantling. Some whip tests had already been analysed during dismantling, especially after the first cut of the target. The measurements on the whip tests after dismantling showed a moderate contamination of the hot cell of ZWILAG. The highest contamination was found in the regions where the target was moved and cut pieces were stored (before packing). The alpha contamination, coming from the polonium isotopes produced during the irradiation, was measured to be on the order of a few Bq/cm^2, with localised hot spots of 250 Bq/cm^2 at the positions where cut target pieces were stored. High gamma dose rates were measured on the filter system of the hot cell. This was a clear indication that the specially installed suction system served well to hinder a spread of contamination by aerosols produced during cutting. For the filter system a peak dose rate of 800 μSv/h was measured, while gamma dose rates on the floor of the hot cell ranged from 10 to 80 μSv/h; side walls and the crane runway showed even lower gamma dose rates.

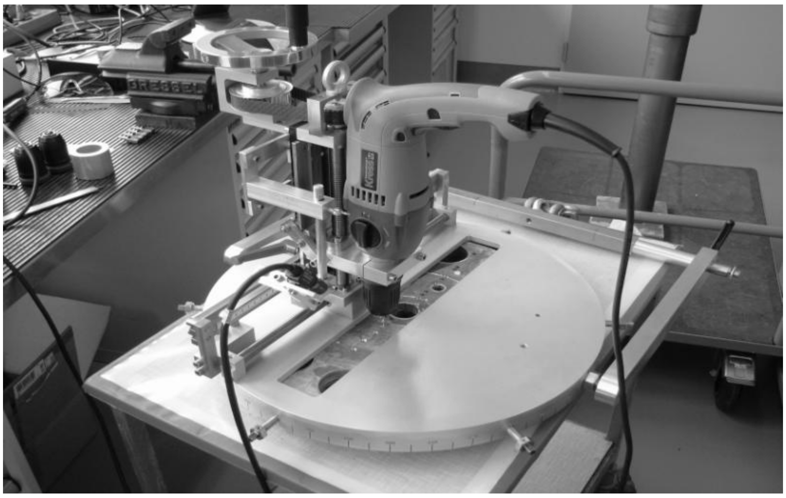
The preparation of the PIE sample in the Hot Laboratory (HL) of PSI – An outlook

Nine sample pieces and the LD will be transferred from ZWILAG to PSI in the TC3. These pieces represent different parts of the target. Four pieces and the leak detector are from the lower part of the target. They mainly consist of the lower liquid metal target container (LLMC), the flow guide tube (FGT), fill and drain tubes and frozen LBE. One of the pieces is the beam entrance window (BEW) from the lower target enclosure (LTE). The LTE is a cylindrical double walled aluminium shell, placed around the LLMC that is closed on one end; the closed end the BEW. The sample pieces from the upper target part ($\varnothing_o$ = 404 mm) contain parts of the cover gas system, pieces of one of the electromagnetic pumps and parts of the heat exchanger of MEGAPIE.

In a first step the aluminium beam window will be investigated to determine the average proton beam footprint on MEGAPIE. A map of the ^{22}Na activity across the BEW will be measured through a pin hole. The activity of ^{22}Na produced from the aluminium is directly proportional to the proton fluence at a specific point of the BEW. Therefore, a time-averaged proton beam profile can be reconstructed, which will be used to evaluate radiation damage as well as temperatures in the PIE samples. Such investigations have already been done with the beam entrance windows of several standard SINQ targets at PSI to evaluate irradiation conditions of the so-called STIP samples.

In a next step ~50 LBE samples will be taken from the different parts of the target using a special drilling device (Figure 7).

Figure 7: Drilling device to retrieve LBE samples from the target sample pieces



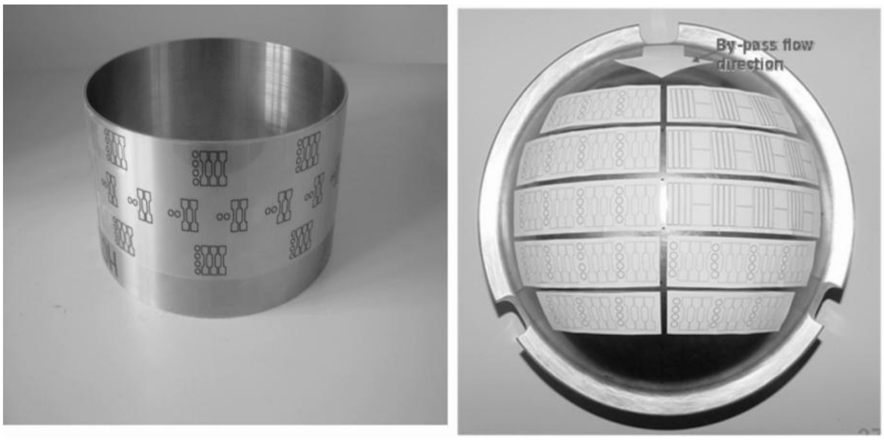
These samples will initially be analysed by gamma spectroscopy. There are strong indications that the distribution of radionuclides inside the LBE might not be homogenous although the LBE was constantly pumped through the target. Subsequently a radiochemical separation of safety relevant non-gamma emitting radioisotopes shall be done and their amount will be studied with different techniques; a special focus shall be put on the alpha-emitting polonium isotopes. The goal of these studies is to create a validation basis for nuclear reaction models used for the design of MEGAPIE and to get a deeper insight into chemical processes inside liquid metal spallation targets. This information is not only of interest for the scientific community, but is also requested by the Swiss authorities in order to review the quality of the theoretical predictions for the declaration of waste from the accelerator facilities at PSI. All devices needed to extract the LBE samples have been tested in the hot cells of HL and are ready for usage.

After the LBE sampling, structural materials have to be cleaned from the LBE. This will be done by heating the target sample pieces in a special oven to a temperature of 200°C (the LBE melting point is at 125°C). The temperature of the sample pieces should on one hand be high enough to melt the LBE, on the other hand with increasing temperature the production of aerosols as well as the release of radioisotopes increases. Therefore, to prevent contamination of the hot cell in the Hot Laboratory the oven is a closed system, which can be vented via a special filter system consisting of HEPA 16 filter and charcoal filter impregnated with sulphur. The design and fabrication of the oven and filter system are finished. The molten LBE is collected in a tank below the oven and will be disposed with the whole oven at the end of the PIE sample preparation. Currently the system is in the testing phase.

Thereafter the structural materials will be raw cut using a grinder disk. From these large pieces the small PIE samples (grouped in four categories) will be cut using a diamond disk saw or an EDM machine. However, the cutting with the EDM machine will not immediately be possible. It is expected that a thin layer of LBE will remain on the surface facing the LBE. Therefore, tests have been conducted using specially prepared samples with a layer of ~20 μm of LBE on them. The LBE cleaning procedure has been tested. It consists of four main steps: The raw cut samples will be placed in a hot bath so that the LBE remains melted and can be wiped off the samples with cloth. Then the samples are cleaned with acetone and put into diluted nitric acid to remove the rest of the LBE sticking to the surface. The process of LBE removal from the raw cut samples is finished by again cleaning the samples with acetone. After this last cleaning step PIE samples can be cut with the EDM machine. Tests for raw cutting and cutting with the diamond disk as well as the EDM machine are made with 1:1 mock-ups of the structural materials from the different target sample pieces (Figure 8).

Figure 8: 1:1 mock-ups of structural material parts from the different target sample pieces

Mock-up of the flow guide tube (316L) with indications of the PIE samples (left);
mock-up of the BEW (T91) with indication of the cutting scheme (right)



All in all approximately 750 PIE samples of structural materials as well as of LBE will be manufactured from the different structural parts of MEGAPIE, according to [10]. A portion of these PIE samples will be analysed directly at PSI, while the remaining PIE samples are retrieved by the international partners of the MEGAPIE project. According to the schedule shipment of the PIE samples to the partner laboratories will start in April/May 2012.

Conclusion

The dismantling of the MEGAPIE target was successfully finished in 2009. The MEGAPIE target was shipped from SINQ to the hot cell of ZWILAG. The cutting of the target into 21 pieces with a band saw could be finished according to the time schedule. Nine target sample pieces are ready to be delivered to the hot laboratory (HL) of PSI. Moreover, a piece of material was found in the lower part of the aluminium safety hull. The material composition of this object will be investigated in the HL of PSI as a part of the PIE sample preparation. The other remains of the target have been prepared for final disposal. After dismantling the hot cell of ZWILAG has been fully decontaminated and is fully accessible again. Currently the needed machinery for the PIE sample preparation is tested in the hot cells of the HL. It is envisaged that the target sample pieces produced during the dismantling phase of MEGAPIE in ZWILAG will be shipped to the HL of PSI beginning of 2011. The subsequent PIE sample preparation is scheduled to last until April/May 2012, so that PIE samples can be retrieved by the MEGAPIE partners at PSI in 2012. Subsequently a concerted PIE investigation programme will be performed at the project members' hot cells.

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