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MEGAPIE - TEST

Final Report

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PU: public
RE: restricted to a group specified by the partners of the [MEGAPIE-TEST] project
CO: confidential, only for partners of the [MEGAPIE-TEST] project
M: Management, **S/T**: Scientific/Technical reports, **MT**: Mid-term, **nnn** = number

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1. Executive Summary

The transmutation of the Minor Actinides (Am, Np and Cm) separated from the spent nuclear fuel as unloaded from nuclear power plants is studied in the European Union with an aim to ease the disposal strategy of the nuclear waste. A way to transmute such radioactive elements is to use Accelerator Driven Sub-critical systems (ADS). These systems require a neutron spallation target (heavy liquid-metals such as lead or lead-bismuth eutectic) located in a sub-critical core. The neutrons in the spallation target are produced via spallation reactions by impinging a high energy proton beam on such a heavy liquid-metal target. Generally, a 1 – 2 MW neutron spallation target would be required for a sub-critical system having a sub-criticality factor (k_{eff}) between 0.95 and 0.98 and a core power between 50 – 100 MW_{th}. In order to get a high energy intense neutron source, use of heavy liquid metals mentioned above as spallation material has been envisaged. But, this type of heavy liquid metal systems to be irradiated in a proton field have never been built, even though in the past several conceptual studies have been carried out. Therefore, an initiative was launched in 1999 to build and safely operate the MEGAPIE (MEGAwatt Pilot Experiment) Pb-Bi eutectic (LBE) spallation target with a continuous proton beam supplied by SINQ at PSI, Villigen (CH). The SINQ facility is a cascade of three accelerators (a Cockroft-Walton column as pre-accelerator and two cyclotrons) that deliver a proton beam of about 590 MeV and a current up to 1.8 mA with a total proton beam power ranging between 0.7-1 MW.

One of the main objectives of the MEGAPIE-TEST Project is to develop and validate the design and high power (~ 1 MW) operation of the heavy liquid metal (LBE) spallation target, producing innovative know-how and expertise in the areas of heavy liquid metal technologies, material research, safety and licensing.

After a feasibility study, performed by the MEGAPIE consortium, the conceptual designs of the target and its ancillary systems (i.e. heat removal system, cover gas system, fill and drain system and the insulation gas system) were started. The design team was supported by different R&D groups in the area of neutronics and nuclear assessment, thermal-hydraulics and structure mechanics, materials and liquid metal technologies. The conceptual design was guided among others by the SINQ boundary conditions (e.g. beam entrance from the bottom of the target) and by the results obtained from the R&D groups mentioned above. For instance the beam power deposition profile, calculated with MCNPX and FLUKA numerical codes, has been used to design and study the overall ability to cool the target and maintain the structural integrity. The isotope production calculations made with MCNPX and FLUKA, have also been used to design the cover gas system. The ferritic / martensitic 9Cr “T91” and the austenitic “AISI 316L” steels were selected for the liquid PB-Bi eutectic container and were assessed in terms of corrosion and irradiation performances under MEGAPIE relevant conditions before their use in the final operation.

Parallel to the conceptual design phase the preliminary safety report was prepared and submitted to the Swiss safety authority (BAG) to start the licensing procedure for the irradiation of the MEGAPIE target having the following characteristics. The target is designed for a beam power of 1 MW and 6 Ah of accumulated charge. It contains about 82 l of LBE serving as target material and primary heat removal fluid. The 650 kW of thermal heat is removed by forced convection using an in-line electromagnetic pump with 4 l/sec capacity. The heat is evacuated from the target through 12 mono-wall cooling pins via intermediate oil and water cooling loop systems. Safe enclosure of the radioactive liquid metal and the gases and volatiles produced during normal irradiation and hypothetical accident conditions is provided. The total activity in the LBE attains about 4.10^{15} Bq. About 2.10^{14} Bq is the α-activity mainly from Po-isotopes. In addition, about 8 Nl of gases like hydrogen, He and radioactive noble gases as well as 15 g of volatiles like Hg and I are produced, which have to be contained and/or evacuated. Different concepts have been worked out how to handle the different species and have been evaluated with respect to normal operation and accident conditions. The final design is based on a 3 barrier concept, laid down in a preliminary safety analysis report, which was submitted to the licensing authorities and approved.

An overview of the conceptual design of the MEGAPIE target experiment is as follows: the lower part of the target represents the beam entrance window, which is hemispherical and is made of T91 steel. The thermal energy deposited there is removed by LBE driven by an electromagnetic pump (EM) and evacuated through an LBE/oil heat exchanger (HX), which is located in the upper part of the target. The heat exchanger is connected to an external heat removal system via an intermediated oil/water loop. The beam entrance window is cooled both by the main flow and by a cold LBE jet extracted at the HX outlet, which is pumped by a second EM pump. LBE main flow in the target is guided by a tube slanted at the bottom. The upper part of the target, where both the free surface of the LBE and the insulation gas is contained, is made of AISI 316L steel. The top end the target head, where all supplies to the target and instrumentation lines are fed, is welded to the AISI 316L tube.

After having fixed the conceptual design of the target and the ancillary systems the project entered into the engineering design phase and thus all necessary activities were conducted for the manufacturing phase, which was accompanied by a Quality Assurance system. Components such as the Electromagnetic Pump System, the beam entrance window and the cooling pin of the heat exchanger have been built first as prototype and tested in order to assess their performances. The target and its ancillary systems have been integrated and tested out-of-beam in the so called MEGAPIE Integral Test Stand (MITS).

The objectives of the MITS experiments were to first integrate all systems, to check their functionality by simulating normal operating conditions and transients (e.g. beam trip, beam interrupts, loss of coolant) postulated for the MEGAPIE target in SINQ. The results of the single component tests have been combined with the results obtained at the MITS to assess the overall target performance. The assessment showed that the thermal-hydraulics performances of all components of the target did show safety margins of 25%. Realistic and significant margins to shut-down of the MEGAPIE target without loss of its structural integrity in the case of 'not-normal' operating conditions have been identified. While in some cases discrepancies between calculation and experiments have been detected in certain single component tests, none of these discrepancies were found to be beyond acceptable limits.
Finally, after having satisfied all requirements asked by the BAG regulatory authorities, including a viable solution to protect SINQ against fire risk due to the presence of the organic oil and the demonstration of handling an all encompassing reference accident case as defined by the BAG, the target and the ancillary systems were dismantled from the MITS and remounted in the SINQ target location. In this position all systems were re-checked before starting the high power irradiation phase.

An irradiation procedure, as agreed with the safety authorities was followed, before ramping up the proton beam power to its maximum power, i.e. 1.4 mA at 575 MeV. The target has been successfully irradiated up to 2,8 Ah and with an availability of the order of 95%. During the operation of the MEGAPIE experiment which was conducted between August and the end of 2006, results obtained show that there was an 80% higher neutron flux as compared with a standard solid (lead with steel cladding) target. This improved performance of the SINQ spallation facility has permitted to carry out associated experiments at SINQ with higher precision. The objective to safely operate a LBE heavy liquid metal spallation target has therefore been achieved with full satisfaction with an added bonus of 80% more neutrons for associated experiments.

The experiment, as planned, was stopped at the end of December 2006. The post irradiation examination of the now frozen target will continue for the next couple of years and will deliver invaluable information about the composition and behaviour of materials used in the experiment. This feedback will flow into the design and operation of new SINQ-like spallation neutron sources. The design of accelerator driven sub-critical systems will also benefit enormously from the experience gained here. For future industrial projects involving the transmutation of nuclear waste with sub-critical accelerator driven systems, MEGAPIE has turned out to be one of the key experiments in the chain.

2. Objectives and strategic aspects

The MEGAPIE-TEST project belongs to the “Partitioning and Transmutation” activities foreseen in the component of “Safety of the fuel cycle” of the key action “Nuclear Energy” of the 5th Euratom Framework Programme. Partitioning and Transmutation (P&T) techniques could contribute to reducing the radioactive waste and its associated radiotoxic inventory. The Megawatt pilot experiment (MEGAPIE), represents a key experiment in the demonstration of the transmutation of nuclear waste via an ADS device. In parallel the experiment would benefit also the spallation neutron users, since the neutron yield wouldfrom the LBE would be significantly increased with respect to standard solid targets. During the course of the project, valuable experience will be gained in the engineering design of such a target together with its safety and licensing aspects.

At present the MEGAPIE target represents the reference experiment for the window target development in the frame of the ADS development and has been considered as the reference experiment of the FP6 Eurotrans Project. MEGAPIE Post Irradiation examination is beyond the scope of this project and will be subject of a future investigation for which finances have to be sought.

3. Scientific and Technical performance

WP1 - Target Development

Task 1.1 DESIGN

1. Target Design

The target has been designed to accept a proton current of 1.74 mA. Thermal energy (650 kW) is deposited in lower part of the target where flowing LBE enter the riser. This thermal energy is removed by forced convection. LBE is driven by the main in-line electromagnetic pump, then pass through a 12-pin heat exchanger (THX) and return to the spallation region. The heat is evacuated from the THX through a diathermic oil loop to an external intermediate water cooling loop and then finally goes into the PSI existing cooling system. The beam entrance window is cooled both by the main flow and also by a cold LBE jet extracted at the THX outlet, which is pumped by a second EM pump through a small diameter pipe down to the beam window. The thermal hydraulic system behavior has been modeled with RELAP5 code for normal and transient operations (beam trips and interrupts). The operating conditions were chosen in order to keep the LBE temperatures below 400 °C and the maximum flow speeds at about 1 m/s. The target main properties are shown in Table 1. The target itself is conceived in nine sub-components, which were manufactured separately and assembled subsequently:

- Central rod (CR), inserted in the upward LBE flow path, includes a 20 kW heater to avoid uncontrolled freezing of LBE during operation when the beam is off. CR holds also the neutron flux meters and fills up the central part of the target and reduces the amount of LBE.
- Main flow guide tube is the barrier between the rising and down coming LBE flow. The guide tube is equipped with a number of thermo-couples to monitor the temperature field above the spallation zone.
- Electromagnetic pump system was designed by the Institute of Physics (IPUL) in Latvia. It consists of a concentrically arranged bypass pump and an in-line main pump. Both pumps are equipped with electromagnetic, three-coil flow meters, respectively.
- Target heat exchanger (THX) is an assembly of 12 counter-flow pins concentrically arranged. Performance of pins has been experimentally investigated (Agostini, 2002) and numerically assessed (Maciocco, 2003). It was necessary to implement a spiral in the oil path to increase the contact length. The main problem in the design of the THX was to comply with the complex thermal conditions and to limit the resulting

thermo-mechanical stresses. This has been accomplished by attaching the pins to the inlet and outlet oil distribution boxes by flexible bellows and inserting thin shrouds as heat shields. The heat exchanger forms also the upper enclosure of the LBE and the gas expansion tank.

The lower enclosure of LBE is formed by the

- Lower liquid metal container (LMC) made of the martensitic steel T91. The beam entrance window is hemispherical with a wall thickness tapered from 1.5 mm in the centre to 2 mm at the outer rim. The energy deposited in the beam window by a 1.74 mA beam current calculated with CFX4 and the FLUKA codes is of the order of 5 kW. CFD modelling and FEM calculations were used to design the beam window cooling system, by considering specially the proper control of the temperatures and stresses in the material. Different designs of cooling systems have been investigated finally leading to the reference design of a bypass jet flow along the long axis of the beam footprint and a slanted guide tube. Temperatures have been calculated for the target window, the central rod and the guide tube for this configuration. Corresponding stress calculations using the above data as input yielded a maximum stress in the beam window and the guide tube of 55 and 63 MPa respectively. The lower liquid metal container, the flange of the guide tube, the heat exchanger and the central rod constitute the LBE containment.

The second containment is formed by three components. A gap between both containments is filled with He at a pressure of 0.5 bar . These components are:

- Lower target enclosure (LTE), a double walled, D2O cooled hull made of AlMg3, which is designed to contain any leakage of LBE. The material for this part has been chosen for minimum neutron absorption and sufficient strength to any temperature the shell might reach. The reversed spherical shape of the LTE has been adopted because it allows the LBE in case of a leak to flow into the lower edges of the LTE. This avoids accumulation of LBE in the centre where the beam hits the target. Remaining LBE in the beam interaction zone would lead to a strong power deposition and could provoke the rupture of the aluminium double walled shell. Its proper functioning has been assessed by FEM calculations (Dury 2003) and dedicated experiment (Samec 2006).
- Upper target enclosure (UTE) is formed by a stainless steel tube. The UTE main functionality is to contain the insulation gas, and in case of accident to resist to overpressure and eventual mechanical shocks. This tube is welded to the Target Head (TH).

- The TH consists of the main flange, which positions the target on the support flange of the central tube of the SINQ facility, and the crane hook. All supplies to the target and instrumentation lines are fed through the target head.

The last sub-component is the

- Target top shielding, which connects the hot part to the target head. The LBE containing part of the target is thus suspended to the target head and allowed to expand freely. The component also contains tungsten to shield the target head area from the intense radiation of the LBE and the noble gases and volatiles collected in the gas expansion tank.

1.2 Manufacturing and Performances

ATEA REEL in France started manufacturing definition process in November 2002 in close collaboration with PSI and SUBATECH. The procedure applied for each Lot was to perform a Detailed Design Review and a Readiness for Manufacturing Meeting before starting the manufacturing process (machining, welding and assembling). Detailed Design Review was held to determine when a Lot was sufficiently defined to be manufactured (verification of the drawings, engineering and design documents). For all target sub-systems, manufacturing drawings were made and discussed in detail with colleagues from PSI. Step-by-step open design issues were solved and integrated in the drawings to come up with a final set of drawings for the manufacturer. A series of design calculations were performed to backup the target design.

The manufacturer checks all drawings. All open points (design and feasibility) were discussed in detail with the manufacturer. Manufacturing was started after dedicated Readiness for Manufacturing Meetings. Each Readiness for Manufacturing Meeting was held to evaluate systematically one sub-component set of documents (general specifications, particular quality assurance program, drawing set, detailed specifications, engineering and design documents, manufacturing and sub-assembly plan, test inspection plan, schedule, cost update). The MEGAPIE target was delivered to PSI in June 2005.

In Figure 1, we can see the target handling before its implementation in the SINQ hall at PSI. The commissioning of MEGAPIE target started on August 14, 2006. At a relatively stable and constant beam current of 40 µA, which corresponds to about 25 kW of beam power, the target accumulated a total charge of 60 µAh. On the 15th of August, the power was stepwise increased to 150 kW (250 µA proton current). On the 17th of August, the power was stepwise increased to full power 700 kW (1200 µA proton current). After some 10 minutes time with stable proton beam at each step, the beam was interrupted to follow the temperature transients in the target. All systems operated in a very stable manner at all power levels. Normal user operation was started on August 21 and was planned to continue until the normal annual winter shutdown starting on December 23, 2006.

Main specifications			
Length	Weight	LBE volume	Gas expansion volume
5.35 m	1.5 t	82 l	2 l
Gas pressure	Design pressure	Design temperature	Insulation gas
0-3.2 bar	16 bar	400°C	0.5 bar He
Materials			
Lower liquid metal container	Upper container	Lower target enclosure	
T91 ferritic / martensitic	316L stainless steel	$AlMg_3$	
Heat removal and beam window cooling			
Deposit heat	Main pump	Bypass pump	
650 kW	EM pump (4 l/s)	EM pump (0.35 l/s)	

Table 1: MEGAPIE target main properties.

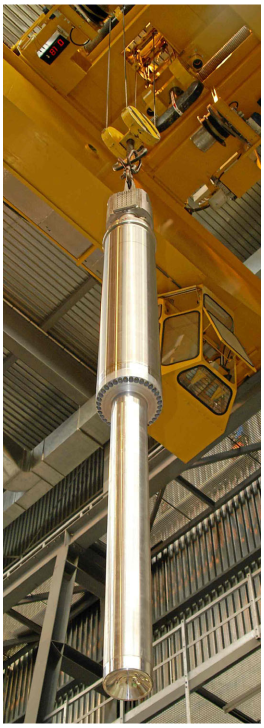


Figure 1: MEGAPIE target handling before implementation in the SINQ hall at PSI.

2. Ancillary Systems Design

The main MEGAPIE ancillary systems directly necessary for the target operation are the heat removal system (HRS), the cover gas system (CGS), the insulation gas system (IGS) and the fill and drain system (F&D). The basic functional requirements to the systems are described in the safety analysis report [1]. For the technical layout we refer to [2-5]. The present description mainly focuses on our experience with the design and functionality.

2.1 Heat Removal System (HRS)

The HRS [2] consists of two subsystems: an intermediate cooling loop with oil Diphyl THT as cooling medium, connected to the heat exchanger pins in the target, and second a back-cooling water loop (WCL). The oil loop, operating between 160°C and 230°C, is primarily necessary to remove about 0.6 Megawatt of heat load deposited in the liquid lead bismuth eutectic (LBE) by the proton beam. As a second function, it must also be capable to manage a controlled hot-standby operation after beam trips or scheduled beam interruptions to prevent freezing of the target.

The general layout of the system proved to be sound. Oil as cooling medium turned out to be a reasonably good choice. The heat removal capacity of the system was rather over dimensioned. Oil degradation by radiolysis and pyrolysis was found to be much less than anticipated. The main drawback of using oil is the need for fire protection which was achieved by making the atmosphere inert in target head enclosure chamber TKE and in the beam transport vault.

When delivered to PSI the oil loop had several major and minor deficiencies, which were discovered during the commissioning and test phase and repaired on site. Obviously, the hurdles from design to realization related to component selection, manufacturing and accompanying quality assurance had been underestimated. From that stems our main conclusion that home-made is best made, as experienced with the WCL, and reliance is good, control is better.

2.2 Cover Gas System (CGS)

The CGS [3] must handle the volatile radioactive inventory of spallation products released from the LBE in the target. Handling of radioactive gases and volatiles imposes stringent requirements on safe and remote operation, on retention of radioactivity, like second containment and tightness, and on shielding.

The chosen design, in principle, proved sustainable; in practice, meeting the stringent requirements turned out to be rather complex and expensive. One lesson learned with the system was, that 'leak-tightness' for gases in the conventional definition is not the same as for radioactive gases: In spite of successful He leak tests according to specification a leak from the decay tank into the 2nd containment was detected by the very sensitive detector controlling the circulating gas. Although clearly detectable, the leak was sufficiently small such that the inventory could be released weekly by venting of the 2nd containment through the controlled exhaust system. A further lesson was to care for redundancy (if possible double) of vital sensors in such a delicate system: one pressure transducer inside the enclosure controlling and recording the plenum gas pressure failed, most likely due to radiation damage, although qualified for radiation resistance up to a total Gamma-dose of 1 MGy. Switching to the remaining redundancy solved the problem at that time, but after that no redundancy remained.

A further critical issue is gas sampling, indispensable to control the inventory before venting. Reliable and quantitative gas sampling is a difficult action and can be a hazardous job which needs special precautions, not at least to prevent or minimize radioactive exposure of the executive personnel. Our initial concept using a glass phial and a needle to perforate the covering membrane turned out not to be a viable option. Rather, a qualified steel gas mouse with valve and flange connection was used.

2.3 Insulating Gas System (IGS)

The IGS [4] fills the volume between the inner hot part of the target and the outer cold hull by an insulating gas. The concept envisaged was filling with He at a pressure of 0.5 bar, benefiting from lower activation on the expense of a higher heat leakage compared to filling with Ar. During preheating the empty target it turned out that evacuation was necessary to prevent excessive heat loss. After the target was filled with liquid metal, during refilling the isolation volume with He we experienced that 4 out of 7 electric heaters in the lower central target were destructed, probably caused by electric discharges. The loss of heaters did not hamper or inhibit further operation, but another draining and refilling with liquid metal would not have been possible any more.

One of the accident scenarios which needed to be safely handled was water ingress from a leaking safety hull into the insulating gas volume with the consequence of steam production and possible pressure built-up. This was accomplished by installing a 40 mm exhaust pipe combined with a rupture disk and a steam condenser vessel outside the insulation volume.

Designed as closed volume the pressure in the IGS was expected to remain constant during target operation, only reacting to temperature variations. Instead, starting with the first beam a continuous gas pressure increase by ~5 mbar/h was observed. Thorough analysis gave evidence that most likely oil from the HRS is leaking into the IGS volume, decomposed by radiolysis during beam operation. The gas produced further contained small amounts of

(radioactive) cover gas, entering through a second (small) leak. The gas production urged a weekly venting of the IGS. The measures taken to cope with this problem were the installation of a 180 l decay vessel in the cooling plant and regular (weekly) venting into the exhaust system after a sufficient decay period and gas sampling.
The lessons learned: do not rely on closed volumes, expect radioactivity everywhere and provide devices to handle that (for the case).

2.4 Fill and Drain System (F&D)

The initial baseline for the F&D system required draining of activated LBE from the target after the operation period. A detailed design for that was elaborated; however, the draining option was recognized to bear considerable risks, immediate ones for accessing the TKE and more general ones related to licensing. As well, it had required considerable extra expenditure in the technical realization: besides the standard equipment like heaters for the LBE vessel, the valves and the pipes combined with appropriate thermal insulation, the active draining option would have imposed the need of radiation shielding, second containment, radiation-hard components and remote operation, similar to the CGS.
Viewing these difficulties the decision was taken to abandon the initial concept in favour of only inactive draining and final freezing of the LBE in the target after completion of the irradiation experiment [5]. The experience showed that switching to the only non-active draining (filling & freezing) was essential for the realization of the irradiation phase in time. The inherent final freezing imposes mechanical stressing of the hull and window material due to the well-known volume expansion of solidified LBE. Hence, post-irradiation adulterations of the materials properties are not completely excluded. This drawback is handled by controlled slow freezing of the LBE in the lower target volume.
The finally realized concept is sound; the system is reasonably safe and easy to operate. The experience during commissioning recommends providing sufficient trace heaters and place controlling thermocouples at the coldest points to prevent clogging. The missing oxygen control did not impose a problem.

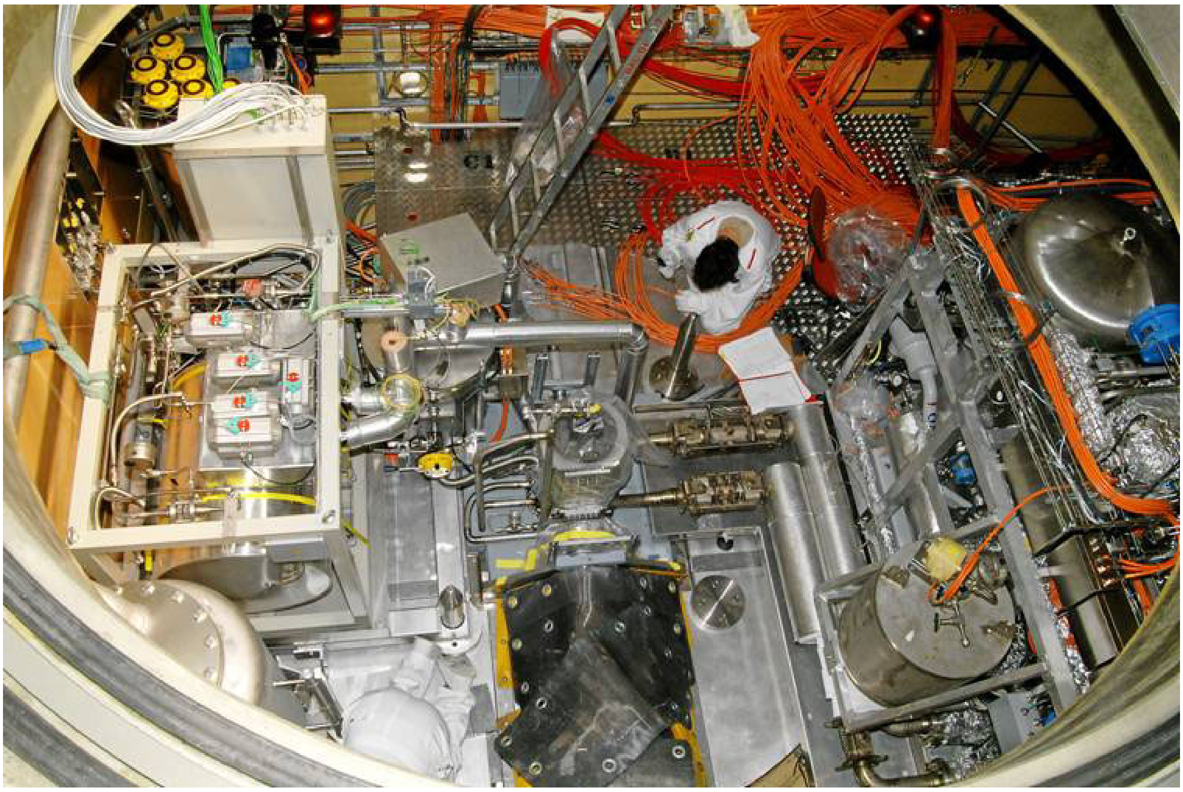


Figure 1: View from top into the TKE (situation of April 2006). The target head is in the centre, still without the cables connected which are in preparation in the rear, the oil loop of the HRS at the right, the F&D system at the left, and the CGS in the left rear corner (partly hidden behind the connector box of the F&D.

Task 1.2 Design Support and Validation

1. Neutronic and nuclear calculations

As far as neutronic and nuclear assessment of the MEGAPIE target is concerned, the main tools used during the design phase were Monte Carlo transport codes. By neutronic design it is intended the calculation of important quantities such as neutron fluxes, power deposition in the target, shielding, dose rates, activation, gas production, and radiation damage, using the chosen codes, and the effects of these calculations on the target design. Clearly the impact of the neutronic design is essential for instance for the design of the target windows, for the target shielding, and for the handling procedure after irradiation.

The work followed several steps: first, a benchmark of the most widely used Monte Carlo codes, consisting in a code intercomparison was performed [1]. The benchmark led to the choice of the FLUKA and MCNPX codes for the following work.

Second, the two codes were used for the neutronic design of the target. The details of the neutronic design work are reported in Ref. [2] and references therein. Some of the most Iimportant results were the following:

Target performance: a comparison between the neutron flux with MEGAPIE and the SINQ solid target showed that the MEGAPIE target would deliver 40% to 50% more thermal neutrons to the instruments served by SINQ as compared to the SINQ solid target.
Power deposition: Approximately 85% of the beam power is dissipated in the target-moderator system (71% in the LBE), the rest is dissipated in the surrounding shielding. Detailed beam power deposition on the structural materials was also calculated.
Isotope production: A comprehensive study of isotope production was undertaken, and several related topics were addressed: target activation and dose rates, radiation damage on the structural materials, gas production during irradiation and subsequent handling.

2. Materials

The purpose of the following discussion is to assess the lifetime of the MEGAPIE target. This assessment is mainly focussed on the Lower Liquid Metal Container (LLMC). Nevertheless, the in-service behaviour of the Lower Target Enclosure (LTE) and of the inner target components are also briefly discussed hereafter.

The LTE is an important target component whose failure would put an end to the target operation. It is made of AlMg3, which was used for all safety hulls of the SINQ- solid targets. Two safety hulls (those of targets 4 and 5) were operated without problems up to more than 10 Ah proton charge which is well above the 3 Ah maximum proton charge expected at the end of the MEGAPIE operation. Two other safety hulls reached more than 6 Ah. Therefore, the MEGAPIE LTE should not cause any problem up to 3 Ah.

A failure of one of the target internal structures would not lead to an automatic end of the MEGAPIE irradiation experiment, although it could seriously affect the target operation. Some of these internal structures, which are made of 316L, will experience no or little radiation damage (pumps, heat exchanger). As for the main/bypass flow guide tubes, central rod, fill and drain tubes, the calculated peak damage for a 3 Ah proton charge is less than 2.5 dpa. Given these irradiation conditions and the operation temperature range, 316L will retain significant ductility, toughness and fatigue resistance [1]. Further, although the sensitivity of 316L to liquid metal embrittlement (LME) has been less studied than in the case of T91, it was shown that the low cycle fatigue life of 316L in LBE at 260°C was little affected compared to the fatigue life in air [2]. In addition, the corrosion rate at low oxygen content and in flowing LBE evaluated to be ca. 0.1 mm/year, should have very little impact on the mechanical resistance of these components. Therefore, and given the fact that the maximum stresses in the irradiated parts are relatively low (about 60-70 MPa), the 316L components should safely operate up to the maximum envisaged proton dose and should not represent a life-limiting factor for the MEGAPIE target.

The LLMC, and in particular the beam window, is obviously the most critical component. The determination of its lifetime is a real challenge, since multiple possible causes of damage are present and acting synergetically: corrosion/erosion by flowing LBE, irradiation embrittlement by energetic protons and neutrons, Liquid Metal Embrittlement (LME)/Liquid Metal Accelerated Damage (LMAD), cyclic mechanical and thermal loadings.

The corrosion/erosion of T91 in flowing LBE has been studied a temperature of 400°C with a velocity of 1m/s and low oxygen concentration and was evaluated to be less than 130 μm/year based on experimental data on T91 and pure iron. The actual corrosion rate will probably be lower than this value, which corresponds to pure iron, due to the presence of a protective oxide on T91 at the beginning of the irradiation and also because the nominal maximum operation temperature is 350 rather than 400°C. The reduction in the window thickness corresponding to this corrosion rate (< 60 μm in 5 months of operation) would not unacceptably weaken the component from a mechanical point of view. As such, corrosion/erosion is not a life-limiting factor for the target. However, the effect of a possible grain boundary attack as a result of corrosion/erosion has to be evaluated and this point is discussed below.

By contrast to corrosion/erosion, irradiation embrittlement in a spallation spectrum is a critical issue with regards to the safe operation of the target. A main concern is the risk of sudden brittle failure of the window due to the irradiation-induced shift of the DBTT and to the corresponding large decrease of the fracture toughness. Using impact/small punch test data measured using T91 and other martensitic steel samples irradiated in SINQ, the DBTT shift as a function of irradiation dose/He production was evaluated [3]. It was shown that the DBTT should remain below the minimum operating temperature (i.e. 230°C) up to proton charge of about 3.4 Ah which corresponds to a damage of 8-9 dpa. The Linear Elastic Fracture Mechanics analysis presented in [4], with as hypothesis the presence of a large crack on the inner surface of the window, demonstrates that the brittle fracture risk is negligible, at least up to 8-9 dpa.

This analysis, however, does not take into account possible LME/LMAD effects. T91 is prone to LME if there is plastic deformation and intimate contact with the liquid metal as illustrated in [5-8]. Such conditions are not encountered at the beginning of irradiation since the stresses in the MEGAPIE window are low and the material hardens substantially with irradiation. Moreover, the presence of the native oxide should be able to prevent wetting during the preconditionning and the start up procedure. Furthermore, LISOR results [9] have shown that an oxide layer, which would provide an additional protection, should form on the surface irradiated by the proton beam. However, due to the production of hydrogen and other reducing spallation elements, it is expected that the oxygen content in the liquid metal will slowly decrease, at an unknown rate. Dissolution of the protective oxide layer may then occur, possibly leading to intergranular attack, as was for instance observed on T91 exposed for 4500 h to flowing Pb-Bi at 400°C and low oxygen concentration [6].

Intergranular attack provides defects that can play the role of crack initiation sites which may propagate by cyclic loading in LBE leading to a strong reduction of the low cycle fatigue life [10]. However, fatigue crack formation and propagation is very unlikely under MEGAPIE normal operating conditions. The general trend is that the reduction in fatigue life in LBE compared to fatigue life in air disappears at low stress/strain values which is the case for the MEGAPIE window. Also, the intergranular attack induced by pre-immersion in LBE at 613°C in the specimens used for low cycle fatigue tests was pronounced. At lower temperature, the attack will be less severe. Moreover, if a small crack were to form, due to the very low values of the stress intensity range ΔK to which the crack would be submitted, its growth rate would be very small (< 10-5 mm/cycle). Therefore, there is a very low probability that a crack of a few tenths of mm depth would form on the window inner surface. In addition, in the presence of such a surface defect, and taking into account the measured reduction in fracture toughness of irradiated T91 due to LBE [11] down to a value of 40 MPa m1/2, the LEFM analysis presented in [4] still predicts that the brittle fracture risk is negligible.

Based on the above discussion, it can be concluded that a failure of the LMC is unlikely within the projected service time of the target, under normal operating conditions.

3. Thermal-Hydraulics, Heat Transfer and Structure Mechanics

3.1 Background

Within the MEGAPIE research programme (Bauer et al., 2001), an R&D group was set up to address issues relating to the overall coolability and structural integrity of the lower target hull and safety vessel. Specifically, coolability relates to the efficient transport of heat from the heat-producing regions to the heat exchangers, and the protection of critical structures – particularly the window, through which the proton beam enters the target –from over-heating (local hot-spots) and excessive thermal gradients, which would result in high stress concentrations.

The time-scale set for MEGAPIE was always such that much of the design work needed to be carried out at the same time as the R&D support. Often, the target design changed faster than the time required to perform the detailed computer simulations. As a consequence, many of the early Computational Fluid Dynamics (CFD) simulations of the lower target did not refer to the very latest target design, but the experience gained enabled later simulations to proceed much more efficiently. This was particularly important as the design approached maturity, and results from CFD calculations were needed promptly.

3.2 Objectives

Given the principal objective of the R&D group's activity to deal with issues relating to the overall coolability and structural integrity of the lower target, it is worth noting that it is not straightforward to verify the cooling principle by means of an integral test experiment, because of the difficulty of realistically reproducing the volumetric heating effect at representative power levels ($1GW/m^3$) without actually using a beam. Consequently, the studies focus on the use of advanced numerical tools, both for the thermal hydraulics simulations and the associated structural analyses. Of necessity, a high level of confidence in the computations must be demonstrated, and consequently special-effects experimental tests using actual and simulant materials formed an integral part of the programme.

A considerable amount of support R&D was carried out over the duration of the project. The Group performed thermal-hydraulic and structure-mechanics investigations to fulfil the project objectives placed upon it. These being:

- to define the lower target flow configuration, within the geometric constraints imposed by the physical boundary conditions (geometrical confinement, LBE inventory, pump capacities, THX power, etc.);
- to identify, and evaluate, optimum target window design to minimise thermal loads and pressure drops, and to avoid hot-spots and flow instabilities;
- to demonstrate reliable cooling of the lower target enclosure (LTE);
- to demonstrate the structural integrity of the liquid-metal container (LMC) and its internal components, and that of the LTE;
- to provide best-estimate safety margins on target coolability and structural integrity under operational flow conditions;
- to investigate, quantify, and make recommendations regarding, abnormal target operation (including possible accident scenarios).

Most design studies (i.e. those relating to steady-state operation of the target) undertaken by the group were carried out with an assumed beam current of 1.74mA, which was the expectation at the beginning of the project. However, the policy decision to reduce the beam current to 1.4mA was taken into account in some later design calculations, and all analyses of transients were undertaken for the reduced beam current.

3.3 Results of Design Studies

For the presently-accepted beam footprint, slightly better window cooling and less severe guide tube stresses were predicted for the case in which the bypass flow was aligned with the minor axis of the elliptical beam footprint. However, for other considerations, this was not adopted as the final design option. From optimisation studies of bypass shape and position, an optimum bypass nozzle design consisting of a slightly elliptic cross-section, positioned under the large-gap end of the guide tube and slanted at 15o to the vertical, was identified as giving the best window cooling and least vulnerability to slight changes in geometry. These characteristics were calculated as being marginally superior to those of the reference design (rectangular nozzle shape of 10mmx20mm, with discharge parallel to the window surface and situated as close as possible to it). However, the latter were adopted for the final design.

It was predicted that better window cooling and, particularly, less severe temperature differences (and associated stresses) in the lower part of the guide tube are obtained if the guide tube is slanted at the bottom (vertical distances to target hull 15mm/25mm or 10mm/30mm), with bypass flow on the large-gap side. The option 15mm/25mm was adopted for the target design.

Following an in-depth CFD parameter study, a bypass mass flowrate of at least 2.5 kg/s (through a nozzle of cross-section about 200 mm2, resulting in a discharge velocity of 1.2 m/s) was recommended to minimise window heating and maintain flow stability in the lower target region. This corresponds to a main mass flowrate of 37.5 kg/s. Evidence from LBE experiments, however, suggested that the option of a bypass/main mass flowrate ratio of 3.0/37.0 kg/s should be kept open.)

From the stress analyses performed in combination with the numerical thermal-hydraulics studies, the benefits of fitting spacers between the guide tube and the target hull were identified to limit the bending of the guide tube caused by differential heating in the riser. Detailed studies have shown that the spacers could be situated above the spallation zone, if necessary, and still be effective in limiting lateral bending of the guide tube.

Combined thermal-hydraulic and stress-analysis calculations have demonstrated that there are very large safety margins on LTE coolabilty, with no serious hot spots or stress concentrations for steady-state operation with a D2O flowrate of 2.2kg/s. Finite Element Method (FEM) analysis of the “target catcher” ring has shown that the arrangement is effective in preventing contact of the LMC and LTE in the event of total rupture of the target hull, and that stress levels at the supports can be tolerated.

3.4 Operational Transients

Coupled CFD/FE analyses have shown that, under normal operating conditions, maximum stress levels are kept within satisfactory limits: 46 MPa for the window and 49 MPa for the guide tube, with no increase of stresses during beam interrupt and restart events.

CFD analyses has shown that the effects of beam wandering by up to 2mm at the window are small: the maximum window temperature varies by 2°C, and elsewhere by 15°C.

Combined experimental/numerical studies have identified a strategy for safe freezing of the LBE in the target at the end of irradiation (LBE can expand by up to 1% volumetric due to recrystallisation after freezing). It is commonly agreed that the LBE should be kept hot (at about 90oC during recrystallisation, followed by slow cooling (about 1oC per hr) to room temperature, and that bottom-to-top freezing of the target should be ensured to limit stresses. The details of the control procedures to be followed with the target in-situ remain to be worked out in detail.

3.5 Abnormal and Accident Transients

It is predicted that, with the slanted guide tube, the target could still be operated if the bypass pump fails (though at reduced power) without overheating of components. Likewise, it is predicted that the structural integrity of the LMC would not be compromised in the event of failure of the main pump, but that further operation of the target is not recommended.

Accidental over-focussing of the beam due to partial or total bypass of the Meson Target E has been identified as a serious event. For beam focussing in excess of 35%, the window temperature does not stabilize, and structural failure can be anticipated. Higher degrees of focussing reduce the time available to shut off the beam, and for 100% focussing this time reduces to 200ms. However, new safeguards against beam over-focussing are now installed.

Coupled thermal-hydraulic and stress-analysis calculations indicate that jet impingement of cold (40°C) D_2O from a ruptured LTE onto the hot (~400°C) outer surface of the window would not lead to a brittle fracture of the LMC. The converse situation of LBE leakage into the space between the LMC and LTE hulls has also been analysed, both numerically (with beam heating), and in terms of a full-scale leak test (no heating). All indications are that the LBE would be contained, with no serious structural damage, nor blockage (through plastic deformation) or local boiling of the D_2O in the LTE cooling circuit. However, the peak temperature in the D2O reaches 145°C, only 15°C below saturation under prevailing circuit pressure (6 bar).

3.6 Validation Studies

The flow visualisation tests HYTAS have provided high-quality velocity measurements in a 1:1 MEGAPIE geometry at close to prototypic flow conditions (Re□60’000 in HYTAS, Re≈120'000 in MEGAPIE). The flow is seen to be complex and time-dependent, with a critical value of the main/bypass flowrate (15) necessary to stabilize conditions over the window. CFD analysis has begun, but detailed measurements have come late in the project, and a comprehensive code-validation exercise remains to be undertaken.

The 1:1 scale LBE tests carried out under the acronym KILOPIE-1 have produced useful results only for the KILOPIE-TC tests in which there was direct measurement of the window internal temperature. Measured HTCs were in the range 15'000 to 20'000 W/m2K, which are in accord with expectations from earlier tests using Hg, and with CFD predictions. It has not been possible to reproduce heat fluxes from the window which are prototypic for MEGAPIE.

Temperature measurements obtained in the LBE from the Heated Jet series of experiments (no window heating) have provided information on the stability of the bypass jet flow, and indications of the fluctuations to be expected in MEGAPIE. There are indications that the reference main/bypass mass flowrate ratio (37.5/2.5) may not be low enough to ensure stable conditions over the entire window, and that a ratio of 37.0/3.0 would be advisable, though this does result in penetration of the bypass jet into the opposite annulus. This option should be kept open, and tested numerically. First numerical simulations have been performed, but wider utilisation of the data is needed for CFD validation.

Through appropriate benchmarking exercises (the EU project ASCHLIM and the MEGAPIE Benchmark), confidence in the CFD thermal-hydraulic predictions made for the MEGAPIE project has been established. In particular, the k-ε turbulence model, including the use of a turbulent Prandtl number to model heat transfer via the Reynolds analogy, if used correctly, is able to reproduce the mean-flow conditions and heat transfer reliably.

3.7 Final Comments

The R&D Group has conducted a balanced programme of numerical and experimental work aimed at first defining and then proving the robustness of the lower target design. For the vital issue of window coolability, the picture which emerges from the available evidence is a consistent one. With adequate bypass flow maintained, a HTC in excess of 15'000 W/m2K has been predicted and measured over the heated part of the window, sufficient to keep the outer window temperature below the design value of 400°C (370°C/342°C for a beam current of 1.74mA/1.40mA, respectively); the maximum inner surface temperature is about 35°C lower than this. With inadequate or no bypass flow, a HTC of 5'000 W/m^{2}K has been predicted and measured over the heated part of the window, sufficient to limit the maximum window temperature to 530°C – hot, but a long way from compromising its structural integrity. The HYTAS and Heated Jet Experiment have provided information on the stability of the flow field to be expected in the MEGAPIE geometry, but in the absence of the strong buoyancy forces which will be present when the target is irradiated. To date, no direct numerical data regarding flow stability and fluctuations are yet available: Large Eddy Simulation (LES) computations are underway, but are very CPU intensive, and results are not available at the time of writing.

Task 1.3 and Task 1.4: Safety and Licensing

1. The Licensing Process

Design, Construction and Operation of the MEGAPIE experiment has to comply with Swiss Law and Regulations. From the radiation protection point of view, the following ordinances have to be respected:

- Law on Radiation Protection (StSG)
- Regulation on Radiation Protection (StSV)
- Regulation on Handling of Open Radioactive Sources
- HSK rules R-07, R-25 and R-41

The following legal bodies are involved in the licensing process

The **Swiss Federal Office of Public Health (BAG)** is the responsible authority for all non-nuclear installations at PSI. **The Swiss Federal Nuclear Safety Inspectorate (HSK)** is the competent authority for activities in the **Interim Storage of the Swiss NPP (ZWILAG)** and the **PSI Hotlab**, where dismantling, investigations and waste conditioning are planned. HSK is also competent for the licensing of transport containers. **The National Cooperative for the Disposal of Radioactive Waste (NAGRA)** evaluates specifications for the final waste disposal, which are then approved by HSK.

The SINQ operation is based on the license No. AG-0444.13.001 issued by the Federal Office of Public Health on June 27, 2000. Rule 60.M04 of this license stipulates that an additional license is needed, if targets will be used having a significantly higher hazard potential than those described and qualified during the SINQ licensing process. Since only solid Zircaloy and Lead targets were qualified, a liquid Lead-Bismuth Eutectic (LBE) target requires additional licensing due to its high Polonium inventory. Rule 60.M14 stipulates that the release of activity calculations have to be updated for liquid metal targets for the relevant target material before installation. With MEGAPIE being the first liquid metal target, these calculations have to be performed.

PSI has been dismissed from the duties derived from the emergency ordinance in case of accidents in nuclear installations, which requires that the dose of the radioactive fall-out for the public is markedly below 1 mSv for accidents with a probability larger than 10^{-6}/year. The MEGAPIE experiment therefore has to prove that this dose limit can be kept. In addition, emission limits have to be respected for normal operation and incidents. The air-born emissions are referenced to the accumulated dose at the closest habitation calculated with the code ESS41. Theses limits have been set for SINQ at 10.5 μSv for the annual accumulated dose, 2.5 μSv for the 3-months accumulated dose and 200 μSv for the short term dose per event.

2. The Preliminary Safety Report

The Preliminary Safety Assessment Report (PSAR) constitutes the basis of an application by PSI to the competent authority for a permit for construction of the MEGAPIE target system and its experimental operation in the SINQ facility. It deals with the following topics:

- Design, construction and operation of the experimental target system with a liquid lead-bismuth eutectic, which is to be installed in the SINQ spallation neutron source of PSI, quality management and functional tests of this target system prior to installation.
- Measures to cope with credible accidents in which radioactivity may be involved.
- Radiation protection measures, especially those taken to minimize personnel doses and collective doses and to limit radioactive emissions.
- Decommissioning, conditioning and disposal of the radioactive waste.

The Safety Report demonstrates that compliance with the legal regulations about radiation protection, the guidelines of regulatory authorities, and the rules of PSI in-plant radiation protection is ensured in the design. It is divided in 8 chapters:

- Chapter 1 contains a brief description and the justification of the experiment
- Chapter 2 contains a description of the SINQ facility and of the SINQ subsystems relevant to MEGAPIE.
- Chapter 3 is a functional description of the MEGAPIE system and its subsystems.
- Chapter 4 describes the radioactivity and radiation protection aspects in design-basis operation of the MEGAPIE facility.
- Chapter 5 contains a complete list of relevant credible accidents and their potential consequences, their management, and consequences in terms of radiation protection.
- Chapter 6 deals with activities at PSI within the competence of the Radiation Protection and Waste Management Department (ASE).
- The project organization and a basic outline of administrative measures specific to the project, especially the definitions of responsibilities, are summarized in Chapter 7.
- Quality management for MEGAPIE is described in Chapter 8.

The deviation list has been established in 2006 to document the main design changes within the course of the development compared to the PSAR issued in 2002.

2.1 The KSA Expertise

In July 2002 the official request for permission of the experiment was submitted to BAG. Due to the complex matter, BAG asked a technical expertise on the PSAR from the Swiss Federal

Commission for the Safety of Nuclear Installation (KSA). In September 2003, KSA delivered its expertise stating the licensibility of the experiment provided the fulfillment of a number of prerequisites.

2.2 The BAG Licensing Statement and Final Permit

In January 2004, BAG granted the permit for the execution of the experiment imposing 5 milestones to be achieved and 49 prerequisites to be fulfilled. By adopting regular meetings on a monthly basis with BAG, the authorities were kept well informed on the progress of the project and the open issues could be successively cleared. Having cleared all open issues, the final permit for start of the irradiation was received on August 11, 2006.

2.3 The 5 Milestones

BAG defined 4 milestones, which have to be achieved and cleared before starting irradiation

- Inactive Operation of the Heat Removal System
- Inactive Operation of the Cover Gas System
- Inactive Operation of the Target System
- Dismantling and Disposal of the Target
- Active Operation of the Target System in SINQ

Each of the milestones was cleared by an inspection of the existing equipment and of the corresponding QA-documentation.

2.4 The 49 Prerequisites

Based on the PSAR, BAG requested additional details on 52 topics to be submitted prior to the start of irradiation. These topics comprise details on testing, radioactive inventory and radioprotection as well as additional data on release characteristics of volatile spallation products, in particular Po. Draining of the active LBE was a concern, which was eliminated by the project decision to freeze the LBE in the target at the end of the experiment. Organisational aspects and quality management issue were further topics which needed more detailed descriptions. Finally, two key issues were raised, which needed additional efforts and investments to comply with: fire protection and the definition of a reference accident case. These two issues will be dealt with in brief in the following.

3. Key Issues
3.1 Fire Protection

The use of the diathermic oil Diphyl THT® as a cooling fluid in the primary circuit to remove the heat from the target raised concerns about fire protection/prevention in the target head enclosure (TKE). This had not been an issue before at SINQ, where only heavy water had been used. Although we could almost rule out any risk during normal operation, since the flame point of the oil is close to the operating temperature, we may exceed this value during hot standby and in the case of accidents. In order to overcome this flaw, we opted for a system injecting nitrogen into the TKE and the beam transport vault (STK) to maintain the oxygen level below 13%. Tests have shown that the flammability of the oil can be successfully suppressed at that level up to 230C. Fig. 1 shows the equipment, which extracts nitrogen from compressed air by a membrane technique and continuously injects it into both rooms, which are kept at a small underpressure vs. the outside air. The amount of nitrogen to be injected is determined by the degree of underpressure and the leak rate of the rooms. On-site production seemed more economic than procurement of liquefied nitrogen.

Fig.1: LowOx-unit with compressor, puffer tanks, control racks and membrane unit (from left to right)

3.2 The Reference Accident Case

In the PSAR, a number of possible accidents and their impact on the dose to the public have been analysed. It was demonstrated that the limits imposed by the laws could be respected with the measures taken. In order not to check for a large variety of other possible cases, the authorities decided to define an all-encompassing reference accident case, which has to be mastered to get the irradiation permit. The accident scenario was as follows:

- The target boundaries are breached due to an internal or external event and the LBE is spread into the beam transport vault. The target head is damaged and a communication is created between the beam transport vault and the TKE.
- The oil loop is damaged and oil spills within the TKE and down the target. The oil catches fire.
- The outer barrier is breached by rupture of penetrating pipes or ventilation ducts.

Analysis of the scenario identified three source terms for the release of volatiles:

- the expansion volume of the target containing the noble gases and other a small fraction of other volatiles as mercury and polonium

- the LBE spill in the transport vault

- a small film of LBE adhering on the wetted surfaces of the target (0.4% of the total mass).

Due to the slow cooling of the target by the ambient air, the release of the volatiles from the film became the dominating source term.

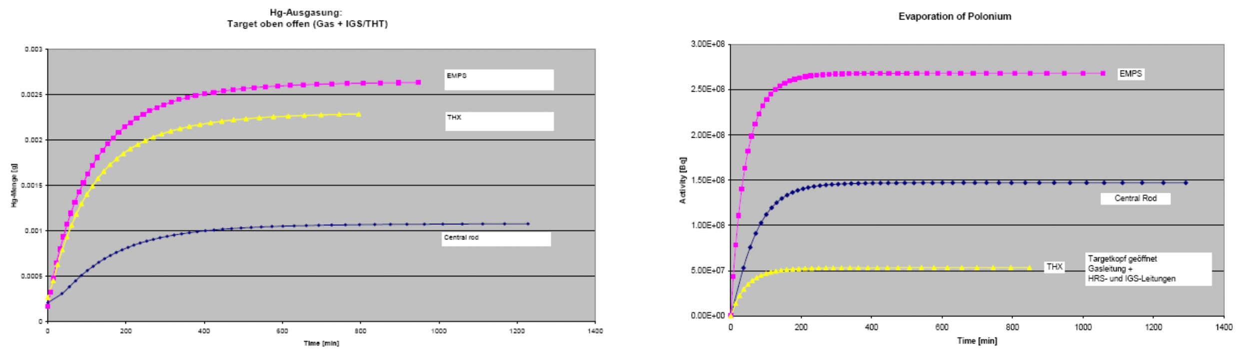


Fig.2: Release curves for Hg (left) and Po (right)

Fig. 2 shows the release over time from the target film.

Calculations of the impact to the public showed that only the internally initiated event, in which the outer barrier stays intact, could be managed with the planned upgrade of the ventilation system. For externally initiated events, such as earthquakes, additional upgrading was required, which consisted of

- equipping all ventilation ducts penetrating the barrier with earthquake resistant dampers, which close at a given seismic event

- strengthening the TKE outlet duct to resist the seismic event and connecting it to an autonomous, earthquake-proven filter unit, which automatically starts after the event. In addition, a mobile filter unit was kept as backup.

Fig. 3 shows the evolution of the maximum dose to the public in the case of such an event and the effect of the delayed start of the filter unit. It shows, that due to these measures, the dose can be kept below the stated limit of 1 mSv. Only after more than 60 min delay in starting the filter unit, the total dose would exceed the limit. With the ingestion dose not being relevant in this case, the grace time for starting the filter unit extends to days, which was considered acceptable. Fig. 4 shows the autonomous filter unit, which is equipped with an earthquake switch and a UPS.

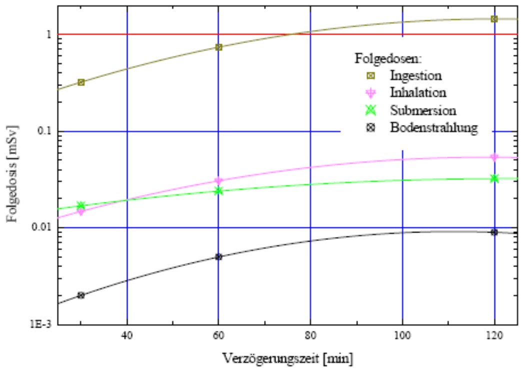


Fig.3: Dose to the public as a function of delay in start of the autonomous filter unit
Fig.4: Autonomous filter unit

4. Conclusion

The main goal to demonstrate licensibility of such experiments has been achieved. Although safety in design and operation is a prerequisite, the behaviour during severe accidents and the corresponding dose to the public dominates the licensing process. As expected, the control of volatiles is a key issue. A strong effort has to be placed to understand their release behaviour. Oil as coolant required additional efforts on fire protection. A good and open collaboration with the authorities was a key to the success.

WP2 – Target Testing

Task 2.1 Subsystem / Component Testing

1. The motivations for component testing are essentially two:

- to eliminate the uncertainty related to the operational behaviour and endurance of some components,
- to testify the real technical features of the components in order to perform a suitable and well balanced matching with the other principal parts of the target.

Since Lead-Bismuth represented one of the major R&D elements of the Megapie Project, in order to answer to the afore mentioned motivations, a certain number of component experiments in Lead-Bismuth was made.

2. Cooling Pin

The testing method of the cooling pin consisted in generating thermal power by an electric heating rod submerged by circulating LBE; transferring the thermal power from LBE to organic oil by means of the cooling pin; removing the thermal power from the circulating organic oil by means of an air cooler. The transferred thermal power and the pressure drop were measured at different regimes of LBE and oil flowrates. A collateral information consisted of the LBE transverse temperature difference which is accounted for in the assessment of the Nusselt number for LBE. The main results and extrapolation for the Megapie case (Pe = 865; Pe^0.8 = 223) are reported in figure 1. The LBE convection coefficient is a function of the 0.8 power of the LBE Peclet Number. At nominal conditions we infer a convection coefficient of 18100 w/°C*m^2.

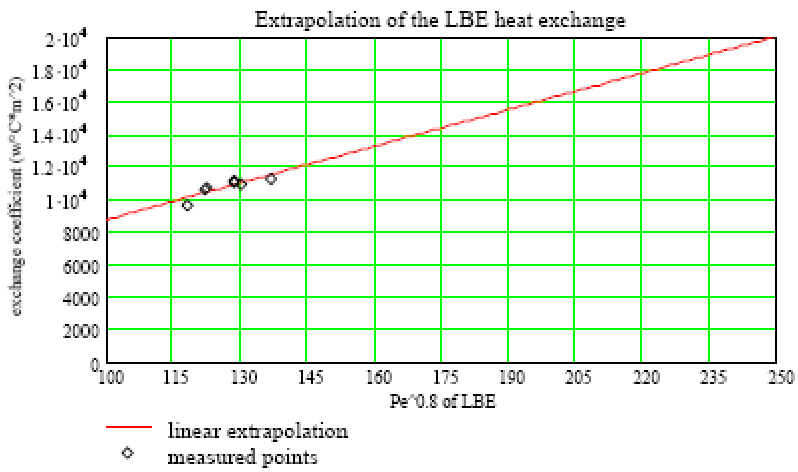


Fig.1 experimental data and extrapolation of LBE heat transfer coefficient in Megapie cooling pin.

3. EM main pump and EM bypass pump

For both pumps the testing method consisted in their operation, at different power, to circulate the LBE contained into a suitable double loop. The double loop was required to operate the pumps at the same time on two different circuits, one for the main pump and the other for the bypass pump. The hydraulic regime was varied by actuation of special flow chocking devices; the measurements of pressure head and flowrate were taken by accurate measurements systems.

The test stand specially developed for “Tandem EM Pump” testing, in flowing LBE, was specifically developed. The measured “Pressure -Flowrate” characteristics of the two pumps are reported in fig.2 (main pump) and fig.3 (by-pass pump). The maximum temperature of the coils did not exceed 440°C at the maximum regime, so respecting the specifications for the required life-time.

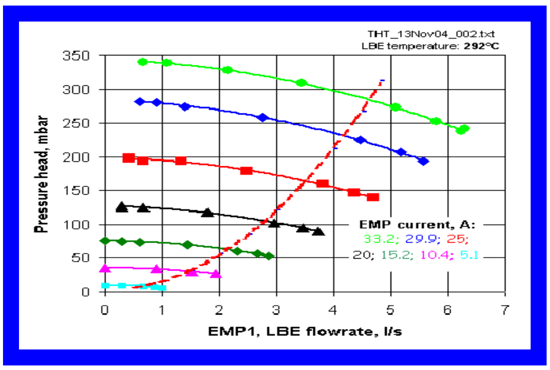


Fig.2. Main Pump measured characteristics

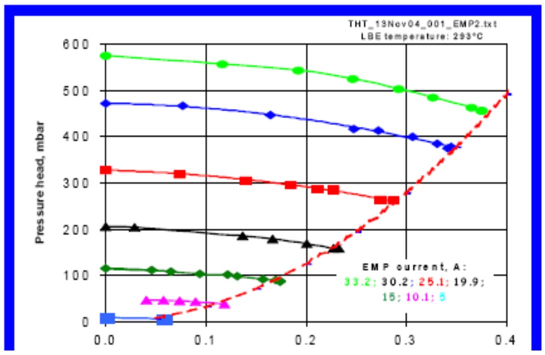


Fig.3. Bypass Pump measured characteristics

4. Target Window

The main goal of the Kilopie experiments is the experimental determination of the local convection heat transfer coefficients (HTC) over the area of the proton beam entry for different flowrates and different thermal fluxes. The local LBE flowrate is determined by complex mixing of main flow and bypass flow, therefore the real situation needs to be reproduced by experiments.

Some thermocouples monitored the bulk temperature of the downward LBE and after inducing an experimental thermal flux, the HTC was deduced by the the transversal temperature difference: difference between wall temperature and bulk LBE temperature. Since the important goal of the experiment is not only the point evaluation of HTC at selected positions but a real HTC 2-D map, an experiment, based on Infra-Red Thermography, was also performed.

The results show the predominant influence of the bypass jet flow for the cooling of the window. The maximum main flow alone achieves about 50% of the cooling effect that can be achieved by the bypass flow at representative flowrates. Even a small bypass flow has approximately the same cooling efficiency as a large main flow alone.

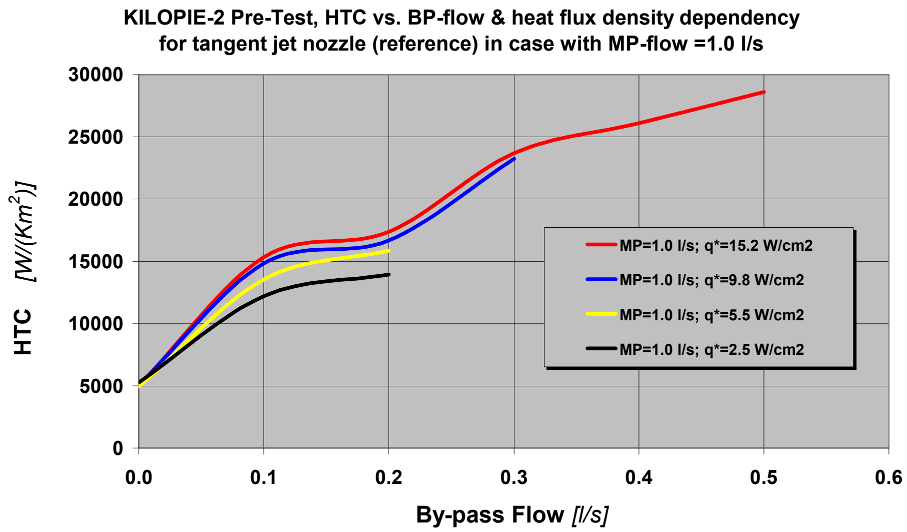


Fig.4 Results of IRT-KILOPIE-2 Pre-Experiment. HTC as function of the by-pass flow for different positions and main flow at 1.0 l/s

5. Instrumentation and Control

5.1 Beam safety and LBE leak detection

Systems which make sure that no liquid metal can leak out of the target are of utmost importance for the safety of the Megapie experiment. In the case of breaking the integrity of the lower target enclosure in the SINQ LBE would spill into the beam line and cause a major accident. While the impact to the environment could be kept within acceptable limits, the situation for the PSI SINQ installations would be very serious (Ref. Safety Analysis Report). Experiments with neutrons would suffer a long interruption.

There are only two ways to damage both the liquid metal container liquid metal (LMC) container inside the target and the safety hull around it, which could be imagined with some very small probability, namely:

- Improper intensity distribution of the incident proton beam
- Continuation of irradiation of the target while a significant quantity of liquid metal leaked into the Lower Target Enclosure (LTE)

To address both scenarios, rapid detection of deviating beam or containment conditions and, common to both, timely switching off of the proton beam is required (Ref. Test Plan). The MEGAPIE target can withstand a non-scattered fraction of 17 % of the nominal beam for an extended period of time. With a completely unscattered beam the peak intensity rises by a factor of about 25, which can cause the failure of the LMC and subsequently also of the LTE after 170 ms. With respect to leak detection the situation is not as critical. Conservative assessment yielded basic conservative requirements for these safety systems:

- The proton beam has to be switched off within 100 ms if 10 % of the protons by-pass Target E (corresponding to an increase in peak intensity by a factor of two)

- The proton beam has to be switched off within 1 second if ½ liter of LBE is collected inside the LTE (corresponding to a level of leaked liquid LBE where about 2 kW of beam power are deposited in this volume)

Beam safety devices newly installed to guarantee a correctly scattered beam at the Megapie target are:

- Transmission Monitor
- Slit KHNY30
- VIMOS

The footprint of the beam is determined by scattering of the protons in a so called Target E. The three independent systems not only provide redundancy but are also truly diverse in that they monitor distinct effects caused by the correct passage of the beam through target E (Ref. Schmelzbach). The beam current is reduced by 30 % after target E; this is checked by the current monitor (Ref. Duperrex). Non-scattered protons have a somewhat higher momentum than correctly scattered ones; they take a different path through the bending part of the beam line beneath the SINQ target (Ref. Rohrer). VIMOS monitors the glowing of a screen heated by the protons just in front of the spallation target; it looks for the issue in question most directly: no spot with high beam density is making the screen glow brighter than expected (Ref. Thomsen VIMOS)

LBE leak detection in the Megapie target relies on two systems (Leak Detectors):

- Thermocouple based LBE Leak Detector (main leak detector)
- Stripe Sensor LBE Leak Detector (ancillary device)

Thermocouples were found out to be the only type of sensor, for which a record of reliable performance in the harsh radiation environment inside a SINQ spallation target existed; standard solid state target are routinely equipped with such temperature sensors. In the Megapie target 6 normal and 9 pre-heated thermocouples were installed at the bottom of the LTE. Leaking metal would be detected as a sharp transient in the monitored temperatures, in case of a sudden substantial leak; gradually developing leaks with very small quantities of LBE would be detected by checking the actual temperatures to expectation values derived

from average beam conditions. Three stripe sensors consist of open condensers, where the impedance, both Ohmic and for high frequency, is monitored. Because of limitations for the possible qualification test of such a device the stripe sensors were classified as ancillary equipment and not as the primary leak detectors (Ref. Thomsen LD).
Redundant information on the status of the LBE containment can be derived from a number of different measurements in the target including cover gas and insulation gas pressure and the level of the LBE.

During the operation of the Megapie target, except for the failure of on non-heated thermocouple, the temperature-based leak detector worked fine. Unexpected behavior of the stripe sensors could be attributed to the effect of radiolysis product from a tiny leak of oil into the insulation gas volume around the liquid metal container inside the lower target enclosure. Even with the resulting strong and varying bias signal, a short circuit due to leaked LBE between the gold electrodes would have been detected.

Task 2.2 Integral Testing

1. MEGAPIE integral test: EMPS, target and other systems integration

Very important milestone before the target system was exposed to the irradiation experiment in SINQ was the MEGAPIE target integral test (MIT) in "Montagehalle" of PSI-West (September – December 2005). This was the first and the only time when the target and the main ancillary systems were tested together before integration in SINQ.
The main objectives of the MIT were: to integrate the liquid metal target and the ancillary system under a single MEGAPIE Control Module; to test and to verify the function of each ancillary systems, electromagnetic pumps system (EMPS) and the target heat exchanger (THX); to set the control parameters and conditions for the irradiation experiment in SINQ; to train the operators for the new liquid metal target.

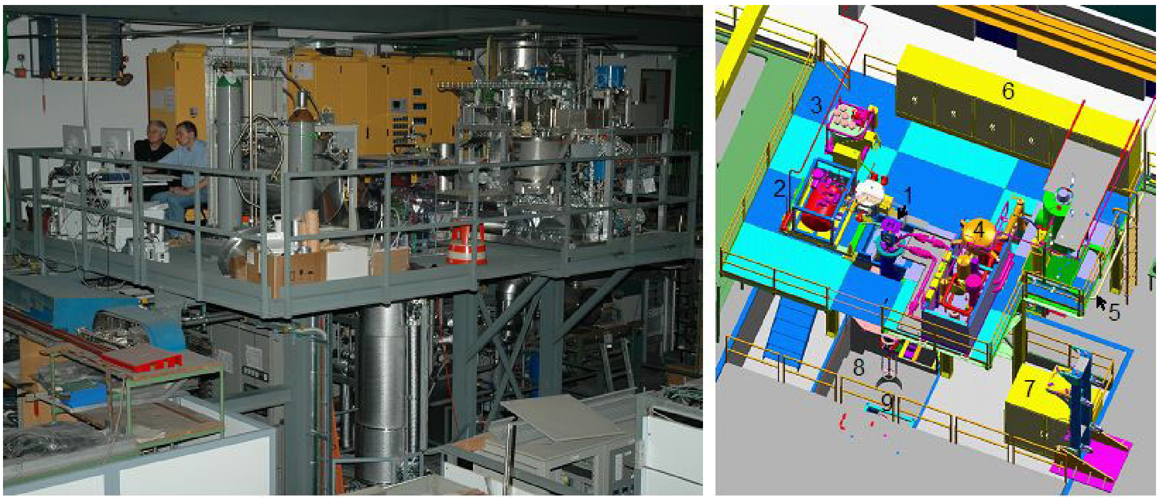


Figure 1. MITS, general view and arrangement of subsystems

The MEGAPIE integral test stand (MITS) general view is shown in Figure 1. The test stand extends over 3 floor levels. The elevated platform bears the target head (pos.1) with its connections to subsystems like PbBi tank (2), the cover gas system (3) and the heat removal system (HRS, pos.4) in the same geometric arrangement as in the SINQ. The control system cabinets (6) are in the back of the platform. On the ground floor and in the basement intermediate water cooling loop and electromagnetic pumps (EMP) power sources are situated.

In the initial stage of the MIT we for the first time filled and operated the target with PbBi, checked functions of ancillary, control systems and EMPS. We revealed and corrected several errors in the target control system and mistake in the electromagnetic pumps electrical connection caused reverse of PbBi flow in the target.

We tested and calibrated the by-pass electromagnetic flowmeter. For this purpose a special loop with a throttled valve and reference Venturi flowmeter was connected to the by-pass guide of the target. We found that performance of the flowmeter is not acceptable, relative error of the PbBi flowrate measurements caused by the pump leakage magnetic flux and PbBi temperature fluctuations reaches 70%. Simultaneously we made sure that the by-pass EMP develops specified LBE flowrate 2.5-2.6 kg/s for nominal pump current 22A.

During the target operation October 21 we observed a failure of the HRS control valve: the stem connecting the valve with actuator jammed in a guide. Analysis of the accident reasons revealed the incorrect design of the actuator support. We repaired the valve and improved the support design.

We checked the target and heat removal system thermohydraulic performances under scaled conditions simulating operation in SINQ with proton beam thermal power 580kW: The proton beam was simulated with 165kW electrical heater. The standard (700kW) water heat exchanger was replaced by low-power one (240kW). Water and oil temperatures and flowrates in the loops were adjusted and maintained in accordance with preliminary calculated scaled conditions.

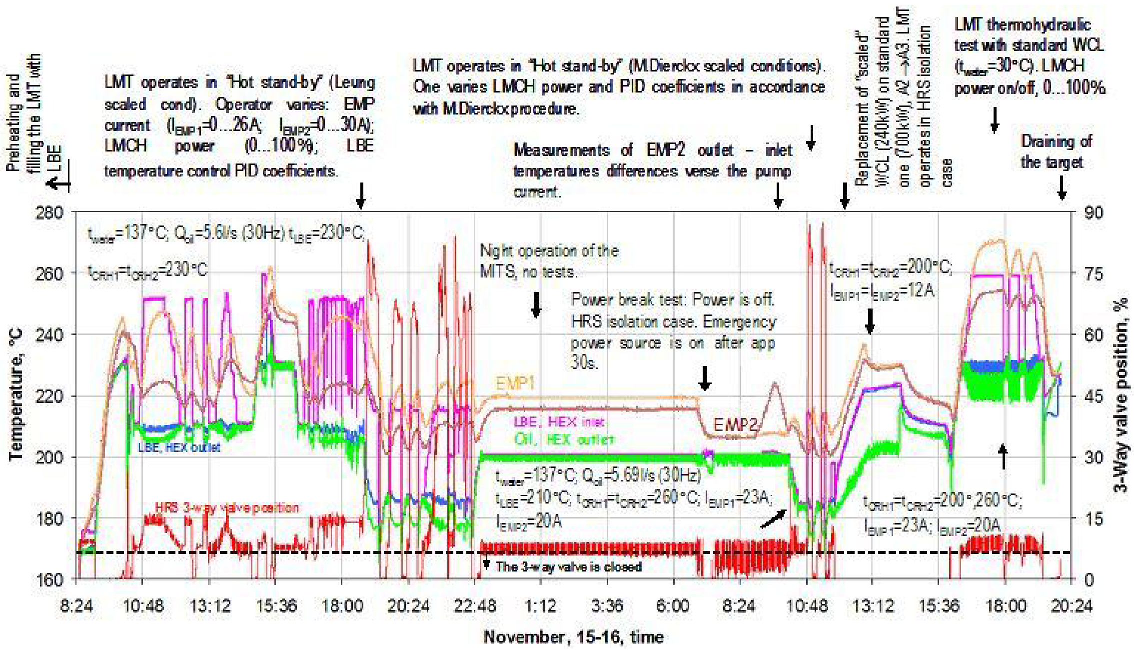
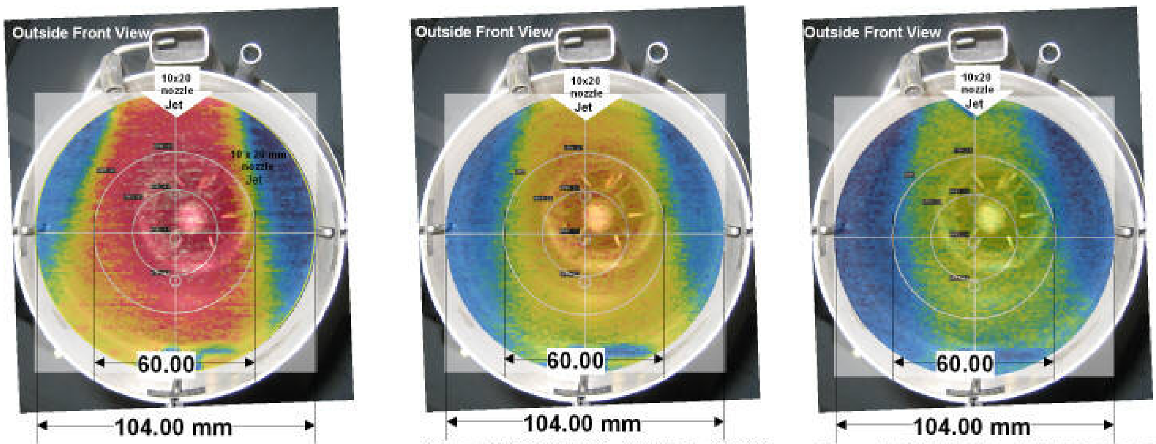


Figure 2. Time profiles of PbBi, oil, EMP temperatures and the HRS 3-way valve position

During the thermohydraulic test we checked the water – water, water – oil and oil – PbBi (THX) heat exchangers performances under steady state conditions corresponding to the full range of the proton beam power. We optimized PbBi temperature control procedure and made sure that the HRS is capable to maintain (±3°K) and comparatively quickly stabilize (during 1 – 2 min after the proton beam trip or interrupt) PbBi temperature in the target. We evaluated the PbBi flowrate from the target thermal balance and certain that the main EMP performance corresponds to the specification (approx. 37kg/s, 22A). Record of the target parameters from the test campaign November 15 – 16 is presented in Figure 2.



Case MP22BP30; MP/BP=11.09 Case MP22BP21; MP/BP=15.85 Case MP22BP15; MP/BP=22.18

Figure 3. Transparent diagrams for 3 flow cases during the experiment overlaid with photography of the jet nozzle and other insertions (MP22BP30 – current of the main EMP is 22A, by-pass – 30A; MP/BP=11.09 – ratio of PbBi flowrates is 11.09)

At the final stage of the MIT we carried out experiments on the target proton beam entry window cooling conditions verification with use of IR thermography and special surface heaters fixed on the window outer surface (methodology by J.Patorski, see 2006 PROCEEDINGS OF SPIE, Volume 6205). Goals of the tests were: Visualisation of the by-pass jet streaming from the nozzle across the window surface (see Figure 3) and determination of the heat transfer coefficients. The tests helped to define optimal by-pass pump currents ensuring reliable cooling of the window by the by-pass jet and check correspondence of the heat transfer coefficients to preliminary defined theoretical and experimental values.

We concluded that our test is successful: we entirely fulfilled the test program; revealed and corrected several mistakes in the target control and electrical connections; verified the target thermohydraulic performances; accumulated experience in the target operation. The project management made decision that the target is ready for SINQ.

Task 2.3 Overall Target Performance Assessments

1. Methodology

A spallation target like the MEGAPIE target is composed of numerous individual components directly linked with each other via electric, thermal and viscous boundary conditions acting on by orders of magnitude different time and length scales in a rather compact arrangement. Hence, a numerical simulation representing all transfer phenomena is far beyond the current numerical capabilities. Especially, due to use of a heavy liquid metal as neutron spallation source transport processes appear and components as well as the associated monitoring/control instruments are required for which at the present inadequate models or only insufficient descriptions are available. Therefore, regarding the overall target performance assessment the main emphasis was focused mainly on this unique feature of the MEGAPIE target. This especially to liquid metals dedicated aspect required several single-effect studies related to the basic functionality of the individual components, which is completely different to systems making use of conventional components for which availability and failure probabilities are well defined and described. Hence, for a unique installation like the MEGAPIE-target the overall performance analysis must be performed on two levels, on the one side micro-scale analysis and evolving from this a macro-scale analysis containing the component interaction. The micro-scale analysis considers on a kinetic rather local level each of the non-standard liquid metal components accounting for their reliability, availability, capability as well as monitoring and control aspects. Afterwards a macro-scale investigation by means of different system analysis codes was performed which incorporated experimental or numerical correlations found on the micro-scale. This rather standardized method considers the normal operation and their regularly in connection with accelerators occurring transients. But, also abnormal scenarios mainly associated with a failure of one or more active functional components was analyzed in the sense to define the time frame on which counter-measures must be initiated to maintain the MEGAPIE´s structural integrity.

2. Micro-scale analysis of the liquid metal components

2.1 Electro-magnetic pumps (EMPs)

The circulation of the lead-bismuth alloy within the target is generated by two independently controllable annular linear induction pumps (ALIPs) immersed in the upwards directed riser flow. While on the upper side located main pump (EMP) is serving the main flow towards the thermal heat exchangers (THX), the outlet bypass pump (EMP2) is guided through a ring shaped collector, which exits to the jet tube directed to the lower target shells. Both pumps depicted schematically in figure 1a have been independently calculated regarding their capabilities, the appearing thermal loads and their design margin in advance of the prototype using two different models a numerical by Freibergs & Platacis (2002 ,2003) and an analytical one by Stieglitz (2003). Both, in advance of the prototype fabrication conducted calculations differed about 10% from each other in the envisaged operational range. The design requirements in terms of flow rate and attainable pressure head are exceeded for the main pump by 30% and for the bypass ALIP even by a factor of two, which was confirmed by the prototype experiments by Dementjevs et al. (2003).

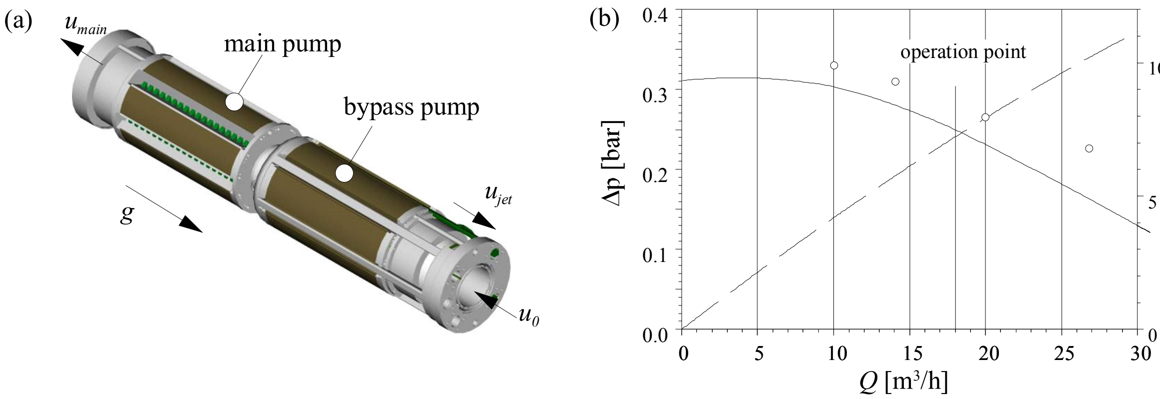


Figure 1: (a) sketch of the arrangement of the electromagnetic annular induction pump system. (b) comparison of the computed and measured pressure head as a function of the flow rate for the main pump (Stieglitz & Zeininger, 2005)

2.2 Liquid metal flow meters

The flow rate measurement is recorded for each stream by an electro-magnetic frequency flow meter (EMFM), for which the measurement principle is that the motion of an electrically conducting fluid within an imposed field B produces an induced field B' being proportional to the flow rate in the first order. This method involves an effect depending on the specific electric fluid conductivity □which is a function of the temperature. The attraction of the EMFM is that its indication is directly electrical, inertialess, continuous and no transducer is required; moreover, no electrical connections to or inside the flow channel are necessary. Despite this attractive feature the prototype and the integral tests conducted by Freibergs & Platacis (2006) and Jecabsons (2006) exhibited results of only qualitative nature. Buchenau et al. (2006) analyzed the EMFM in detail recently and were able to identify the potential failure source and countermeasures, which could not be embedded before the MEGAPIE-start up. Based on the prototype tests it is more reliable to assume the existence of a certain flow rate by the magnitude of the electric power supplied to the pumps and the temperature readings and the discrete positions. Since, especially the pressure flow-rate distribution as a function of the supplied electric power to the pumps is quite well known by the calculation and the prototype experiments within a threshold of ±15% this reading with the supplementary calculation can be used to establish the required flow rate combination between main and bypass flow rate in order to ensure a sufficient beam window cooling.

2.3 Liquid metal heat exchanger (THX)

The heat released in the LBE by the Proton beam is transferred through a secondary oil operated system via twelve equally circumferential spaced pin heat exchangers, in which in each the oil is pumped through a cylindrical tube u-turned and guided spirally upwards to a collector. The heat transfer in each pin from the helically flowing Diphyl-THT oil to the counter-current flowing LBE occurs in an annular small gap of 1mm width along a height of about 1.3m. Complementary to an analytical assessment using different heat transfer correlations a fully 3D computational fluid dynamic calculation was performed by Buono et al. (2001, 2002). The deviations between analytical descriptions and numerical solutions were differed by about ±25% depending on the different correlations available for LBE and oil. Since the heat transfer within the heat exchanger is mainly determined by the oil exhibiting a two orders of magnitude lower heat transfer coefficient the oil side determines the characteristics and therefore a geometrically scaled 1:1 experimental test was performed. It demonstrated that the CFD calculations yield a conservative assessment in terms of the heat transfer capability. The safety margin in terms of the heat transfer is more than a factor of two according to the technical capabilities of the secondary coolant side, so that a reduced performance of this loop does not yield to a failure of the target. Also the temperature limit of the oil with a boiling point of 380°C is by more than 150°C not reached.

Based on the CFD data a thermal stress analysis and fatigue calculations were performed using a finite element method (FEM) and the RCC-MX method (Cadiou, 2004). Both methods evaluating the structural integrity showed safety margins of a factor of two.

2.4 Thermal-hydraulics of the lower target shell

A unique feature of the MEGAPIE target represents the lower target shell, where the turbulent LBE-flow acts both as coolant and neutron source. The challenging task to design this lower target region without exceeding the material acceptable temperature, stress and irradiation limits demanded an extensive CFD study, first to generate a feasible set-up discovering the leading effects and in the later stage to optimize the aspect ratios and the detailed geometry matching the available pump capacities. In advance a benchmark exercise was launched studying the limits of different commercial and home made CFD codes, which are summarized in the report of Smith et al. (2002). The iteration steps to the final design are reported in Tak and Cheng (2001) and Roubin (2001-2003).

As a result, a sufficient cooling of the beam window in the MEGAPIE set-up is only achieved if the flow is appropriately conditioned. This is realized in a cylindrically shaped geometry, in which the main flow is guided in an annular gap downwards and then u-turned close to a hemispherical shell into a slanted riser tube. In order avoid stagnating fluid domains leading to unacceptably high window temperatures a jet flow is injected in direction of the lower shell. The absence of detailed turbulence models describing the heat transfer in liquid metals adequately required an extensive experimental program supporting the CFD data. Because a heat production scenario as in MEGAPIE is out of pile hardly feasible three experiments were defined clarifying the following issues

1. The isothermal water experiment HYTAS (Lefhalm et al. 2005) is studying the flow pattern, the velocity distribution by optical and acoustic measurement methods and compares them to numerical computations.
2. In the context of the heated jet experiments (Daubner et al. 2004, 2005) a heated jet is injected into the cold main flow investigating the thermal mixing in the lower shell. Since the temperature is acting as a passive scalar in such a set-up besides the thermal energy exchange in the lower shell also HYTAS data can be evaluated in a LBE configuration.
3. Finally, in the KILOPIE series the heat transfer from the beam window is evaluated by means of heat emitting temperature sensing surfaces (HETSS) simulating the heat release of the proton beam in the MEGAPIE beam window, see Patorski et al. (2001).

Of course, the volumetric heat generation cannot be simulated in out-of-pile experiments, but, they can be computed quite reliable also for low Prandtl number fluids once the flow pattern and velocity distribution is verified by the previous described series, see Smith et al. (2002).

In the figures 2 the HYTAS set-up as well as flow visualizations in the lower target shell obtained by laser light sheets (LLS) are shown for a main to bypass flow rate ratio of Qmain/Qjet=15 as it may appear in MEGAPIE. The illuminated regions in the LLS exhibit the streamlines of flow. The flow pattern detected is rather complex and composed of different single effects interacting with each other. As figure 2b shows a large scale recirculation zone is formed in the riser tube for $\phi=0°$. The combined momentum of jet and main flow leads to a strong deflection of the main part of the fluid flow towards the riser tube side opposite the nozzle exit. Here, an area with a high velocity jet is observed. At the boundary between the recirculation domain and high velocity region a set of counter-rotating vortices is visible, see figure 2c. The introduction of the jet extinguishes the small reciruclation area close to the inner side of the riser tube at $\phi=180°$ totally. Due to the jet flow the stagnation point is shifted to the opposite side of the nozzle. For Qmain/Qjet=15 it is approximately located at r=55mm, □=180°. A closer view on the light-sheet shows a peculiar feature of this flow rate combination with respect to the MEGAPIE application. The streamline in figure 2d shows that the jet hits the wall close to the centerline at about $r\approx20$mm, $\phi=0°$ and then detaches from the wall. However, in this part of the window the highest surface heat flux appears and thus requires the best heat transfer characteristics. A part of the jet re-hits the hemispherical shell again for $r\approx30$mm, $\phi=180°$.

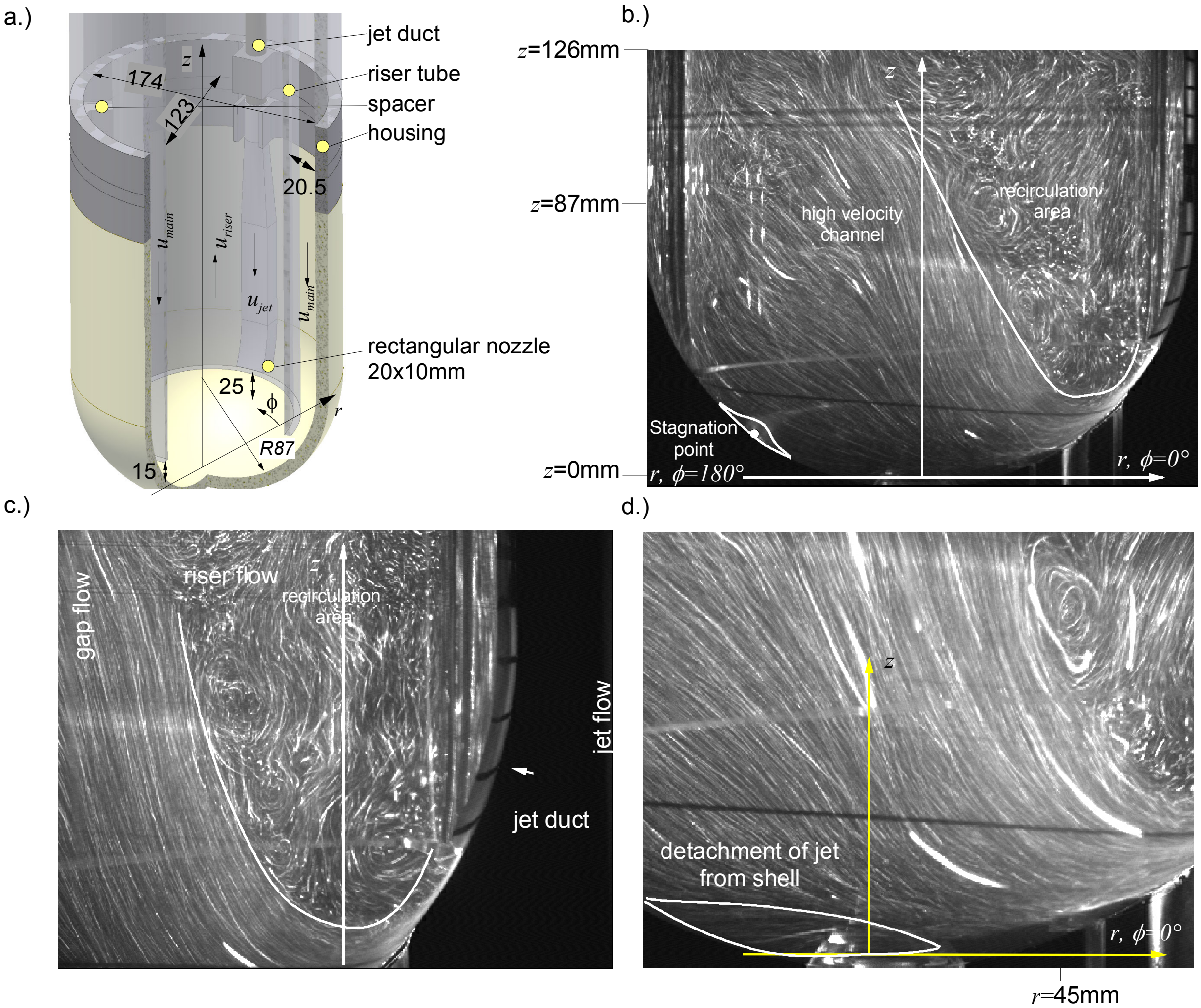
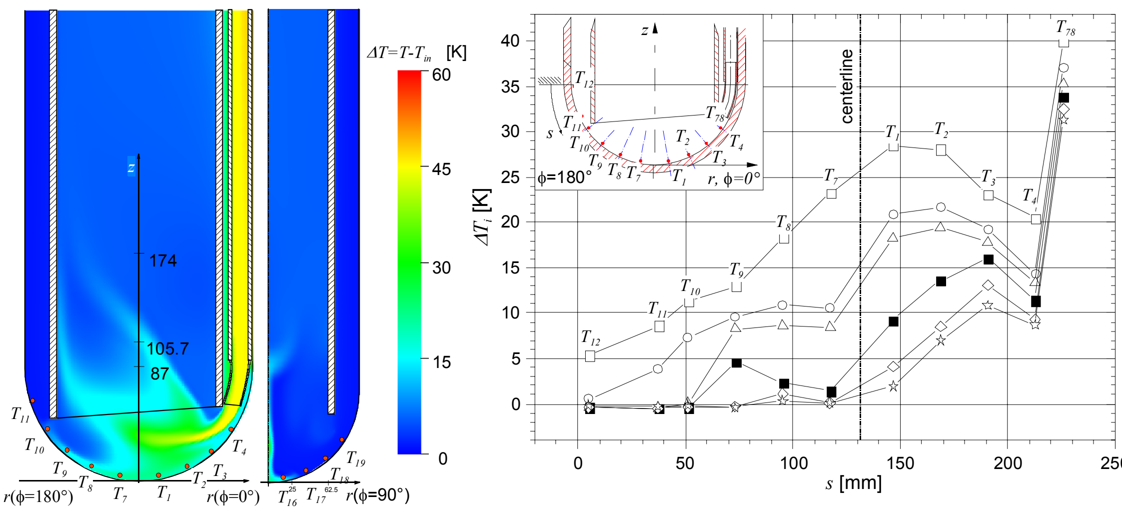


Figure 2: a.) Geometric dimensions of the HYTAS Set-up (Lefhalm et al., 2005) and introduced coordinate system. b.)-d.) LLS-Photographs of the fluid flow in the MEGAPIE-HYTAS water experiment for a slanted riser tube with a jet flow Q_{main}/Q_{jet}=15 for ϕ=0°-180°, Re_{main}=5.9·10^4 b.) Lower shell with different flow regions; c.) close view on the jet flow exiting the nozzle and the adjacent riser flow; d.) close-up of the streamlines at the shells center.

A parametric study regarding the flow rate rations exhibited that only for Qmain/Qjet≤12.5 the jet covers sufficiently the whole lower shell in both planes ϕ=0°-180° and ϕ=90°-270°.

For all MEGAPIE relevant Reynolds numbers the flow is strongly time dependent and the fluctuation intensities are of the order of the mean velocity. A comparison with the CFD data confirmed the established flow pattern in dependence of the flow rate ratio, however, the quantitative values differed considerably although a major effort was spent to realize far upstream an experimentally via LDA measured proofed symmetric and fully developed inflow of the main flow in the gap. The HYTAS experiments also exhibited that the MEGAPIE design is sensitive to marginal deviations of symmetry leading to the induction of secondary flows and to upstream history effects. However, their magnitude of 10-15% does not affect the general heat transfer capability beyond this range.

The heat jet experimental series fulfilled two aims. On the one hand it offered the capability to use temperature readings as a tracer to conclude on the velocity distribution in order to verify the HYTAS campaigns and on the other hand to investigate the thermal mixing of the flow in the shell region and downstream in the riser tube, which allows to determine the flow rate ratios for which the flow covers the shell, their stability and the temperature distribution in the riser tube. This thermal missing is important since almost all power is generated as volumetric heating and an insufficient mixing could lead to a distortion of the riser by differential thermal elongation with all the accompanying consequences. The figures 3 show computed and measured temperature distributions along the lower shell. The figures 3a, b show that the fluid mixes nearly complete in short distances downstream the riser tube, while the figure 3c exhibits that only for flow rate ratios of Qmain/Qjet≤12.5 the jet covers the whole lower shell confirming the HYTAS data. The minimum flow rate required to transfer the heat was found to be about 60% of the main pumps capacity at nominal power. All flow pattern detected were time dependent, but the temperature fluctuations recorded were all larger than 1Hz not leading to a fatigue of the beam window by thermal cycling, see Daubner et al. (2005).



(a) (b) (c)

Figure 3: Calculated temperature difference contours for Q_{main}/Q_{jet}=15 in the (a) *r-z*-plane(ϕ=0°-180°) and (b) *r-z*-sector (ϕ=90°). c.) Measured temperature distribution as a function of the geometry adapted coordinate *s* in the plane ϕ=0°-180° for different flow rate ration Q_{main}/Q_{jet}. (□) Q_{main}/Q_{jet}=7.5, (O) Q_{main}/Q_{jet}=10, (Δ) Q_{main}/Q_{jet}=12.5, (■) Q_{main}/Q_{jet}=15, (◊) Q_{main}/Q_{jet}=17.5 and (ζ) Q_{main}/Q_{jet} =20.

The remaining issue to be clarified by the KILOPIE series was the determination of heat transfer coefficient h at the fluid wall interface of the beam window facing the proton beam. Therefore, the HETSS technique was developed (see fig. 4), with which both the heat flux can be simulated and the temperature distribution can be evaluated. Moreover, the HETSS technique enables a visual access to the heat transfer capability by infrared-thermography.

The experiments were carried out both at PSI and at the KALLA loop at the Forschungszentrum Karlsruhe. The confirmed that a sufficient heat transfer coefficient is obtained for almost the same flow rates as detected in the heated jet series.

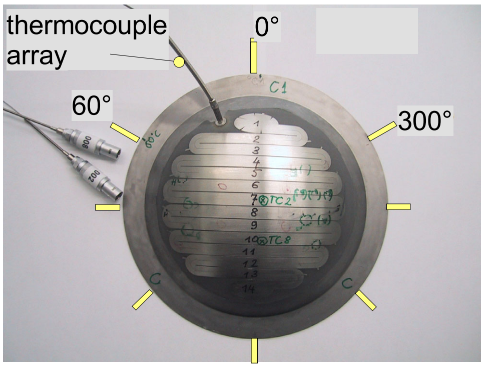


Figure 4: Experimental set-up of a HETSS attached to a 0.5mm stainless steel shell together with thermocouples for the MEGAPIE design.

3. Macro-scale analysis of the whole target

Essentially new compared to conventional water cooled solid targets are the liquid metal components of MEGAPIE and their connected secondary and ternary systems. The previously described micro-scale analysis formed the basis of the macro-scale analysis describing the component interaction. Of course, the LBE system is connected to the general heat removal system (HRS) and is thus significantly influenced by it. However, the HRS consists of components commercially available components (pumps, valves, flow meters, piping and geometries) operating with standard media (oil and water) so that in this context a detailed micro-scale study was not performed. Each of these components was described in its performance and characteristics with the data delivered by the manufacturer or determined in experimental campaigns.

The HRS is designed as a triple loop system composed of the primary LBE loop containing the target, the pumps, the lower target shell and a 12 pin oil/LBE heat exchanger. The oil operated intermediate cooling loop (ICL) consisting of pump, a three-way valve and an oil/water heat exchanger (IHX) is connected to the water cooling loop (WCL), which transfers itself the thermal energy to the coolant plant located in the building.

The macro-scale analysis on the energetic level was performed with two different system analysis codes (Relap-5 and ATHLET), which demonstrated their capabilities and validity in numerous benchmarks. Related to the MEGAPIE the functional diagram depicted in figure 5 was developed and different scenarios were calculated.

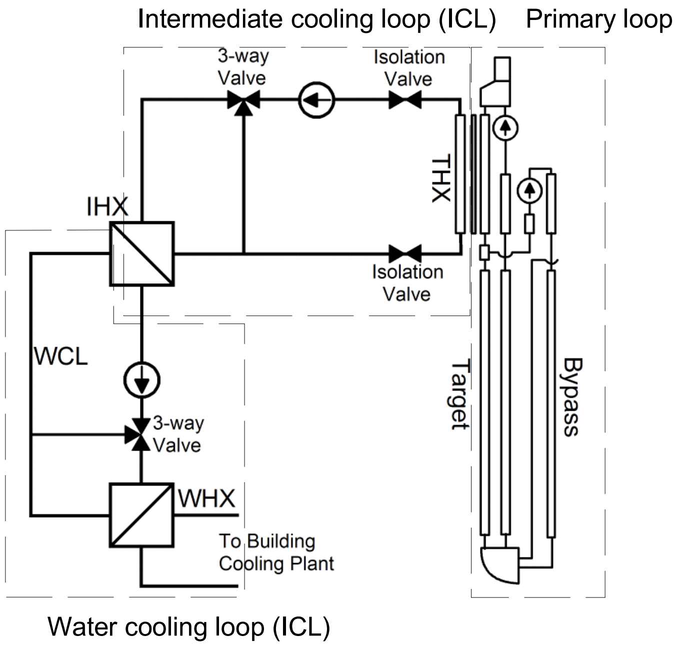


Figure 5: Functional diagram of the MEGAPIE heat removal system (HRS).

Apart from fission reactor simulations spallation targets face very often transients associated with the operation of the accelerator. Typical incidents are beam trips, beam interrupts and beam restart which require a dedicated strategy to operate the target within an acceptable temperature range.
A beam trip is a scenario, in which the beam gets abruptly lost and the power released within the target decreases immediately to zero. After at maximum 20s the beam recovers linearly in a ramp of 20 seconds to the fully power. Such a regularly many times a day appearing incident requires in MEGAPIE only an adjustment of the three-way valves in the ICL and WCL, see Chen and Cheng (2005). More delicate is a beam interrupt in which the beam is shut off instantaneously and for a substantial time no beam recovery is obtained. It requires about 100 seconds after the event a supplementary heating of the LBE in the primary system, which is realized by switching on a 22kW strong electrical heater located in the center of the riser tube of the target. Associated with this procedure the lowest temperature in the target will appear at 118s after the incident with about 220°C which is considerably above the melting point of LBE.

Besides the normal operation transients accidental situations were analyzed, which are initialized by the failure(s) of individual active components in the HRS. According to this analysis the associated countermeasures are specified and the events were classified into three main groups:

- The target can be operated with marginal loss of performance.
- The target can be restricted operated for a certain time
- The target must immediately shut down.

Since the component interaction is treated on an energetic level locally an excess of the maximum tolerable temperatures or stresses may occur, which depends on the accidental event and induce additional failures. In order to avoid an additional effort to consider these cases again in terms of a micro-scale analysis temperature/stress margins as well as time thresholds were defined, for which no local excess can be expected. For instance regarding the time scale a failure of an active component like a pump (loss of flow accident) should require counter-measures in terms of the time periods to react, which are considerably larger than the detection time by the programmable logic controller (PLC) installed in the MEGAPIE target (1second) plus the active operation of the counter-measure. Among the large amount of potential incidents defined in advance several rather MEGAPIE specific are and the related action formulated below.

- Failure of the main electromagnetic pump (EMP). If the proton beam remains on buoyant convection leads immediately to a remaining flow rate of 20% of the nominal one. The temperatures at the beam window and in the riser tube increase by 100°C within 120seconds. This is the time scale for which a restricted operation is possible before a shut-down is initiated.
- Pump trip in the ICL. About 5 minutes after the trip the LBE temperature rises up to 500°. Then the oil in the ICL starts boiling. Also this event allows a restricted operation before a shut down is performed.
- Pump trip in the WCL. Here, a boiling of the water is calculated to occur 90seconds after the event allowing a restricted operation.
- Loss of one or more heat sinks while the proton beam remains on. In this case of incident in principle three critical temperatures appear, the limiting LBE temperature (TLBE=550°C) and the boiling temperatures of the oil (Tboil,oil=341°C) and water (TH2O=140°) at the individual pressure levels. Such an incident occurring at nominal power level leads first to a boiling of the oil after about three minutes. Within this time frame the target can be operated with restricted performance.
- Also an unregulated cooling is potentially possible in absence of the proton beam, which may cause a local LBE freezing. However, the thermal inertia and heat capacity of the MEGAPIE design is so large that even in case of using the full cooling capability of the ICL and WCL a potential solidification could conservatively assessed earliest after 230s, which is considerably larger than the operational time of both PLC and all active components.
- Also the three-way-valves (TWV) may fail in the sense of a blockage or an electric supply defect. In case of the TWV defect in the WCL with a pass through of only 30% of the nominal flow rate MEGAPIE can still operate without any changes. More problematic is the TVW in the ICL, for which a proper functioning is required requiring

at least a pass through of at least 60%, because the thermo-physical properties drastically change close to the boiling point increasing the uncertainty threshold.

The analysis of all considered time dependent potentially occurring MEGAPIE modes either the normal operation transients but also the abnormal or accidental events led to time frames easily to be detected by a PLC and/or an operator. None of these scenarios is at the edge of the inertia of the participating individual components, which documents the robust thermo-mechanical design of MEGAPIE.

The system analysis was confirmed by an out-of pile experiment called MITS, in which the whole HRS of MEGAPIE was checked with the same components as later to be set into operation in the SINQ-facility of PSI, except for the lower target shell. In the MITS experiments (Medium Integral Test Stand) the heat production in the lower target shell was simulated by a set of cylindrical heaters generating a relevant portion of the power of the SINQ to conclude from MITS on the future in-pile experiments, see Leung et al. (2005,2006). All individual tests allowing a transfer from the MITS to the in-pile experiments showed minor deviations in the range of ±10% from the predictions of the system analysis codes, if the individual measurement devices in the sub-systems were calibrated properly.

4. Summary

Within this study the overall performance of the MEGAPIE target is assessed with the main focus on the LBE components unique to this installation. This refers both to the micro-scale analysis conducted on a rather local detailed study and a macro-scale analysis treated on an energetic level describing the component interaction of the LBE system with the subsequently arranged oil and water loops for different prescribed normal and abnormal operation transients.

Related to the micro-scale analysis all major LBE components like the pumps, the pin heat exchangers (THX) and the lower target shell show safety margins of at least 25% or with respect to their maximum capability. A set of out-of-pile experiments for each component conducted at prototypical dimensions and MEGAPIE relevant temperatures and flow rates, which all were supported by CFD and stress analysis codes demonstrated and proofed this threshold. Only the electro-magnetic frequency flow meter showed an unacceptable performance for several reasons very recently explained. However, a reliable operation can be ensured if the electric power supply is monitored during operation with an acceptable accuracy.

The computational analysis of all pre-defined transient operation scenarios either occurring during normal operation but also in an accidental mode revealed acceptably large time scales for the detection and the resulting initiation of countermeasures to operate the target safe. The simulations were performed using different codes and showed in comparison with a benchmark experiment conducted with the MEGAPIE-module except for the lower target shell a reasonable agreement. Despite the fact that during the detailed CFD, stress and design calculations to built the individual components several single-effect studies exhibited discrepancies to the corresponding experimental tests none of the found disagreements added up to a large uncertainty factor, which demonstrates the robust and reliable design of the MEGAPIE-target.

WP3 - Synthesis

Task 3.1 Feedback for Pb-Bi Target Design Studies

In table 1 the question sheet, concerning the MEGAPIE target, prepared in the frame of the PDS-XADS project is reported:

Section 2: Requested actions and results	Milestones
Reporting on evaluation of Megapie operation with respect to	
Operation of Megapie:	FP 6
- Operation and instrumentation of a spallation target cooling system	
- Analysis of target LBE and target atmosphere	
- Review of physical data and models	
- Influence of typical accelerator operation on target material behaviour	
- Experience with target handling	
- Long term behaviour of spent targets in the target store	FP6 and later
Post irradiation:	FP 6 and later
- Radiation damage of structure materials	
- Mechanical properties of structure materials as function of radiation damage	

The MEGAPIE experiment is considered a key experiment for the demonstration of the feasibility of a high power liquid metal spallation neutron target for future ADS based on a window concept. The design of the target and design related research studies as well as the testing and first beam-on experience is covered by the MEGAPIE-Test project within the 5th Framework Program. Within the FP6, Eurotrans project, the Post Test Analysis (PTA) of the experiment and the operational data collected during the execution is going to be performed.

During the irradiation experiment measurements are made to operate, survey the safety limits and to monitor the status of the target and the corresponding ancillary systems. The target is equipped with almost 100 thermocouples, 2 pressure sensors, 2 flowmeters, neutron flux monitors and 3 leak detectors. Thus several hundred signals are extracted from the target and the other systems. In addition samples of the cover gas, the diathermic oil and the cooling water will be taken.

In the design phase, the behaviour of the target system during the different operational (steady state at different power levels, transient during beam trips and interrupts or start/stop operations) and off-normal conditions has been assessed by modelling. This predicted behaviour has been verified during the component and integral off-beam tests and the corresponding models have been adapted.

The goal is to analyse and interpret the data collected during the irradiation experiment and dedicated tests and compare them with the predicted performance. The PTA will thus provide unique information on the operational performance of the target and the capabilities to understand and predict it.

The topics to be analysed and the expected results are:

1. Neutronics: neutron flux measured in the central rod just above the spallation zone and thermal neutron flux measured at the neutron beam ports will be used to verify the calculations made with MCNPX and FLUKA codes and benchmark neutron yields
2. Heat removal system: The system behaviour has been modelled by RELAP5, SIMULINK and ATHLET. The behaviour will be analysed based on these models
3. Beam window cooling: The flow conditions at the beam window have been simulated by CFD/LES modelling and experimentally. The temperature measurements close to the beam window will allow to verify the assumptions made in the models and deduce the beam window temperature, which cannot be measured during the experiment
4. Cover gas analysis: will provide information on the spallation product production and the release characteristics of the volatiles
5. Radiation Monitoring: will provide information on the radiological implications of a liquid metal target in comparison to the currently used solid targets
6. Analysis of specific components and their performance with time allows to conclude on their suitability for the intended operation in the harsh environment.

These are in particular

a. Target
b. EMP and Flowmeters
c. Target Heat Exchanger
d. Leak Detectors
e. Instrumentation
f. Beamline Diagnostics
g. Heat Removal with diathermic fluid
h. Fill & Drain System

Post irradiation examination

The Post Irradiation examination is not included in the FP6 time frame. The PIE programme is under preparation and it includes the issues which are addressed in the QS (i.e. Radiation damage of structure materials; Mechanical properties of structure materials as function of radiation damage, corrosion behaviour of structure materials under neutron and proton irradiation and spallation product analysis in the LBE).

Furthermore, the safety aspects treated to prepare the MEGAPIE irradiation (e.g. Po behaviour in the liquid metal, solid state expansion of the LBE, etc.) have been of valuable support to prepare the irradiation of structural materials in contact with LBE, in experimental reactors. This irradiation program is running under the FP6 project, Eurotrans.

Task 3.2 and Task 3.5: Planning of MEGAPIE irradiation phase and beam-on reporting

1. Getting ready for beam

After a systematic check of the functionality of the target system and of the ancillary components, the target was preheated and filled with LBE. Off-beam operation in the Hot Standby Mode; i.e. at a LBE temperature of 230C over 17 days was used to recheck proper functioning of the system and compare it with the integral test behaviour. The preheating temperature of >140C in the target bottom was achieved within about 1 day. For this, the Cover Gas Pressure was raised to 1.75 bar Ar, the IG gas pressure was reduced below 1 mbar and the LTE cooling water flow was reduced. The LBE and the filling pipe temperatures were set at 250C. Readiness for filling was declared on July 28. Filling was then accomplished within about an hour. 926 kg of LBE were filled into the target. During adjustment of the IG gas (0.5 bar He) a sparking phenomenon destroyed 4 of the 6 central rod main heaters, which reduced the available heating power from 22 kW to 8.6 kW. With the 7 kW heat input from the pumps, LBE could be easily maintained at temperature. We decided, however, to reduce the IG pressure to about 20 mbar to reduce heat losses. Hot Standby operation was used to verify pump flow direction and performance, recalibrate the flow meters and the Flow Measuring System based on heat balance, determine the heat losses to the second enclosure and simulate the isolation case (loss of heat sink). We also tested the Control System, checked the safety systems and experienced operation in manned and unmanned operation. Finally, the F&D vessel was disconnected and removed from the TKE. During this period, the final upgrade of the ventilation system and the installation of the inertisation system were accomplished followed by a final inspection of the authorities. The TKE and beam transport vault were closed and an oxygen level <12% was established. On August 11, the permission for irradiation was obtained by BAG. Readiness for beam was declared and PSI gave the permission to go on beam.

2. The first protons

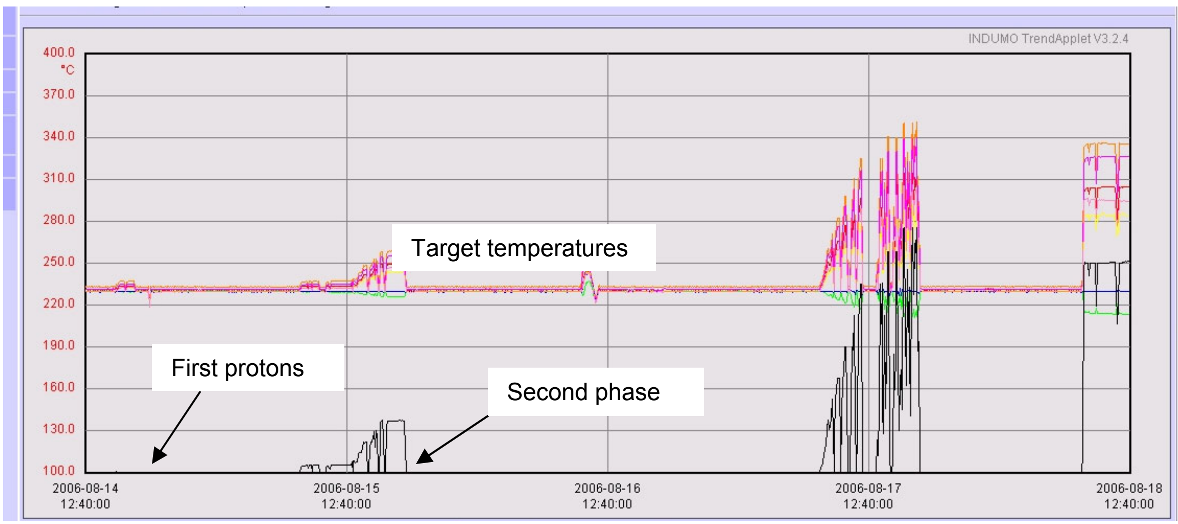
On August 14, 2006 first protons were sent onto the target. According to the start-up plan, the proton current level was limited at 40 μA over a period of 3.5 hours, yielding a total charge of 60 μAh. This phase served to measure the first neutrons on the beamlines and perform an end-to-end test of the beam interlock triggered by the slit system. In addition, a check of the response of some target systems, like the LBE leak detector and the neutron flux meters in the central rod, on the proton beam, a first mapping of the dose rate distribution in the TKE and delayed neutron measurements were made. The beam power of 29 kW had only a very small effect on the thermal balance in the target. Since all systems performed as expected, the go-ahead to higher power was given.

3. Measurable effects

In a second phase, one day later, the beam current was ramped up in 50 μA-steps to 250 μA within 7 hours and was kept at that level for about 2 hours. With 100 kW thermal power, the heat input corresponded to almost that provided by the heaters at MITS, a corresponding temperature rise was observed in the target and the heat removal system started to operate. The temperature control could well be followed during short intermittent beam stops. After an accumulated charge of about 800 μAh, the beam was stopped and fresh gas samples of the cover gas were extracted. In addition, a second set of γ- and n-dosimeters was retrieved from the TKE. Since the systems performed according to expectations, it was decided to ramp the beam up to full power.

4. Approaching Full Beam Power

In the third phase, 36 hours later, the beam current was ramped up in 100 to 150 μA-steps up to 0.9 mA in a period of 4 hours. A further increase up to almost 1.2 mA caused triggered a large amount of beam trips caused by beam instability. This was a first severe challenge for the target, which was mastered perfectly. Total beam operation in this phase lasted about 9 hours. During this period measurements of the neutron flux meters in the central rod, of the VIMOS beam monitoring system were made. The LBE leak detectors were now fully heated



by the beam and their margins could be adapted. Radiation mapping around the SINQ target block and in the neutron guide hall was performed. In this period a charge of 2.7 mAh was accumulated. Since the target operation was as expected, it was decided to continue normal operation under continuous observation (manned control room), but limit the beam current at 1 mA in order to assure a beam stable as possible. Fig. 1 shows the evolution of the beam on SINQ during the 3 phases and the corresponding temperature response within the target.

5. Operational Experience

Normal operation was started the next day, on August 18, at a maximum beam current of 1 mA. After a break over the weekend, operation resumed until Wednesday for the regular service shutdown of the accelerator. Resuming operation on Thursday, we switched to unmanned operation given the very satisfactory performance, but kept the current limited to 1mA until August 31. After that we continued to operate at a 1.25 mA peak current until September 28. After that, the peak current was raised to maximum (what value?)by maintaining stable beam operation.

6. PTA

A comprehensive analysis of the operation has started as part of the DEMETRA Domain of the EUROTRANS IP of the European 6th Framework Program with the aim to interpret the collected data during operation and dedicated tests and to compare them with the predictions. The topics to be analyzed comprise

- Neutron flux measurements in the central rod above the spallation zone, at the neutron beam ports and in the two irradiation stations are used to verify the MCNPX and FLUKA calculations and benchmark neutron yields.
- The system behaviour is re-assessed and compared with the model predictions made with the RELAP5 code. Other codes may be used for comparison. The heat transfer characteristics of the target heat exchanger will be analyzed in detail.
- The beam window cooling has been simulated using CFD. Temperature measurements close to the beam entrance window will be evaluated to conclude on the validity of the models.
- The overall system behaviour over 4 months of operation will be analyzed and the performance and degradation of individual components will be assessed.
- The data collected during operation will be processed and stored and made available for other evaluations on request.

Task 3.3 Planning of MEGAPIE Post Irradiation Examination (PIE) Phase

PIE of MEGAPIE target

The significance of the MEGAPIE project is not only due to such that it is the first liquid metal (LBE) target being working at one-MW level, but also because it will provide valuable materials data for the R&D of future ADS.

In the MEGAPIE target, the components in the lower part (heavy irradiation region) of the target were made of either martensitic steel T91 or austenitic steel 316L (SS 316L). Both steels are the main candidate materials for the European XT-ADS and the irradiation damage and LBE corrosion effects of these steels are intensively studied in the EU FP6 EUROTRANS program. By the end of operation, the MEGAPIE target will receive about 3 Ah proton charge. The peak proton fluence at the beam window will be about 2×10^{25} p/m^2. Plus the contribution of neutrons, the maximum irradiation dose at the bean window will be about 8 dpa. Such an irradiation experiment, a relatively high dose of high energy proton and neutron irradiation together with corrosion of flowing LBE, is unique and will not be available in near future elsewhere. Therefore, the PIE of these components should be as detailed as possible.

The PIE of MEGAPIE includes surface inspections, microstructural examinations, chemical analysis, and mechanical tests. Surface inspections will be performed for studying LBE corrosion of the steels by means of optical microscopy, scanning electron microscopy, electron probe microanalysis etc. Microstructural examinations will be done to get information of microstructural changes induced by irradiation using transmission electron microscopes. Chemical analyses will also include radiochemical analyses using ICPMS, XRD, γ- and α-spectrometry techniques to reveal both radioactive and non-radioactive elements. Mechanical tests will be such tensile, bending and small punch tests to evaluate the degradation in mechanical properties caused by irradiation and LEB corrosion and embrittlement.

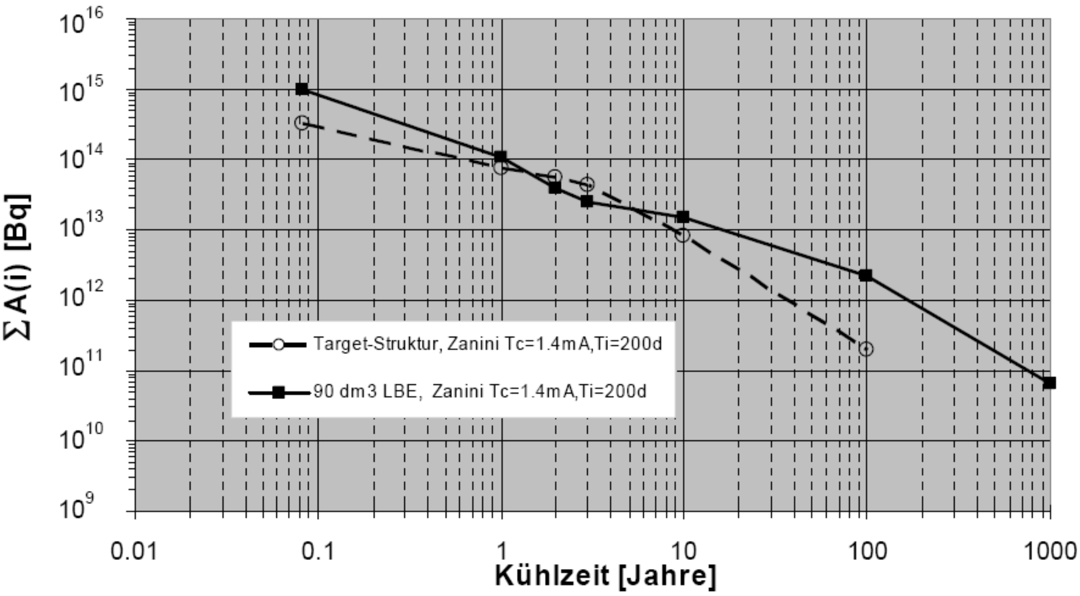
The PIE of MEGAPIE target has been planned such that the different components will be investigated to different extends. For the important parts of the liquid metal container and flow guide tube, where the irradiation dose and temperature are high, detailed surface inspections, microstructural examinations, chemical analyses, and mechanical tests will be performed. While for those components such as the tubes in the EM-pump and heat exchanger, where irradiation effects are negligible, only LBE corrosion will be inspected. For a special component, LBE, detailed chemical and radiochemistry analyses are planned to obtain the information of the production, transportation and precipitation of spallation transmutation and corrosion products.

The PIE will be carried out by a joint effort of all the MEGAPIE partners. The tasks could be distributed to the partners who have proper experimental facilities, hot-cells and relevant equipments. The PIE will be started in 2009 when the samples are extracted from the components in hot-cells at PSI. The main part of the PIE should be completed in 2009 and 2010.

Task 3.4 Planning of Decommissioning Phase

1. Activation calculations and nuclide inventory

The MEGAPIE target will be activated in a mixed radiation field consisting of protons, fast and thermal neutrons as well as pions. The nuclide inventory for the different components of the target has been calculated using the particle transport code FLUKA [4]. In order to estimate the buildup and decay of nuclides, FLUKA was coupled to ORIHET [5]. Details on the total nuclide inventory can be found in [6]. The largest amount of activity in the target is located in the 90 liters of LBE. Since the LBE is circulated, this activity is distributed homogenously. For the structural materials one finds a dependence of the activity on the location. Materials in the lower part of the target are more highly activated than parts from the upper region. The total activity of the target as a function of cooling time is depicted in Fig. 3. The dimensioning and design of shieldings were made using Microshield [7].



2. Target transfer in the SINQ hall

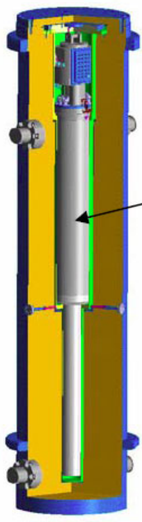
After the planned irradiation time of 200 days the MEGAPIE target will stay in the irradiation position for approximately 30 days. During this time the LBE is solidified under controlled conditions. In addition short lived radioisotopes will decay.

The decay heat after 30 days is calculated to be 300 W. Spontaneous melting of the LBE dur-ing subsequent handling can therefore be ruled out (melting temperature of LBE is 123 °C).

All cooling circuits and the cover gas system will be drained, rinsed and dried. All connections of the target to the supportive systems will be removed. The exchange flask mounting needed for the transfer will be installed in the TKE and in the target storage site (TL).
The transfer of the MEGAPIE target from the target block to the TL will be done with the SINQ exchange flask (Fig. 4). The procedure is the same as if a solid target would be transferred. As soon as the target is in its final storage position in the TL the exchange flask, all mountings and supportive structures will be removed. The MEGAPIE target will stay in the TL – actively cooled – for approximately 8 months.

3. Transport to ZWILAG

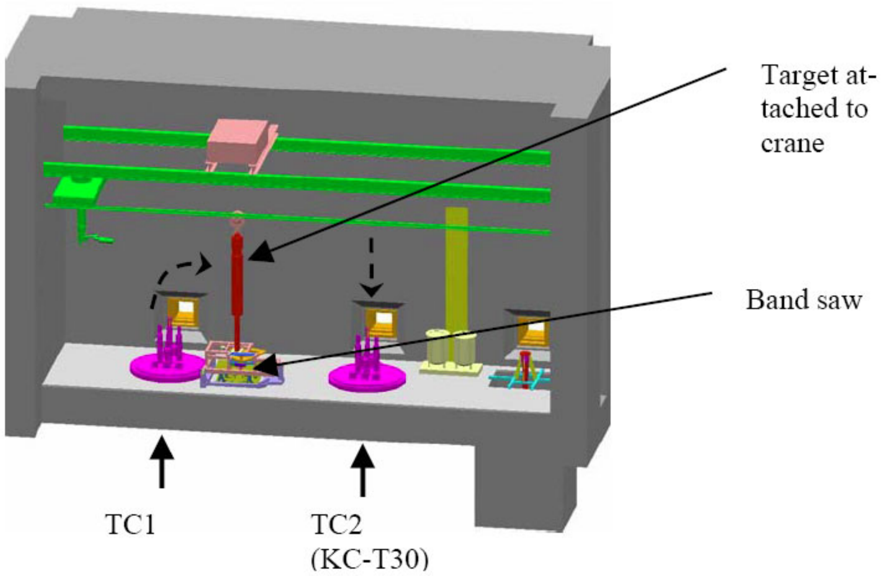
For operational and radiological reasons it is not possible to dismantle the MEGAPIE target in the hot cell on the west side of PSI. Therefore, the target must be transported to the hot cell of ZWILAG using a specially designed steel container (TC1) (Fig. 5). This container consists of 2 main parts. The inner part of the container serves as an enclosure of possible contamination and the outer part is shielding. The container is designed to directly connect to the hot cell at ZWILAG.
Using the SINQ exchange flask the MEGAPIE target will be moved from the TL into the transport container. The transport container (TC1) will then be lifted on a special transport vehicle and transported to ZWILAG. The vehicle will pass over the Aare bridge, driving on a public road for approximately 1 km before the site of ZWILAG is reached. Therefore, the transport is subject to the regulations for the transport of radioactive materials ADR/SDR class 7 [8]. ZWILAG assumes the role of the carrier and attends to the quality assurance for this transport.



As the A2-Index of the calculated nuclide inventory after 9 months cooling time is approximately 3000, a certified type B container would be required for the transport. However, PSI will apply for a transport under special arrangement at the authority (HSK) accordant to chapter 1.7.4 in ADR. The application will describe measures to be taken as a compensation for the specifications of the ADR/SDR that are not met. These concern in particular the integrity of the transport container after a drop from 9 m height, a water immersion check, drop test and a heating test. In addition, due to the high exposure of the MEGAPIE target a safeguarding plan will be prepared by PSI.

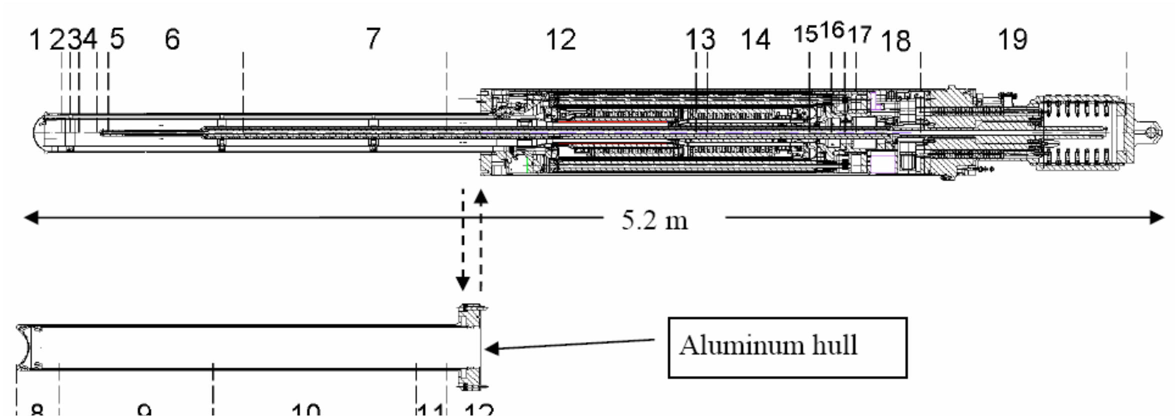
4. Dismantling of the MEGAPIE target

In the hot cell of ZWILAG the target will be cut into pieces. 92 % of the total weight of the MEGAPIE target will immediately be packed in steel containers and prepared for final disposal. The remaining 8 % are transported to the hot cell on the PSI East for further investigation. These 8 % of the weight which correspond to 15 % of the total activity of the target will be disposed together with other waste from the hot cell of PSI East.



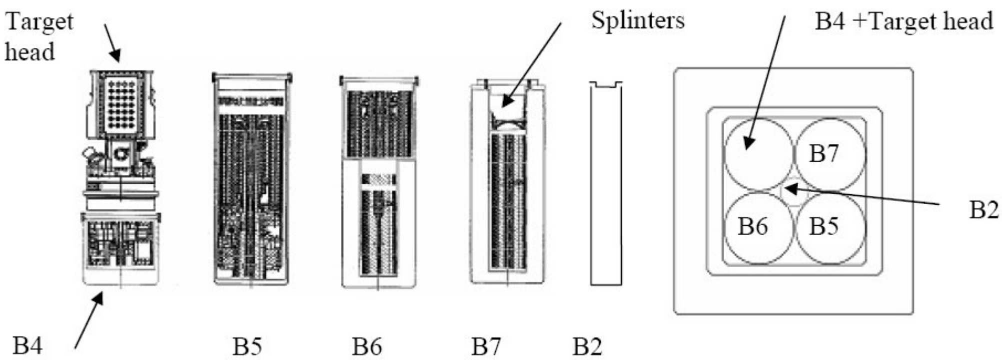
First the container will be docked to one of the locks of the ZWILAG hot cell and the MEGAPIE target will be pulled into the hot cell with the crane. The target is placed in a special rack and the aluminum hull is screwed off the target. Subsequently the target is lifted in a special separator equipped with a band saw and cut piece by piece from bottom up (Fig. 6). The sawing of the MEGAPIE target will be done without any cooling. Splinters are going to be collected with a suction system. The cutting positions for the 19 pieces are shown in Fig. 7.

The target is cut into 7 pieces until the flange of the aluminum hull is reached. The hull is then attached again to the target and cutting is continued.



5. Packing

The cut target sections are cleaned and packed as tight as possible into “primary containers” – see Fig. 8. These “primary containers” consist of steel, have a cylindrical shape and possess reinforced shielding if necessary. Containers that are filled with aluminum or parts that had contact to LBE will be closed with a lid that is then remotely welded on the container. This inhibits the production of hydrogen due to contact of aluminum with concrete. In addition a spread of α – contamination is ruled out. The primary containers will be packed into a stan-dard PSI concrete container – KC-T30 (TC2) which is located at the second lock of the hot cell in ZWILAG (see Fig. 6). The TC2 is closed with a concrete lid and is brought to the “Umladebucht”. Here the container can remotely be filled with concrete and the lid sealed. To avoid interim storage of the raw waste PSI is aiming for an ELFB1 to be available at that time. The filled container will reach IP2 limits for the transport after about 15 years. The calculated α - activity will be below the limit for α – toxic waste (20 kBq/g) after ten years.



It is intended to store the container for 1 or 2 years in the MAA of ZWILAG. An immediate transport of the waste to the BZL is not possible because of the high exposure of the con-tainer. According to recent calculations of dose rates to the public after a plane crash, storage in BZL would be possible 3 years after end of irradiation [9].

4. Assessment of Results and Conclusion

The objective of the MEGAPIE-TEST project was the development and validation of the design and the operation of the heavy liquid metal spallation target MEGAPIE producing innovative know-how and expertise.

The main milestones, as reported in the MEGAPIE-TEST work programme were:

- To reach the necessary detailed knowledge of the mechanism of heavy liquid metal spallation target
- To check for show stoppers
- To gain data base and experience
- To verify the feasibility of a 1 MW target and to propose design strategies for a large scale ADS spallation target.

Large and detailed knowledge on the mechanism of heavy liquid metal spallation target has been gained by a step-by-step approach. First a conceptual design and associated R&D activities have been conducted in order to validate all design choices. The second step was the experimental characterisation of the single components and subsystems, working on prototypes. Finally, before irradiation an out-of-pile test of the real target has been performed.

In this context the MEGAPIE-TEST consortium has gained a large experience to work at a multi-laboratory level and in a multi-disciplinary frame on a one well defined project. In addition, important experiences have been gained in the structuring of the collaboration between a design team and R&D teams active in the different laboratories and disciplines and to face and solve safety and licensing issues related to the experiment. Examples that can be given here are e.g. the selection of the neutronic codes FLUKA and MCNPX and their validation by ad hoc experiments performed outside the MEGAPIE project. The experimental validation of the beam window cooling capability with water and LBE experiments is a further example. Moreover, the detailed analysis of all experimental data on materials behaviour under MEGAPIE relevant conditions helped in assessing the selected containment materials.

Moreover, in Europe there is already a wide knowledge in the area of heavy liquid metal technology, as it is reported in the OECD/NEA Handbook. With the MEGAPIE experiment, this knowledge has been enlarged to the handling of heavy liquid metal systems under irradiation in a proton field, which is an important step forward for the development of sub-critical but also critical transmutation systems cooled with HLM.

By taking into account the results achieved so far within the MEGAPIE project, it became evident that important step forward has been obtained in the area of neutronics and thermal-hydraulics code validation for HLM systems. Moreover, an increased confidence has been gained in the procedures needed to assess the structural materials and in the area of component (e.g. pump systems, coolability of beam window) testing.

The activities and results obtained during the integral test and the irradiation phase of MEGAPIE are valuable from a scientific, operational and organisational point of view. For instance, the first analysis of neutronic data gathered during the irradiation of MEGAPIE has confirmed the calculations performed during the design phase, i.e. with the MEGAPIE target and increased neutron flux is obtained with respect to previous solid target irradiated in SINQ.

Moreover, the integration of the target and the ancillary systems, the first operation and then the execution of the integral test and the irradiation allowed getting confidence with the start-up and routine operation of this innovative system as well as to train the operators.

The next steps of the MEGAPIE project are a comprehensive analysis and interpretation of data collected during irradiation. This activity is financed within the 6th Framework Programme Eurotrans.

Furthermore, after the dismantling of the target an extensive PIE is foreseen to complete the evaluation on the components and materials performances under irradiation and thus complete the assessment on liquid metal neutron spallation target.

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WP1 – Target Development

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WP2 – Target Testing

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