The MEGAPIE-TEST Project

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Abstract

The goals of the MEGAPIE initiative are to design, build and operate a 1MW heavy liquid metal target. The first step towards the realization of the MEGAPIE target was the feasibility studies, which outlined the entire project. Contextually to the feasibility studies the conceptual design phase started with the establishment of R&D working groups assisting the design and validation of both the target and its ancillary systems. In this framework the EU project MEGAPIE-TEST has been structured in three work packages with tasks concerning the finalization of the engineering design, the components and subsystem testing, the integral test and the first irradiation period. The

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MEGAPIE-TEST consortium is composed by the 14 partners: FZK, PSI, CEA, ENEA, SCK-CEN, CNRS /IDFE, IN2P3, LMPGM, EMN, ISMRA, UNIV-NANTES, U-PSUDXI, USTL.

Currently the engineering design of the target has been finalized, its manufacturing has been launched and the design activities on the ancillary systems were almost completed.

R&D activities in the fields of materials, thermal – hydraulics, structural mechanics, neutronic and nuclear assessment and liquid metal technologies were performed in order to assist specific design issues. Some Subsystem and component tests were also performed and the preparation of the integral test is an ongoing activity.

1. Introduction

The MEGAPIE (MEGAwatt Pilot Experiment) initiative was launched 1999 by CEA, PSI and FZK in order to design, build and operate a 1MW liquid Lead – Bismuth Eutectic (LBE) spallation target [1]. In November 2001 the EC jointed the initiative via the MEGAPIE-TEST project finalized for the “Partitioning and Transmutation” activities foreseen in the component of “Safety of the fuel cycle” belonging to the key action “Nuclear Energy” of the 5th Framework Programme.

Partitioning and Transmutation (P&T) techniques could contribute to reduce the radioactive inventory of nuclear waste and its associated radiotoxicity. Sub-critical Accelerator Driven Systems which have as main components a proton accelerator, a spallation target and a sub-critical core, are potential candidates as dedicated transmutation systems. A particular favorable characteristic of ADS, i.e. sub-criticality, allows a maximum transmutation rate while operating in principle in a safe manner [2]. Following a first phase of R&D focused on the understanding of the basic principles of ADS (e.g. the program MUSE), the programs 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 sub-critical core (e.g. the TRADE initiative). Therefore, it can be acknowledged that MEGAPIE represents in the ADS roadmap a key experiment.

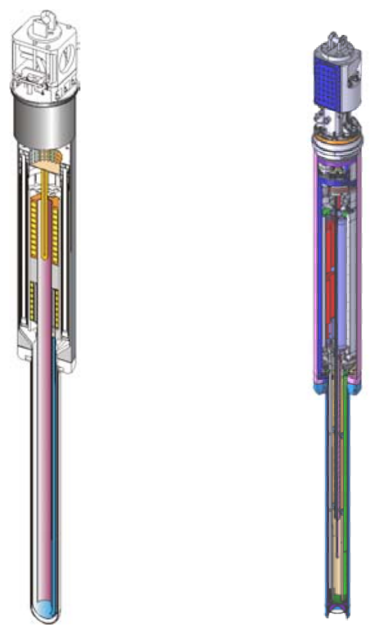
The original idea of the MEGAPIE initiative was to take advantage of past studies performed on HLM spallation target and together with the fact that the proton beam power on SINQ was rapidly approaching 1 MW made PSI a natural location for a test experiment. The experiment would benefit both, the neutron source SINQ by increasing the neutron yield and the ADS community in their quest on the demonstration of the feasibility of such a system.

2. Conceptual design of the MEGAPIE target

The MEGAPIE target is shown schematically in figure 1. The liquid metal container filled with LBE (being both spallation material and coolant) is irradiated with a proton beam of about 1 MW of power, coming underneath the target block. The area where the proton beam enters the target, is the beam window and it is one of the most critical part of the system having a fairly small thickness and it suffers cyclic solicitations, irradiation and corrosion damages. The spallation reaction occurs in the LBE and, in addition to the production of neutrons and spallation products, a considerable amount of heat will be deposited in the target system. The evacuation of the heat deposited and in particular at the window is performed by forced circulation of the LBE obtained with the Electro magnetic pump system, through the by-pass and the main flow. The heat exchange occurs at the top part of the target system, were a heat exchanger having 12 cooling pin is located. On the central rod heater units and instrumentation (e.g. thermocouples) useful to run the experiment are installed. The target head assures the connections (e.g. electrical) for the operation of the system. The liquid metal container is enclosed in a "safety hull", which is double walled and has liquid heavy water circulating in it. Key parameters of the target system are summarized in figure 2.

In figure 3 the target system is schematized together with the ancillary systems. These are the cover gas system to handle the gas produced during the spallation reaction, the fill & drain system for filling the target with liquid LBE, the secondary heat exchanger and the insulating gas system, which guarantees the presence of insulating gas between the safety hull and the liquid metal container.

As described previously, after the definition of the conceptual design of the target and the feasibility assessment, the project entered in the phase of the engineering design, when the MEGAPIE-TEST project has started.



a) b)

Fig. 1: a) first conceptual design of the target system; b) present conceptual design of the target system.

2.1. *Work Plan of the MEGAPIE-TEST project*

The objective of the MEGAPIE-TEST Project is to develop and validate the design and the operation of the heavy liquid metal spallation target MEGAPIE. The main milestones of the project are:

- To gain a detailed knowledge of the performance of a heavy liquid metal spallation target;
- To gain a data base and experience on design, licensing and safety issues;
- To verify the feasibility in beam-off and beam-on conditions of the LBE system and
- To propose best design strategies for a large-scale ADS spallation target.

The analytical / numerical / experimental approach to develop and test the LBE spallation target, resulted in dividing the MEGAPIE-TEST Project in three work-packages:

- WP1- Target development,
- WP2- Target testing,
- WP3- Synthesis.

The three work packages aim 1) To prepare the engineering design of the target and the ancillary systems; 2) To characterize the target subsystems / components by separate-effects tests and numerical modeling; 3) To characterize the complete target system by integral tests; 4) To plan the irradiation experiment, the post-irradiation examination and the decommissioning. Finally, since the MEGAPIE-TEST project would cover the commissioning and the first phase of irradiation, the reporting on these two steps is also included.

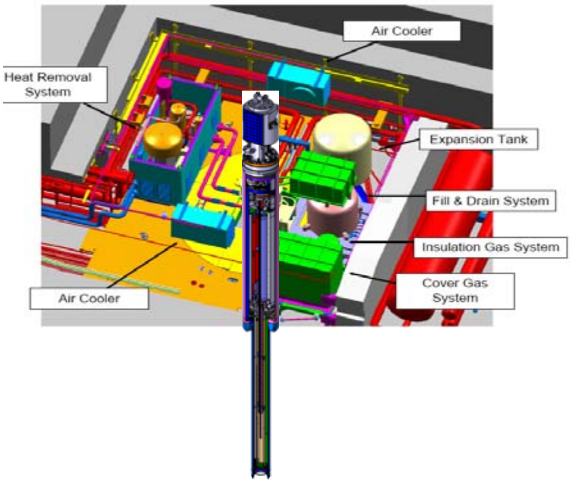


Figure 2: Schematic of the target and the ancillary systems (collage).

2.2. *Work package 1: target development*

The work package 1, under the responsibility of CNRS – SUBATECH, has the following objectives:

- Preparation of the engineering design of the target and the ancillary systems taking into account the boundary conditions of the SINQ Facility.
- 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, thermalhydraulics, mass and heat transfer, structure mechanics and liquid metal technology, using analytical, numerical and experimental approaches.
- Assessment of safety and reliability aspects, which might endanger the integrity and operability of the target.
- Preparation and definition of licensing requirements and criteria.

The detailed description of the target development is given in the reports presented at the project review meetings [3, 4].

The design of the target, performed by CNRS-SUBATECH in collaboration with PSI has advanced and presently detailed design reviews are performed by the project management of the MEGAPIE initiative together with the designer group and the manufacturer (the selected manufacturer for the target is the French company ATEA).

The link between the designer and the R&D support groups is documented in the experimental and computational activities performed. Some relevant R&D design issues are given in the following (not exhaustive) list:

a) The characterization in representative conditions of the materials selected for the different parts of the target (e.g. the target enclosure, the lower and upper liquid metal container).
b) The selection of the secondary coolant.
c) The prediction and optimization of the thermal – hydraulics behavior of the system (e.g. main and by-pass flow, geometry of the by-pass nozzle).
d) The structural mechanics (e.g. the evaluation of thermal stresses and strains)
e) The prediction of the neutronic and nuclear (e.g. the prediction of the spallation products, the heat deposition, the irradiation damage of the materials and the neutronic spectra).
f) The study of the solid LBE expansion properties and the LBE freezing procedure for the consolidation of the LBE freezing inside the liquid metal container after the completion of the irradiation experiment. This study supports the simplified fill & drain system (designed by ENEA) were the LBE can be drained from the target only after the integral test, whilst the activated LBE will not be drained.

As far as the material selection: 1) $AlMg_3$ alloy is foreseen for the lower target enclosure; 2) the martensitic steel T91 for the lower liquid metal container and 3) for the remaining parts (e.g. central rod, upper target enclosure, upper liquid metal container etc.) the austenitic steel AISI 316L.

$AlMg_3$ alloy and AISI 316L steel have been selected on the basis of the predicted thermal, mechanical and environmental (i.e. compatibility with LBE and irradiation) solicitation and of the knowledge available for these two materials.

The T91 steel was indicated as one of the most promising materials to withstand the foreseen window solicitations, mainly in terms of irradiation, corrosion and cyclic loads due to the beam trips. A detailed description of the criteria for the selection of these materials can be found in the documentation of the MEGAPIE initiative [5].

As previously discussed, the most critical part is the lower liquid metal container, which will be made in T91 steel. The T91 steel will be exposed during operation to the high power proton beam and the flowing liquid LBE. Indeed, the predicted maximum damage at the window after 1 year irradiation at 6 A h is 14.5 dpa and about 1600 appm of He will be produced [6], the highest temperature will be about 350 °C and the LBE flow rate about 1 m/s. In normal operation conditions the maximum stress level will be about 50 MPa. It is worthwhile to mention that the window will suffer also the solicitations due to the beam – trips occurring normally at the SINQ facility.

Up to now a great effort has been performed to characterize this material in terms of corrosion resistance (ENEA, CEA), mechanical degradation in presence of the liquid metal (ENEA, CEA, CNRS-LMPGM, CNRS-IDFE) and evaluation of the proton / neutron irradiation on the mechanical properties (PSI, CEA). It has been pointed out that the corrosion resistance of the T91 steel is strongly dependent from its surface state [4]. The estimated corrosion rate at 400 °C is between 40 μm/yr [4] for a LBE flow rate of 1 m/s, and 86 μm/yr for a LBE flow rate of 2,2 m/s [4]. Considering the mechanical degradation of the T91 steel when exposed to the liquid metal it has been shown in the frame of the EU project TECLA [7] that in normal heated conditions the steel does not suffer instantaneous liquid metal embrittlement (ILME), whilst in hardened and notched condition ILME could be observed. Tensile tests performed on T91 corroded samples (fig.4) show the decrease of the elongation and of the area reduction factor [8]. Low Cycle Fatigue tests performed in LBE at 1 Hz and 300 °C, did show a reduction of the fatigue lifetime of the steel with respect to the same tests in air (fig.5).

As far as the behavior of the T91 steel under irradiation, samples irradiated at SINQ up to 9 dpa at 275 °C did show a "linear" increase of DBTT with dose (fig. 6). An attempt performed to estimate the window lifetime gave a value of 3 - 6 months in the MEGAPIE conditions, using DBTT as a criterion but without taking into account LBE effects [4]. On the other hand a linear elastic fracture mechanics evaluation 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. Despite the fact that this study seems to be more encouraging concerning the resistance of the T91 steel, it was pointed out that LBE effect were not taken into account [4].

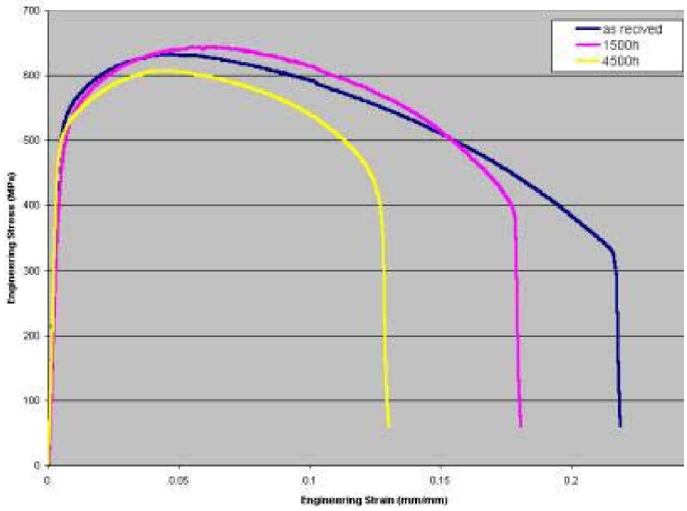


Fig. 3: Tensile test results obtained on T91 steel as received and corroded for 1500 h and 4500 h in the LECOR loop at ENEA-Brasimone [3]. The experiment evidenced an effect of the LBE on the tensile properties of the steel.

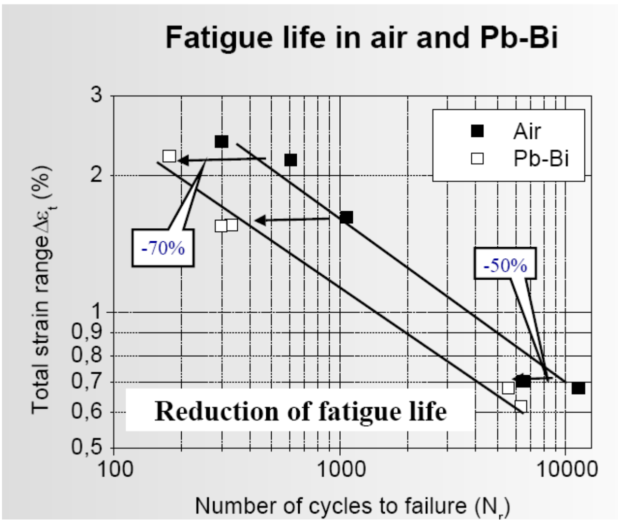


Fig. 4: Low Cycle Fatigue life of T91 steel in air and in LBE. A reduction of fatigue life on LBE could be observed [3].

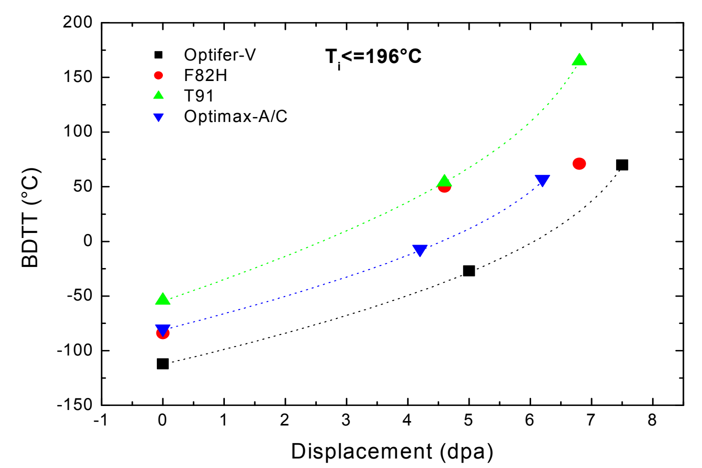


Fig. 5: DBTT vs dpa data obtained on the steels irradiated at SINQ (STIP-I) [4]. The T91 steel exhibit a DBTT of 230 °C (temperature corresponding to the hot – standby of the MEGAPIE target) at about 8,6 dpa and 730 appm of He.

2.3. *Work package 2: target testing*

Work package 2, lead by PSI, has the objectives to characterize the target subsystems / components (heat removal system, electromagnetic pump system, beam window, gas systems, instrumentation and control system) by separate-effects tests and numerical modeling. Additionally, the complete target system will be characterized by integral tests to validate the thermal-hydraulics performance under steady-state and transient conditions, the operational limits, the safety margins, the reliability, the fill and drain system and the instrumentation and control system.

The tests performed in this work package are in out-of-beam conditions. Hereafter some examples of component tests presently performed or under preparation will be described.

The Beam Window: The MEGAPIE window facing the proton beam has to withstand surface heat fluxes up to 140W/cm^2 and in case of miscellaneous beam focusing up to 200W/cm^2. Although this is only a minor part (<10%) of total heat released in the target, it represents one of the most critical issues to be solved technically. In order to minimize the heat release in the structural material, the window itself is made of a 1.5 mm thin sheet.

Regarding the thermal – hydraulic issues, two problems has to be experimentally solved, in order validate CFD codes currently being used for the design: the turbulent mixing of cold and hot streams in liquids with low molecular Prandtl number and the simulation of the coolability of the window at MEGAPIE similar surface heat fluxes. To solve the first problem the HEATED JET experiment (FZK) is under preparation and the KILOPIE experiment (FZK) have been foreseen [4] to solve the second problem.

The importance of the LBE experiments were also highlighted in the frame of the thermal – hydraulics benchmark exercise [9], where, for instance, the experimental assessment of the turbulent Prandtl number (a measure of the turbulence heat transfer), seems to be mandatory to use appropriate models for the thermal – hydraulics simulations of the target.

The turbulent mixing issue can be easily treated within the THEADES loop of KALLA by injecting overheated lead bismuth (ΔT=120°C) via the bypass tube into the relatively cold main flow (Heated – Jet experiment).

For the coolability issue, in order to simulate a MEGAPIE relevant surface heat flux, an electric resistance heating systems which reaches surface heat fluxes up to 140 W/cm^2 will be adopted. It consists in principle of a 50 µm thick nickel foil, which is glued to dish and DC current heated. Attached to the nickel foils are spring loaded needles, with which local potential differences can be acquired. The measured local potential differences correspond to local heat transfer coefficients and are thus reflecting the local temperatures. Using the HETSS heating and acquiring technique different proton beam shapes as they appear in SINQ can be simulated and investigated in the KILOPIE – experiment (see figure 7).

Heat removal system: The heat removal is obtained through the 12 pin target heat exchanger located on the top part of the target, see figure 8.

First experimental results on the target heat exchanger performances were carried out by ENEA on the cooling pin configuration. In these tests it was demonstrate that the LBE pressure drop in the cooling pin is not significant. The other parameters measured were the heat transfer coefficient on the LBE, the bayonet global exchange coefficient and the convection coefficient on the organic coolant side (see figure 9). A detailed description on the procedures and results are reported in ref. [10].

The Electromagnetic pump system (EMPS): Two electromagnetic pumps of the annular linear induction type were foreseen for the main and the by-pass flow. These pumps were designed and tested at IPUL (Riga) in collaboration with PSI. First, the engineering, manufacturing and testing of the EMPS prototype has been performed and second, the detail design, manufacturing and acceptance test of the final EMPS will be accomplished. The activities on the prototype pump are almost completed. As an example in fig. 10 the pressure – flow rate characteristics are reported.

Cavitation risk analysis of the prototype EMPS were also performed for an LBE temperature in the range 180 - 400°C and a cover gas pressure in the range 0.1-1.5bar. Cavitation in the EM pump's inlet (as typical noise, vibrations, P-Q failure) has not been observed even during He bubbles injection in the flow (approximately 0.1%, volumetric) and cover gas pressure ≥0.15bar.

2.4. *Work package 3: Synthesis*

This work package, lead by CEA, has the objective to give a feedback from the MEGAPIE development to a future ADS spallation target design. Further, the planning of irradiation experiment, post-irradiation examination and the decommissioning are also items of this work package. The commissioning phase and the first operation period under beam-on conditions (including start-up operations, steady-state situation, transients, shut-down operations) will be reported.

This work package will give results in the second part of the project (2004-2006).

3.Summary and perspectives

In this report some major results of the R&D activity have been summarized, in particular in the field of materials, thermal – hydraulics and component development support.

The engineering design of the MEGAPIE target system is completed and the manufacturing phase has started with some delay on the MEGAPIE initiative original schedule. The engineering design phase of the ancillary systems is also completed and the manufacturing phase of these systems has started. For these systems one major critical point is the fill and drain system, due to the choice of LBE freezing after irradiation and the consequent LBE solid state expansion. This issue still needs a comprehensive R&D summary.

The component and subsystem testing program is underway and some examples (beam window, target heat exchanger, electromagnetic pump) have been given.

The integral test (out of beam) program definition, for the overall target performance validation, is in preparation.

The planning of the irradiation phase, the post-irradiation phase and the decommissioning are presently at a conceptual level and they will be worked out in the next future.

Finally, the target irradiation in the SINQ beam is presently foreseen for mid 2005.

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