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# MEGAPIE Target : a relevant demonstration for ADS

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**ABSTRACT**

Partitioning and Transmutation (P&T) techniques could contribute to reduce the radioactive inventory and its associated radio-toxicity. Sub-critical Accelerator Driven Systems (ADS) are potential candidates as dedicated transmutation systems, and thus their development and more particularly the spallation target, is a relevant R&D topic. Thus, 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). Many studies, 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. 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. The target has been built in France then shipped to Switzerland : 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 will be tested off-beam. The already performed steps, conceptual and engineering design, manufacturing and assembly, safety and reliability assessment, then the irradiation at SINQ PSI, decommissioning, post irradiation experiments, waste management will bring to ADS Community a unique relevant design and operational feedback.

***KEYWORDS***
*Transmutation, Accelerator Driven Systems, spallation target, lead-bismuth, Megapie.*

## I. INTRODUCTION

Partitioning and Transmutation (P&T) techniques could contribute to reduce the radioactive inventory and its associated radiotoxicity. Sub-critical Accelerator Driven Systems (ADS) are potential candidates as dedicated transmutation systems, and thus their development is a relevant R&D topic in Europe. Following a first phase focused on the understanding of the basic principles of ADS (e.g. the programme MUSE), the R&D has been streamlined and focused on practical demonstration key issues. These demonstrations cover high intensity proton accelerators (beam current in the range 1 – 20 mA), spallation targets of high power and their effective coupling with a subcritical core. Presently there is general consensus that up to 1MW of beam power solid targets are feasible from a heat removal point of view. For higher power levels liquid metal targets are the option of choice because of their higher heat removal capability, higher spallation material density in the volume, lower specific radioactivity,…

Therefore, a key experiment in the ADS 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. The minimum design service life has been fixed at 1 year (6000 mAh).

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. Calculations of the radial distribution of the undisturbed thermal neutron flux for the LBE target in comparison to the former Zircaloy and current steel-clad solid lead target were done with different nuclear codes ; nevertheless, variations between various codes enlightened the necessity of flux assessment by direct measurement.

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. (Fig.1).


Fig. 1 : The MEGAPIE partners

Many studies, 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.
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, 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, result of the conceptual and detailed design studies, the studies related to the main critical issues which have been addressed, will be described. Finally the next steps will be introduced.

## II. MAIN CHARACTERISTICS OF THE MEGAPIE SYSTEM

### 1. Main constraints and options

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.

Lead bismuth eutectic (Pb44.5%-Bi55.5%) has been selected, due to its attractive neutronic and physical properties : heat transfer coefficient, low melting point (125°C); nevertheless bismuth induces to the production of activation products i.e. polonium,...

The reasons for the choice 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 are the following ones [2] [3] : Compared to austenitic steel 316L, T91 has :
- higher strength.
- much better resistance to heat deposit (due to a lower thermal expansion coefficient and a higher thermal conductivity). As a result, thermal stresses are about twice as high in 316 as in T91 for a given geometry and heat deposit.
- better corrosion resistance in Pb-Bi due to a low nickel content.

Furthermore, for applications under irradiation up to high doses at temperatures higher than about 400°C, T91 has additional advantages over 316 :
- much lower swelling.
- better resistance to the “high temperature helium embrittlement” phenomenon.

Of course, the main weakness of martensitic steels is the existence of the Ductile-to-Brittle Transition temperature (DBTT) which is shifted as a result of irradiation. This shift is small for 9Cr martensitic steels up to high doses at irradiation temperatures higher than 400°C. At lower irradiation temperature, a significant DBBT shift occurs.

## 2. Description of the target

A sketch of the target and its main properties are shown in Fig. 2. 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) (Fig.3). 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

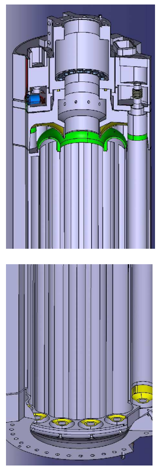


Fig. 2: Thermal Heat Exchanger

- 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.

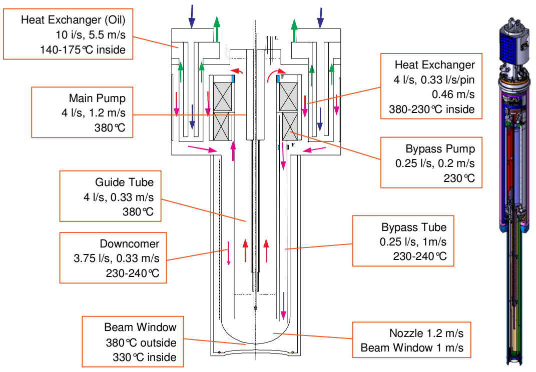



Fig.3 : Megapie target

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

## 3. Description of ancillary systems

Whereas the target has been designed by CNRS-SUBATECH with the contribution of CEA and IPUL, the ancillary systems were designed by PSI, ENEA and Ansaldo. The main systems are :

- the Heat removal system already described above The Heat Removal System, HRS, with Diphyl THT® oil a cooling medium and an intermediate water loop, already described.
- the Cover Gas System, CGS, to cope with the overpressure in the target and to assure the confinement of all radioactive gases produced by the spallation process (about 8 liters) and a regular and controlled venting. The gases are collected in the target expansion tank and periodically evacuated via filters into a decay tank.
- the Insulation gas System, IGS.
- the LBE Fill and Drain System, F&D, with a double containment and an appropriate system for disconnecting the tubes after operation.
- the Beamline adaptations including advanced beam monitoring : implementation of Catcher, funnels, collimator slit, VIMOS (beam position visualization system).- the Handling devices for the target decommissioning, storage, dismantling and disposal.
- the Control system with the adaptation of the SINQ infrastructure.

All connections to the target have to pass by the target head. Components handling radioactive products under normal operation are placed in a second containment filled with He at a pressure below ambient. Activity is continuously monitored.

## III DESIGN SUPPORT AND VALIDATION

The main relevant design issues were focalised :

- on the structural integrity of the target in order to keep all active material confined inside the target and this for normal operating conditions and hypothetical accidents,
- on performances of the heat exchanger to evacuate the deposited heat;
- on performances of the electromagnetic pump system,
- on the (freezing) properties of the LBE and the behaviour of the spallation products,
- on the integrity and the cooling of the beam window.

These, and other, relevant issues streamlined the activities performed within the scientific design support by all the project partners. The main results are the following ones :

- neutronic benchmark and a detailed assessment of the nuclear reactions were carried out to determine relevant input data for the design and safety assessment of the target : beam power energy deposition, p/n flux distribution, activation, isotope production in LBE, activation and damage of structures; these data contributed to the prediction of the neutronic performances of the target, assessment of the beam window life duration, design of radiation shielding, validation of handling and waste management strategy,…
Production rates of volatiles in a proton irradiated LBE target were measured at the ISOLDE facility (CERN). Several isotopes were measured : the measured quantities overall agree with the expectations from the calculations using the FLUKA and MCNPX codes.(Fig.4) [4]. The

release of Ne, Ar, Kr, Xe, Br, Cd, Te, I, Hg, Po, and At radioisotopes was investigated. Little or no Po should be released at 600°C and of course at lower operating temperature. Hg isotopes are expected to be completely released at 600°C and partially at lower temperature[5].
About 2% of the beam power is dissipated in the T91 lower liquid metal container and in the AlMg3 lower target enclosure. Considering the average between the results from FLUKA and MCNPX, the peak power deposition is 900 W/cm$^3$ in the T91, and 315 W/cm$^3$ in the AlMg3.

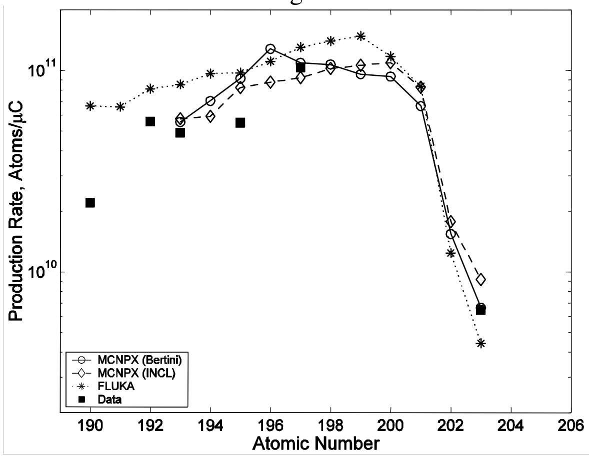



Fig 4 : Production rates for Hg isotopes Measured points (*black squares*) are compared with calculations: *open circles*: MCNPX (Bertini/Dresner model combination); *diamonds*: MCNPX (INCL4/ABLA); *stars*: FLUKA

- thermo-hydraulic and thermo-mechanical modelling of the systems and components under normal, transient and accidental conditions , including experimental validation; were performed [6,7]: they have demonstrated that there are very large safety margins on Lower target enclosure (LTE) coolability, with no serious hot spots or stress concentrations, particularly on beam window (Fig. 5), for steady state operation.
The by-pass nozzle was optimised by CFD calculations. The effects of beam wandering by up to 2 mm at the window were shown to be negligible. It has been also predicted that if the by-pass pump fails the target could still be operated without overheating of components. However, it was decided not to continue operation of the target if this occurs. Several experimental studies for window-cooling were performed to validate the design : LBE tests Kilopie (PSI and FZK) for HTC (heat transfer coefficient) estimation, flow visualisation tests HYTAS and Heated Jet experiment (FZK) for the study of the stability of the flow field; Large Eddy Scale simulations by CEA are underway to analyse this stability, close to the window.
At the end of its experimental life the liquid LBE of the target vessel will be frozen in the target. A re-crystallisation process occurs in the solidified LBE (roughly 1.5% in the solid state with time) and produces volume expansion in time, which could lead to undesired plastic stresses in the target. Due to a better understanding of the LBE freezing process, it seems feasible to sufficiently control the LBE expansion to avoid damage to the structural materials, which would jeopardize PIE.

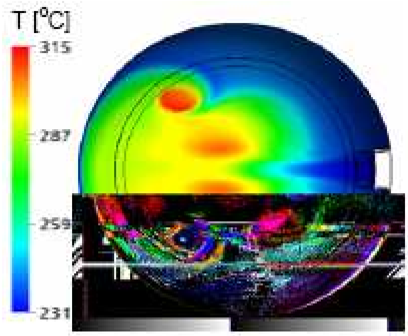
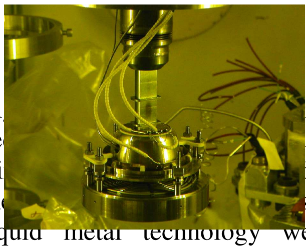



Fig.5 : Temperature contours at the window surface with heat generation in the fluid.

- material properties under irradiation, corrosion behaviour and risk of liquid metal embrittlement were investigated.
At the irradiation temperature of the MEGAPIE window, T91 will suffer a large DBTT shift (about 35K/dpa) and it has been shown that a T91 window could be irradiated up to 22 weeks (with 30% safety margin) if the DBTT is to remain below operation temperature. However, due to the very low values of the stresses in the window, the operation time could in principle be further extended.
Regarding the maximum window temperature of ca. 370°C, the low stress level of 60 MPa (thermal stress) and the existence of oxide layers on the T91 surface at the beginning, LBE corrosion, Liquid metal embrittlement(LME) and Liquid metal accelerated damage(LMAD) [9] should not be a limitation for the envisaged operation time of the MEGAPIE target of about half a year.
LiSoR experiment (Liquid Solid Reaction) [8] has been performed in order to investigate the effect of simultaneous interaction of Irradiation (Beam energy 72 MeV, Beam current 30 μA), LBE (lead bismuth eutectic without O control) and Mechanical stress . It was shown that oxide layers are formed

during proton irradiation on the steel surface. These oxide layers on the steel surface protect steel against corrosion and embrittlement, by limiting wetting. In Fig.6 , one can see the foot print obtained after 724 hours of irradiation, corresponding to 1 dpa.



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- i[illegible] ion phenomena over-m[illegible] s dealing with heavy liquid metal technology were also analysed : cooling performance of the pins of the THX was in agreement with the design, LBE-water interaction was investigated and vapour explosion was excluded, LBE-organic oil interaction should have no detrimental effect on the target integrity, lead-bismuth eutectic (LBE) preparation and out-gassing procedure for fill and drain system and target before filling were defined in order to limit the plugging risk.

## IV TARGET MANUFACTURING

The target has been manufactured (Fig.7) by ATEA (Reel Frères) in Nantes (France). The main feedback (view from ATEA) was the solutions found to solve difficulties for manufacturing due to variety of materials : 316L, T91, Tungsten,… complex geometry,...The local cooperation between main designer (Subatech), Quality Assurance (PSI) and manufacturer was greatly appreciated. The Institute of Physics (IPUL) in Latvia has designed, validated the pump concept by testing a prototype and manufactured the two pumps.

Fig.7 : Target built by ATEA

## V FURTHER MEGAPIE STEPS

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, which have already been commissioned. , and will be tested out-of beam. The integral tests will consist 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,….
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The results will contribute to Safety and Reliability assessment and then to Target Licensing. An overall reliability study has been performed by USDOE-LANL, which is documented by all the studies already performed within the framework of Design Support (see paragraph IV). Special attention has 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 in a preliminary safety analysis report, which has been submitted by PSI to the Swiss licensing authorities.
The irradiation is foreseen to start next May 2006. Post-test analysis, Post irradiation examination and Waste management will be performed from 2007 to 2009.

## VI CONCLUSIONS

The target has been designed, manufactured, and installed for integral tests, before irradiation foreseen in May 2006. Most of ancillary systems have been manufactured and commissioned and the beam-line has been equipped with validated beam control system.
The Scientific Design Support of this international project was an example of collaboration between design and research teams.

The two next short term key challenges for PSI and its partners are first to validate the safe operability of the target during integral tests then to accomplish the different steps of the Licensing procedure, prior to decision for irradiation.

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