



Final Summary Report on Target Design

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MEGAPIE – TEST

(CONTRACT N° FIKW-CT-2001-00159)

FINAL SUMMARY REPORT ON TARGET DESIGN

(DELIVERABLE D13)

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WP1 TARGET DEVELOPMENT

DELIVERABLE D13

FINAL SUMMARY REPORT

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Dissemination level :

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

Abstract :

The present document is the D13 deliverable report of work package 1, Target Development, from the MEGAPIE-TEST project of the 5th European Framework Program. Deliverable D13 is the final summary report on the activities performed within WP 1. The due date of this deliverable was the 11th month after the start of the EU project.

In this original schedule, it was foreseen to complete the engineering design of the target and the ancillary systems at the end of the first year of the MEGAPIE-TEST project (i.e. November 2002). However, this activity has been extended for six month due to several unexpected technical problems, which needed more time to be solved.

The second step, i.e. the manufacturing phase, is on the critical path of the MEGAPIE-TEST project. Presently, the manufacturer (ATEA) has indicated to deliver the target to PSI in the middle of 2005. Assuming that this date is realistic, it can be foreseen that the integral out-of beam test will be conducted during the end of the year 2005 and the beginning of the year 2006. It can be assumed that the irradiation of the MEGAPIE target will start during the second quarter of 2006.

Given these new boundary conditions, the co-ordinator, together with the partners of the MEGAPIE-TEST project had obtained from the EC an extension of the contract of the MEGAPIE-TEST project with a 24 months amendment. The contract amendment gives a revision of the work-plan, the due dates of the deliverables and the milestones. The new due date of deliverable D13 is December 2004. The content of the present work package 1 final summary report reflects the status of the MEGAPIE target and ancillary system development at this stage. The technical design details of the MEGAPIE target are presented in deliverable D09, Design report.

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1 INTRODUCTION

1.1 The Importance of the MEGAPIE-TEST Project in the Frame of P&T Studies

Partitioning and Transmutation (P&T) techniques could contribute to reduce the radioactive inventory and its associated radiotoxicity. Sub-critical Accelerator Driven Systems are potential candidates as dedicated transmutation systems, where the main characteristic of ADS (i.e. sub-criticality) is particularly favourable and allows a maximum transmutation rate while operating in a safe manner. For these reasons, waste transmutation using ADS has become a relevant R&D topic in Europe. Following a first phase of R&D focused on the understanding of the basic principles of ADS (e.g. the programme MUSE), the programmes have 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 (~ 1 MW, like MEGAPIE) and their effective coupling with a subcritical core. Thus, the MEGAWatt Pilot Experiment (MEGAPIE), an international initiative, which was launched in 1999 in order to design, build, operate and explore a liquid lead-bismuth spallation target for 1 MW of beam power¹, represents a key experiment in the ADS roadmap². The decision to install the MEGAPIE target into the Swiss spallation neutron facility SINQ at PSI fitted also with the appreciation that liquid metal targets represent the most promising solution for increasing significantly the thermal neutron flux used for irradiation purposes.

The EU MEGAPIE-TEST has the objectives to develop, improve and validate expertise, knowledge and experience about the design and operation of a heavy liquid metal (HLM) target and to verify its feasibility under realistic operating conditions. The main results expected at the end of the project are: development and comprehensive testing of a liquid metal spallation target both under beam-off and beam-on conditions. An important milestone, to be reached at the end of the project, is the availability of all the elements for the development of future heavy liquid metal spallation target.

The project has been divided into three work packages (WP 1: *Target Development*, WP 2: *Target Testing* and WP 3 *Synthesis*). The present document constitutes the final summary report of WP 1.

1.2 Main Objectives of WP 1

The main objectives of WP1, Target Development, can be summarised as follows:

¹ G. S. Bauer, M. Salvatores, G. Heusner, J. of Nucl. Mater., 296 (2001) 17-33.

² The European Technical Working Group on ADS, Ed. ENEA, April 2001, ISBN 88-8286-008-6.

Preparation of the complete design of the target with ancillary systems by taking advantage of the MEGAPIE feasibility study and the existing MEGAPIE design work, and considering the boundary conditions of the SINQ Facility (see figure 1-1).

Definition of critical issues and required R&D needs which are inherent in the design and operation of a spallation target.

- Solution of target 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. Selection of best design options according to evaluation criteria established earlier.
- Assessment of safety and reliability aspects which might endanger the integrity and operability of the target; definition and evaluation of countermeasures. Preparation and definition of licensing requirements and criteria.

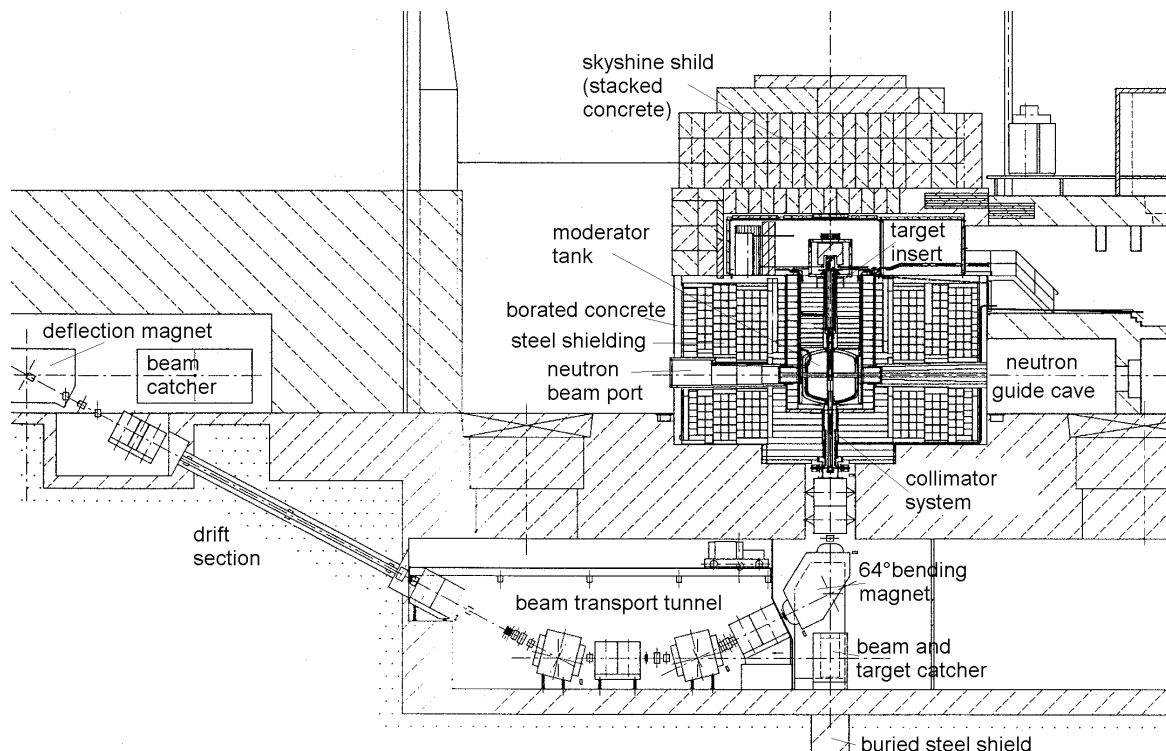


Figure 1-1 : Vertical cut through of the SINQ facility

The progress of the target design during the MEGAPIE-TEST project can be followed up in previous reports issued in the frame of this project (see Deliverables 08 and 10 and the scientific technological reports). This report summarises the status of the target and ancillary systems design mainly based on the presentations made at the 5th Technical Review Meeting in Nantes, 24-26 May 2004.

In particular:

- The contributions to the general target and ancillary overview were from : F. Gröschel and W. Wagner (PSI).
- The contributions to the target design were from : A. Cadiou, J.S. Stutzmann, T. Kirchner, M. Vatre (CNRS), L. Cachon, G. Laffont (CEA), J.M. Gautier (LPC Caen), S. Dementjev (IPUL).
- The contribution to the ancillary design were from : W. Wagner (PSI), G. Corsini (ANSALDO).

2 GENERAL OVERVIEW

The MEGAPIE Initiative has experienced important changes from the administrative and technical point of view since its start and some serious technical challenges have surfaced, which cause additional efforts and have caused some delay according to the original schedule. This might have some consequences on the progress and schedule (delivery dates) of the 5th European Framework Project MEGAPIE–TEST as it is directly linked to the MEGAPIE–Initiative.

Considerable progress, however, has been made in the design and on a number of issues relevant to the design and operation of the target.

2.1 Target Design Overview

2.1.1 Main MEGAPIE target parameters

The main MEGAPIE lead bismuth eutectic (LBE) target parameters are summarised in the following table 2-1 :

Target geometry

| | |
|------------------------------|--------|
| Overall length of the target | 5.35 m |
| Weight (empty, without LBE) | 1.5 t |

Proton beam

| | |
|---------------------------------|---------|
| Reference proton beam intensity | 1.74 mA |
| Proton energy | 575 MeV |
| Heat deposition | 650 kW |

Liquid metal

| | |
|---------------------------------|-----------------------------|
| Coolant and spallation material | Lead bismuth eutectic (LBE) |
| LBE volume | 82 l |
| Wetted surface | 8 m ² |
| LBE temperature range | 230°C – 380°C |
| Max. flow rate | ~ 1 m/s |

Beam window

| | |
|-----------------------|---------------|
| Beam window material | T91 |
| T91 temperature range | 330°C – 380°C |
| Expected dpa rate | 20 – 25 dpa |

Tableau 2-1 : Main MEGAPIE target parameters

2.1.2 Brief functional description of the MEGAPIE target

Figure 2-1 shows a schematic view of the different MEGAPIE target sub-systems and the list of ancillary systems.

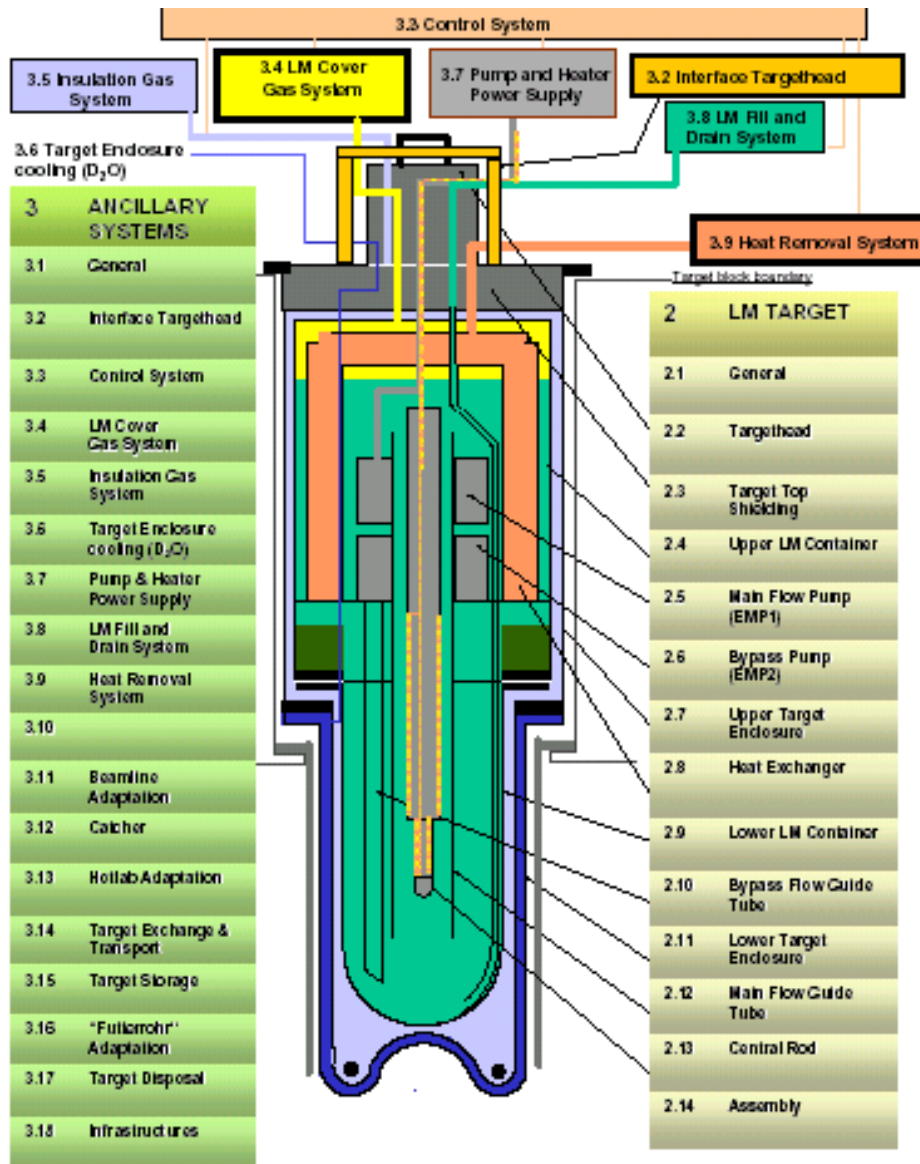


Figure 2-1 : Schematic view of the MEGAPIE target with its target sub-systems and ancillary systems.

The proton beam penetrates the target via two windows, the double-walled enclosure hull and the inner beam window, from below. The double-walled enclosure hull (Lower Target Enclosure, LTE) is cooled by a forced convection heavy water flow. The inner beam window is cooled by the liquid LBE. The LTE and the beam window are separated by an insulating gap filled with Helium.

The LBE flow is provided by two electromagnetic pumps: an axis-symmetric main flow down an annulus (between Main Flow Guide Tube, MFGT, and Lower Liquid Metal Container, LLMC) and an additional flow via a by-pass tube. Due to the large height of the target, the

character of the flow is mixed convection. The combination of main flow and by-pass flow ensures the cooling of the beam window.

The spallation heat which is produced in the lower part of the MFGT (in the region up to 30 cm above the beam window), is removed via double walled heat exchanger pins to an intermediate cooling loop and finally to an existing secondary cooling system. The fluid of the secondary system is high-pressure heavy water, D₂O.

In the centre of the MFGT, an instrumentation pin (Central Rod, CR) is inserted which holds instrumentation for the measurement of the neutron flux density and thermo-hydraulic data.

A shielding plug is provided in the top part of the MEGAPIE target, in order to avoid excessive radiation levels in the target head room from direct gamma radiation from the liquid metal.

From the description above the main target sub-systems are:

- ✓ the double containment composed of a double walled lower target enclosure (LTE made of AlMg3 with a concave sphere shape) and the liquid metal container (LMC) that contains the LBE;
- ✓ the central rod equipped with heaters, instrumentation and neutron monitors;
- ✓ the 12 pin single walled target heat exchanger;
- ✓ the electromagnetic pump system, the main pump for the main flow and a second pump for an LBE by-pass flow across the beam window;
- ✓ the helium insulating gas system;
- ✓ the cover gas system.

2.2 Relevant design issues

The main relevant design issues are 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. The main items are given in the following list:

- ✓ neutronic benchmark and a detailed assessment of the nuclear reactions to determine relevant input data for the design and safety assessment of the target;
- ✓ thermo-hydraulic and thermo-mechanical modelling of the systems and components under normal, transient and accidental conditions, including experimental validation;
- ✓ investigation of material properties under irradiation, corrosion behaviour and the risk of liquid metal embrittlement;
- ✓ assessment of the LBE properties and the behaviour of the spallation products.

This report summarises the status of the activities developed in the design support and validation task based on the presentations made at the 5th Technical Review Meeting in Nantes, 24-26 May 2004.

2.3 Overview of the Ancillary Systems

Figure 2-2 shows an isometric view of the ancillary systems necessary for the target operation, as they are planned to be installed, inside the shielding of the SINQ target block.

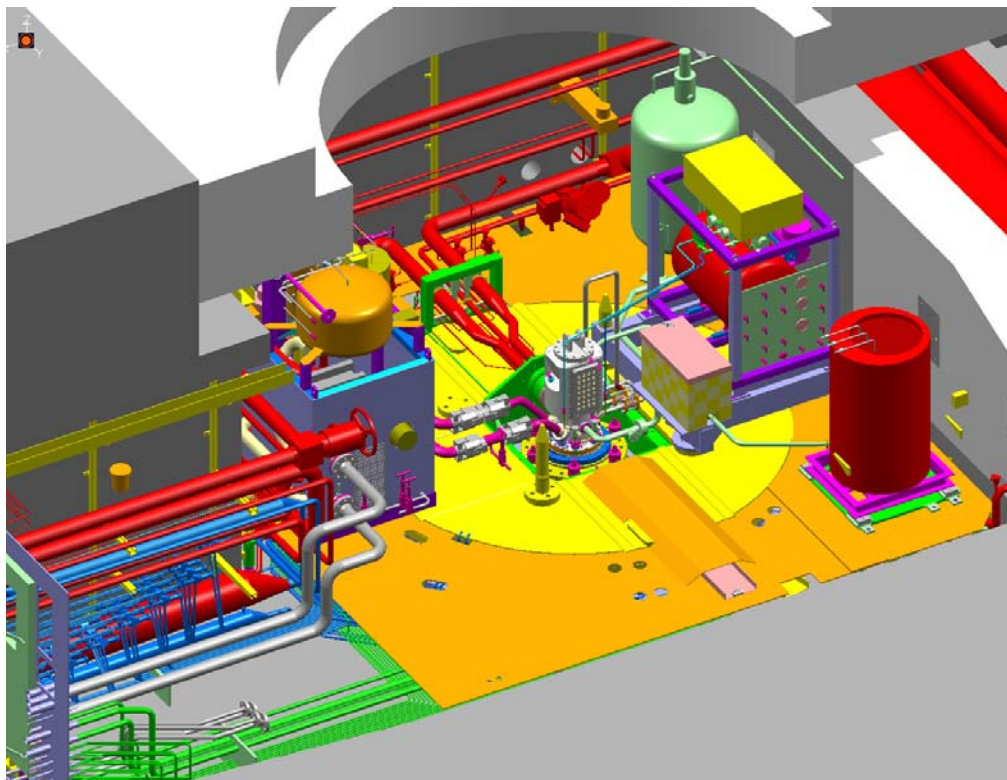


Figure 2-2 : Isometric view of the MEGAPIE ancillary systems in the TKE, showing the target head in the centre, the intermediate oil cooling loop of the heat removal system at the left, the cover gas system, the fill and drain system and a voluminous steam condenser at the right.

The ancillary systems designed are:

- ✓ The Heat Removal System, HRS, with Diphyl THT® oil a cooling medium and an intermediate water loop;
- ✓ The Cover Gas System, CGS, to cope with the overpressure in the target and to assure the confinement of all gases and a regular and controlled venting;
- ✓ The LBE Fill and Drain System, F&D, with a double containment and an appropriate system for disconnecting the tubes after operation;
- ✓ The Insulation gas System, IGS

Before the irradiation phase, these systems will be tested in a dedicated test stand (see figure 4-1).

3 TARGET DESIGN (Subtask 1.1)

The design subtask has been based on the MEGAPIE feasibility study and divided into:

- ✓ the Conceptual Design phase:
concentrating on the identification of critical issues, selections of a reference technical design and reference materials, analytical sizing of individual components, definition of instrumentation and operation control, identification of possible sources of failure and consequences, outline design for ancillary systems;
- ✓ the Engineering Design phase:
concentrating on the numerical optimisation of single components and complete system, identification of component and system failure modes including lifetime expectancy of the system, engineering design of ancillary systems and the preparation of a Quality Assurance Plan for manufacturing and testing

The geometrical boundary conditions and the fact that the MEGAPIE target has to fit to the existing SINQ facility at PSI fixes the main dimensions of the target as shown in figure 3-1. An outer view of the complete target is shown on the right side of the figure.

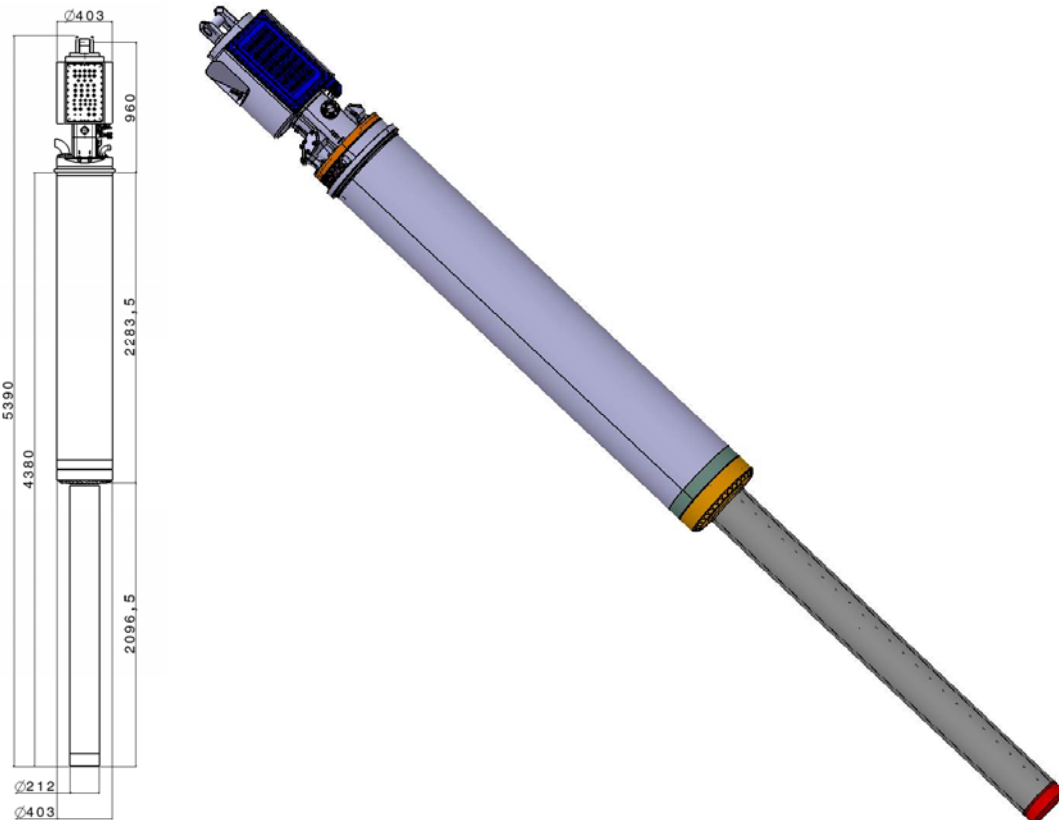


Figure 3-1 : Main dimensions of the MEGAPIE target and a complete view of the target

The target is composed of:

- ✓ Major structural elements:
Upper Target Enclosure (UTE), Lower Target Enclosure (LTE), Upper Liquid Metal Container (ULC), Lower Liquid Metal Container (LLMC);
- ✓ Major components:
Target Heat Exchanger (THE), two Electromagnetic Pumps (EMP1 and EMP2), Target Head (TH), Target Top Shielding (TTS), the Central Rod (CR) and the Main and Bypass Flow Guide Tube, LBE leak detector.

For the target components and structural elements, the engineering design phase and the detailed design phase are finished. The detail design calculations and reports are in progress.

3.1 Target Head

Target Head (TH) is a part of the secondary confinement of the target. It is constituted by a 316 L body, two flanges for electrical connections, one hook, plugs for oil and D₂O feeding of the target.

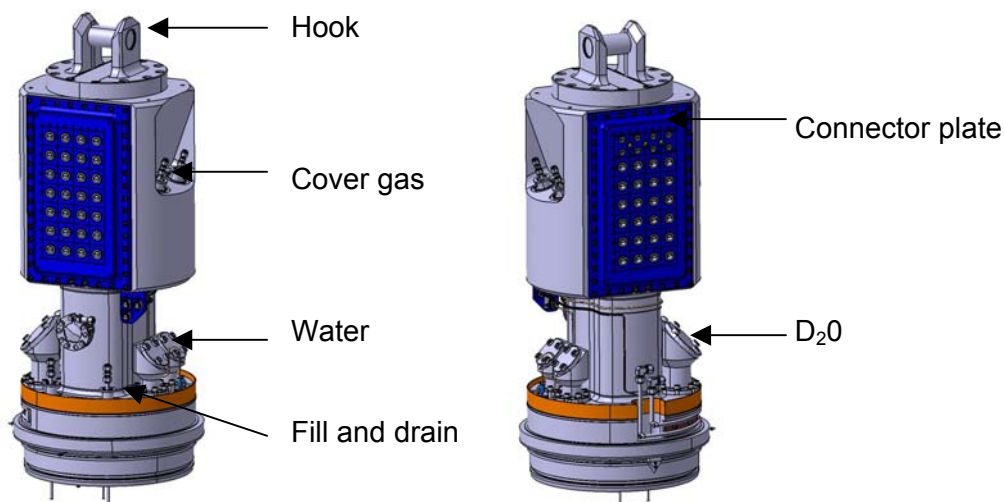


Figure 3-2 : 3D view of the target head.

A 3 dimensional view of the TH is shown in figure 3-2. The TH assures the interface of the target to the different ancillary systems. All electrical signals and power supplies, pipes and tubes have to pass through the TH. All cables, oil, water and cover gas pipes as well as the fill and drain (F&D) tubes for the LBE have to be designed adequately for an easy disconnection after the target operation. It has to be conform to the safety requirements assuring confinement of radioactive products during all handling steps of the target after irradiation.

The main access ports to the inside of the target are (see figure 3-2):

- The target hook system at the top to insert and extract the target into SINQ. This hook will be manufactured out of a special steel (42CD4) with an optimum mechanical behaviour (At a load of 10 t, corresponding to the maximum weight of the crane in the SINQ hall, the stress is about 143 MPa and the resulting displacement 85µm).
- The Ar cover gas in and outlet with its second containment.
- The insulating gas inlet for He at 0.5 bar.
- Two connector plates for electrical cables at the front and backside of the target head.
- The oil and heavy water (D₂O) in and outlet pipes and the LBE fill and drain tubes.
- The pumping flange (diameter 40 mm) serves to evacuate the target. At the outside of this pumping access, a safety valve will be connected in order to release the overpressure from the insulating gap in case of an accidental LBE – water interaction inside the target.
- Small contact leak detectors are mounted on the top flange in order to detect oil, water or a leak coming from the connectors.
- The tightness of the target with respect to SINQ target guide tube is achieved by a Viton seal at the lower part of the target head. Thermomechanical design calculations showed a strong temperature asymmetry due to the in and outlet temperature (60°C and 200°C respectively) of the heat exchanger oil. To avoid any problems with overheating of the Viton seal a dedicated seal cooling will be tested during the tests phase. According to the results, this cooling system will be mounted or not and might be replaced by a simple air-cooling.

3.2 Target Top Shielding

The Target Top Shielding (TTS) is composed by : two D₂O distribution boxes, two DIPHYL distribution boxes, and a set of steel and tungsten massive parts for gamma shielding.

The TTS is the part located just below the target head and covers the space between the TH and the top of the target heat exchanger.

At this level, the oil distribution boxes (for the thermal heat exchanger) and the water distribution boxes (for the lower target enclosure) are located for the in and out-streaming fluids. Due to their particular shape, special attention had to be paid to the stress levels and requested the adaptation of the design. A linear static analysis with the 16 bars design pressure showed that stresses and displacements are within acceptable limits (oil boxes: 117 MPa and 0.18 mm, water boxes: 111 MPa and 5.2mm).

The LBE fill and drain tubes pass at the outside the TTS down to the lower part of the target. The outer tube diameter is Ø 8 mm (wall thickness 1 mm) and both pipes are heated with heaters performing 150 W/m in order to avoid freezing of LBE in the tubes. For monitoring of the temperature the tubes are equipped with two thermocouples.

Initially it was foreseen to implement in the TTS gas (Hydrogen) and mercury absorbers. Based on a project decision these absorbers were skipped due to the absence of qualified systems and therefore also for safety and reliability reasons. Hydrogen will be managed together with the other gases produced in the target. For mercury it was decided to implement a catalyser in order to condense the mercury vapours. The catalyser will be mounted on the water boxes in order to be kept at low temperature (see figure 3-3).

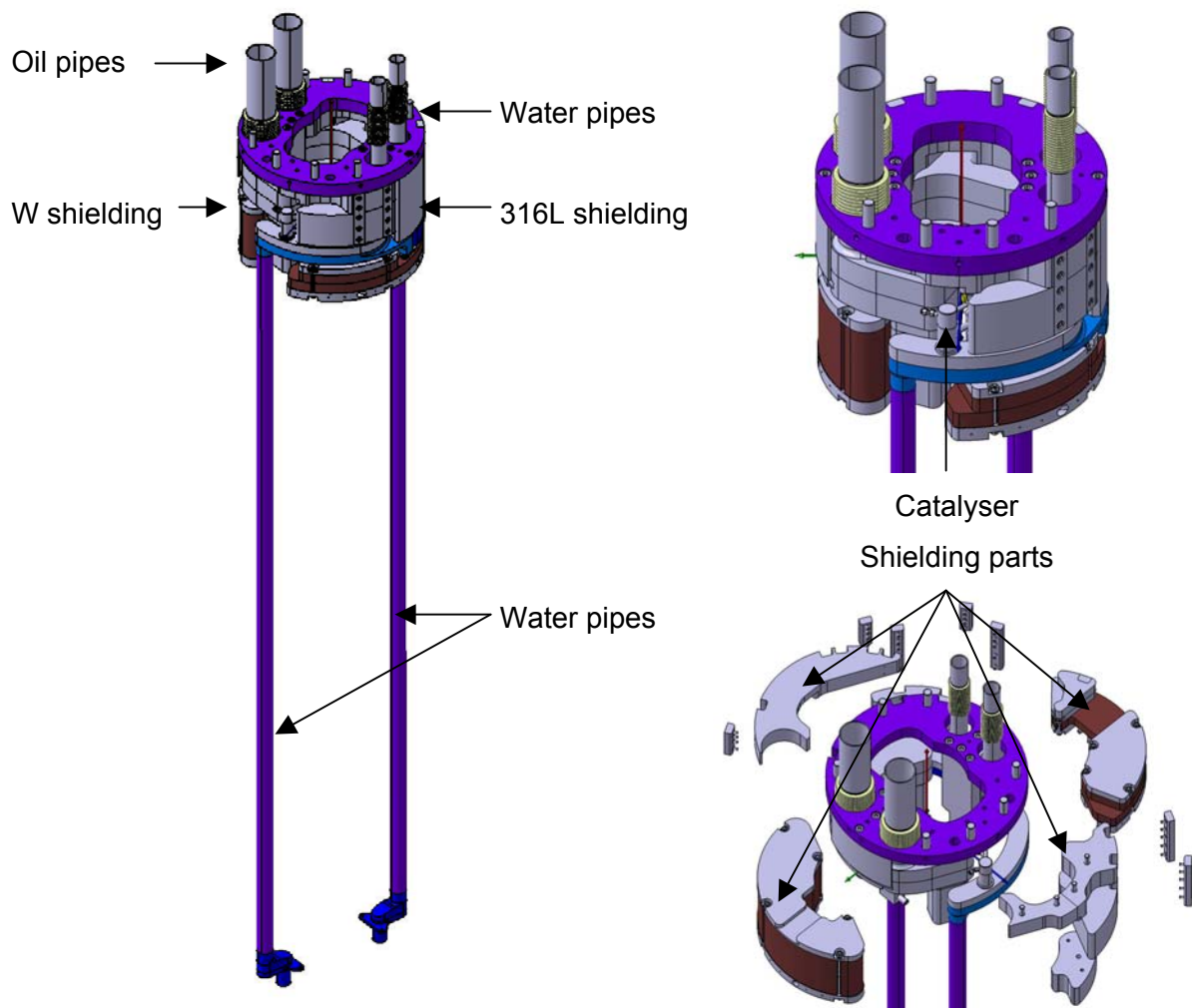


Figure 3-3 : Target top shielding (left) without (right, lower part) and with the shielding blocks (right, upper part)

The free space in-between these different components has to be filled up with shielding material, in a sort of 3D puzzle. The shielding is a critical issue because of the fact that radioactive material is transported via the liquid metal up to the top of the target (cf. section 5.1.1 Neutronics). In solid targets, the radioactive material is localised in the lower part of the target, in region of the beam interaction with the spallation material. This is not the case for MEGAPIE where radioactive material circulates with the LBE throughout the target. The radioactivity in the target constitutes a source term for the activation of structural material surrounding the target (cf. section 5.1.1 Neutronics). To keep this activation (mainly gamma activation) at the requested levels the shielding

is being optimised. Whenever possible, feeds through this shield should be designed to avoid direct sight.

3.3 Target Heat Exchanger and Upper Liquid Metal Container

The Target Heat Exchanger (THE) is made of 12 pins of 120 cm long arranged in circle. Each pin consists of 2 tubes concentrically arranged: the inlet and outlet tubes. Using the diathermic oil Diphyl THT[®] as cooling medium (cf. section 5.4.3 LBE-organic oil interaction), it was necessary to implement a spiral in the oil path to increase the contact length. The main problem in the design of the THE was to comply with the complex thermal conditions and to limit the resulting thermo-mechanical stresses. A good agreement has been reached by connecting the pins to the inlet and outlet oil distribution boxes by flexible bellows and by inserting thin shrouds as heat shields. The heat is removed from the THE 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. The major components of THX are (see figure 3-4):

- Diphyl distribution boxes (DDB), where the distribution of coolant in pins is made,
- The pins, which represent the surface exchange to remove the heat of the target,
- The liquid metal enclosure, including the Upper Connecting Flange (UCF), the Upper Lead Bismuth Container (ULMC) and the Lower Connecting Flange (LCF). This set is the upper liquid metal containment of the target.
- The instrumentation, made of thermocouples, is employed to control of efficiency of the THX.

Principal running parameters are :

- Flow rate of the LBE: 0.4 l/s;
- Diphyl flow rate: 10 l/s;
- Inlet temperature of LBE can be lowered beneath 350°C;
- To avoid liquid metal embrittlement, the minimum surface temperature on the liquid metal side should stay at least about 50°C above the melting point, i.e. above 175°C for the LBE.

The actual THE design can be separated into 3 parts:

- Diphyl distribution boxes that allow the uniform distribution of the oil into the 12 heat exchanger pins. The in and outlet diphyl boxes have to be thermally insulated with respect to the LBE. To reduce thermal stresses, bellows assure the binding between the two tubes of each pin and the diphyl boxes. The shape of the containment wall in

the inlet should be designed to avoid zones of stagnant fluid, where impurities could be collected or bubbles could be trapped.

- The upper liquid metal container assures the bond with the lower liquid metal container. It also has to centre the two electromagnetic pumps and to guide the liquid metal around the pins.
- The heat exchanger pins are constituted of two coaxial tubes. The inside thick tube collects two functions : inflow duct and shielding because of its high thickness.

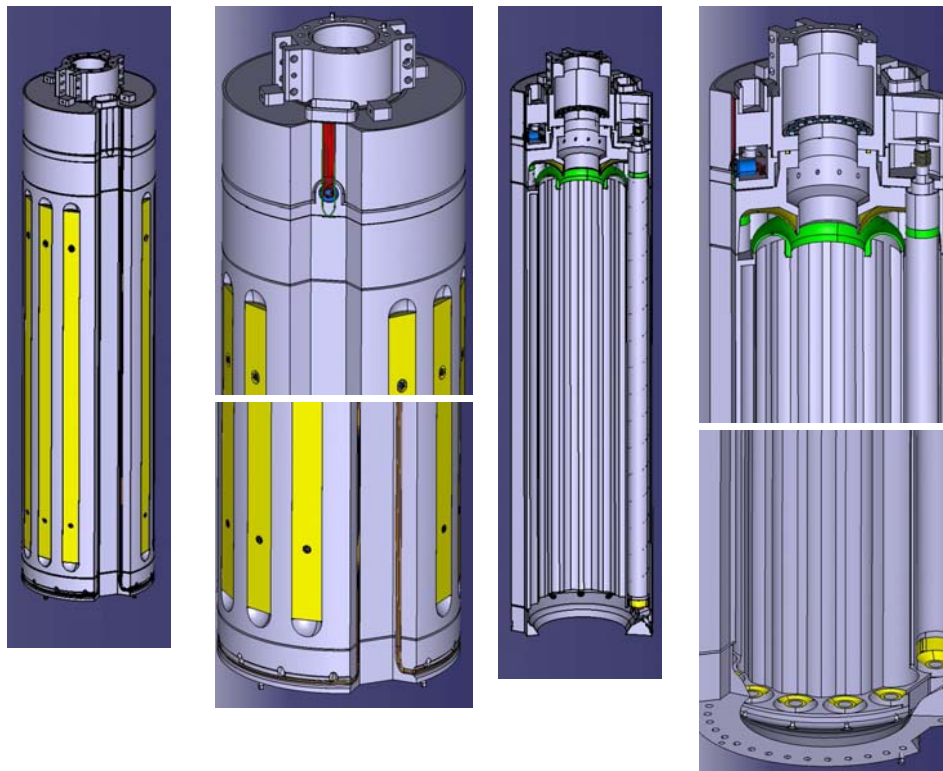
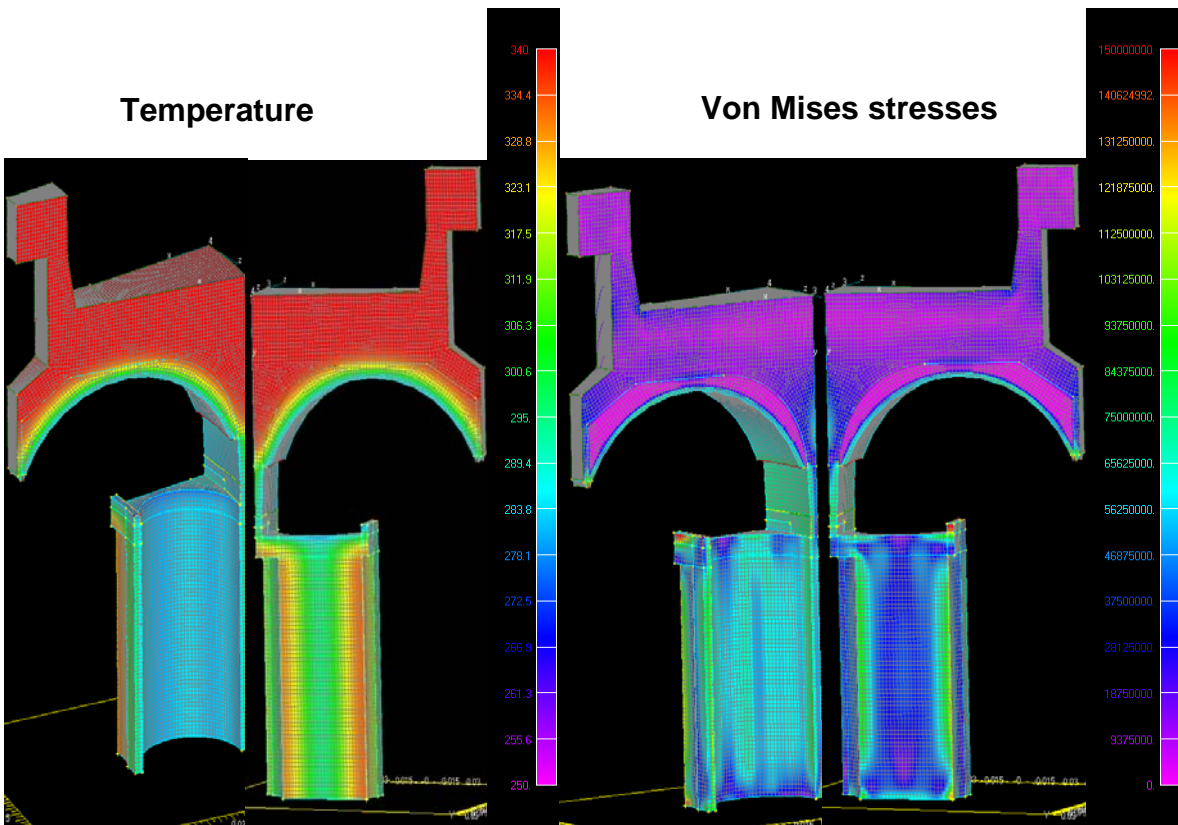


Figure 3-4 : General view of the Target Heat Exchanger (left) and vertical cutted view (right)

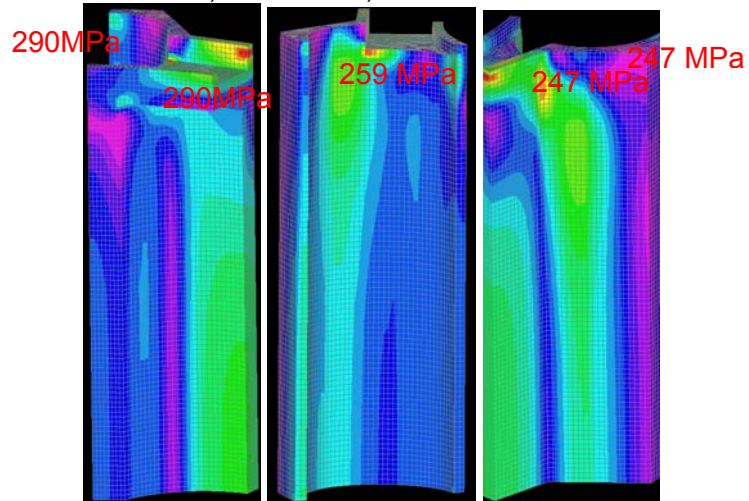
Numerous thermo-mechanical calculations have been performed on the THE design using NASTRAN code. They can be classified in 3 classes according to the following running conditions :

- ✓ **Accidental conditions** : this scenario is corresponding to a leak of Diphyl in LBE or a leak of Diphyl out of the liquid metal containment. These calculations are only related to the LBE containment : UCF, ULMC & LCF. They are performed on 1/24 of the total geometry.
- ✓ Normal **steady state thermal conditions**, corresponding to the normal operation : Their aim is to demonstrate the efficiency of the thermal insulation of the “Y shape” of the outer tube and the Pin Thermal Insulation.
- ✓ Normal **thermal transient conditions**, corresponding to a beam shutdown : these calculations corresponding to the thermal transient situation can be performed separately on :

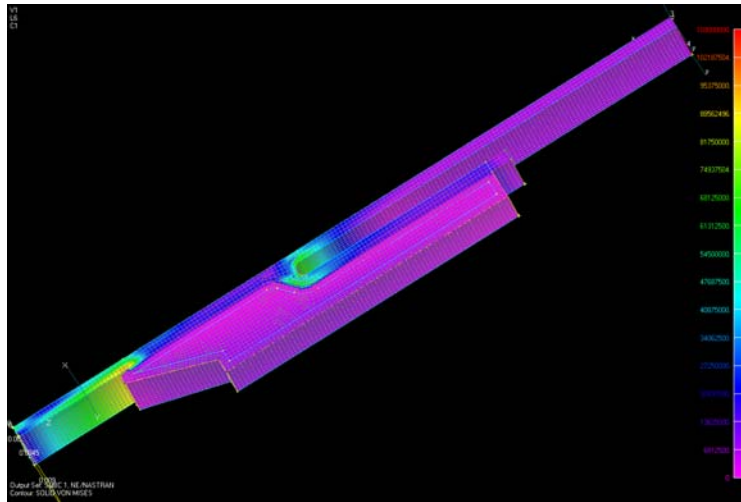
- the LM container, "duct" area,



- the LM container, "web" area,



- the pins.



Some fatigue calculations have been required to conclude to the validation of the design of the LMC “duct area” and the LMC “web area” in transient mode, in regard of the expected service life of 10 000 cycles. Calculations according to the fatigue curve at 350°C of 316 L (appendix 1) from RCC-MX [2], give for the pessimistic case, a number of cycle higher than $2 \cdot 10^4$, higher than the 10 000 cycles required. It must be reminded that the F.E. calculations have been performed assuming pessimistic thermal loads.

The results of these calculations allow to validate the THX updated design. The corrosion effect due to LBE was not taken into account. This device, made of AISI 316 L steel grade, is able to run up to 10 000 cycles in MEGAPIE conditions.

3.4 Electromagnetic Pump System

TO BE CHECKED AND APPROVED BY IPUL AND PSI

Design of MEGAPIE Target electromagnetic pump system (EMP-system) has been developed in collaboration between PSI and Institute of Physics of the University of Latvia. It maintains lead bismuth eutectic (LBE) flow in the target to ensure reliable cooling of beam entrance window.

There are two electromagnetic pumps (main pump, EMP1, and bypass pump, EMP2) to transport LBE and two flow meters (one in main flow and one in the bypass flow).

The main pump is responsible for a transit flow between the LBE container and heat exchanger elements mounted on the periphery of the target.

The by-pass pump is responsible for a flow through the special nozzle situated radial in the container to destroy the flow symmetry (see figure 3-5). The EMPS is mounted in steel housing to protect it from LBE.

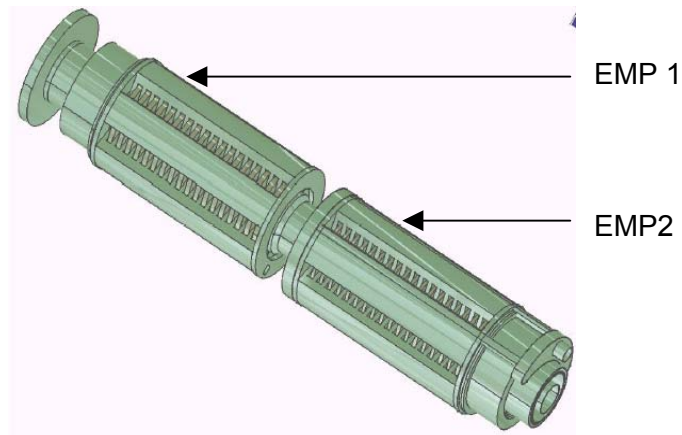


Figure 3-5 : View of the electromagnetic pump system

Main characteristics are:

For the mainstream pump:

- Straight through pump with upward flow;
- Nominal flow rate for LBE: 5 L/s;
- Nominal operating LBE temperature range 180 °C to 400 °C;
- Maximal operating temperature of EMP coils: 450 °C;
- Pressure drop in the outer loop: 0,2 bars.

For the bypass pump:

- Straight through pump with upward flow and redirection downwards in the bypass tube;
- Nominal flow rate for LBE: 0,5 L/s;
- Nominal operating LBE temperature range 180 °C to 300 °C;
- Maximal operating temperature of EMP coils: 450 °C;
- Pressure drop in the outer loop: 0,5 bars at 0,5 L/s.

One of structural features of EMP and flow meters design and production is the fact, that products are not serial production and each time there is a need for choosing and fabrication of special equipment and tooling: tooling for assembling of magnetic yokes, of coils, of stamps for cutting slots into steel sheets and other. The consequence of operations at EMP-system production is following:

1. Production of tooling;
2. Cutting of the sheets for magnetic cores and yokes of pumps;
3. Cutting out slots in magnetic yokes;
4. Production of coils;
5. Production of the details of the channels of pumps;
6. Assembling of magnetic yokes and cores;

7. Annealing of the cores;
8. Production, tests and graduation of flow meters;
9. Assembling of by-pass pump including its fixing at lower flange;
10. Assembling of the main pump;
11. Assembling of joint for pumps and flow meters;
12. Assembling of ampoule;
13. Annealing of ampoule;
14. Checking and tests of assembled EMP-system.

The main constructive data and characteristics of pumps for EMP-system at nominal regimes are shown in the following tables:

| Parameters | Main pump | Bypass pump |
|---------------------------------------|------------------|--------------------|
| Pressure, atm | 0.2 | 0.5 |
| Flowrate, L/s | 5.0 | 0.35 |
| Active power, kW | 8.2 | 6.8 |
| Power, kVA | 9.8 | 8.14 |
| Phase current, A | 30.3 | 30.1 |
| Density of current, A/mm ² | 6.0 | 6.0 |
| Voltage, V | 108 | 90 |
| Induction in passive magnetic core, T | 1.2 | 1.14 |
| Temperature, °C | 480 | 320 |

| Weight, kg | Main pump | Bypass pump |
|---------------------------------|------------------|--------------------|
| Inductor, electrical steel 3413 | 46 | 35 |
| Core, electrical steel 3413 | 8 | 7 |
| Steel plate | 62 | 61 |
| Windings, copper | 10 | 7 |
| Pump, without frame | 64 | 60 |

| Design | Main pump | Bypass pump |
|--|------------------|--------------------|
| Wire, POZ-700, mm | 1.6 x 3.15 | 1,6 x 3.15 |
| Thickness of the LM in the channel, mm | 15.0 | 5.0 |
| Thickness of the channel wall, mm | 1,5 | 1,5 |
| Width of the prong, mm | 9 | 9 |
| Width of the slot, mm | 11 | 11 |
| Height of the slot, mm | 29.6 | 21.2 |
| Height of the yoke, mm | 20 | 18 |
| Number of the windings in the slot | 2 x 12 | 2 x 8 |
| Inner diameter of the inductor, mm | 127 | 150 |
| Inner diameter of the core, mm | 64 | 108 |
| Thickness of the core, mm | 12.4 | 12.2 |
| Number of pairs of the poles | 1 | 1 |
| Number of the slots/poles/phases | 3 | 3 |
| Number of slots of the inductor | 18 | 18 |
| Number of packs of the inductor | 6 | 6 |
| Boundary dimensions | D 228x370 | D 228x370 |

Taking into account rather hard conditions of operation excluding any possibility for repair and change of separate parts the documentation and construction of EMP-system must correspond to the Detailed Design and Quality Insurance Rules. Any changes or deviations from Detailed Design must be approved by MEGAPIE Project Management.

The following procedures for manufacturing and assembly are foreseen:

1. To carry out initial tests of materials used for construction of system.
2. To design and to manufacture the machining auxiliary attachments for fabrication of details and parts of construction.
3. To manufacture the inner element of the channel of EMP1 applying annealing of the core (tubes 62 x 2 mm and 92 x 1.5 mm).
4. To fabricate the outer element of the channel of EMP1 (using X-ray tests for the strength and leak-proofness), and the core of EMP2 (tubes 106 x 2 mm and 125 x 1.5 mm).
5. To fabricate the yokes for EMP1 and EMP2.
6. To fabricate the inductors for EMP1 and EMP2 (with boring orifices for the channel, _ 126 mm and _ 149 mm).
7. To fabricate the coils for EMP1 and EMP2 applying impregnation, drying and baking.
8. To assemble the inductor of EMP1 with coils, to solder the outputs according to the scheme, to make impregnation and drying to insure electrical isolation.
9. To assemble the inductor of EMP2 with coils, to solder the outputs according to the scheme, to make impregnation and drying to insure electrical isolation.

10. To fabricate the inner element of the channel of EMP 2 (using X-ray tests for the strength and leak-proofness), tubes 135 x 1.5 mm and 112 x 1.5 mm).
11. To fabricate the outer element of the channel of EMP 2, tubes 148 x 1.5 mm and 125 x 1.5 mm).
12. To fabricate the elements of by-pass decoupling tract.
13. To fabricate the flow meters for EMP 1 and EMP 2.
14. To fabricate the EMP 2 (the channel with by-pass, inductor and flow meter) in full assembly.
15. To assemble the inductor of EMP 1 with flow meter.
16. To assemble EMP 1 and EMP 2 on the channel of EMP 1.
17. To install the assembly into the outer housing (tube 232 x 2 mm), to compound the air cavities, to dry the compound, to fix and to weld necessary welds.
18. To carry tests for strength and leak-proofness.
19. To make the milling of base surface to be perpendicular to the housing surface.
20. To assembly the EMP-system applying leak-proof spacers, to attach the joint flange and to carryout the tests for leak-proofness.

As during the operation of EMP-system it will be exposed to thermal and mechanical loads, and also to action of liquid metal heat transfer medium, all parts of ampoule must be checked and tested in accordance with standard demands.

The tests are foreseen to carry using 4 methods: 1. All butt welds to test using X-ray tests. 2. Edge welds to test using Dye-penetrating method. 3. Bulk cylindrical elements to block and to test using corresponding gas pressure. 4. To carry out leakage-proofness using He-leakage method.

Special attention must be given to the elements having the contact with liquid metal. It is to the channel of main pump with the core, the channel of by-pass pump and housing. Leakage and even micro cracks may lead to short circuiting of pumps windings, of core plates and as a result to damage of all EMP-system.

So the channel of by-pass will be divided into parts and will be tested separately according to mentioned methods:

- inner part of the channel;
- outer part;
- lower collector together with tubes;
- after welding tubes with upper collector;
- then all assembly.

In the same way also the channel of the main pump will be tested separately.

- inner part of channel with core
- outer part
- assembled channel.

And at last fully assembled ampoule will be tested:

- to test joint elements of housing and pump assembly
- to test under pressure the channels of the pumps
- to test the strength of outer housing by gas pressure (10 bar)
- assembled ampoule will be tested using He-leakage method.

Electrical resistance will be checked between phases of power supplying cables and housing, short-circuiting of coils, Q-meters and workability of thermocouples. For each tests and checks corresponding protocols and acts will be prepared.

3.5 Upper Target Enclosure

Compared to the other target components the Upper Target Enclosure (UTE) is a simple cylinder made out of stainless steel A316L, with connecting flanges (see figure 3-6). The lower part is connected to the lower target enclosure. No particular cooling is foreseen for the upper target enclosure.

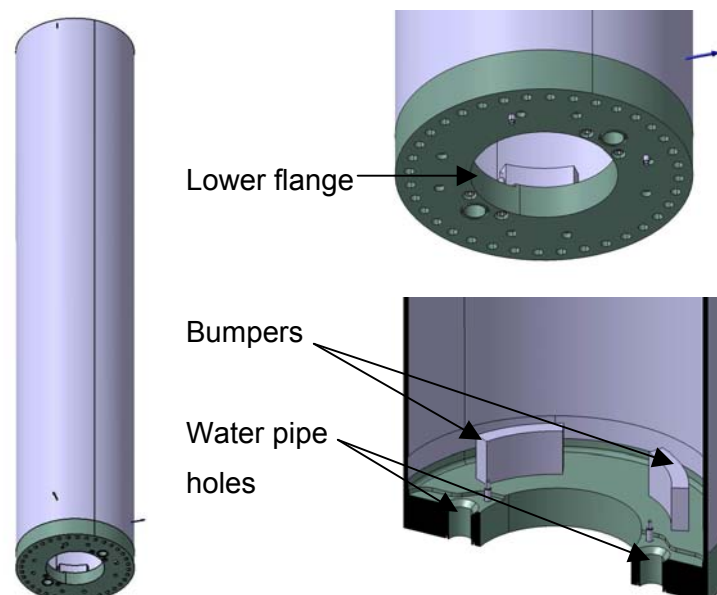


Figure 3-6 : Views of the Upper Target Enclosure

3.6 Lower Liquid Metal Container

The Lower Liquid Metal Container (LLMC) is a part of the primary confinement. It is constituted by a shell with thickness varying from 4 to 1.5 mm and an interface flange with the Main Flow Guide Tube (MFGT).

The LLMC is one of the critical structural parts of the MEGAPIE target. In particular the beam window is exposed to severe constraints: proton and neutron irradiation, thermal and mechanical load and the presence of flowing LBE. The structural material for the target container is martensitic (French designation T91 type) steel (cf. section 5.2.3 State-of-the-art on the T91 steel characterisation under MEGAPIE relevant conditions). For the Upper Liquid Metal Container (see above) the use of austenitic (316L type) steel is considered, which is more readily available and easier to weld. This is contingent upon sufficiently high liquid metal corrosion resistance, because the highest temperature gradient in the system will occur along the heat exchanger. In order to facilitate the transition between two different materials the two parts will be joined by a flange system.

Figure 3-7 shows the LLMC with a zoom on the beam window region (right). For buckling reasons the thickness of the cylindrical part is 2 mm in the lower part and 4 mm in the upper part.

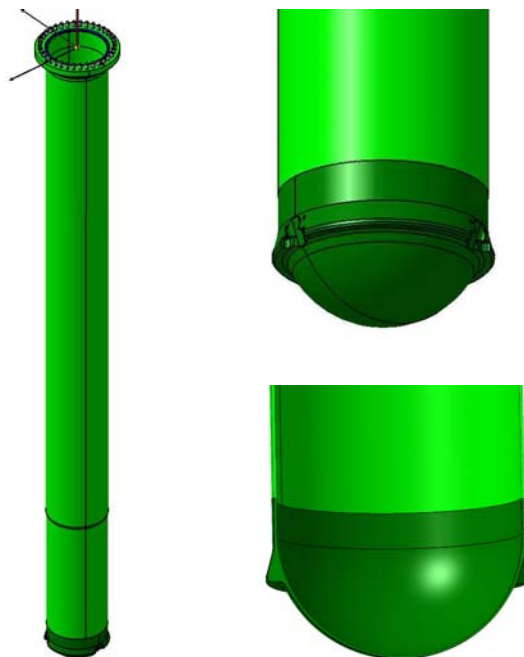


Figure 3-7 : The lower liquid metal container (left) showing a cut through the 1.5 mm thick beam window (right).

LBE leaks out of the liquid metal container into the gap filled with helium must be detected very rapidly. Dedicated leak detectors are under investigation that allow to detect very small quantities of LBE. One solution is strip detectors fixed to the liquid metal container and

thermocouples. A system of springs maintains the strip detector on the inner part of the lower target enclosure.

Investigations are ongoing for this LBE leak detectors. The feasibility of such a procedure is currently being assessed.

3.7 Lower Target Enclosure

The whole target container will be surrounded by a second enclosure, the Lower Target Enclosure (LTE), with helium gas in-between. In the lower part this enclosure will be double walled with heavy water cooling as is the present target shell (cf. section 5.4.2 LBE-water interaction). The material for this part will be chosen for minimum neutron absorption and sufficient strength at any temperature the shell might reach in the case of a breach of the target container. Presently, Aluminium ($AlMg_3$) is the favoured material, the same as for the actual solid SINQ targets.

The reversed spherical shape of the LTE (see figure 3-8) 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.

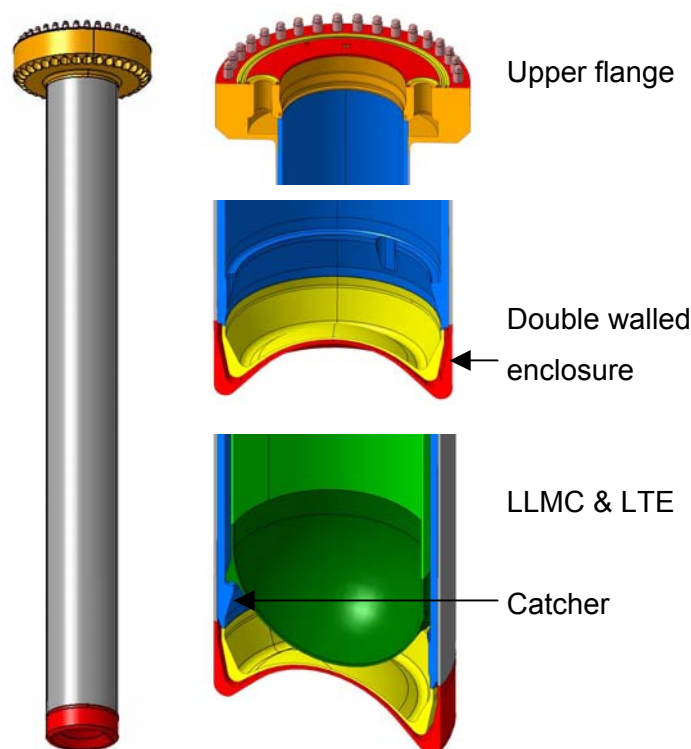


Figure 3-8: The lower target enclosure (left) showing a vertical cut (right) through the upper flange and the double walled enclosure

3.8 Main Flow Guide Tube

The Main Flow Guide Tube (MFGT) separates the down-coming cooled LBE on the outside from the up-streaming hot LBE in the inside. Main components (see figure 3-9) are the MFGT itself, made out of A316L stainless steel, the interface flange, for the electromagnetic pump and three spacers to keep the components in the defined position in hot as well as in cold conditions. A zoom on the lower part of the MFGT shows the by-pass tube for the additional window cooling, the fill and drain tubes and thermocouples for the temperature measurement in the lower part of the target.

The final shape of the by-pass tube outlet, the length of the fill and drain tubes as well as the position of the thermocouples are not yet finally fixed. Their final design will depend on results of thermo-hydraulic calculations performed by the MEGAPIE scientific design support and also results of experiments performed at FZK with PSI support (Heated Jet and KILOPIE LBE experiments and HYTAS water experiment).

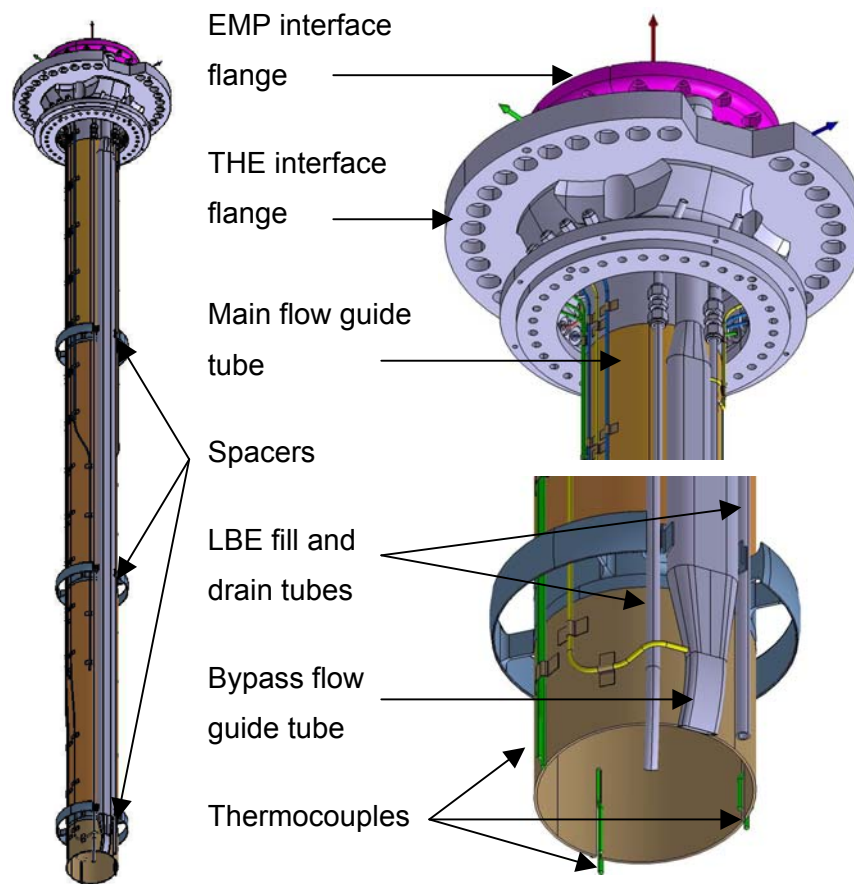


Figure 3-9 : Views of the main and bypass flow guide tubes

3.9 Central Rod

The Central Rod (see figure 3-10) will be inserted from the top into the MEGAPIE target. The CR fills up the central part of the target and reduces the amount of LBE. It is equipped with two heaters for the heating up of the target prior to the filling in of the LBE and to avoid uncontrolled freezing during operation when the beam is off. Neutron detectors will be install (small fission chambers designed by CEA) in the bottom part inside the CR to measure the thermal and fast neutron fluency.

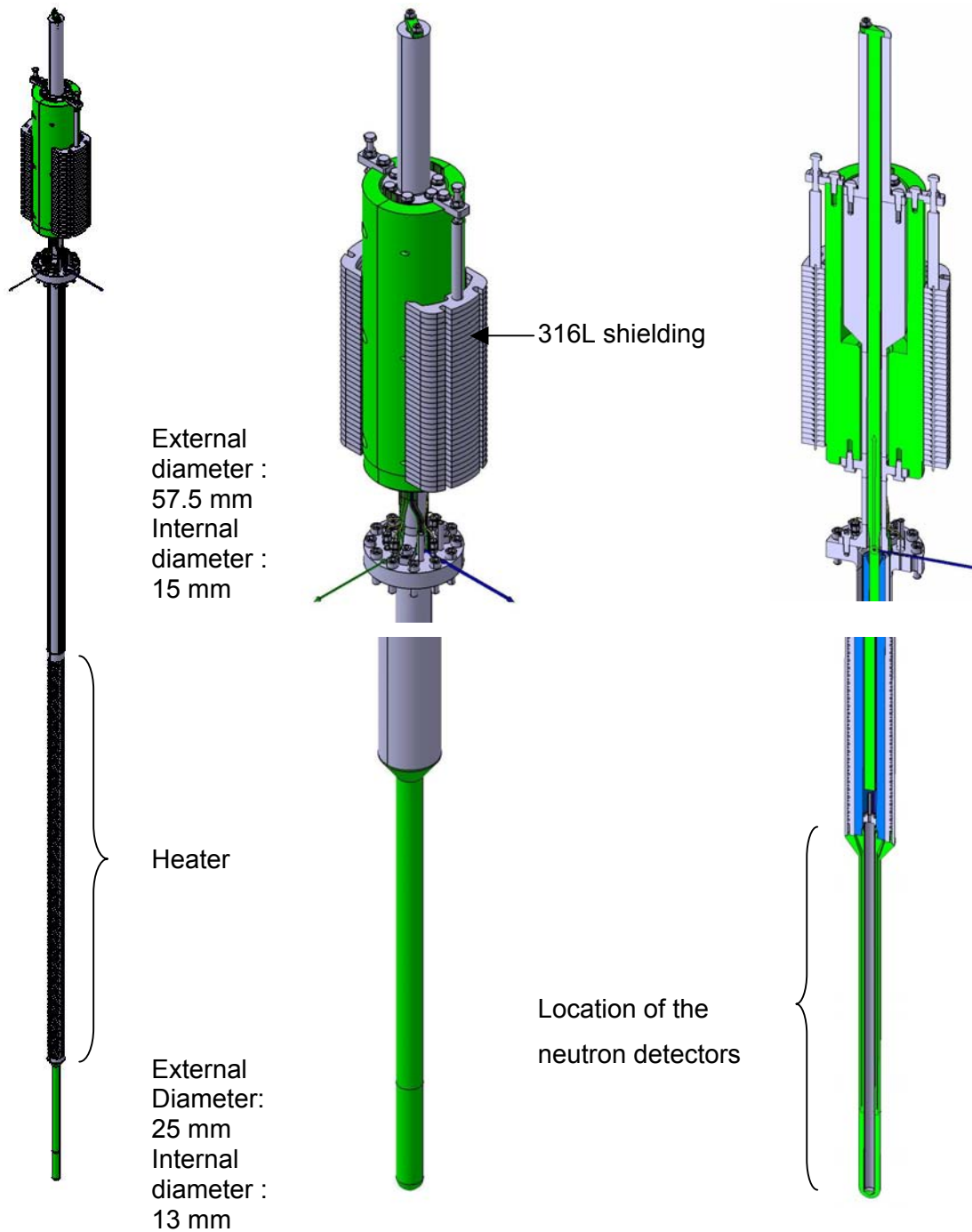


Figure 3-10 : The central rod (left), zoom of the upper and lower part (middle), cuts through the central rod (right)

3.10 Manufacturing

The detailed design of the target is finished and the manufacturing phase is started. The main institutes involved in the design are CNRS/IN2P3/SUBATECH, PSI and CEA for the Heat Exchanger.

After an international Call for Tender, ATEA has been chosen. ATEA is a member of REEL group and localised in Carquefou (France).

A step by step approach is used to manufacture the target, based on the different Lots:

- ✓ Lot 1: Upper Target Enclosure
- ✓ Lot 2: Lower Target Enclosure
- ✓ Lot 3: Target Head
- ✓ Lot 4: Target Top Shielding
- ✓ Lot 5: Heat Exchanger & Upper Liquid Metal Container
- ✓ Lot 6: Lower Liquid Metal Container
- ✓ Lot 7: Main & By-pass Flow Guide Tube
- ✓ Lot 8: Central Rod
- ✓ Lot 9: Assembly

The procedure applied for each Lot is to perform a Detailed Design Review and a Readiness for Manufacturing Meeting before starting the manufacturing process (machining, welding, assembling).

Detailed Design Review try to determine if a Lot is sufficiently defined to be manufactured. The main task is the verification of the drawings, engineering and design documents. For all target sub-systems, manufacturing drawings were performed 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 and all open points (design and feasibility) will be discussed in detail with the manufacturer. Manufacturing will than start after dedicated Readiness for Manufacturing Meetings.

Readiness for Manufacturing Meeting evaluates systematically one set of documents to perform the manufacturing, assembly and test process signed by the PSI. Main documents to perform the RfM review are: 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.

Then, manufacturing sequence for each Lot can be summarised as follow: process definition (technology, tools, qualifications), procurement of material and instrumentation, machining, assembling procedure, pressure test.

After three years in the framework of the MEGAPIE-TEST WP1, each sub-system of the target is released after a Readiness for Manufacturing Meeting. All pieces are machined. Welding and assembling phases are started. According to the manufacturing planning, the delivery date for the target is foreseen for the end of April 2005.

4 ANCILLARY SYSTEMS DESIGN (Subtask 1.1)

The MEGAPIE target, operating with liquid Lead-Bismuth-Eutectic (LBE), requires a number of ancillary systems to be fit for operation. These can be grouped in three categories:

- ✓ The operational ancillary systems, i.e. those which are immediately necessary for the target operation. These are the heat removal system (HRS) to extract the heat deposited in the liquid metal by the proton beam, the cover gas system (CGS) to handle the gases and volatiles produced during the spallation reaction, the insulation gas system (IGS) which guarantees the presence of insulating gas between the safety hull and the liquid metal container, and the fill and drain system (F&D) for filling the target with liquid LBE, all systems together with a common control system.
- ✓ Others are implemented into the beam line serving two purposes: i.) the visualization system VIMOS and the beam-canalising slit in QHJ30, both independently to prevent fatal accidents by unintentional loss of beam scattering in target E, and ii.) a new LBE catcher and guiding funnels to minimize the consequences of accidental spilling of liquid LBE into the proton beam line.
- ✓ A third category serving the target handling, transport, dismantling and disposal, which includes activities at ZWILAG and at the PSI hotlab.

Special attention has to be paid on the Fill-and-Drain System, the Cover-Gas System and the Insulating Gas System, in particular with respect to the required interfaces and double enclosure concept, the latter to some extent also affecting the target head interface. Directly related to the target heat exchanger is the heat removal system as one of the main ancillary systems. The arrangement of the systems in the TKE is now well elaborated (see figure 2-2). Regarding the beam line adaptation, there are still ongoing considerations for a special beam collimator to prevent a focussed beam from hitting the target, in conjunction with the VIMOS system for visualizing possible beam focussing. A further important task, the hotlab adaptation, has finished its feasibility study in collaboration with the hotlab operation division.

4.1 Liquid Metal Cover Gas System

The Target Cover Gas System (CGS) is located near the northeast corner of the TKE, connected to a 'Small Box' positioned close to the target head. The CGS system is currently in the detailed design phase. The main component parts of the CGS are a relatively large-volume decay tank, a vacuum pump and interconnecting tubing fitted with 6 solenoid valves for remote operation in the main box, and 4 in the small box. As the CGS is containing to a large extend radioactive

gases all components of the system have to be confined in a secondary containment to prevent any release into the TKE.

Extraction of cover gas will be necessary whenever the pressure increase due to the gases produced in Pb-Bi by spallation will reach a defined pressure, max. 0.2 MPa. The functions of the cover gas system are:

- to extract periodically these gases, to restore the start pressure (0.02 MPa).
- to let the radioactivity of volatiles (mainly noble gases) decay
- and to emit the remaining gas through an aerosol and active carbon filter into the controlled air exhaust of the accelerator plant when its airborne radioactivity is well below the allowed limits.

Vapours of volatile elements - mainly Hg and Po - are adsorbed within the expansion tank. The production rate of hydrogen isotopes and He determines the frequency of extractions, expected to be typically once per 1-2 months. This periods result from R&D support on neutronic/nuclear calculations done at PSI, LANL, CNRS ... to be checked/confirmed by ISOLDE experiments which will give more information on the spallation product production.

Gases shall be extracted by the cover gas system only during beam-downs. The gas is cooled from approximately 240 C to 50 C by streaming slowly through the cold trap built inside the upper target shielding, where the main part of remaining vapours condense. The decay tank stays always at under-pressure. Gas samples can be taken for radioactivity checks before each main action.

In spring 2004, the CGS received its final design updates and interface definitions, after re-assessment of expected and tolerable radiation levels in TKE and confirmation of the necessary shielding in TKE around the decay tank, valves and pipes. In this course, a simplified sampling procedure with unshielded sampling device was defined and approved, using a glass phial and a needle to perforate the covering membrane. The procedure defines sampling of fresh cover gas after a short target irradiation period with defined maximum charge received, and regular (or occasional) sampling of decayed gas before venting. Furthermore, the pressure transmitters (Kistler), vital components of the CGS to control the plenum gas pressure and quantify the sampling and venting inventory, were qualified for radiation resistance up to a total Gamma-dose of 1 MGy. They were found to resist this dose in a dry state, without a silicon oil buffer. The silicon oil showed degradation by gas release and was found not suited for high-dose applications.

4.2 Insulating Gas System

The IGS fills the volume between the lower liquid metal container and the double-walled safety hull by an insulating gas. The initial concept of a filling with Ar was changed in favour of a filling with He at a pressure of 0.5 bar, benefiting from lower activation on the expense of a higher heat leakage through He. The expected heat leakage of about 20 kW can readily be handled after filling the target with liquid LBE but would hamper the preheating before filling. Therefore during preheating a temporarily Ar-filling will be necessary.

The IGS was engineered at PSI, the P&ID scheme, signal lists and specification of components are finished. The final design update will be done after the completion of the HRS commissioning. One of the accident scenarios that needed to be looked at was water ingress from a leaking safety hull into the insulation gas volume with the consequence of steam production and possible pressure built-up. According to calculations the consequences of such an event can well be handled by a 40 mm diameter exhaust pipe and a steam condenser vessel outside the insulation volume.

The system has to assure the following functionality:

- Surveillance of integrity of the confinement (leak detection into the insulating gap);
- Evacuation of D₂O vapour in case of a leak into the insulating gap;

The selection of He gas system (He at 0.05MPa in normal operation) is based on the following arguments :

- The gas must be chemically inert;
- He is better than Ar due to its lower specific activation;

The system is composed of the gas filling tubes and the evacuation tube equipped with a certain number of valves. The evacuation of the insulating gas goes via the steam condenser vessel to the controlled exhaust system.

4.3 Liquid Metal Fill & Drain System

The liquid metal Fill & Drain System (F&D) of Megapie is intended to provide:

- frequent filling and draining of the target with LBE at the integral test stand (MITS),
- the initial filling of the target with LBE at the irradiation position in TKE,

Following the initial baseline, a design was elaborated for the F&D system which had allowed to drain activated LBE. However, the manipulation of the irradiated LBE was recognised to be a very critical and risky operation and very demanding on terms of safety. Particularly the following items had to be addressed:

- Pipe plugging (to be prevented during the phase of final or intermediate LBE draining).
- Final squeezing and cutting of pipes for the remote disconnection (separation of the drain vessel from the other parts of the system). This double operation has to assure that there will be no release of LBE and contaminated gas out of the tubes.
- Valve failure;
- Recrystallisation: The volume increase after freezing represents one of the main drawbacks of LBE. The volume increase can turn into stresses of the container walls and of its internals.
- Seal filling by fresh LBE: The final sealing of the vessel containing the irradiated LBE is performed, in order to assure a sufficient radiation shield, by pouring on the free level of the frozen irradiated LBE a layer (100 mm) of un-irradiated LBE.
- Overall functionality must be guaranteed by a series of tests performed at the nominal operating conditions following the complete F&D procedure, except for the final cutting.

An additional major issue in conjunction with active draining was the double containment of the F&D system. The Polonium concentration in the contaminated LBE is such that the vapour emission and sputtering that will condense on the surrounding surfaces will produce a contamination beyond the limits. Even if the design of radioactive containment and manufacture has been made with the higher standard, for safety reason one has to assume that a failure may happen producing a leakage. Therefore the parts of the system containing activated LBE (like the CGS as mentioned above) must be enclosed in a secondary containment that prevents any spill into the TKE in case of an LBE leak. The secondary containment must assure early leak detection out of the primary containment wall, the collection and containment of the leaked matter so that extraordinary provisions can be made to restore a safe situation inside the TKE. The secondary containment has an impact on the operation required when equipment and components have to be disconnected for independent handling and transportation.

Viewing these considerations the concept of active draining was abandoned in favour of only inactive draining and final freezing of the LBE in the target after completion of the irradiation experiment.

This design amendment allowed several significant simplifications for the F&D system: No need for approved radiation-hard components, no need for a second containment, no device for crimping and cutting of pipes contaminated by irradiated LBE. On the other hand, the inherent final freezing implements 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 possible. This drawback is intended to be minimized by controlled freezing and crush zones implemented in the lower target volume.



Figure 4-1 : The MITS at PSI in March 2004: The oil loop in place at the right hand corner of the platform (thermally insulated, but still uncovered), the WCL underneath, and the racks of the control system in the rear. A wooden plate covers the target reception flange in the middle of the MITS.

For operating the F&D system at the MITS (see figure 4-1), besides the regular draining vessel positioned above the target head a second draining vessel located underneath the target is necessary, primarily for emergency draining by gravitation, but also for ease of frequent regular draining on the test stand. This part of the F&D system will not be transferred to the TKE; there only the upper vessel with the necessary piping and gas supply can be used.

4.4 Heat Removal System

The Heat Removal System (HRS) of Megapie is designed to transfer heat from the target heat exchanger (THX) and dissipate it to the cooling water circuit via the intermediate heat exchanger (IHX). The target heat removal will be effected by means of an organic coolant Diphyl THT, Bayer.

The HRS consists of two subsystems: an intermediate cooling loop (ICL) with oil Diphyl THT as cooling medium, connected to the heat exchanger pins in the target. The ICL is back-cooled by a secondary water-cooling loop (WCL). The oil loop, operating between 160°C and 230°C (the LBE temperature in the target varies between 230°C and 330°C) is primarily necessary to remove the about 0.6 Megawatt of heat load deposited in the liquid 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. Unintended freezing would be fatal because solid LBE is known to expand after solidification by an enduring phase transformation which would stress the LBE container and thus inhibit a continuation of the experiment.

The main functions performed by the HRS are:

- LBE cooling during normal beam operation, by removal of heat from the LBE coolant;
- Control of the LBE temperature, on the cold leg, during normal beam operation, beam trips and extended shutdown phases;
- Provide a barrier to prevent any release to the environment of radioactive isotopes from the LBE circuit;
- Confine any ingress of radioactive isotopes from LBE side, further to accidental rupture of THX pins;
- THX heating up, to accept LBE filling;
- Minimise the frequency of conveying to the gas venting system the gases formed in the diathermic fluid as a consequence of radiolysis and pyrolysis;
- Monitor and collect small leakages of the diathermic fluid from any point of the HRS.

Power transients, which are caused by the relatively frequent proton beam trips or interrupts, require a control system that enables one to keep the target temperature variations within acceptable limits. First simulation results show that the temperatures can be maintained sufficiently far above the melting temperature of Pb-Bi.

The main arguments for the selection of the organic coolant for the intermediate cooling circuit of MEGAPIE are

- low vapour pressure (3mbar at 158°C)
- satisfactory heat transfer capability (0.15 kJ/(kg*K) for LBE at 300°C)
- tolerable decomposition and irradiation effects under the operating conditions

Based on a certain number of irradiation experiments (sealed capsule in a TRIGA reactor, electron irradiation experiment, analysis of early experiments under reactor conditions) extrapolations of the data to MEGAPIE conditions were performed with the conclusion that the max. decomposition of THT (23wt%) would be of no concern for risk of fouling. The radiolysis is likely to be half that figure.

4.5 New Safety Devices in the Beam Line

Three new devices are foreseen in the beam line for safeguarding MEGAPIE against perforation of the target by an insufficiently scattered proton beam; these are VIMOS, a slit in QHJ30, and upgraded current monitors at Target E. Each of these novel or upgraded systems on its own should be capable of switching off a narrow incident beam before any damage is done to the liquid metal target. Two of the systems have already been installed during the latest shut down at the beginning of 2004. First test results have proven the principal working of these devices.

4.5.1 VIMOS

The actual beam at the SINQ target will cause the glowing foil in the VIMOS hat to emit IR and visible light accurately tracing the incident intensity distribution.

Experiments in a dedicated mock-up facility had yielded the following characteristics for VIMOS:

- Observable area on glowing foil: ~ 10 x 11 cm
- Resolution: ~ 1 mm
- Depth of field: ~ 1 mm @ focus and ~ 50 mm @ target
- Minimum detectable temperature of glowing foil: ~ 900 °C

These values have been confirmed under the real conditions in the beam line.

4.5.2 Slit KNHY30 in QHJ30

The slit KNHY30 in the quadrupole magnet QHJ30 takes advantage of the fact that scattered protons take a slightly different path compared to non-scattered protons due to their different energy / momentum. The largest separation of about 20 mm between the centres of these two fractions of the beam occurs inside QHJ30. Two initially adjustable jaws will be aligned and locked such that only correctly scattered protons can continue to the SINQ target whereas the lower jaw of the slit will block particles with too high energy.

Already shortly after switch-on of the accelerator first tests have been performed to position the copper jaws. As soon as the slit was positioned first sensitivity checks were performed by slightly changing the trajectory of the protons before Target E. This led to an immediate increase in the readings of the ionization gauge MHI37 downstream of the slit and it also produced a jump in the detected charge on the lower jaw. With appropriately selected thresholds both signals very reliably trigger an interlock.

4.5.3 Catcher and Funnels

A new LBE catcher and guiding funnels to minimize the consequences of accidental spilling of liquid LBE into the proton beam line are designed and manufactured, and have been installed and tested in-place during the latest accelerator shutdown in Spring 2004.

4.6 Target Handling: Concept for Transport and Dismantling

The actual concept for transport and dismantling of the irradiated MEGAPIE target – which is to be confirmed in a more detailed study and which requiring official licensing in several steps – is to transfer the target to the hot cell at ZWILAG in a specially build container, after a certain cooling time in the SINQ target storage. After visual inspections and dimensional measurements on the LMC in the hot cell, the Target will be cut into pieces und packed into a shielded transport container (PSI RA-waste container KC-T30). The container will be transferred to the hot cell at hotlab in order to remove the LBE from the target pieces and extract samples for the PIE investigations.

Later the same container can be used for the interim storage at PSI (location has not been defined) and for the final storage of the conditioned target. At this time the activity will be low enough to remove the steel cladding, remaining a normal licensed KC-T30 container.

5 DESIGN SUPPORT AND VALIDATION (Task 1.2)

5.1 Neutronics

5.1.1 Summary of the past activities in the neutronic and nuclear assessment

This section describes briefly the past main achievements in the neutronic and nuclear assessment, relevant for the design of MEGAPIE. All the important aspects relevant to neutronic performance, power deposition, radiation damage, isotope production, and radioprotection issues were treated. References are given where these results are discussed in detail. In sections 5.1.2 and 5.1.3, the most recent achievements are described.

Target performance

Proton and neutron fluxes in the MEGAPIE target have been calculated. Detailed MCNPX models have been developed of the SINQ facility with the Mark 3 target and calculations were performed for this and the MEGAPIE target. A comparison between the neutron flux with MEGAPIE and the SINQ solid target was made in Ref. [1]. Results showed that the MEGAPIE target will deliver 40% to 50% more neutrons to the instruments served by SINQ as compared to the Mark 3 target.

Power deposition in the target

Calculations of the beam power deposition distributions are essential for the thermohydraulics CFD analysis of the lower target. Power deposition was calculated using the codes FLUKA and MCNPX [2,3]. The results from the two codes agree within 5%.

Approximately 85% of the beam power is dissipated in the target-moderator system (71% in the lead-bismuth), the rest is dissipated in the surrounding shielding.

The power deposition in the lead/bismuth eutectic (LBE) was studied in detail. It was found that the power deposition could be described by an analytical function such as [4]:

$$P_d(x, y, z) = G(z)D(x, y, z)$$

where $G(z)$ describes the longitudinal distribution of the peak of the power deposition, for $x=y=0$; $D(x,y,z)$ is fitting the evolution of the axial component of the power deposition. This term has a Gaussian dependence on x,y , with a σ with a quadratic dependence on z .

Beam power deposition on the structural materials was also calculated. 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.

Results from the thermohydraulics calculations using the neutronic results as input are in Ref. [4].

Radiation damage to structural materials and dyphil oil

Detailed neutronic calculations were performed using a measured beam profile [5]. Radiation damage in the T91 window and in the safety hull, using the damage cross sections from Ref. [6] and helium production were calculated [3]. From these calculations it can be derived that the peak damage and helium production rates at the beam window are 2.6 dpa/A·h and 215 appm He/A·h, respectively. In the centre, the proton contribution to dpa is as important as the neutron one. As far as the distance from the centre increases, the neutron contribution becomes dominant. These results have been used in Ref. [7] in the frame of a research work to assess the lifetime of the target.

A neutronic analysis of the dose rate to the THT oil, the working fluid in the secondary loop of the MEGAPIE Pb-Bi cooling system, was performed [8]. The dose received by the oil is dominated by the activated LBE. For the 77-Kg inventory of oil in the secondary loop, the absorbed dose is 0.2 W·h/g after 6 A·h of operation.

Isotope production in the target

This field of research has received a lot of attention in recent years, mainly because of the research in the ADS (see for instance the HYNDAS program) and more research is in progress. In the case of MEGAPIE, it is important to evaluate the radioisotope inventory for safety reasons. Moreover, the amount of gas produced (especially H and He) is important for the gas handling procedure.

The precision in the numerical estimates of the nuclide production is limited by the models used and by the nuclear data libraries available. The strategy adopted consisted in a code intercomparison [2,9,10], followed by a comparison with experimental data. This work is still in progress as new experiments are being carried out.

We discuss here the comparison between FLUKA and MCNPX. Overall there is a good agreement between the calculations; concerning the individual isotopes, for which the production rate is higher, for the ones close to the mass of the target, in general agreement within a factor of 2 or better is found. This result is important since Hg and Po are the most important elements as far as radioprotection is concerned. However, for other isotopes, and especially for the lighter elements, because of the different spallation/fission models used, and the different libraries for interaction of neutrons with the target material, larger differences are found.

In Ref. [2] a first attempt to evaluate the uncertainty of the FLUKA predictions was performed, based on the comparison between measured residual products at different proton energies. Calculations were compared with the data from Ref. [11]. In general, the ratio between data and calculations is about a factor 2-3 in the spallation region, and almost a factor of 10 in the fission region.

It must be noted that since these calculations were performed, following recent experimental results (see for instance [12]), and the development of new spallation/fission models, both MCNPX and FLUKA include different models to estimate the residual nuclei (in the case of FLUKA, different parameters in the model yield to different production rates in the fission region which fit better to the data). While the new models will not affect significantly the calculated production of Hg and Po isotopes, for other important elements such as Xe and I, significant differences can be found.

A new experimental campaign was started which will provide a further benchmark of Monte Carlo codes by comparing with results with an extended target. As shown in Section 2 and in Ref. [13], preliminary results show a better agreement between data and calculations, also in the fission region.

Radioprotection issues

Radioprotection issues were discussed thoroughly in the safety report [14]. In this comprehensive work, all the relevant topics related to safety aspects were treated, such as: radiation from the target in SINQ and in the TKE; dose rates from the cooling circuits in the TKE; radiation from the expansion tank in the TKE; activity in LBE and in the expansion tank; measured activities; first concepts for the target transport.

Additional issues in support to this work were considered in Ref. [15]. Using a Monte Carlo description of the target, the dose rates in the TKE room above the target, where personnel access may be needed at times, were calculated. Contributions from the activated lead-bismuth and from the volatile species produced were calculated. Results indicate that the dose level is of the order of 40 mSv h⁻¹ after shutdown, but it can be reduced below the mSv h⁻¹ level with slight modification to the shielding. Neutron spectra and dose rates from neutron transport, of interest for possible damage to radiation sensitive components, were also calculated.

5.1.2 Measurement of volatile Elements production rates in an LBE target at ISOLDE (IS419 experiment)

Following the interaction of the high-energy proton beam with the target of an accelerator driven system (ADS), nuclides are produced, many of which have high volatility. In MEGAPIE, this problem has been considered in great attention, and a cover gas system has been designed to handle the produced gas [16]. We performed a dedicated experiment to study the production rates of stable and radioactive volatile elements in an LBE target irradiated by a proton beam of the energy of the order of the energy of the SINQ synchrotron (590 MeV). The experiment was performed at the ISOLDE facility at CERN [17].

Experiment description

The spallation target used in the experiment consisted of a cylindrical tantalum container, 20 cm long and with 1 cm radius. A measurement run was performed in May 2004 with a target filled with liquid LBE (547 grams). A second run was performed in September with a liquid Pb target. The target temperatures were between 400 °C and 600 °C. Protons pulses of 1.4 GeV and variable intensity (up to 10^{13} protons/pulse with a rate of one pulse every 16.8 s) impinged on the target. Following spallation reactions, the produced volatile elements exiting the liquid metal were ionized by means of a plasma ion source, then accelerated to 60 keV and sent to the magnetic mass separators and to the beam lines where the measuring stations were placed. Yields were measured using three different techniques of common use at ISOLDE.

1) Online yields of stable isotopes and of some radioactive ones were measured by a Faraday cup inserted in the beam line.

2) For short-lived β emitting isotopes, beams were directed to a dedicated tape station and yields were measured with a plastic scintillator detector.

3) For longer lived ($T_{1/2} \geq 5$ min) γ -emitting radioisotopes, ion beams were implanted on thin Al foils, then after irradiation an offline γ detection was performed using a calibrated HPGe detector.

In order to obtain the absolute production rates from the measured yields, the efficiency of the ion source had to be measured. For this purpose, known amounts of different gas mixtures (consisting of Ar/Xe, He/Ne/Ar/Kr/Xe, and $^3\text{He}/\text{Ar}/\text{Xe}$ mixtures) were leaked into the ion source, having thus the possibility to measure the efficiencies at any time during the experiment.

First results

The ^4He current was measured by a Faraday cup for 6 s after the arrival of the proton beam on the target.

The ionization and transmission efficiency from the ion source to the Faraday cup was measured to be 0.05 % for ^3He . Assuming the same transmission efficiency for ^4He , the production rate for ^4He is 0.77 atoms/p, with a systematic uncertainty of about 20 %. This value is in good agreement with calculations with MCNPX, giving 0.84 atoms/p (with Bertini/Dresner models) and 0.43 atoms/p (INCL4/ABLA models).

Collection measurements were performed for a number of isotopes. We investigated the release of Ne, Ar, Kr, Xe, Br, Cd, Te, I, Hg, Po, and At radioisotopes.

In Figure 1 the measured cumulative production rates for radioactive Hg and Xe isotopes are presented. Longer-lived Hg isotopes are expected to be completely released at the temperature of 600 °C for this kind of target. The ionization efficiency was not measured for Hg, as it was only measured for noble gases. Based on previous results from the literature, we considered an efficiency of a factor 1.5 higher than the measured Xe efficiency of 3.7(11) %.

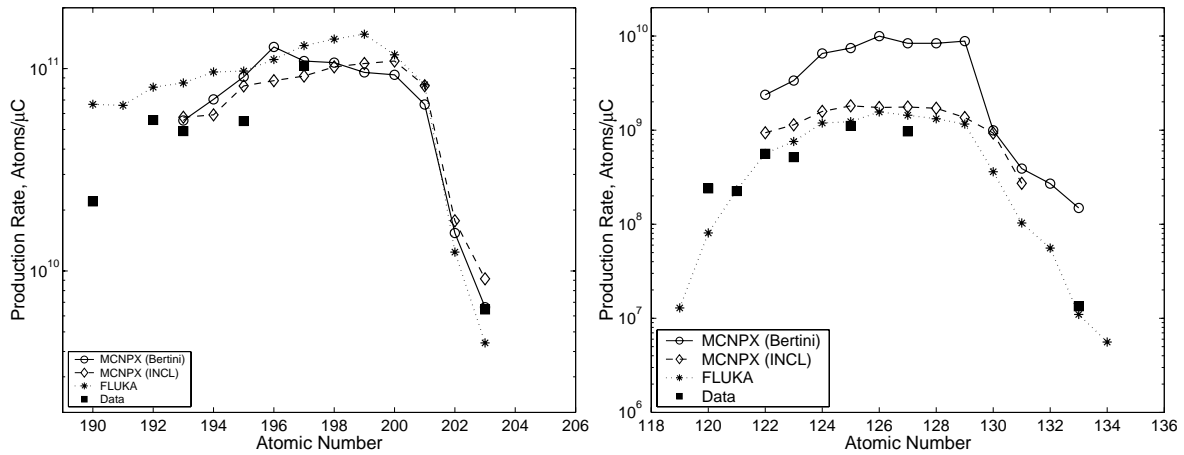


FIGURE 1. Production rates for Hg isotopes (left) and Xe isotopes (right). Measured points (*black squares*) are compared with calculations: *open circles*: MCNPX (Bertini/Dresner model combination); *diamonds*: MCNPX (INCL4/ABLA); *stars*: FLUKA.

The measured values are in line with expected cumulative production rates calculated using the Monte Carlo transport codes FLUKA and MCNPX. The two codes were coupled with the evolution codes ORIHET3 and SP-FISPACT, respectively. In the case of MCNPX, results are here shown with two different model combinations for the intranuclear cascade and evaporation models. The circles represent results from using the Bertini intranuclear cascade model with the Dresner evaporation code. The diamonds are obtained using the recent INCL4/ABLA model combination. The trend observed in the data as a function of the atomic mass is well reproduced by the three calculations for Hg.

In the case of Xe there is a clear disagreement between the Bertini/Dresner values calculated with MCNPX, and the results from the other two calculations. The data, with an ionization efficiency of 3.7 % for Xe isotopes seem to favor the other two results, thus confirming recent experimental findings from the HYNDAS experiments [18].

While production of Hg isotopes from Pb/Bi target is due to direct spallation, the Xe and I isotopes are the results from a later stage of the spallation process, the fission of highly excited spallation fragments or as a two-step process due to neutron induced fission from high energy spallation neutrons. Thus the evaporation neutron models, the Dresner and ABLA, are probably most responsible for the differences observed in the calculations.

Similar results as for Xe are obtained for the iodine isotopes. However, I is not completely released and observed production rates at 600 °C are about a factor 10 lower than the calculated FLUKA and MCNPX (INCL4/ABLA) values.

Among the other isotopes measured, it is of particular interest to discuss the Po and At. Production rates of $^{207,208,209,210}\text{At}$ of the order of 10^7 atoms/ μC (assuming the same ionization efficiency as for Hg) were measured, with values an order of magnitude lower for ^{206}At . Such production rates are not of concern for an ADS. Production of At comes from several possible reactions of Bi, but the most likely, given the high proton energy, is $^{209}\text{Bi}(p, \pi^- xn)^{210-x}\text{At}$. The At

decay is responsible for the observed small quantities of Po isotopes, which contrary to At is expected to be produced in large amounts. However, as found in Ref. [19], little or no Po should be released at 600 °C.

Of the other isotopes measured, no release of Br was observed, while very little amount of Cd isotopes were detected. For the Kr isotopes, some problems during the measurement rendered the analysis questionable and such measurement was repeated with the Pb target.

5.1.3 Calculations in support of the target disposal

Calculations of the activation of the MEGAPIE target are important to define the concept for the handling and disposal of the target after irradiation. The concept is under study [20]. After irradiation, the target will be transported to the ZWILAG, and there cut into pieces and successively stored in dedicated containers. The specific activity of each of the pieces is required. In particular, the following data are of interest: 1) about 7 sections of the lower part of the target, each 30 cm long; 2) the AlMg3 flange, 3) the total upper section (without the target head); 4) the target head; 5) the Pb/Bi.

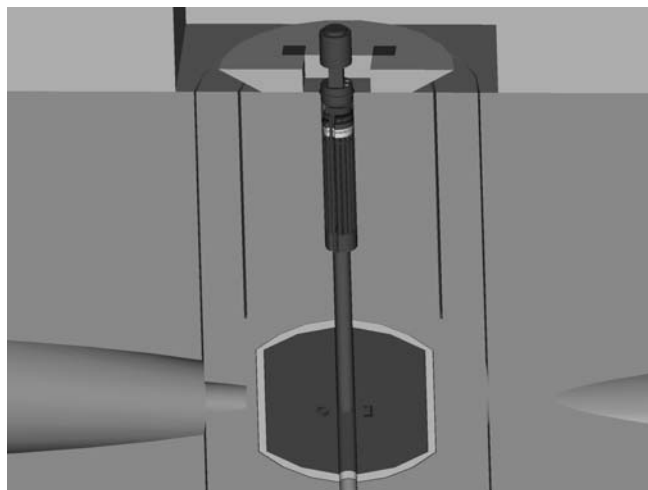


FIGURE 2. FLUKA geometry of the MEGAPIE target and of the surrounding SINQ facility.

Calculations have been performed using two FLUKA models developed to study this problem. A 3D view of one of the two models is represented in Fig. 2. The lower part of the target has been divided in seven sections 30 cm long. The remaining upper part and the target head constitute larger sections.

For the material compositions, and in particular for Pb/Bi, T91 and AlMg3, new analyses have been carried out at PSI on existing samples. The measured material compositions have been used in the calculations.

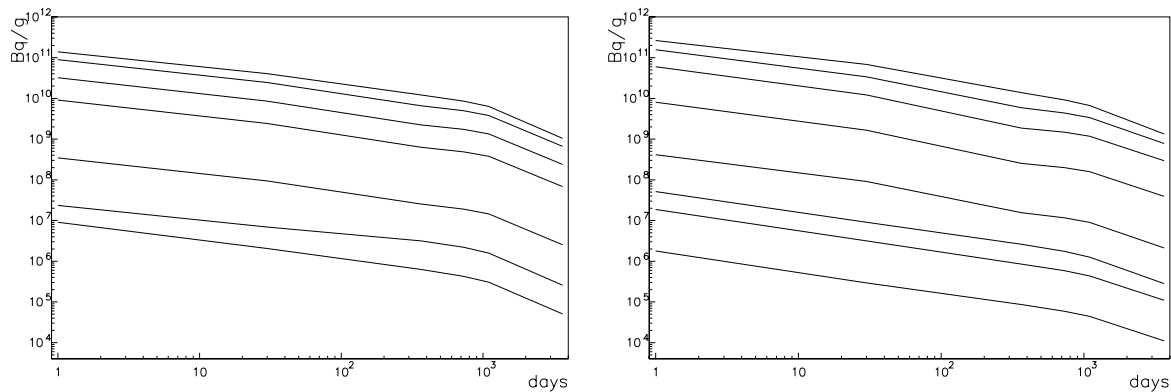


FIGURE 3. Specific activity (Bq/g) of T91 (left) and 316L (right) as a function of decay time, after 200 days of irradiation at 1.4 mA. The curves refer to the lower seven sections (each 30 cm long) in which the target will be cut, the upper curve being the lowest section.

In Figure 3 the specific activity for T91 and 316L in the lower seven sections are shown. For 316L, also the results for the flange between the upper and lower enclosure is shown. Obviously, the activation of the upper components is much lower. The flux reduction along the target implies difficulties in calculating the activation of the upper part, especially if impurities are taken into account. For this purpose, the neutron flux along the length of the target was calculated. The flux will be folded with existing activation cross section data, to extract the results for the upper part of the target.

These results will be used as input for the definitions of the concepts for the target handling after irradiation, and for its disposal.

5.1.4 Conclusions and outlook

During the last year, the main topics in the neutronic and nuclear assessment were two: the measurement of volatile elements production rates in proton irradiated PB/Bi target at the ISOLDE facility at CERN, and the calculations of the target activation for the target disposal.

Production rates of volatiles in a proton irradiated LBE target were measured at the ISOLDE facility. Several isotopes were measured. The preliminary results from this experiment are important for two reasons: *i)* the measured quantities overall agree with the expectations from the calculations using the FLUKA and MCNPX codes. Since these codes were the main ones used in the neutronic design of MEGAPIE, including the specifications for the cover gas system, it follows that these results are a positive assessment of such design. *ii)* these results allow a benchmark of the Monte Carlo codes and models used. While it is true from the first conclusions that in general all the Monte Carlo predictions are satisfactory, differences are found for specific elements such as Xe. Therefore the present results allow to conclude that the FLUKA and MCPNX with the INCL4/ABLA models represent the experimental production rates with better accuracy than the MCNPX with the Bertini/Dresner model. For the coming months, activities will concentrate in finalizing the data analysis, in particular for the second measurement run with the Pb target. If

possible, an additional experimental run at lower proton beam energy (600 MeV) and perhaps with a target with a larger diameter will be performed during 2005.

Activation calculations have been performed for the MEGAPIE target. For the calculations, activation calculations will be completed for the whole target. Additionally, dose rate calculations from the γ from the activated LBE in the target will be performed. This calculation will take into account the actual geometry of the LBE loop inside the target.

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5.2 Materials

5.2.1 Fatigue experiment

Feed back experiences of in service damaged components suggest that fatigue damage is one of the most frequently reported. This however is difficult to predict because of the influence of many factors (microstructure, environment, loading spectrum, surface roughness...) as occurred in the case of the window.

The work performed during the period aims to document the fatigue behaviour of the T91 martensitic employed for the window [1-2].

Low cycle fatigue tests are carried out at 300°C in air and liquid lead bismuth eutectic on cylindrical smooth specimens (10mm in gage length and 10mm in diameter) under total strain amplitude control at a strain rate of $4 \cdot 10^{-3} \text{ s}^{-1}$ and a strain ratio $R_\epsilon = \epsilon_{\min}/\epsilon_{\max} = -1$. Special attention is focused on the form of the strain waveform. Different strain amplitudes and insertion of tension hold time are studied as indicated in Fig. 5-1.

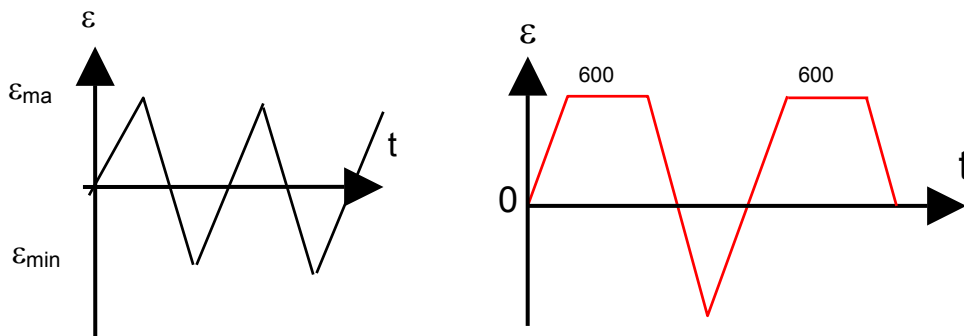


Figure 5-1 : strain waveform employed for testing the T91 at 300°C in air and liquid Pb-Bi

The T91 is tested after conventional heat treatment (austenitization at 1050°C and tempering at 750°C).

The main results show that the cyclic stress strongly decreases from cycle to cycle at the beginning of the test and then tend to saturate. This cyclic softening is typical of the T91 steel (Fig. 5-2).

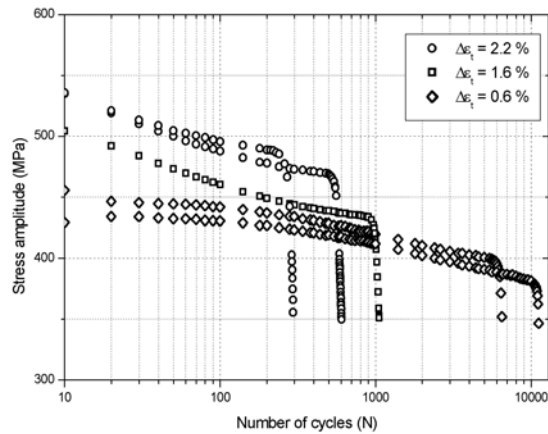


Figure 5-2 : Evolution of the stress amplitude with the number of cycles tests in air at 300°C

It observed as well in air and as in liquid Pb-Bi with the same magnitude resulting thus from a pure effect of microstructure.

Cycling the specimen with the triangular wave form in presence of the liquid Pb-Bi leads to a strong reduction in the fatigue resistance which is decreased by a factor of about 2 as compared with air. However, at low strain range ($\Delta\epsilon_t = 0.3\% - 0.4\%$), the difference in fatigue life between air and liquid lead bismuth vanishes. Insertion of a 10min tension hold time at 300°C does not involve any stress relaxation of the steel neither in air nor in liquid Pb-Bi. For tests conducted in air, the fatigue resistance of the T91 steel is not affected by the strain waveform. But a synergetic effect between hold time and liquid Pb-Bi appears, the fatigue resistance in liquid Pb-Bi being reduced by a factor 1.5 with the hold time period instead of continuous cycling.

Fig. 5-3 summarizes the effects of cycling condition on fatigue resistance of the T91 steel.

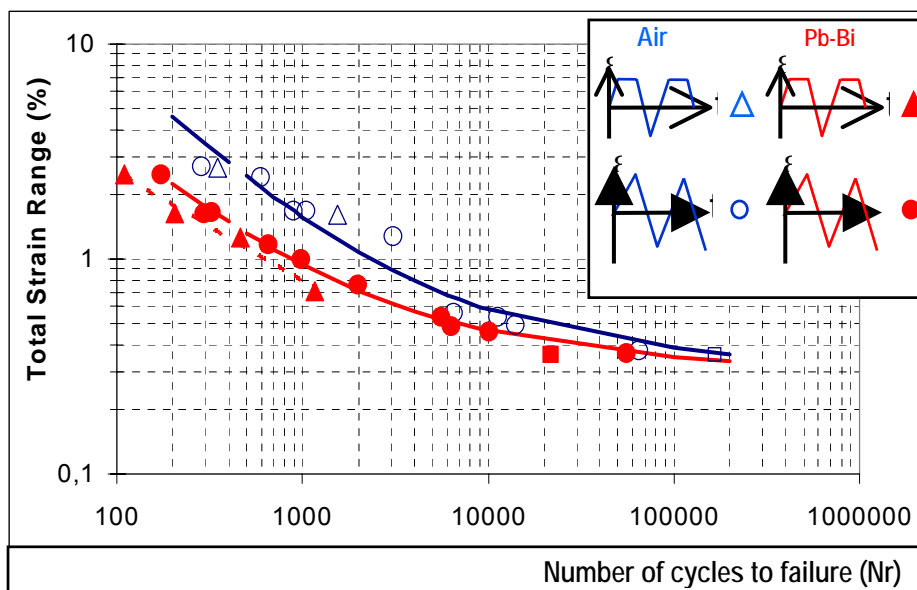


Figure 5-3 : effect of environment (air or Pb-Bi) and of signal strain waveform on the fatigue resistance of the T91 steel tested at 300°C

Metallographic observations on transversal cuts of specimen clearly show that the density of short cracks was high in the case of specimens fractured in air (Fig. 5-4 A) but low in the case of liquid Pb-Bi (Fig. 5-4 B).

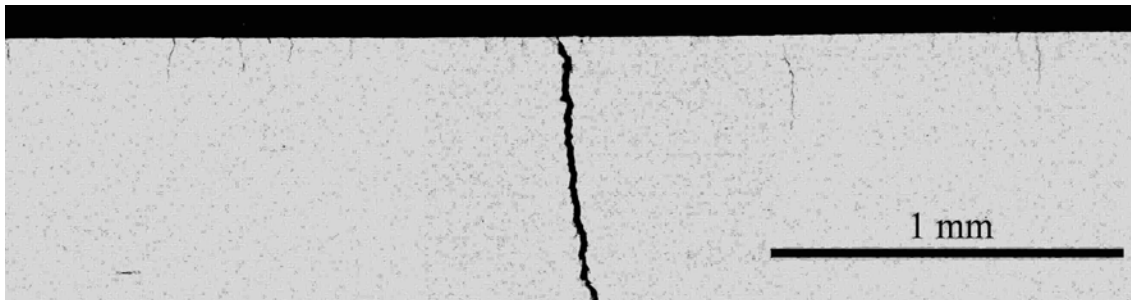


Figure 5-4 A : Transversal cut of the T91 steel after fatigue failure in air at 300°C, $\Delta\varepsilon_t = 2.2\%$



Figure 5-4 B : Transversal cut of the T91 steel after fatigue failure in liquid Pb-Bi at 300°C, $\Delta\varepsilon_t = 2.2\%$

The accelerating effect of liquid Pb-Bi on growth rate of short cracks can also be suspected on growth rate of longer cracks. Indeed, the fracture surface was macroscopically flat after testing in liquid Pb-Bi while it contains inclined planes after fracture in air but at a microscopic scale, the distance between fatigue striations was respectively considerably larger.

(LMPGM: J.-B. VOGT, I. SERRE, A. VERLEENE and A. LEGRIS)

5.2.2 Damages induced in T91 either by contact with Pb-Bi or by helium implantation

The main questions addressed during the Nov 2003 – Nov 2004 period are directly related to the production of damages in T91 steel induced either (1) by contact with LBE, or (2) by helium implantation. We consider that it is a key issue for MEGAPIE, knowing that T91 steel was selected from the beginning of the MEGAPIE-TEST program for its excellent mechanical properties, its good corrosion resistance without irradiation, and last but not least due to the fact that T91 steel keeps its excellent metallurgical properties (no swelling, low DBTT shift...) under irradiation. In the following, we concentrate on the conditions and characteristics of damages production. We also report on the oxygen solubility limits in Pb-Bi obtained recently by V. Ghetta.

1) Determination of oxygen solubility limit in Lead-Bismuth

In 1998, when the European countries started to work on compatibility of Lead and LBE with structural materials in the frame of the ADS project, the expertise was known to be Russian

(IPPE-Obninsk) for over twenty years. In 1998, the only available expression of the oxygen concentration (at.%) at saturation in LBE was the one proposed by Orlov:

$$\log_{10} (x_{O(LBE)}^{sat}) = 2.31 - 3400/T_{(K)}$$

Oxygen control systems are now redeveloped in Europe. Of special interest is the new experimental device, developed by V. Ghetta [3-4], since it gives access to accurate measurements of: i) the oxygen activity a_O in LM (Lead, LBE), ii) the oxygen activity coefficient γ_0^∞ and iii) the oxygen solubility limit $x_{O(LM)}^{sat}$ over an extended temperature range (200 to 650°) (see Fig. 5-5). The author uses the classical thermodynamic reference $a_O = 1$ for the pure gaseous oxygen at 1 atm, and the Henry law $a_O = \gamma_0^\infty x_O$, which is valid for the studied low oxygen concentrations, so that γ_0^∞ is solely temperature dependent. One gets rid of the conventional hypothesis of $a_O = 1$ in an oxygen-saturated LM, which implies accurate knowledge of the concentration at saturation, which is just one of the wanted data.

Experimentally, an electrochemical pump-jauge ensemble, using the oxygen pressure in air as measurement reference, is introduced in the LM bath under controlled cover gas, permitting to follow, in parallel:

- The emf E of the gauge (in V), related to the activity by the relation:
$$E = \frac{RT}{2F} \ln \left(\frac{a_O}{(P_{O_2}^{air})^{1/2}} \right)$$

where $P_{O_2}^{air}$ designates the oxygen partial pressure of the ambient air, with $F = 96500$ C being the Faraday constant and R the gas constant (8.314 J/K mole);

- The oxygen flux through the pump, and thus the change in oxygen concentration in LM by measuring the cumulated ionic current passed through the pump over a certain time interval,

$$\Delta x_O = \frac{QM}{2Fm}$$

with M the lead or LBE molecular weight and m the total mass of the LM bath.

By repeating the measurements with increasing oxygen content starting from the completely reduced LM (under flowing hydrogen), over a range of temperatures, one obtains $\gamma_0^\infty(T)$. From the measurement of the oxygen activity at saturation, deduced from emf measurements, one deduces the temperature variation of the oxygen solubility limit, represented in Figure. 1 for LBE, compared to the ones predicted by Orlov, together with reliable literature data for pure Bismuth. A complete description of the Ytria-stabilized Zirconia (YSZ)-based pump-sensor device can be found in [3]. One noticeable advantage of the method is that there is no need for thermodynamic data, not always accurately known, to obtain the results. In the future, this pump-jauge system could be used to calibrate the Bi/Bi₂O₃ or In/In₂O₃ internal reference sensors which could be implemented in a future ADS, Lead or LBE cooled fast reactor system.

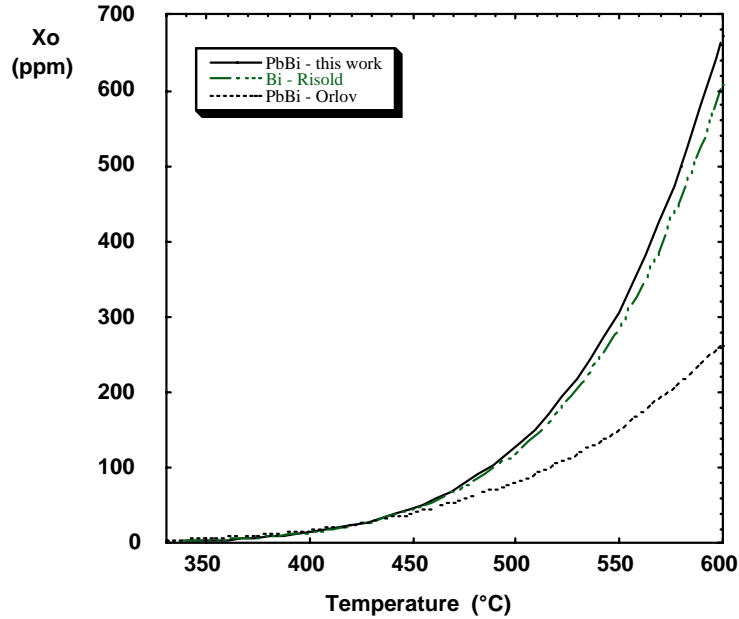


Figure 5-5 : Temperature dependence of the oxygen solubility limit in LBE using the unique Orlov expression available in 1998 compared to the new values obtained by V. Ghetta [4] and to reliable data of the literature for pure bismuth.

2) Embrittlement of T91 steel by Lead-Bismuth

Considering how oxidizable is this 9%Cr martensitic steel, and thus passivable in a variety of environmental conditions, a very poor wettability by liquid metals is expected and now definitely proved. This has important consequences (see Fig 5-6). So long as the passive film formed on T91 remains adherent and protective, this material should be a priori protected against Liquid Metal Embrittlement (LME) and other damage processes like cavitation and Stress Corrosion Cracking [5-8]. In fact, one must keep in mind that LME is also strongly dependent on the stress-strain state of the material and that this point still need to be clarified.

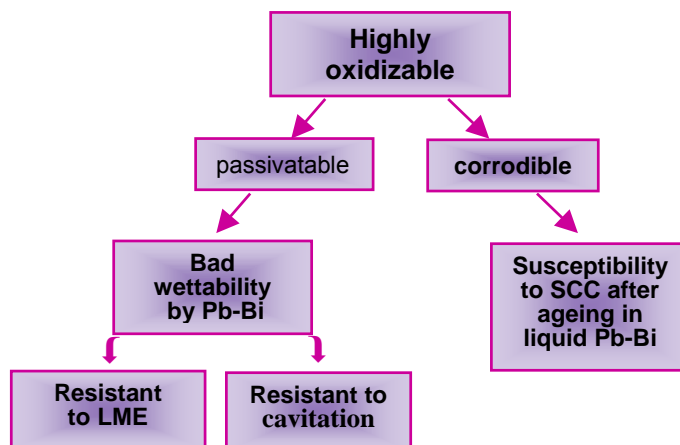
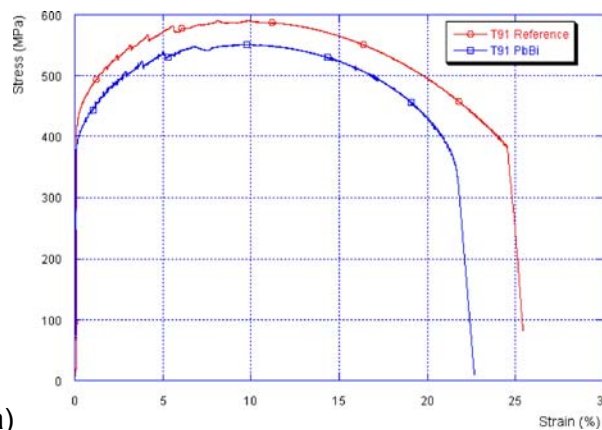


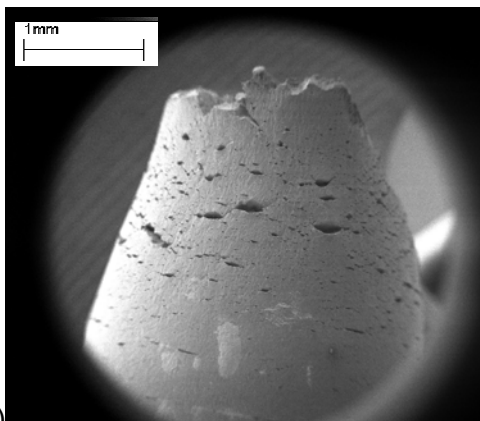
Figure 5-6 : Schematic drawing recapitulating the expected consequences of the oxidation of T91 steel on its resistance to Liquid Metal Embrittlement (LME), cavitation and Stress Corrosion Cracking (SCC) [5-8].

During the last year, it was shown without ambiguity by T. Auger et Coll. that the “T91/Pb-Bi” couple is prone to LME [5-6]. Other cases of LME concerning steels in contact with heavy liquid metals or alloys can be found in the literature. But in most cases, either the contact conditions between the material and the embrittling species are un-completely described or the interface can be considered as contaminated by impurities which could participate to the embrittling process.

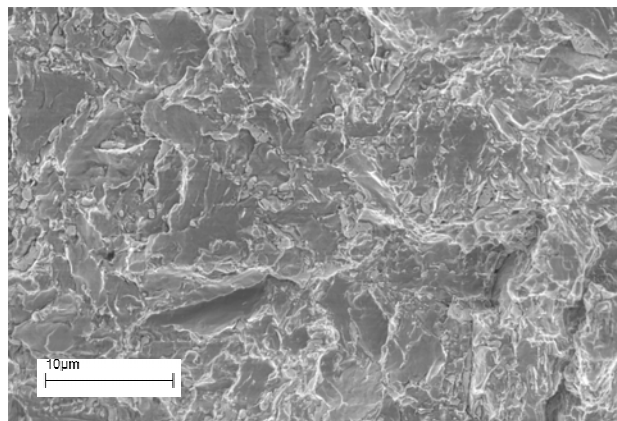
We concentrate on the contact conditions at the “T91 steel/Pb-Bi” interface. LME was obtained in case of direct contact between the steel and the embrittling species, using Surface Physics techniques available in the laboratory. Lead-Bismuth was deposited by PVD under UHV on the gauge length of the test bars previously cleaned by ion beam sputtering. Note that the surface state of the specimens was followed by Auger Electron Spectroscopy. Tensile tests conducted on so prepared specimens at 340°C produce clear LME effects as observed below:



a)



b)



c)

Figure 5.7 : In case of direct “T91/Pb-Bi” contact, LME effects are produced: a) decrease in strength and elongation to rupture as a result of tensile test under flowing He ; b) multi-cracking of the gauge length of the specimen, as a result of transgranular

(TG) failure initiated at the surface and c) top view of a TG rupture facies.

A mixed brittle/ductile rupture is observed. Brittle fracture occurs only at the periphery of the fracture surface. Brittle crack propagation is controlled by liquid metal supply at the crack tip due to the limited amount of Pb-Bi deposited (the coating thickness being of the order of few hundreds of nanometers). The ductile behaviour is recovered once no more liquid metal can be supplied at the crack tip. Therefore, the mechanical degradation displayed with the tensile curve (Fig. 5-7.a) would be more important in the presence of a larger reservoir of liquid metal. The rupture occurs mostly by quasi-cleavage in areas wetted by Pb-Bi as can be seen on Fig. 5-7.c.

It appears now important to study the role played by the plastic deformation in the LME process. This strongly suggests to introduce the physics of fracture concepts to improve the understanding of LME. In the future, this approach should allow to predict the lifetime of structural materials in contact with Pb-Bi.

3) Helium implantation in T91 steel and high purity iron-chromium alloys

There is an abundant literature on helium implantation effects in 9-12%Cr containing martensitic steels, like T91 steel grade and others like DIN 1.4914 or F82H largely studied for fusion applications. Nevertheless the origin of the hardening and embrittling effects produced by irradiation is not yet completely clarified. This means that the nature and exact role of the radiation-induced extended defects still need to be carefully investigated. To this aim, we decided to proceed step by step, in other words to irradiate first high purity Fe-Cr alloys produced in CECM (Fe-6%Cr, Fe-9%Cr and Fe-12%Cr), and then make the comparison with the T91 steel irradiated in similar irradiation conditions.

Specimens were implanted at 400°C, with 8 keV He⁺ ions using the CSNSM medium energy implanter IRMA in Orsay, at a dose rate of 10¹² He⁺/cm².s and various doses varying from 10¹⁵ to 3.5 10¹⁶ He⁺/cm². In these conditions, the TEM microstructure was significantly modified, due to the production of helium bubbles, dislocation loops and clusters whose distribution is varying with the dose. This is not the place here to comment the results concerning the helium bubbles and dislocations loops, even if there is an effect of the alloy composition, as expected.

We concentrate on the completely new results concerning the radiation – induced clusters [9-12]. Indeed, in the literature, chromium precipitation in Fe-Cr alloys or more precisely formation of the Cr rich α' phase was recently admitted in Fe-Cr alloys above a Chromium concentration of 8%. Also very recently, models attempted to reproduce this above mentioned defect structure

produced by irradiation: this is an important step in the actual European multi scale modelling approach with the objective of being able to make reliable predictions concerning the evolution of irradiated structural materials.

And we just found that precipitation of such α' phase is not so obvious [12]. On Fig. 5.8, we show the nucleation phase of clusters on small sessile dislocation loops, observable at all radiation doses in Fe-9%Cr. A precise analysis of those clusters and of the matrix composition around revealed that these ones are depleted in chromium (enriched in iron) with respect to the matrix.

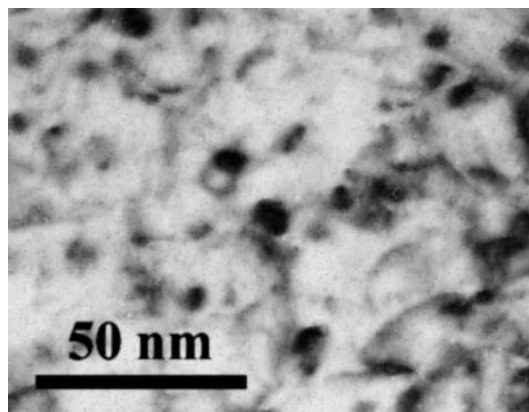


Figure 5-8 : Nucleation of clusters depleted in chromium (6 to 7 wt.% according to the EDX analysis) on small dislocations loops observed in high purity Fe-9%Cr irradiated at a dose of 10^{16} He⁺/cm² and a temperature of 400°C.

A comparable study conducted on a Fe-6%Cr and a Fe-12%Cr has shown that chromium depleted clusters are also produced in the former case, but chromium enriched precipitates (σ phase) in the latter case.

In the future, it is intended to take into account those findings to improve modelling of irradiation effects in structural materials.

(CECM:T. Auger, V. Ghetta, G. Lorang, J. Majimel, D. Gorse,
in collaboration with M.O. Ruault of CSNSM, Orsay)

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5.2.3 State-of-the-art on the T91 steel characterisation under MEGAPIE relevant conditions

An important topic of the MEGAPIE project is the characterisation of the chosen beam window material, i.e. the T91 steel. This component will be exposed during the spallation target operation to the high power proton beam and the flowing liquid LBE. The predicted maximum damage at the window after 1 year irradiation at 6 Ah is 14.5 dpa and about 1600 appm of He will be produced [1], the LBE highest temperature will be about 350 °C and the flow rate about 1 m/s. Further, beam trips occurring normally at the SINQ facility as well as accelerator maintenance periods cause temperature transients to the system.

Therefore, the materials characterisation should be aimed to assess the corrosion and mechanical resistance under these given conditions. Up to now a large effort has been devoted to the characterisation of the T91 steel in terms of corrosion resistance [2-4], mechanical degradation in presence of the liquid metal [2-3, 5-7] and evaluation of the effect of proton / neutron irradiation on the mechanical properties [3, 8].

Corrosion resistance

Corrosion rates estimated experimentally at 400 °C are between 40 µm/yr [9] for a LBE flow rate of 1 m/s, and 86 µm/yr for a LBE flow rate of 2,2 m/s [4]. Both these results were obtained in experiments where the oxygen content in the LBE was less than 10⁻⁷ wt. %, therefore no protective oxide layer was produced on the steel surface. This oxygen content has been considered representative for the MEGAPIE conditions, since no oxygen control and monitoring system has

been foreseen in the target. The estimated corrosion rates indicate that in the given testing conditions the corrosion resistance of the steel does not represent a critical issue.

Mechanical properties in LBE

A number of tensile and fatigue tests have been performed on the T91 steel in LBE [3, 5, 7, 10]. These tests were conducted under very dissimilar conditions among them and generally they were of qualitative type. For these reasons, it is not possible to combine numerically these results for the estimation of the MEGAPIE window performance. However, some trends can be observed from these experiments: generally all experiments showed that the surface condition of the steel has an influence on the mechanical properties degradation when the material is in contact with the liquid metal. For instance, by creating an “intimate” contact between the LBE and the steel surface a reduction of the tensile properties have been observed [3, 7]. It seems that the presence of the native oxide layer can delay the occurrence of this intimate contact, preventing the degradation of the tensile properties [7]. Thus, the specification and survey of the surface conditions (roughness, presence of microcracks and eventually a pre-oxidised state) are important parameters, which can affect the performance of the beam window. Moreover, the reduction of the low cycle fatigue lifetime in LBE might not have consequences on the MEGAPIE system provided that there are no localised stresses [5].

Mechanical properties under irradiation

As far as the behaviour of the T91 steel under proton / neutron irradiation, samples irradiated at SINQ up to 9 dpa at 275 °C exhibit an increase of DBTT with dose. An attempt to estimate the window lifetime gave a value of 3 - 6 months in the MEGAPIE conditions, using the DBTT results as a criterion [11]. This assessment has been done without taking into account LBE effects.

Moreover, a linear elastic fracture mechanics evaluation [12] shows that the presence of a surface crack will not lead to sudden brittle failure of the window under normal operation conditions, since T91 steel should retain sufficient toughness even after months of irradiation in a spallation spectrum. This study is encouraging as far as the resistance of the irradiated T91 steel, though a worsening of the mechanical properties of the irradiated steel, due to the presence of the liquid metal cannot be excluded.

LBE – irradiation combined effect

The proton irradiation and liquid metal combined effect on the mechanical behaviour of the T91 steel will be tested with the LISOR experiment. Preliminary LISOR results have been obtained on T91 steel after a short (1h) irradiation, showing essentially no difference with respect to not irradiated samples [13].

Presently, the experimental campaign on the T91 steel is going on. Further experiments are underway at PSI (STIP and LISOR experiments) and SCK-CEN (neutron irradiation experiment) to assess the combined effect of irradiation and LBE on the mechanical properties of the steel.

In summary, with the present experimental results available, it can be assumed that the corrosion rate of the T91 steel in the MEGAPIE conditions does not represent a critical issue. Further, it has been shown that the T91 steel should retain sufficient toughness in its irradiated state and it can be assumed that the degradation of the mechanical properties of the steel due to LBE can be, at least, delayed by a controlled surface preparation. Concerning the LBE – irradiation combined effect, more experimental results which will be available in the next future will help to the clarification of the performance of the T91 steel in the window condition of the MEGAPIE target.

(C. Fazio, FZK)

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5.3 Structure Mechanics

A main critical component of the MEGAPIE target is the ” window”, the thin hemispheric lower part of the target container, which operates under severe temperature, corrosion and irradiation conditions, being crossed by the proton beam and in contact with the active spallation area of the target. The target window is exposed to a high thermal load and cooling adequately its surface is a key problem of the project. A bypass flow is designed to enhance the cooling effect of the main LBE flow. The thermo-mechanical behaviour of the window and of the lower part of the target for different designs and under normal, abnormal and transient conditions, as well as during the EOL freezing, has been studied, with FEM stress analysis, in order to meet the design safety requirements. All the thermal-mechanical stress analyses have been carried out by ENEA starting from the temperature distributions provided by CFD calculations performed by PSI.

The main thermo-mechanical problems which have been investigated are :

1) Steady-state.

Steady state stresses in normal operating conditions. Analyses have been performed for different designs (flat and slanted guide tube), for different beam currents (1.74 mA or 1.4 mA at the target window), for different beam orientations (0° or 90° to the bypass flow), and for different estimates of the heat deposition profile.

2) Nozzle optimization.

An optimization study of the nozzle design has been carried out based on the window stress level (steady state). The effects on the stresses of the window, in normal operating conditions, of four different designs of the by-pass nozzle shape, proposed by previous CFD optimization studies, have been analyzed by means of structural analysis simulations and compared.

4) Focussed beam

Structural analysis simulations have been carried out for the transient following an accident situation in which there is instantaneous, partial or total, loss of the upstream de-focusing target, Target E, during operation.

5) Beam trip.

Mechanical behaviour of the target during a beam trip (transient). This transient is due to the shutdown of the proton beam for any reason. Suddenly the spallation neutron source is cut out and no more heat is generated inside the LBE and the window, while the main and bypass LBE pumps keep cooling the target window. The temperatures in the window drop rapidly and the thermal stresses during the transient have been verified.

6) Pump trips.

Safety considerations have required the analysis of the consequences of the lack of cooling, due to a possible failure of the LBE pumps, on the target stresses. Two cases have been analysed: the failure of the main EMP, while the bypass jet flow continues to cool the window, and the failure of the bypass pump with the main pump still running. The worse case is the second one, when the window is lacking the concentrated cooling power of the bypass jet flow.

7) Target freezing.

At the end of its experimental life the liquid LBE of the target vessel will be frozen : one possible design solution is to solidify the LBE inside the target itself, without draining it before in an external special tank. One important problem arises in this case: a recrystallisation process occurring in the solidified LBE produces volume expansion in time. The expanding LBE will exert high pressures on the containment walls, what could lead to undesired plastic stresses in the target. The objective of the freezing process in the actual target should be not to exceed the elastic limit in the beam window due to LBE expansion during recrystallisation. The stress state in the lower part of the target hull and in the window has been studied for different heights of the solidified LBE layer in the bottom of the target and for different LBE yield stresses. Moreover the possibility to reduce the mechanical stresses, by introduction of suitable crushing volumes in the bottom part of the target, has been assessed by detailed numerical simulations.

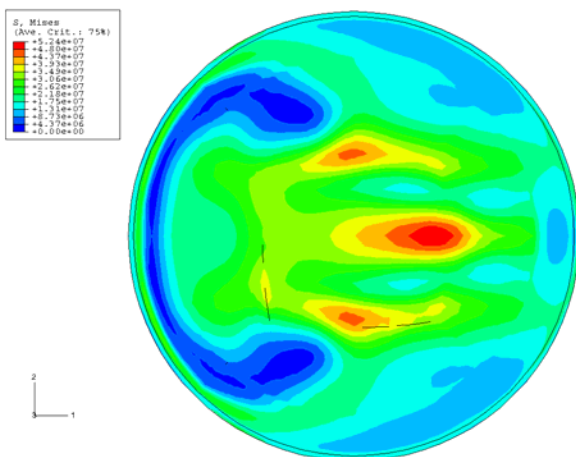


Fig.: Mises stress distribution on the inner surface of the window (steady-state)

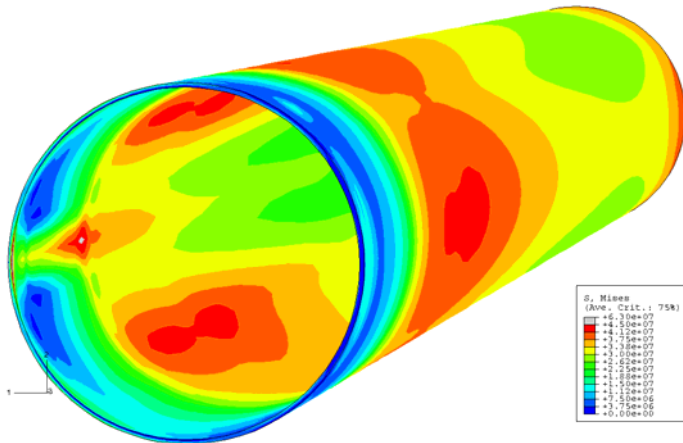


Fig.: Mises stress distribution on the guide tube (steady-state)

5.4 Liquid Metal Technology

5.4.1 Recrystallisation

The eutectic mixture recrystallisation is the key process that must be understood in all its aspects in order to avoid harmful and dangerous events in LBE vessels.

A phenomenological interpretation has been suggested as a result of laboratory activities.

Recrystallisation is a phenomenon that takes place at the level of crystal grain atoms, passing from a state of non-equilibrium towards a state of equilibrium. In adjacent grains different phases are segregated; these form crystal cells with different interatomic distances. When temperature varies with time, the atoms migrate through the grain boundaries, passing from one crystal form to another.

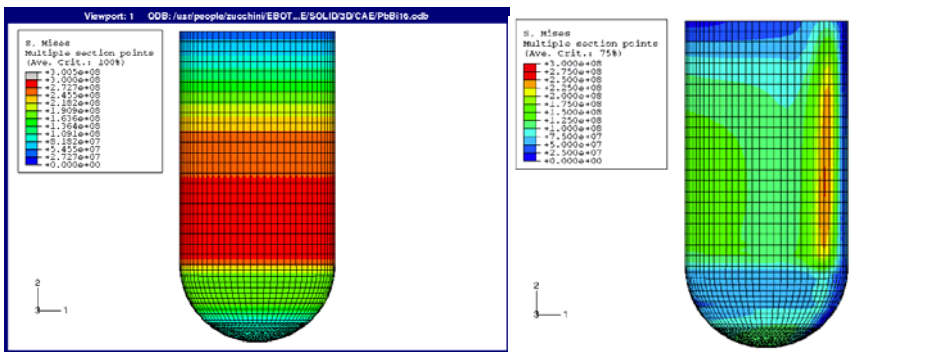
During freezing the solid alloy gets richer in γ phase and, with time, at a generic temperature T lower than T_f (the melting temperature), the excess γ phase precipitates. The γ phase is richer in Bi than the β phase, and bismuth (unlike lead) expands on solidification. So the γ phase precipitation and the atoms' migration from grain to grain (i.e. recrystallisation) tend to generate a volume increase.

A stress state, induced by the LBE expansion in structures, has been studied for the MEGAPIE case by means of a Finite Element Model. The stress analysis is based on full elastic-plastic FEM simulations, which produce the stress distributions in the model as a function of LBE expansion. The model was implemented in the ABAQUS thermo-mechanical code and employed to verify the Megapie Target Vessel.

From compression tests and numerical analyses some useful recommendations for the designers were deduced, i.e.:

- It is advisable to cool LBE in batches from bottom to top, according to the geometry of the container (tall or flat). The height of the first layer must be kept as low as possible.

- The presence of internal structures in the tanks must be reduced to a minimum.
- It is necessary to work in conditions of minimal LBE yield stress
- It is advisable to distribute crush volumes inside the vessel.



a b
Fig, Stresses of Megapie vessel without (a) and with (b) crush volume

5.4.2 LBE-water interaction

The target container of MEGAPIE is enclosed with a safety hull having a double wall structure cooled by pressurised heavy water. This solution significantly decreases the risk to contaminate the beam line with the activated spallation source in case of a leakage from the target container.

Nevertheless, the probability of a liquid metal / water interaction remains not negligible and, in principle, could lead to a rapid or long term pressure increase that could damage the structures of the beam line causing an extension of the accident to the containing chamber which has a pressure resistance up to 20 bar.

The incidental scenario is the following:

Water

$p = 5.5 \text{ bar}$; $T = 40 \text{ }^\circ\text{C}$; $M = 7.5 \text{ kg}$ (foreseen leakage before the closure of the valves)

Pb-Bi

$T = 270 \text{ }^\circ\text{C}$; $V = 80 \text{ l}$

The target geometry foresees three walls to be ruptured: target container and double walled safety hull.

In order to consider also the most dangerous cases three different events have to be taken into account:

- 1) The liquid metal can flow downward and reach a large volume placed under the collimator blocks. In this case the free volume is 1000 l
- 2) The liquid metal is stopped by the upper collimator block. The free volume is 26 l
- 3) The liquid metal is stopped by the intermediate collimator block. The free volume is 72 l

A simplified model, proposed and tested in [Y. Sibamoto et al., *Neutron radiography flow visualization of liquid metal injected into an empty vessel and a vessel containing saturated water*, Nuc. Tech. 133 (2001) 119-132], was applied to Megapie target.

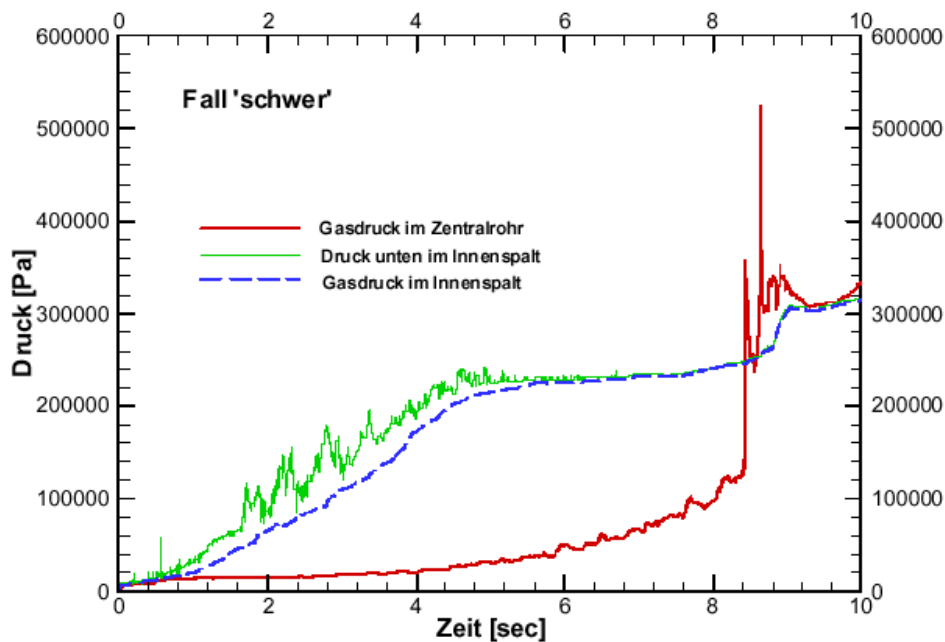
The results, referred to the incidental scenarios 1) and 2)-3), are reported below as a function of the initial liquid metal average temperature. The water temperature was fixed to 40 °C

| T_{LBE} [°C] | T_{fin} [°C] | p for 2)-3) [bar] | p for 1) [bar] |
|----------------|----------------|-------------------|----------------|
| 270 | 221.3114 | 23.6 | 17.1 |
| 300 | 244.9607 | 36.5 | 17.9 |
| 330 | 268.61 | 54 | 18.7 |
| 360 | 292.2593 | 76.5 | 19.6 |

A quick thermal exchange, between the LBE and water, leading to the occurrence of steam explosions is very unlikely because:

- the temperature of the liquid metal is below 400 °C [Y. Kurata, *Summary of PbBi-water interaction experiments at CRIEPI in Japan*, Presentation at Meagapie meeting]
- the free volume allows a rapid steam expansion

The Megapie behaviour during the rapid initial pressure transient was calculated by Mattina code which has been developed in FZK to predict thermal- hydraulic transients during severe accidents in Light Water Reactors.



Pressure evolution during the first 10 s as was calculated by MATTINA code

The conclusions were that the Mattina calculations, which are very accurate and well fitted to the existing geometry reports a maximum pressure lower than 10 bars.

In case of further pressurization due to the reach of thermo-dynamic equilibrium, the Target rupture disk failure would protect the containing chamber.

As for the final pressurization, it is evident that the final value, that can be reached at the end of the process, is dominated by:

- the thermo-dynamic conditions of the mixing fluids, with special regard to the initial temperature of the PbBi alloy,
- the free volume for steam expansion.

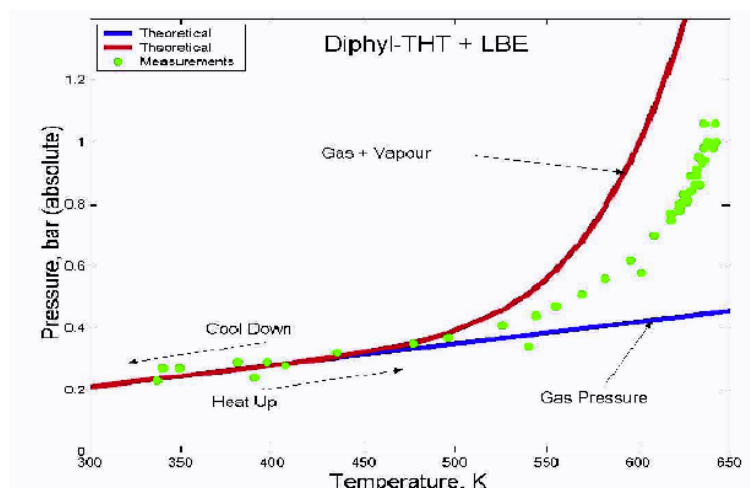
It has to be pointed out that these last comments are relevant to the incident scenario 2) and 3) which have, due to the geometry of the beam line, a low probability of occurrence. In fact, if the accident follows the scenario 1), the foreseen pressure evolutions are always lower than 20 bar.

5.4.3 LBE-organic oil interaction

The Megapie target uses as a coolant the Bayer Diphyl THT fluid. The main concern is the target pressurization in case of heat exchanger leakage and interaction with LBE. For this reason dedicated experiments were performed.

Other concerns are:

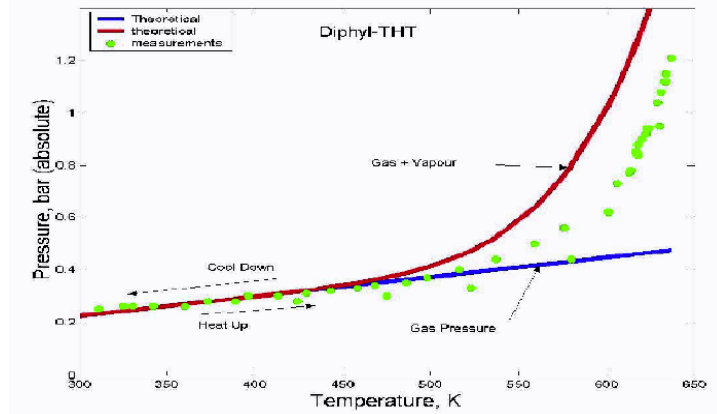
- Long-term exposure of the DTHT to the 350°C temperature of the LBE,
- Radiation of the DTHT from the activated alloy to degrade its performances
- Increase of viscosity to change the flow characteristics,
- Production of solids to cause blockages.



The blue lines indicate the Boyle law.

The red lines indicate the theoretical value resulting from Boyle law + DTHT Vapour Production (Bayer source).

The pressure rise $P(T)$ was measured up to 360 °C in a closed volume containing DTHT and DTHT+LBE. The experimental data evidenced a lower pressure rise than expected.



Conclusions :

- There is no rapid gas generation at elevated temperature,
- Long-term exposure (7 days) to 360°C LBE did not show any further vapour production
- No visible solids, nor apparent change in DTHT viscosity was observed at qualitative analysis,
- The Diphyl- THT heated with LBE became darker amber colour than the one heated without LBE,
- There is a cloud of black suspension in the oil; speculation is that lead oxide came from the ingot surface.
- DTHT was gamma-irradiated by a 1E07 Gray dose:
 - No increase of fluid viscosity was observed
 - No formation of solids was observed.

5.4.4 Polonium issue

One of the most important problems in Lead-Bismuth plants is represented by the release of gaseous and radioactive Polonium from Bismuth activation (spallation).

Such Polonium, for obvious reasons of environmental safety, must be contained and recycled inside the plant, after its retransformation into a non-dangerous isotope.

To this aim, a qualitative and quantitative estimation of the radioactive gas released inside an ADS Lead-Bismuth plant is particularly important: so it is possible to adequately dimension the necessary devices for its abatement or containment.

This has led to an extensive study of Polonium chemistry, and in particular of the (sometimes volatile) binary, ternary and also quaternary alloys that Polonium can form with the other elements of the Periodic Table.

1) Numerical studies

In the frame of the studies on liquid metal systems for the MEGAPIE plant, Neuhausen et al. [1] applied one of the existing state-of-the-art models, i.e. the Miedema model, which enables the computation of fundamental thermodynamic quantities (H, S, G). From these one can calculate the composition of the solid, liquid and gaseous phases in the chemical equilibrium state. The much more complex problem of kinetics, on the contrary, has not yet been faced with.

Here it is given a brief summary of their work, which combined calculations and laboratory experiments by them performed.

The Miedema model is a semi-empirical one. It calculates, in particular, formation and mixing enthalpies in binary metallic systems, both solid and liquid. Other types of enthalpies (adsorption and so on) can also be computed.

The model is a “cellular” one, in the sense that the atoms of different elements are represented as simple geometrical cells, which vary in form and orientation when two metals A and B form an AB alloy.

It can be applied not only to Polonium, but also to the other elements of the same group, the so called “chalcogens” (Oxygen, Sulphur, Selenium, Tellurium).

Neuhausen et al. considered only Pb and Bi as target materials, only Iron and Iron oxide (FeO) as building materials. The considered spallation products are only Po, H₂ and Barium (as representative of the active elements).

Notwithstanding the simplicity of the assumed conditions, the model lead, among other results, to a prediction of the comparative stability of binary polonides. This is shown and explained in Fig.1.

A study of the adsorption enthalpies deduced by the code suggested the use of lanthanides as adsorption materials for Po. It must be noted, however, that in presence of O₂ the latter is preferentially absorbed on lanthanides.

Other results concern the release of Po from the eutectic Pb-Li alloy. Though, from pure Li, Po release should be very low, from Pb-Li, due to the reduced thermodynamic activity of Li, a Po volatility similar to that from Pb-Bi is expected.

| | | | | | | | | | | | | | | | | |
|--------------|---------------|---------------|---------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|-------------|-------------|--------------|--------------|-------------|-------------|
| Li(3) 51 | Be(4) 46 | | | | | | | | | | | | B(5) 70 | C(6) 96 | N(7) 87 | O(8) 80 |
| Na(11) 54 | Mg(12) 28 | | | | | | | | | | | | Al(13) 13 | Si(14) 46 | P(15) 40 | S(16) 12 |
| K(19) 70 | Ca(20) 123 | Sc(21) 106 | Ti(22) 53 | V(23) 7 | Cr(24) 20 | Mn(25) 13 | Fe(26) 27 | Co(27) 14 | Ni(28) 10 | Cu(29) 6 | Zn(30) 4 | Ga(31) 4 | Ge(32) 25 | As(33) 20 | Se(34) 2 | |
| Rb(37) 75 | Sr(38) 128 | Y(39) 124 | Zr(40) 103 | Nb(41) 12 | Mo(42) 38 | Tc(43) 30 | Ru(44) 32 | Rh(45) 4 | Pd(46) 31 | Ag(47) 1 | Cd(48) 2 | In(49) 9 | Sn(50) 0 | Sb(51) 4 | Te(52) 5 | |
| Cs(55) 79 | Ba(56) 149 | La(57) 132 | Hf(72) 84 | Ta(73) 15 | W(74) 53 | Re(75) 54 | Os(76) 41 | Ir(77) 22 | Pt(78) 6 | Au(79) 15 | Hg(80) 1 | Tl(81) 9 | Pb(82) 4 | Bi(83) 3 | | |

Fig.1 Comparative stability of binary Polonides

horizontally hatched boxes = no reaction is observed with Po

vertically hatched boxes = reaction is observed, but the product is not well characterized

cross hatched boxes = contradictory results

diagonally hatched boxes = reaction is observed, reaction product characterized

2) Last experimental results and conclusions

As for the last experimental activity, Neuhausen et al. [2] studied in a laboratory the evaporation characteristics of Po and of its light homologues Se and Te from the liquid Pb-Bi eutectic. Their devices are schematised in Fig.2.

They worked at various temperatures, in the range from 482 K to 1330 K, under Ar/H₂ and Ar/H₂O atmospheres. For the analyses they used γ -ray spectroscopy.

In the temperature range of interest for technical application, Po release is slow: in the short-term (1 h) experiments, measurable Po quantities evaporate only for temperatures >973 K.

Some long term experiments (fig.3), however, showed that a slow evaporation of Po takes place also about 873 K. The resulting fractional loss of Po in the melt is about 1%/day. The evaporation rates of Se and Te are smaller in comparison with Po.

The presence of H₂O, in the limits of experimental errors, seems not to enhance the evaporation phenomena.

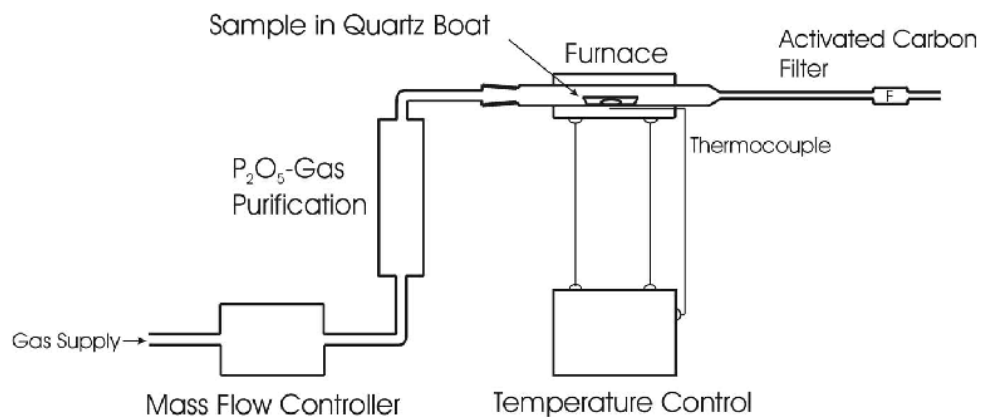


Fig.2 Experimental apparatus

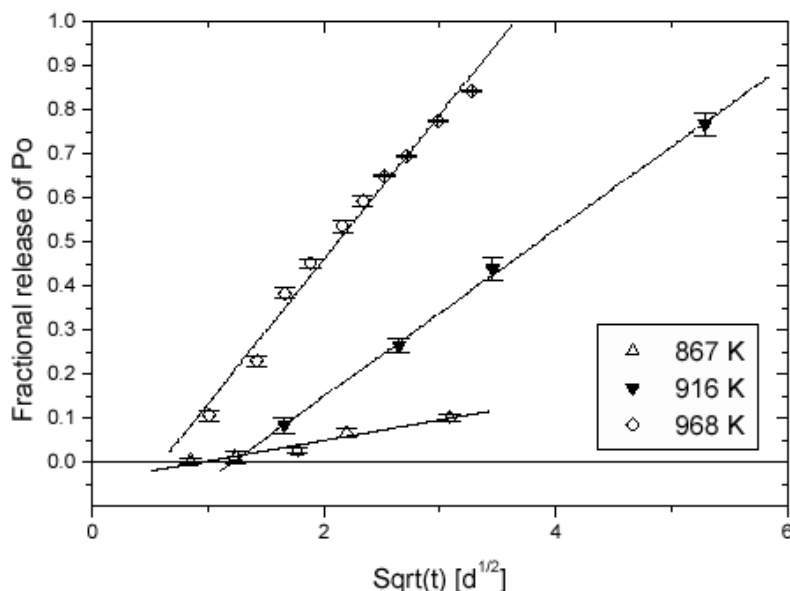


Fig.3 Measured values of fractional release of Po as function of temperature and time

3) Bibliography

[1] J. Neuhausen (PSI), "Summary of theoretical modelling work on the behavior of Polonium", presented in brief form at the MEGAPIE meeting of 29-30/2004 in C.R.Brasimone, Italy.

[2] J.Neuhausen (PSI), U.Koester (CERN) and B.Eichler (PSI), "Investigation of evaporation characteristics of polonium and its lighter homologues selenium and tellurium from liquid Pb-Bi eutecticum", submitted for publication to Radiochimica Acta.

6 SAFETY AND RELIABILITY ASSESSMENT (Task 1.3)

For this task, we refer to the Preliminary Safety Report (D11 deliverable of this project, delivered in April 2004), which is a written description of the MEGAPIE project necessary to justify and obtain a permit. The permit is to cover all aspects of the MEGAPIE experiment. Consequently, the Safety Report comprises these topics:

- ✓ Construction of an experimental target system with a liquid lead-bismuth eutectic (MEGAPIE), which is to be installed in the SINQ spallation neutron source of PSI instead of the solid targets used so far.
- ✓ Quality management and functional tests of this target system prior to installation in SINQ.
- ✓ Operation of this target system for irradiation with the high-energy proton beam from the accelerator facility of PSI up to an integral beam current of 6000 mAh on the MEGAPIE target.
- ✓ Subsequent transfer of the target system to a transport device in which it is carried to the Hot Laboratory of PSI where material samples are taken and their properties are studied.
- ✓ 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.
- ✓ Approaches to conditioning 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.

Earlier conditions and criteria contained in expert opinions by HSK, or in permits and clearances of SINQ, are met where they are applicable to MEGAPIE.

The Safety Report does not cover any later routine replacement of previous SINQ targets by targets with a liquid lead-bismuth eutectic. For that step, the results of studies of the experimental target system must be evaluated and the appropriate adaptations to the target design must be planned. Should that measure then be considered meaningful, PSI will file an application for clearance to that effect with the competent regulatory authorities.

The two regulatory authorities, the Bundesamt für Gesundheit (BAG) (Federal Health Office) and the Hauptabteilung für die Sicherheit der Kernanlagen (HSK) (Central Department for the Safety of Nuclear Installations), are responsible for various sectors of PSI. The MEGAPIE project as a whole affects both areas of competence:

- ✓ on the one hand, SINQ which, being part of the accelerator facility of PSI-West, is under the regulatory responsibility of BAG;
- ✓ on the other hand, the Hot Laboratory in PSI-East, for which HSK is the competent regulatory authority, also for transports of radioactive materials to the Hot Laboratory.

The Safety Report primarily constitutes the basis of an application by PSI to BAG for a permit for construction and experimental operation of the MEGAPIE facility with an SINQ target system of a liquid lead-bismuth eutectic.

Those parts of the project, which are under the regulatory competence of HSK, are also briefly addressed in this Safety Report although they will not be subjects of the application for a permit filed with BAG. They comprise adaptations of the hot cells required to transfer the target system to the Hot Laboratory, for which PSI will apply for the necessary clearance when necessary, and the transfer of the target system and work in the hot cells, for which approved techniques of the Hot Laboratory will be employed. Prior to transfer of the target system, the Hot Laboratory will draft a detailed plan of work and of radiation protection measures on the basis of which these steps will be reported to HSK as a matter of priority. For formal reasons, the Hot Laboratory will express its obligation to BAG to contribute its share to the MEGAPIE project.

7 LICENSING (Task 1.4)

The MEGAPIE target is designed for a beam power of 1 MW and 6000 mAh of accumulated charge. It will contain about 82 l of lead-bismuth eutectic (LBE) serving as target material and primary heat removal fluid. The 650 kW of thermal heat will be removed by forced convection using an in-line electromagnetic pump with 4 l/sec capacity. The heat will be evacuated from the target through 12 mono-wall cooling pins via an intermediate oil and a water cooling loop system.

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 $4 \cdot 10^{15}$ Bq. About $2 \cdot 10^{14}$ Bq will be α -activity mainly from Po-isotopes. In addition, about 8 NI 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 to the licensing authorities.

The D12 report "Preliminary Licensing Report", delivered in May 2004, describes the experience made up to now within the licensing process. A first milestone has been achieved with the reception of the draft statement of the competent authority on the licensibility of the experiment.

8 CONCLUSION

In the present document we summarised the design status of the target and the corresponding main ancillary systems of the MEGAPIE spallation target. The design is accompanied by a strong effort in R&D activities where the available results have been discussed in this report.

Within the MEGAPIE initiative and the MEGAPIE-TEST project we have for the first time engineers and designers working in close interaction with teams working on related design support and R&D activities. Although it is not evident to get both sides progressing in parallel an important progress has been achieved. Already today relevant information is available on the feed back for the future design of ADS spallation targets, as a preparation for the work to be done within WP 3 of the MEGAPIE-TEST project.