MEGAPIE SPALLATION TARGET: DESIGN IMPLEMENTATION AND PRELIMINARY TESTS OF THE FIRST PROTOTYPICAL SPALLATION TARGET FOR FUTURE ADS

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Abstract

The MEGAPIE target has been designed, manufactured, set-up and fitted with all the ancillary systems on an integral test stand in Paul Scherrer Institute for off-beam tests dedicated to thermo-hydraulic and operability tests, carried out during the last months of 2005. It was then moved for final implementation to the SINQ facility, with the ancillary systems, for irradiation that is foreseen to be carried out from July to December 2006. The results obtained during the integral tests have shown that the target was well designed for a safe operation and allowed to validate the main procedures related to fill and drain, steady-state operation, and transients due to beam trips.

A start-up procedure has been developed, and the operating and control parameters have been defined.

The already performed steps, conceptual and engineering design, manufacturing and assembly, safety and reliability assessment, integral off-beam tests, start-up of irradiation at SINQ PSI, then later decommissioning, post-irradiation experiments, and waste management will provide the ADS community a uniquely relevant design and operational feedback.

Introduction

A key experiment in the accelerated-driven systems roadmap, the MEGAwatt PIlot Experiment (MEGAPIE) (1 MW) was initiated in 1999 in order to design and build a liquid lead-bismuth spallation target, then to operate it in the Swiss spallation neutron facility SINQ at Paul Scherrer Institute (PSI) [1]. It has to be equipped to provide the largest possible amount of scientific and technical information without jeopardising its safe operation. Whereas the interest of the partner institutes is driven by the development needs of ADS, PSI interest also lies in the potential use of a LM target as a SINQ standard target providing a higher neutron flux than the current solid targets.

The MEGAPIE project is supported by an international group of research institutions: PSI (Switzerland), CEA (France), FZK (Germany), CNRS (France), ENEA (Italia), SCK•CEN (Belgium), DOE (USA), JAERI (Japan), KAERI (Korea) and the European Commission.

Many studies supporting design, carried out by the project partners, addressed specific critical issues in the fields of nuclear physics, materials, thermal-hydraulics, mass and heat transfer, structure mechanics and liquid metal technology, using analytical, numerical and experimental approaches.

Moreover, it was necessary to perform safety and reliability assessments in order to demonstrate the integrity and operability of the target; and thus to develop the licensing process. To reach this goal, the design had mainly to consider the structural integrity of the target for normal operating conditions, transient situations and hypothetical accidents, and the capability to evacuate the deposited heat with the heat exchanger and the electromagnetic pump system.

The target was designed by CNRS, CEA, PSI and IPUL, the main components of the target were manufactured in France by ATEA and sub-contractors and in Latvia (EM pumps), then assembled in France. The ancillary systems were designed and manufactured in Italy (Ansaldo, Criotec) and Switzerland (PSI). The target was shipped to PSI in May 2005.

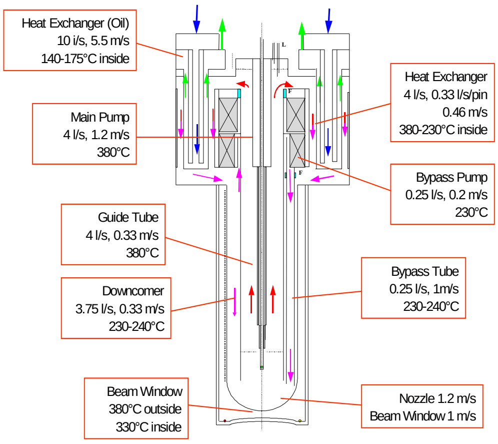
After a description of the target and its main characteristics, the studies and experiments performed prior to irradiation will be described. Finally the next steps will be introduced.

Main characteristics of the MEGAPIE system

The main constraint was first to design a completely different concept of target in the same geometry of the current spallation targets used at PSI. The second one was to develop and integrate two main prototypical systems: a specific heat removal system and an electro-magnetic pump system for the hot heavy liquid metal in a very limited volume. The third one was to design a 9Cr martensitic steel (T91) beam window able to reach the assigned life duration. The reasons for the choice of lead-bismuth eutectic (Pb44.5%-Bi55.5%) and of T91 (0.1C, 0.32Si, 0.43Mn, 8.73Cr, <0.01W, 0.99Mo, 0.19V, 0.031Nb, 0.029N, 0.24Ni) for the beam window which is the most critical component of the target were recalled in [2].

A sketch of the target and its main properties are shown in Figure 1. It is designed to accept a proton current of 1.74 mA, although the probable current in 2005 may not exceed 1.4 mA. Thermal energy of 650 kW deposited in the LBE in the bottom part of the target is removed by forced upward circulation by the main inline electromagnetic pump through a 12-pin heat exchanger (THX). The heat is evacuated from the THX via an intermediate diathermic oil and an intermediate water cooling loop to the PSI cooling system. The cooled LBE then flows down in the outer annulus (4 l/sec). The beam entrance window, welded to the lower liquid metal container, including the beam window, both

Figure 1. MEGAPIE target



manufactured with T91 ferritic/martensitic steel, is especially cooled by a cold LBE jet extracted at the target heat exchanger (THX) outlet and pumped by a second EM pump (0.35 l/sec) through a small diameter pipe down to the beam window. A main flow guide tube separates the hot LBE up-flow from the cold down-flow in the outer annulus; it is equipped with a number of thermocouples to monitor the temperature field in the spallation zone. Attached to the top of the tube is the electromagnetic pump system, designed by the Institute of Physics in Latvia (IPUL), consisting of a concentrically arranged bypass pump and the in-line main pump on top of it. Both pumps are equipped with electromagnetic flow meters. The pump system is surrounded by the THX, designed by CEA, and consisting of 12 pins concentrically arranged and 1.20 m long, where the lead-bismuth eutectic is cooled by diathermic oil Diphyl™ THT. The heat is removed from the THX by an intermediate oil loop designed by Ansaldo. An intermediate water cooling loop designed and built by PSI then evacuates the heat from the oil loop. By this concept, any interaction of LBE with cooling water is eliminated. A central rod is inserted inside the main flow guide tube carrying a 22 kW heater and neutron detectors, provided by CEA. The lower liquid metal container, the flange of the guide tube and the heat exchanger constitute the boundary for the LBE, called the hot part. The second boundary is formed by three components, which are separated by from the inner part by a gas space filled with either 0.5 bar He. The gas will stay enclosed during the experiment and only the pressure will be monitored. The components are the:

- *Lower target enclosure*, a double-walled, D_2O-cooled hull made of $AlMg_3$. The containments of the current targets are made of the same material and experience on its radiation performance exists up to about 10 dpa. The enclosure is designed to contain the LBE in the case of a number of hypothetical accidents, which would lead to the breach of the inner container. The enclosure is flanged to the upper target enclosure.

- *Upper target enclosure*, formed by a stainless steel tube. This tube is welded to the target head.

- *Target head* consisting 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 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 from the target head and allowed to expand with the temperature. The components also contain 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. The main characteristics of the target are recalled in Table 1.

Table 1. Main characteristics of MEGAPIE target

Beam energy	575 MeV	Deposited heat	650 kW
Beam current	1.74 mA (design)	Cold temperature	230-240°C
Length	5.35.m	Hot temperature	380°C
LBE volume	About 82 l	Design temperature	400°C
Weight	About 1.5 t	Operating pressure	0-3.2 bar
Wetted surface	About 8 m^2	Design pressure	16 bar
Gas expansion volume	About 2 l	Total flow rate	4 l/s
Insulation gas	0.5 bar He	Bypass flow rate	0.25 l/s

For the target operation it was necessary to design, manufacture and connect to the target various ancillary systems: heat removal system, cover gas system, insulation gas system, LBE fill and drain system, beam line adaptations, etc. The description of these ancillary systems has been reported in [3].

Integral MEGAPIE steps

In order to demonstrate the target characteristics and safe operability prior to irradiation in 2006, the target manufactured was shipped to PSI and installed, fitted with all the ancillary systems, which had already been commissioned, and has been tested out-of beam. The integral tests consisted of the following:

- filling of the target with lead-bismuth eutectic;
- checking the operability of the main components of the target;
- checking and calibration of the instrumentation (mainly flow meters);
- carrying out the thermo-hydraulic tests with a heater to simulate heat deposition;
- performing transients for qualification of heat removal and control systems.

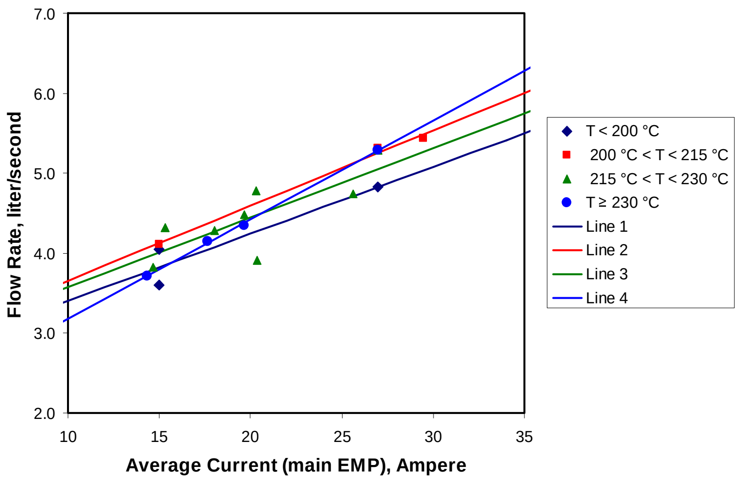
After the first tests, the preliminary results of the target commissioning were positive: mechanical and electrical structures, heat removal system, electromagnetic pumps operate properly, except some difficulties with a flow meter. In Figure 2, the characteristics of the main EMP have been established; the other main operation parameters of the target in steady state are under validation.

Four thermal-hydraulic tests were conducted during the integral tests and provided a good set of the data for the system characterisation.

Control of the target was designed for efficient and safe control, with the following requirements:

- keep the target (window) at a constant temperature of 230°C, not too low to have a safe margin before freezing, not too high to limit thermal stress on the heat exchangers;
- limit temperature excursions during beam transients: beam on/off operations, beam trips and interrupts.
- assure stable target temperature in three reference operating cases: isolation (target isolated from heat removal system), hot standby (awaiting beam operation) and full beam power.

Figure 2. Main characteristics of the main EMP, provided by IPUL (Latvia)



During the integral tests, it was seen that the characteristics of the oil three-way valve are highly non-linear (Figure 3), and that the target heat exchanger performance was better then expected (20 to 40% according different evaluations); the main consequence is that only 40% oil flow through oil/water heat exchanger is required during full beam power operation (Figure 4).

Figure 3. Oil three-way valve characteristics

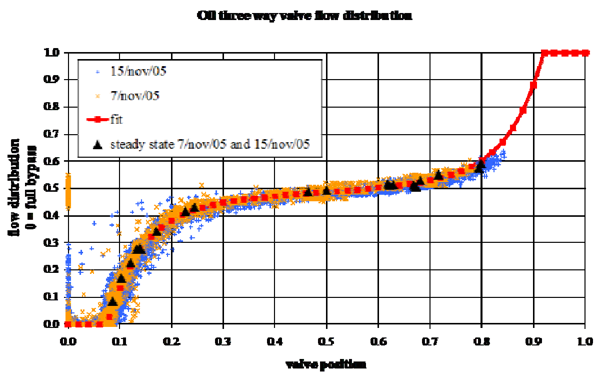
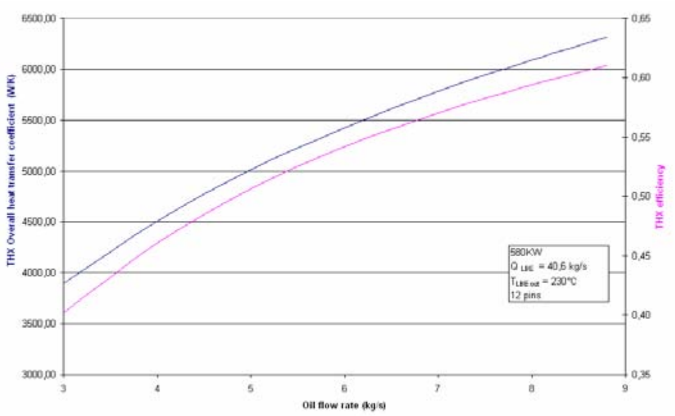


Figure 4. Influence of oil flow rate on heat transfer coefficient



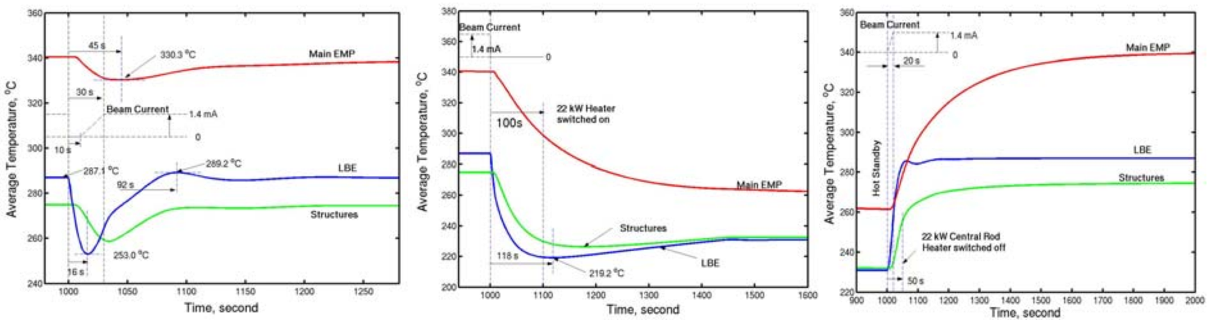
The final conclusion of the integral tests and associated studies was that the overall system will be able to adequately remove the anticipated 600 kW heating of the SINQ proton beam.

Due to the non-linear characteristic of the oil three-way valve, the performance of the temperature control was then improved. Close to the standard PI controller, a digital compensation has been implemented. Further improvement can be reached by implementing a feed forward control based on known beam power.

The analysis of the system characteristics was performed with the main assumption that the main LBE flow rate is computed from the heat balance of known power input.

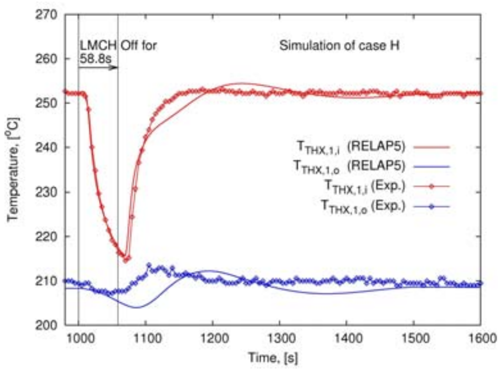
Figure 5 shows a test simulating a beam trip. The average temperatures of LBE, target structures, and the main EMP are reported: a) during beam trip; b) during beam interrupt; c) restarting from hot standby. The figures demonstrate, even before final checking of the control system, the capacity of the heat removal system to react to the transient situation.

Figure 5. Simulation of a beam trip (from [4])



The transient characteristics of both the “protected” and “unprotected” beam trip are simulated by RELAP5, and the results agree well with the experiments, as shown in Figure 6.

Figure 6. Comparison of experimental and calculated temperatures for an unprotected trip



Thus the RELAP model has been more or less verified though it still could be improved first by a better estimation of the thermal masses of LBE and structures (Cp,…), and also of the heat transfer coefficients (using the temperatures of the main and bypass EMPs).

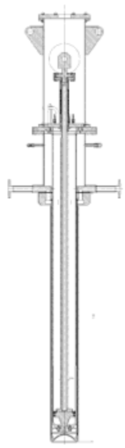
After the integral tests, the bypass flow conditions were still to be determined; nevertheless it was demonstrated that the system had sufficient capacity to cope with about 600 kW of heating in the target and flexible to the changes, though the operating conditions might differ from the predictions.

The experimental data of the LBE oil thermal exchanger of the target were analysed, with analytical heat exchanger calculations [global model, ε-NUT, and numerical model (1-D), finite volumes].

For each of the four campaigns, the computed values complied with the corresponding experimental results. The maximum variance between calculations and experiments was very low, and below the accuracy of the model is about 20%. Thus, the THX heat transfer model used to its design was validated, even if some uncertainties hang over flow rate assessments. A parametric study of sensitivity has also shown that large margins exist on the THX thermal exchange capacity.

Close to the integral tests performed with the target, a full-scale leak test (FSLT) (Figure 7) was performed at PSI with the goal to validate the design of the lower target enclosure (LTE) under worse-case leak conditions, and the leak detector system, implemented in the lower part of the LTE.

Figure 7. Dummy instrumented target for integral leak test



It was demonstrated that the LTE was able to contain LBE. This experiment also allowed to check the leak detector system which had the following main requirements: detect a leaked LBE quantity below 0.5 litres within 1 second with a very high reliability, 100% detection efficiency, a very low false alarm rate, and radiation and temperature resistant.

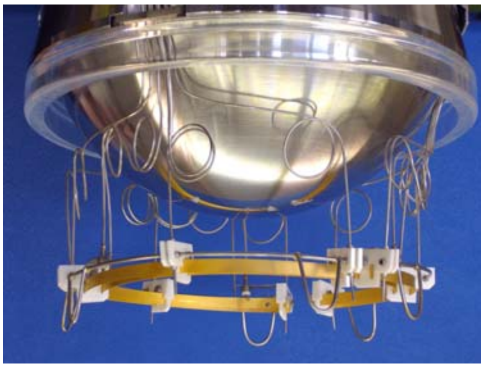
In fact, two different sensors were implemented:

- thermocouples (nine individual and independent sensors, three electrically pre-heated) as main leak sensor;
- stripe sensors type "AC impedance" (three separate units) as shown in Figure 8.

The leak detector system was fully validated during a full scale leak test.

Complementary to the FSLT, within the framework of the general safety assessment, the potential consequences of three simultaneous failures of the target shells were investigated independently with the MATTINA and SIMMER codes, able to model the hypothetical interaction between lead-bismuth alloy and D_2O, inducing water vaporisation and target pressurisation (target can withstand $P < 30$ bar). The accidental sequence was evaluated, vapour explosion was excluded and the structure integrity was demonstrated, the maximum pressure being maintained largely below 30 bar.

Figure 8. Leak detector system



In support of the future post-test analysis phase after irradiation, large eddy scale simulations by CEA are underway to analyse the instability, close to the window. The objectives of the simulations with the CEA TRIO-U-VEF parallelised code are to asses the level of temperature and velocity fluctuations near the window, to gain a more "realistic vision" of the actual flow behaviour and to know qualitatively the variations of the temperature signals in real or virtual thermocouples, and consequently to give realistic data for thermo-mechanical studies aiming to demonstrate the integrity of the T91 window.

An overall reliability study has also been performed by US DOE-LANL and CEA, which is documented by all the studies already performed within the framework of design support.

All these results have contributed to the safety and reliability assessment and thus to target licensing, by the licensing authorities and regulatory agencies (Swiss Federal Office of Public Health, Swiss Federal Nuclear Safety Inspectorate, Swiss Federal Office of Energy, Swiss Federal Nuclear Safety Commission).

Special attention had to be paid to the safe enclosure of the radioactive liquid metal and the gases and volatiles produced during normal irradiation and hypothetical accident conditions. The total activity in the LBE will attain about 4.10^{15} Bq. About 2.10^{14} Bq will be 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 concerning how to handle the different species, and these have been evaluated with respect to normal operation and accident conditions. The final design is based on a three-barrier concept, laid down already in a preliminary safety analysis report, which has been submitted by PSI to the Swiss licensing authorities.

Final target installation in SINQ

At the end of the integral tests the central rod of the target was cleaned, then the neutron flux detector provided by CEA was inserted. The electrical cabling and other connections were installed in the target head. The LBE leak detector was then installed, prior to the final welding lower target enclosure, with a qualified procedure. The LTE tightness was checked by X-ray and pressure and leak test. The target was then installed in SINQ, then connected to ancillary systems: fill and drain, heat removal system, cover gas system, isolation gas system, etc.

The beam has to be controlled, to avoid any damage on the window. For the MEGAPIE target, due to the specific risks induced by the position of the window (bottom of the target) and the choice of a liquid lead-bismuth alloy, four new systems have been installed to watch for correct scattering in target and proper beam transport, in order to fulfil the following requirement: the beam has to be switched off within 100 ms if 10% of the protons bypass the target. One of the new systems is the so-called VIMOS; glowing of a mesh implemented in the beam duct is monitored via special optical measurement chain and software.

In order to fulfil the requirement of 1 mSv criterion for the public, in case of an incidental release, some measures for reduction of the source term were decided and carried out:

- Better sealing of the buildings over/below the target (TKE & STK), when installed in SINQ.
- An inertisation system provided by MESSER was provided to prevent inflammation by the thermal oil under the most extreme conditions; the "LowOx" system reduces the oxygen content to <13% (layout value: 11%) by nitrogen injection.
- Connecting the TKE with the cooling plant to reduce the possible activity concentration in air.
- Upgrade of the ventilation system (earthquake resistant stand-alone exhaust equipment) and of the filter systems (both with activated carbon and particle filters).

Close to the target, a ventilation system was also updated to locally control the temperature.

Target operation

The target can be operated following three main operational modes:

1) *Isolation case*. Target is "disconnected" from the heat removal system by closed isolation valves in oil loop; the two electromagnetic pumps are running (possibly at reduced power) and the target temperature is controlled by the central rod heater.

2) *Hot standby case*. Target is "connected" to the heat removal system; all pumps (lead-bismuth, oil and water) are running in nominal conditions and the target temperature is controlled by the three-way valve in oil loop. Then the system is ready to accept beam operation.

3) *Beam operation case*. Target is operated as in the hot standby case but with beam operation. If during the beam operation status an anomaly in the signals is detected, the beam is switched off and the target will go into hot standby or into isolation if a critical problem is detected. If during hot standby it is not possible to maintain the selected operational conditions, the target will go into isolation.

For the target start-up, three phases were suggested to go to full beam power by the operating team of PSI:

1) *Phase 1: 20-50 μA for 4 h maximum, ~8 kW-20 kW heating*. This phase is mainly dedicated to check all "nuclear" instrumentation, and beam interruption systems. During this phase, no significant heat is deposited into the target so as to obtain reliable thermo-hydraulic data.

2) *Phase 2: 200 μA for 8 h maximum, ~80 kW heating*. This phase is mainly dedicated to check the heat removal system control parameters, dosimetry, etc. However, the reaction of the heat removal system was anticipated to be modest as the oil three-way valve will hardly move. Reaction of the target temperature control to beam interrupts and trips can also be tested.

3) *Phase 3: During this phase, it is foreseen to ramp up to full beam power in several steps: 200 μA, 400 μA, 600 μA, 800 μA, 1 000 μA, 1 200 μA:*
   - for every step several beam trips and beam interrupts should be initiated and the performance of the target temperature control assessed before continuing to higher beam powers;
   - at 400 μA sufficient heat (~160 kW) will be deposited in the target to carry out the thermal balance of the whole system in order to evaluate and adjust the main LBE and oil flow rates;
   - at full beam power, LBE and oil pumping powers can be further fine-tuned to get the required flow rates by once again using the thermal balance method.

Reviews are foreseen after start-up phases, following quality insurance standards, in order to obtain final approval to go to steady state operation, from PSI and the Swiss Federal Office of Public Health (BAG).

Experiment monitoring

During the irradiation phase of MEGAPIE, numerous operating parameters are monitored, including pressure, fluid flow rates and temperatures. Moreover, experimental measurements of neutron fluxes at various positions of the facility, and of gas production; will allow Monte Carlo calculations of the measured quantities to be performed, with the goal of validating codes MCNPX and FLUKA fitted with appropriate models (irradiation phase of MEGAPIE). The activities will concentrate on two main goals:

1) experimental measurements of neutron fluxes at various positions of the facility, and of gas production;

2) Monte Carlo calculation of the measured quantities, with the goal of code validation (FLUKA, MCNPX fitted with appropriate spallation models.)

Neutron flux measurements will be performed in various places with different methods:

1) Measurements at beam lines:
   - with activation foils (measurement of the thermal neutron flux and of the epithermal flux at a single resonance point at 4.9 eV by wrapping the foil with a Cd layer);
   - with Bonner spheres (measurements performed with poly spheres of different radii surrounding ^{3}He detectors, for sensitivity to different neutron energy range (by Lausanne University);
   - time-of-flight measurements performed at the SINQ ICON facility using a chopper.

2) Other neutron measurements:
   - Neutron flux inside the target using micro-fission chambers (Figure 9). Height fission micro-chambers have been set up inside the central control rod for on-line monitoring (neutron energy domain: from thermal to 10 MeV). ^{235}U chambers have been calibrated by gamma and mass spectrometry at ILL. Moreover, the potentiality of such a target in terms of incineration for ^{235}Am and ^{237}Np will be evaluated, thanks to two micro-chambers with these two minor actinides.

– neutron flux with activation Au foils inside D_2O tank (NAA/PNA stations).

– delayed neutrons in the upper part of the target (it is calculated that with a prompt neutron flux in the TKE of about 10^5 n/cm^2/s, the DN flux should be one order of magnitude higher).

Figure 9. Micro fission chambers

During MEGAPIE irradiation, gas and volatile elements are produced, both stable and radioactive. Calculated values of stable gases indicated a production of about 1 l/month (mainly stable H and ^{4}He). Isotope production measurement is very important since spallation models used in Monte Carlo models are much more sensitive to it than to neutron fluxes

Moreover, the knowledge of the production rates of specific radioisotopes is necessary for the assessment of the disposal strategy of the target, and for the post-irradiation examination (PIE) [6]. Samples of the gas produced in the LBE during irradiation will be taken from a specially designed cover gas system, about 1 day after start-up; the sample will be analysed by mass and gamma spectroscopy, and the amount and composition of gases generated (^{4}He, stable and radioactive Ar, Kr, Xe, I) will be determined.

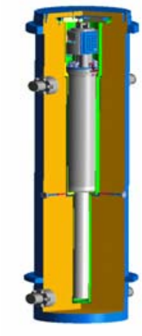
The irradiation started 17 August 2006. Post-test analysis, post-irradiation examination and waste management will be performed from 2007 to 2009.

Further steps

After irradiation, the target will remain about 30 days in the operating position until the decay heat has decreased to about 300 W (to be checked). Controlled freezing of lead-bismuth eutectic (LBE) is necessary due to expansion of solid LBE after re-crystallisation; the expansion can be mitigated if the cooling rate is kept as low as 0.02°C/min from solidification point to 60°C. A specific procedure for freezing the LBE in the lower target enclosure has been suggested and validated by thermo-mechanical calculations using a 2-D ANSYS model.

Then, cooling circuits and gas volumes will be emptied, rinsed and dried, the target will be disconnected and sealed up with blind flanges, then stored for several months. After about one year and a half, the target will be transferred to SWILAG hot laboratories, using a steel container (Figure 10) made of two concentric parts (inner contamination protection and shielding). Then, the target will be cut with a band saw (provided by Behringer), into 19 slices. About 8 wt.% of the target will be transported to the Hotlab at PSI as sample material for post-irradiation examinations. The remaining target pieces (92%) will be conditioned in a steel cylinder in a KC-T12 concrete container (TC2), for storage and disposal. This procedure has been approved by the National Co-operative for the Disposal of Radioactive Waste (NAGRA).

Figure 10. Container for target transportation



The objectives of the PIE are to understand:

- microstructural, mechanical and chemical changes in the structural materials in the target induced by irradiation and LBE corrosion;
- the production, distribution and release of the spallation and corrosion products in the LBE.

PIE will be carried out in an organised effort of the eight partners of the MEGAPIE initiative: CEA, CNRS, ENEA, FZK, JAEA, DOE-LANL, PSI and SCK.

For the structural material the following analyses will be performed:

- non-destructive test (NDT) – ultrasonic analysis of the thickness change at the beam window;
- microstructural, mechanical and surface analyses on the beam window, LLMC tube, FGT and BFT;
- surface analyses on EMP tube;
- chemical analyses on spallation and corrosion products in the LBE and depositing at the Ag-absorber and cold trap (control gas system).

Conclusions

Within the framework of the MEGAwatt PIlot Experiment (MEGAPIE) (1 MW), initiated in 1999 in order to design and build a liquid lead-bismuth spallation target, then to operate it in the Swiss spallation neutron facility SINQ at PSI, many studies have been carried out by the project partners addressing specific critical issues in the fields of neutronics, materials, thermal-hydraulics, mass and heat transfer, structure mechanics and liquid metal technology, using analytical, numerical and experimental approaches. In order to demonstrate the target characteristics and safe operability prior to irradiation in 2006, the target was installed in a PSI test facility, fitted with all ancillary systems, and tested off-beam. The tests demonstrated the operability of the target and ancillary systems in steady-state and transient situations and the control system has been validated. Stress analysis and supporting experiments like full scale leak test validated the design, the confinement strategy and the potential safe operation. Finally, all these experimental results demonstrated the ability of the target to be licensed and irradiated in SINQ. Implementation in SINQ has been carried out and safety systems have been updated or implemented to face events like oil fire, release of contamination, earthquakes, brutal vaporisation of D_2O. Start-up procedures and normal operating conditions have been clearly defined.

Neutron and thermo-hydraulic measurements, and PIE activities have been defined in order to obtain the best benefit of the experience. Target decommissioning and waste management have been defined properly.

The already performed steps, conceptual and engineering design, manufacturing and assembly, safety and reliability assessment, thermo-hydraulic off-beam tests have already brought a uniquely relevant design and operational feedback to the ADS community. Irradiation started 14 August 2006, and this very fruitful experiment will bring a decisive contribution to the development of ADS, an option for the transmutation of minor actinides.

Acknowledgements

All the Paul Scherrer MEGAPIE operating team is acknowledged for the huge work performed to implement the preparation for licensing of the MEGAPIE experiment. In addition to supports from organisations involved in the MEGAPIE partnership, the financial support of the European Union under Contract FIKW-CT-2001-00159 and by the Swiss government under Contract BBW-Nr.01.0298 is acknowledged.

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