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

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ABSTRACT :

The MEGAPIE target has been designed, manufactured then set-up, fitted with all the ancillary systems, on a 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 then moved to the final implementation in the SINQ facility, with the ancillary systems, for irradiation, 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.

The 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 latter decommissioning, post irradiation experiments, waste management will bring to ADS Community a unique relevant design and operational feedback.

I. 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 into 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 jeopardizing its safe operation. Whereas the interest of the partner institutes is driven by the development needs of ADS, PSI interest lies also 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 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 has been designed by CNRS, CEA, PSI and IPUL, the main components of the target have been manufactured in France by ATEA Company and sub-contractors and in Latvia (EM pumps), then assembled in France. The ancillary systems have been designed and manufactured in Italy (Ansaldo, Criotec) and Switzerland (PSI).. The target has been 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.

II. 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 Fig. 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. 650 kW thermal energy 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 is then flowing down in the outer annulus (4 l/sec). The beam entrance window, welded to the Lower Liquid Metal Container, including the beam window, both 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 upflow 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 IPUL (Institute of Physics in Latvia), consisting of the concentrically arranged by-pass 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 Target heat exchanger (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 3 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 AlMg3. 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 leads to the breach of the inner container.. The enclosure is flanged to the :

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

- 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 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.

The main characteristics of the target are recalled in Table 1 :

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:	400ºC
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	By-pass flow-rate	0.25 l/s

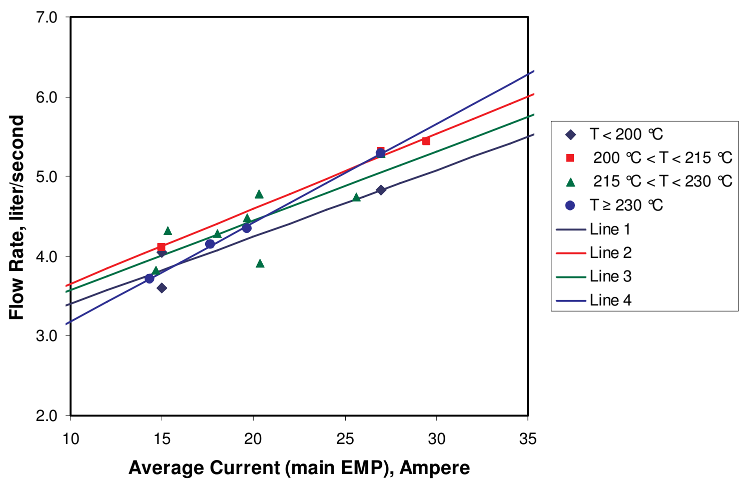
Table 1 : main characteristics of MEGAPIE Target

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, Beamline adaptations,…The description of these ancillary systems has been reported in [3].

III 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 have already been commissioned. , and has been tested out-of beam. The integral tests consisted of the following main tests :

- 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,
- perform transients for qualification of heat removal and control systems,….



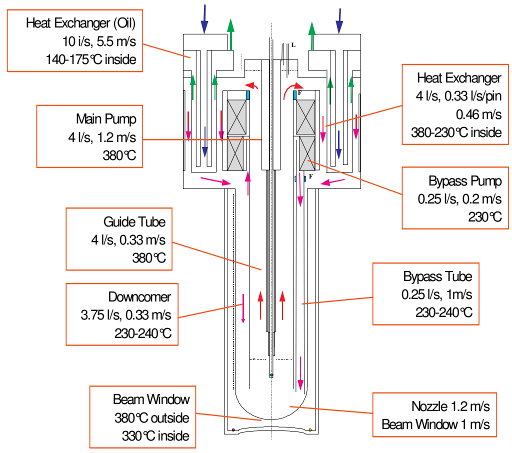


FIGURE N°2 : Main characteristics of the main EMP, provided by IPUL (Latvia)

FIGURE N°1 : MEGAPIE target

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 Fig.2, the characteristics of the main EMP have been established ; the others 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 characterization.
Control of the target was designed for the 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.
During the integral tests, it was seen that the characteristics of the oil three-way valve are highly non-linear (Fig 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 (Fig 4).

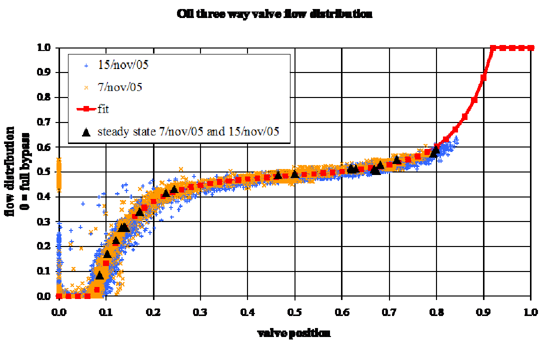


FIGURE N°3: Oil three way valve characteristics.

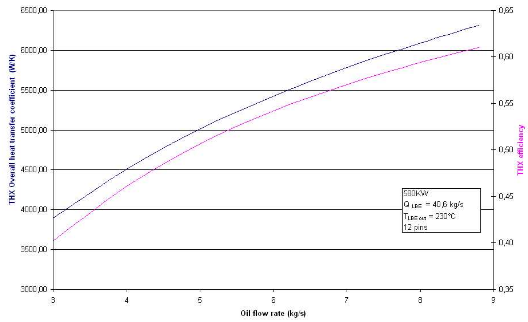


FIGURE N° 4 : Influence of oil flow-rate on Heat transfer coefficient

The final conclusion of the integral tests and associated studies was that the overall system will be able to adequately remove the anticipated 600kW 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.
On Fig 5, we can see a test simulating a beam trip. The average temperatures of LBE, target structures, and the Main EMP (a) during beam trip, (b) during beam interrupt, and (c) restarting from how standby are reported and shows already, before final checking of the control System , the capacity of the Heat Removal system to react to the transient situation.
The transient characteristics of both the “protected” and “unprotected” beam trip are simulated by the RELAP5, and the results agree well with the experiments, as it is shown in Fig.6.

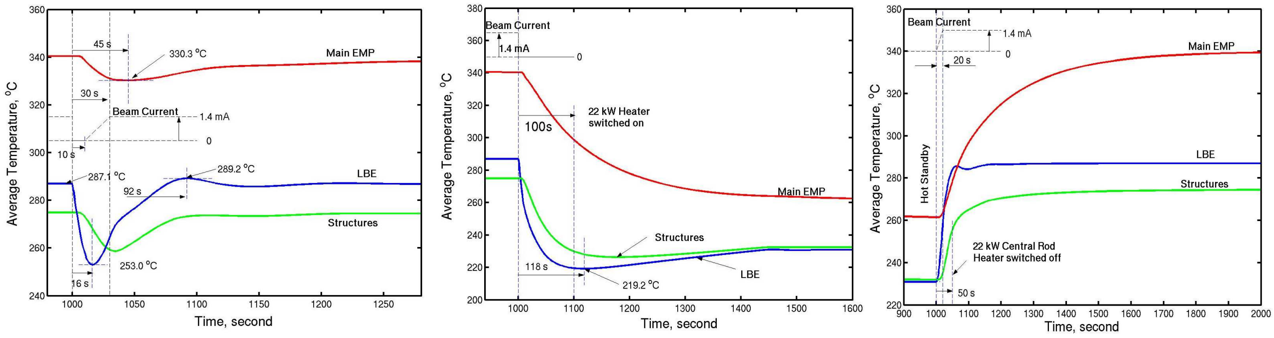


FIGURE N° 5 : Simulation of a beam-trip (from [4])

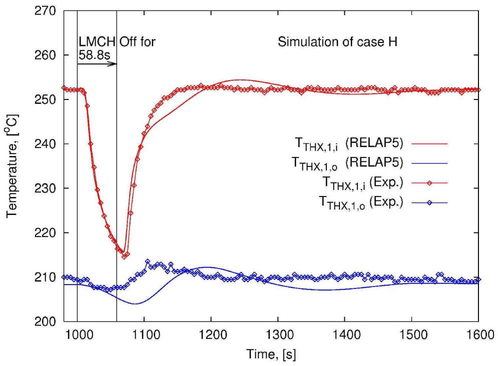


FIGURE N°6 : Comparison of experimental and calculated temperatures for an unprotected trip.

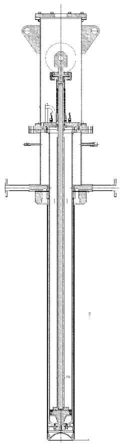
Thus the RELAP model has been more or less verified though it still could be improved first by a better estimation of the thermal masses of LBE and structures (Cp,…), and also of the heat transfers coefficients (using the temperatures of the main and bypass EMPs,),

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 be differed from the predictions.

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

For each of the 4 campaigns, the computed values were complying to 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 rates assessments. A parametric study of sensitivity has shown also 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) (Fig.7) was performed in Paul Scherrer Institut with the goals to validate the design of the Lower Target Enclosure (LTE) under worst case leak conditions, and the leak detector system, implemented in the lower part of the LTE.



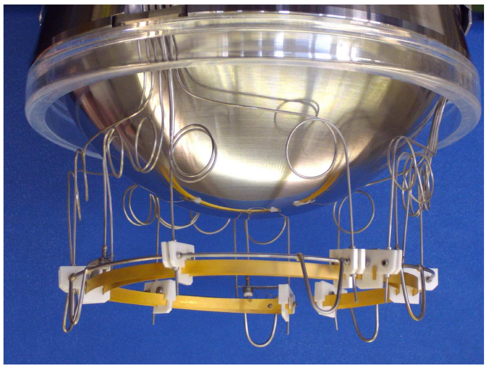


FIGURE N° 7: Dummy instrumented target.
for integral leak test

FIGURE N° 8: Leak detector system

It was demonstrated that the LTE was able to contain LBE. This experiment allowed also to check the leak detector system which had the following main requirements : detect a leaked LBE quantity below 0.5 liter within 1 second with a very high reliability, 100 % detection efficiency, a very low false alarm rate, and radiation and temperature resistant.
In fact, 2 different sensors were implemented :
- Thermocouples (9 individual and independent sensors, 3 electrically preheated) as main leak sensor, and,
- Stripe sensors type "AC impedance" (3 separate units) as shown in Fig 8
The leak Detector system was fully validated during Full Scale Leak Test.

Complementary to the FSLT, within the framework of the general safety assessment, the potential consequences of 3 simultaneous failures of the target shells were investigated independently with 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.

In support to 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 objective of these simulations with the CEA TRIO-U-VEF parallelized 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 been also performed by USDOE-LANL and CEA, which is documented by all the studies already performed within the framework of Design Support.
All these results have contributed to Safety and Reliability assessment and then 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 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 already in a preliminary safety analysis report, which has been submitted by PSI to the Swiss licensing authorities.

IV FINAL TARGET INSTALLATION IN SINQ :

A 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,..

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 fullfill the following requirements : the beam has to be switched off within 100 ms if 10 % of the protons by-pass the target. One of the new system 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 fulfill 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 and below the target, (TKE & STK), when installed in SINQ,
- An inertization 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 in order 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 up-dated to control locally the temperature.

V TARGET OPERATION :

The target can be operated following three main operational modes :

1. Isolation case :

The 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 :

The 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 :

The 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 case” or into “isolation case” if a critical problem is detected. If during the “hot standby”case, it is not possible to maintain the selected operational conditions, the target will go into “isolation case”

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

à Phase 1: 20-50µA for 4h maximum,~8kW-20kW heating

This phase is mainly dedicated to check all "nuclear" instrumentation, and beam interruption system. During this phase, no significant heat is deposited into the target to get reliable thermohydraulic data.

à Phase 2: 200µA for 8h maximum, ~80kW heating

This phase is mainly dedicated to check the Heat Removal system control parameters, dosimetry,... 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.

à Phase 3: :During this phase, it is foreseen to ramp up to full beam power in several steps: 200µA, 400µA, 600µA, 800µA, 1000µA, 1200µA

•for every step several beam-trips and beam-interupts sould be initiated and the performance of the target temperature control assessed before continuing to higher beam powers

•at 400µA sufficient heat (~160kW) 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 flowrates.

•at full beam power, LBE and oil pumping powers can be further fine-tuned to get the required flowrates 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 in steady state operation, from PSI and Swiss Federal Office of Public Health (BAG).

VI EXPERIMENT MONITORING

During 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 codes validation 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)
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 :

a- 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 radius 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

b- Other neutron measurements :

- neutron flux inside the target using micro-fission chambers (Fig 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, potentiality of such target in terms of incineration for ^{241}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)

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 analyzed 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 August 17th 2006. Post-test analysis, Post irradiation examination and Waste management will be performed from 2007 to 2009.

VII FURTHER STEPS :

After the 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-crystallization: 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 Lower Target Enclosure has been suggested and validated by thermo-mechanical calculations using 2-D ANSYS Model

FIGURE N° 9: Micro fission chambers.

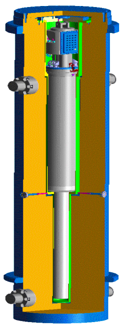


FIGURE N° 10: Container for target transportation

Then, cooling circuits and gas volumes will be emptied rinsed and dried, 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 (Fig 10) made of 2 concentric parts (inner contamination protection and Shielding). Then, the target will be cut with band saw (provided by Behringer), in 19 slices. About 8 (weight) % of the target will be transported to the Hotlab at PSI east as samples material for Post Irradiation examinations. The remaining target pieces (92%) will be conditioned in steel cylinder in a KC-T12 concrete container (TC2), for Storage and Disposal. This procedure has been approved by the National Cooperative for the Disposal of Radioactive Waste (NAGRA).

The objectives of the Post Irradiation Examinations (PIE) are to understand:

(a) microstructural, mechanical and chemical changes in the structural materials in the target induced by irradiation and LBE corrosion,

(b) the production, distribution and release of the spallation and corrosion products in the LBE.

The (PIE) will be carried out with a organized effort of the eight partners of the MEGAPIE initiative: CEA, CNRS, ENEA, FZK, JAEA, LANL-DOE, PSI and SCK.

For the structural material the following analysis 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).

VIII 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 into the Swiss spallation neutron facility SINQ at Paul Scherrer Institute (PSI), many studies have been carried out by the project partners addressed 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 has been installed in PSI Test facility, fitted with all the ancillary systems, then has been tested off-beam. These 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. All these experimental results demonstrated finally the ability of the target to be licensed and irradiated in SINQ. Implementation in SINQ has been carried out and safety systems have been up-dated or implemented to face events like oil fire, release of contamination, earthquakes, brutal vaporization of D2O. 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 has brought already to ADS Community a unique relevant design and operational feedback. The irradiation started August 14th 2006 and this very fruitful experiment will bring a decisive contribution to the development of Accelerated Driven Systems, option for the transmutation of minor actinides.

ACKNOWLEDGMENTS

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

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