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LiSoR, a liquid metal loop for material investigation under irradiation

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Abstract

LiSoR is a liquid metal loop that will use PSI's 72 MeV Philips cyclotron to irradiate stressed steel specimens in contact with flowing lead–bismuth with 50 μA proton beam. Liquid metal–solid metal reactions is a joint effort of PSI and SUBATECH with the support from CNRS and the Institute of Physics from Riga. It has been initiated to explore whether or not liquid metal corrosion and liquid metal embrittlement are enhanced under irradiation in the presence of stress. Numerical simulations showed that the damage levels and gas production in thin specimens induced by 72 MeV protons are, within reasonable limits, comparable to those on the inside of the beam window of a spallation target at 600 MeV, while much less radioactivity is produced. The paper describes the basic features of the experiment, the technical concept of the liquid metal loop with a special emphasis on the test section exposed to the proton beam and some of the relevant safety aspects.

1. Introduction

The LiSoR project is a safety relevant R & D task of the MEGAPIE initiative [1]. MEGAPIE (MEGAwatt PIlot Experiment) is a joint initiative between PSI, CEA, CNRS, ENEA, FZK, JAERI, SCK/CEN, DOE and KAERI to design, build, operate and explore a liquid lead–bismuth spallation target for 1MW of beam power, taking advantage of the existing spallation neutron facility SINQ at PSI.

Among the liquid metal–solid metal reactions, corrosion and embrittlement are the two major phenomena influencing the life time expectancy of such a beam window. One of the major unknowns in liquid metal target development is whether or not liquid metal–solid metal reactions (LiSoR) are enhanced under irradiation in the presence of stress. Since this is a problem that must be solved before a liquid metal target can be irradiated in a proton beam for an extended period of time, the LiSoR experiment has been initiated [2] to explore possible effects of such running conditions.

It will use PSI's 72 MeV Philips cyclotron to irradiate stressed steel specimens in contact with flowing liquid metal. Numerical simulations showed that the damage levels and gas production in thin specimens induced by 72 MeV protons are, within reasonable limits, comparable to those on the inside of the proton beam window at 600 MeV, while much less radioactivity is produced. The beam parameters can also be adjusted in such a way that relevant heating rates at the solid-liquid interface are obtained.

The LiSoR project aims to irradiate steel specimens in a lead–bismuth loop under severe operating conditions

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representative for future liquid metal spallation targets. Material candidates have been selected for MEGAPIE and the role of the LiSoR experiment is to validate this material choice with respect to thermal and mechanical loads in the presence of proton irradiation while exposed to a lead bismuth eutectic. The loop contains test samples that will be exposed simultaneously to the proton irradiation, to flowing liquid metal at elevated temperatures, to fast temperature changes due to the discontinuous operation of the beam (up to 1000 beam interruptions within 6 days) and to mechanical stress.

After irradiation the test samples will be analysed in the PSI hot cells. It is foreseen to perform five irradiation experiments. In order to evaluate the impact of different constraints on the material properties (neutron versus proton irradiation), irradiated steel specimens are specially designed to allow for later tensile tests to be performed for these different irradiation conditions. The goal of the post-irradiation examination (PIE) is to study microstructure changes in surface layers in contact with lead–bismuth and the mechanical properties degradation of the material after irradiation.

The main result of the LiSoR experiment will be the validation of the selected steel for the MEGAPIE target window material. Additional experience will be gained for the licensing, operation and handling of LM-loop under irradiation.

2. Boundary conditions

Operating conditions, loop and irradiation specifications were fixed by the MEGAPIE collaboration in order to make sure that LiSoR irradiation experiment delivers the expected results and that the planned tests are coherent with the MEGAPIE requirements. Additional boundary conditions are related to the safety and licensing requirements and the space limitations due to the location of irradiation at IP1 on one of the Philips Injector I beam lines.

The main parameters of the LiSoR project are summarised in Table 1.

Table 1
Experimental parameters of the LiSoR experiment

Parameter	Value
Irradiation conditions	
Beam energy	72 MeV
Max. beam current	50 μA
Beam power on target	3.6 kW
Max. proton flux	3.1×10^{18} p/m^2/s
Max. current density allowed	50 μA/cm^2
Beam profile on target (gaussian)	0.8 mm ($\sigma_x = \sigma_y$)
Beam structure	Wobbling horizontal $x_{max} = \pm 2.75$ mm Wobbling vertical $y_{max} = \pm 7$ mm
Fluence goal	$>10^{25}$ p/m^2
Beam time per test	~20, 40 days
Radiation damage (20, 40 days)	~1, ~2 dpa
Loop material	316L stainless steel
Test section material choice	
Test section tube material	T91, MANET II
Test section load specimen	T91 and back-up
Test section housing	316L
Liquid metal (LM) loop characteristic	
LM	Lead–bismuth eutectic
LM temperature	300 °C max. at test section inlet
LM analysis	Before and after irradiation
LM speed in the test section	~1 m/s
Mechanical load conditions	
Kind of load	Static load stress
Maximum load	10 kN
Irradiation area	IP1

2.1. Structural material selection

For the design and construction of liquid metal spallation targets, several kinds of steel (martensitic and austenitic) have been identified as the candidate structural materials [3]. For LBE targets ferritic/martensitic steels are favoured. The following points summarises the main arguments for this choice.

- These steels offer a good mechanical strength and a good compromise between heat conductivity and thermal dilatation lowering the thermal constraints in the material.
- They have a satisfying resistance against liquid metal corrosion while in contact with the eutectics PbBi and PbLi, due to only moderate dissolution of Fe and Cr into the liquid metal.
- The steels have been applied successfully in Russian reactors cooled by liquid PbBi.
- Mechanical tests of martensitic steels in contact with PbBi did not show significant liquid metal embrittlement.
- The swelling performances are very good under fast neutron irradiation up to a level of approximately 10 appmHe/dpa.
- From the manufacturing point of view the selected steel candidates have good machining properties (e.g. for welding).

Materials tested in LiSoR will be the same as those foreseen for MEGAPIE. The first choice for the MEGAPIE target window is the ferritic-martensitic steel

Table 2
Main chemical T91 composition (wt%) from Creusot Loire Industrie (France)

Ni	Cr	Fe	Mo	Si	Mn	C	V	P	Nb
0.13	8.26	88.96	0.95	0.43	0.38	0.1	0.2	0.017	0.065

T91 (material number 1.4903), that satisfies a priori the required metallurgical criteria under irradiation mentioned above. The main chemical compositions of T91 is given in Table 2. A standard heat treatment has been applied to the T91 (Phase 1: 1040 °C annealing temperature for 60 min; Phase 2 after an air quench: 760 °C for 60 min). T91 is foreseen for the test samples exposed to the proton beam. The structural material for the liquid metal loop and the housing of the test samples will be standard stainless steel A316L.

2.2. Liquid metal

Liquid lead–bismuth eutectic (LBE) is considered as prototype target and coolant due to the fact that it can produce copious spallation neutrons when bombarded with energetic protons. It is an alloy 44.5% lead and 55.5% bismuth with a melting point of 125 °C and good heat transfer properties. The company Hetzel Metalle (Germany) supplied the eutectic Pb–55.5Bi alloy used for filling the LiSoR loop. The alloy contained a few ppm of impurities (Ag 11.4; Zn 0.53; Cu 10.7; Sn 6.3; Mg <1; Cd 3.0; Fe 0.78; Ni 0.42 wppm).

2.3. IP1 beam line

The irradiation experiment will be performed at PSI using Injector I providing 72 MeV protons at a beam current of 50 μA. The area hosting the LiSoR experiment is the IP1 area shown in Fig. 1. Without requiring major modifications the IP1 area fulfils the requested safety requirements. The IP1 bunker shielding shown in Fig. 2 has been designed for 100 μA beam. The walls and roof of 2 m of steel-filled concrete blocks rated at less than 12.5 μSv/h for a 100 μA beam irradiating a Be target. The access to the bunker is controlled via a lockable door. The bunker has a low air leakage rate and a air filtration system via the central exhaust system is available. The main inconvenient of the IP1 area is the available space. The LiSoR loop and the beam line equipment have to fit on a surface of 1.5 × 2.5 m.

The proton beam line is equipped with a beam wobbler to assure a homogeneous irradiation. The horizontal wobbling amplitude is $x_{max} = \pm 2.75$ mm, and the vertical amplitude $y_{max} = \pm 7$ mm. The beam has a gaussian distribution of $\sigma = 0.8$ mm. The wobbling frequency in both directions is adjusted to meet the requested current density of 50 μA/cm^2.

2.4. Significance of the 72 MeV experiment

The main concern about the significance of the work is whether 72 MeV protons can produce similar irradiation effects in materials as the higher energy protons in real neutron source targets do. Using the HETC code,

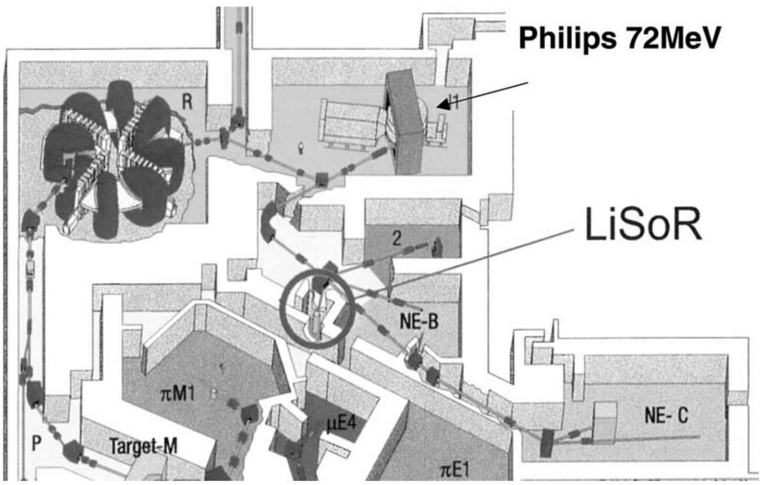

Fig. 1. Sketch of the PSI accelerator complex showing the Philips Injector I and the IP1 area for the LiSoR experiment.

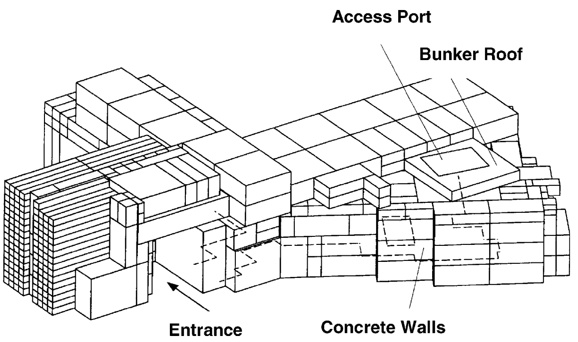

Fig. 2. The IP1 bunker shielding with the access port to the LiSoR loop on the IP1 bunker roof.

one can calculate radiation damage rate, gas (He and H) and transmutation nuclei production rates, as well as energy deposition in materials produced by high energy (generally say $\geqslant 20$ MeV [4]) protons. Instead of performing complicated calculations for steels, we just use results of Fe as a reference. Table 3 presents the calculation results for a 1 mm thick Fe plate irradiated with 72 and 600 MeV protons.

It can be seen that, as compared to 600 MeV protons, 72 MeV protons produce about the same damage, little less than 1/3 He, about 1/2 H, but generate similar amount of transmutation impurities and deposit more energy. Although He and H production is lower, the important parameter, He to dpa ratio (He/dpa), for 72 MeV proton is about 68 appm/dpa which is still much higher than in any neutron (fast, thermal and fusion) irradiation case, where the numbers are 0.5–20 appm/dpa. He and H effects will be seen if they really play an important role. On the other hand, in the target of a neutron source the window receives not only proton irradiation but also more or less equivalent neutron irradiation, which brings the He/dpa down to about 100 appm/dpa. The neutron production by 72 MeV protons is much lower and the contribution of neutrons to radiation damage strongly reduced. Nevertheless, the similar radiation damage rate and reasonably high H and He production rate provide the fundamental significance of the experiment.

Table 3
Results of HETC code calculation for a 1 mm thick Fe plate irradiated with 72 and 600 MeV protons

E_p (MeV)	dpa[a]/p/m^2	σ_{He} (mb)	σ_H (mb)	σ_Z[b] (mb)	E_{dep}[c] (MeV/p)
72	5.2×10^{24}	130	1020	800	5.25
600	4.4×10^{24}	460	1980	770	3.0

[a] dpa, displacement per atom. The number means on average every atom in the Fe plate has been displaced for one time by 72 MeV proton at a fluence of $5.2 \times 10^{24}/m^2$.

[b] σ_Z, production cross section of total transmutation elements except for H and He.

[c] E_{dep}, energy deposited in the Fe plate per incident proton.

3. LiSoR test section

The test section is a key component of LiSoR. It comprises the housing of the test tube, as a part of the liquid metal loop, and the test specimen to be irradiated and exposed to the flowing lead–bismuth. It allows a safe and remote extraction from the loop after irradiation. The load machine on the top of the test section is used to apply mechanical stress on the test specimen. A special interface to the proton beam line on the side of the test section allows the beam entrance.

3.1. Test tube and test specimen

Test tube and test specimen are the two components directly exposed to the proton beam. One particular requirement for the design of the test tube and the test specimen was to have the possibility to extract stressed and unstressed samples from an irradiated and non-irradiated zone. This should allow the PIE to quantify the effect of the coupled influence from proton irradiation, mechanical stress and exposure to the liquid metal. Fig. 3 shows a horizontal cut through the tube and the specimen. The test specimen is located inside the tube in direct contact with the flowing lead–bismuth.

The choice of the test tube cross section is based on a detailed nuclear and thermo-hydraulic assessments. Nuclear simulations were performed with the LAHET and FLUKA codes. The energy loss of the incoming 72 MeV protons is represented in Fig. 4 as a function of the penetration depth. The protons penetrate the lead bismuth via the front side of the test tube and after passing through the test specimen they are completely stopped after a total path length of 10 mm, without reaching the

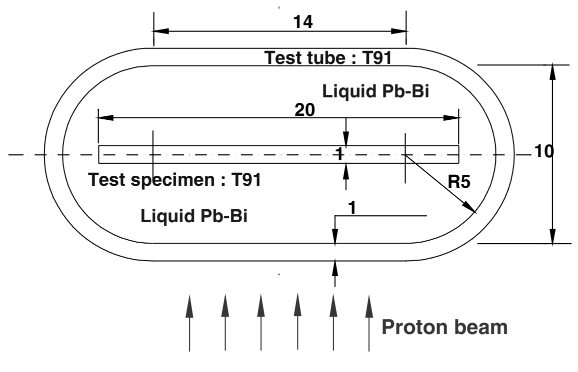

Fig. 3. Horizontal cut thorough the test tube and the test specimen.

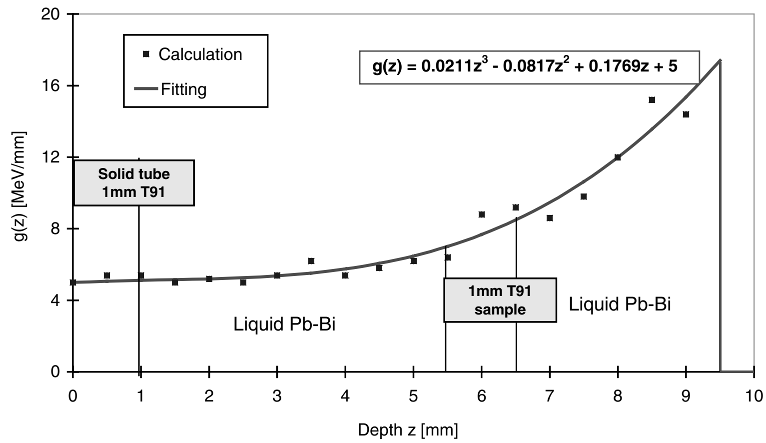

Fig. 4. Energy loss of the incoming 72 MeV protons as function of their penetration depth. The protons pass through the front side of the 1 mm thick T91 test tube, the liquid metal and the T91 test specimen before being completely stopped before reaching the opposite backward side of the test tube.

back side of the test tube. The width of the tube was set accordingly to contain the proton beam. Due to the 20 mm maximum lateral shape of the proton beam, a section length of 25 mm seemed adequate.

The ovoid cross section of the test tube was chosen to provide a flat irradiation area comparable to the test specimen as well as to minimize mechanical stress due to differential pressure between the lead bismuth loop and vacuum (0.25 MPa of total pressure between the two gives rise to 30 MPa of mechanical stress on the tube).

The wall thickness of the test tube was determined by a complete 3D thermo-hydraulic calculation including [5] flow computation, heat transfer coefficient and a precise thermal loading (calculations were performed taking into account a maximum beam current density of 100 μA/cm^2). Based on these calculations the thickness of the test tube has been fixed to 1 mm. This leads to a maximum temperature drop of roughly 350 °C with a LM inlet temperature of 200 °C. A temperature of 550 °C is reached at the hot spot of the T91 test tube inducing a maximum thermal stress of 150 MPa compared to a mechanical stress of 30 MPa. The height of the test tube was set to 90 mm to allow extraction of material samples in the upper part of the tube area that has not been irradiated by the protons. Fig. 5 is a photograph of the final manufactured test tube showing the location of the heterogeneous T91 welds and two additional machined rings that have been added on the circumference of the tube to reduce the burden of mechanical stress.

The inner test specimen is a flat test sample of 50 cm length, 5 mm thickness with a 10 cm reduced section of 1 mm thickness. Although the proton's energy is smaller and the beam spot size slightly larger on the inner test samples than on the outer tube, the thickness of 1 mm gives a power density comparable to the one deposited by the incoming beam in the wall of the outer tube. Fig. 6 details the specimen shape compared to a standard size ruler. The spot corresponds to the irradiation area. Samples from the upper part, not being exposed to the beam, will be analysed for comparison.

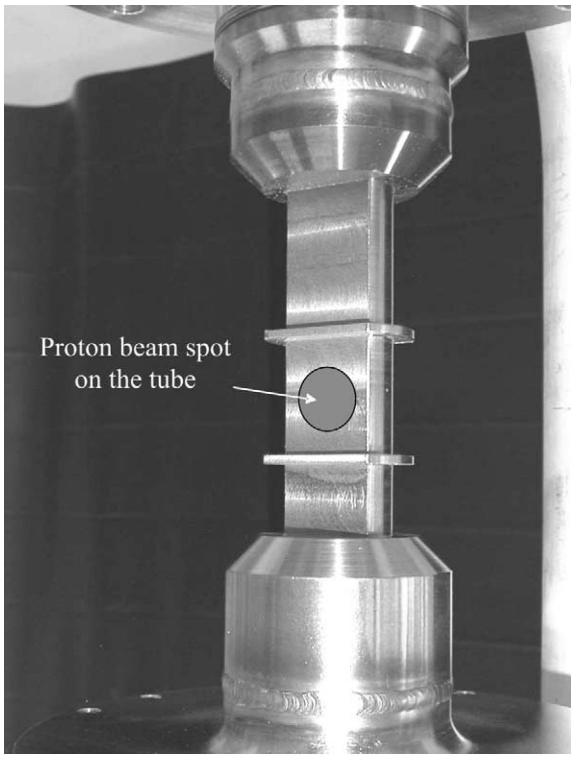

Fig. 5. Machined T91 test tube. The spot indicates the zone irradiated by the proton beam.

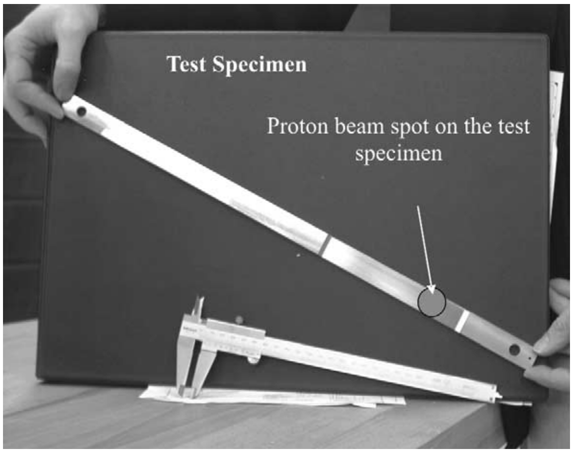

Fig. 6. Test specimen.

3.2. Estimate of the dpa rate

To determine the total dpa rate obtained due to proton and neutron irradiation in the test section the following equation has been used:

$$\mathrm{dpa} = It \sum_{i=p,n} \sum_{E} \sigma(E)\Phi(E)\,\mathrm{d}E.$$

With the following parameters:

- I: beam current of 50 μA;
- t: irradiation time of 20 days;
- $\sigma(E)$ the damage cross section for protons and neutrons and
- $\Phi(E)$ the neutron and proton fluxes.

The damage cross section for protons and neutrons as function of their energy is plotted in Fig. 7 [6]. The proton and neutron energy spectra have been obtained with the FLUKA simulations and are represented in Figs. 8 and 9 respectively. The two curves on both figures correspond to the centre of the beam spot on the front side of the test tube (beam window) and the test specimen (T91 sample). The neutron spectra looks quite similar for the test tube and the test specimen. The proton spectra corresponding to the test specimen is shifted towards lower energies due to the energy loss in the LBE before reaching the specimen. The resulting dpa distribution in vertical direction ($x = 0$) is shown in Figs. 10 and 11 for the test tube and the test specimen respectively. As expected the dominant contribution is due to the proton irradiation. The drop on the edges of the spectra corresponds to the limit of the irradiation spot. The total dpa in the centre of the test tube is about 1.2 dpa and in the test specimen 0.9 dpa. The relative contribution of the neutrons to the total dpa rate is less than 5% in the test tube and slightly higher in the test specimen.

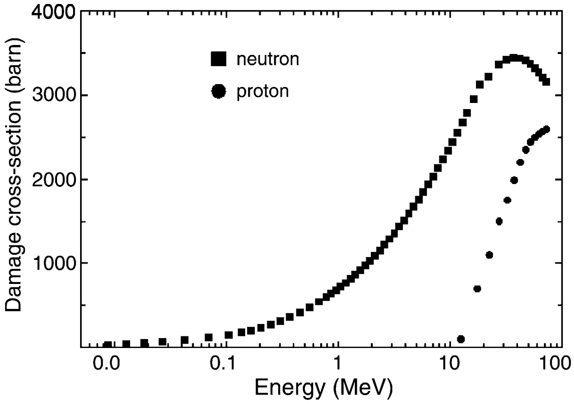

Fig. 7. Proton and neutron damage cross sections as function of the particle energy.

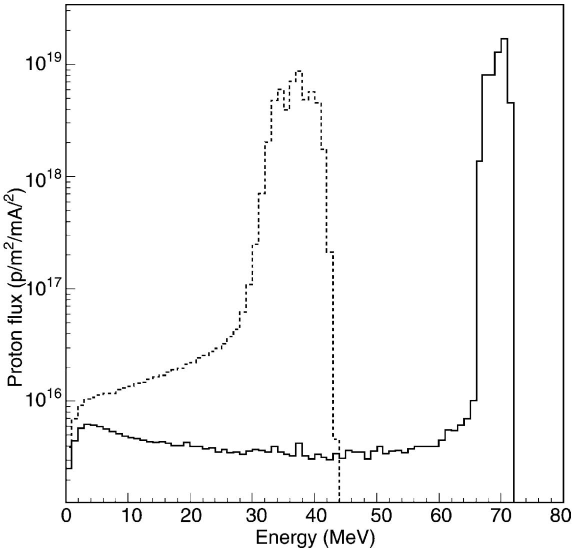

Fig. 8. Proton energy spectra in the centre of the beam spot on the front part of the test tube (beam window: full line) and in the test specimen (dotted line).

3.3. The test section housing

The test section housing has been designed to ensure several functions: It houses the test tube for the lead–bismuth flow and the test specimen. It contains a large squeeze and cut area on the lead–bismuth pipes for remote disconnection. It allows for instrumentation to be mounted and transferred from the vacuum area inside the test section, to normal pressure area outside. It interfaces electrical connections through special connectors of all the instrumentation to the LiSoR control and

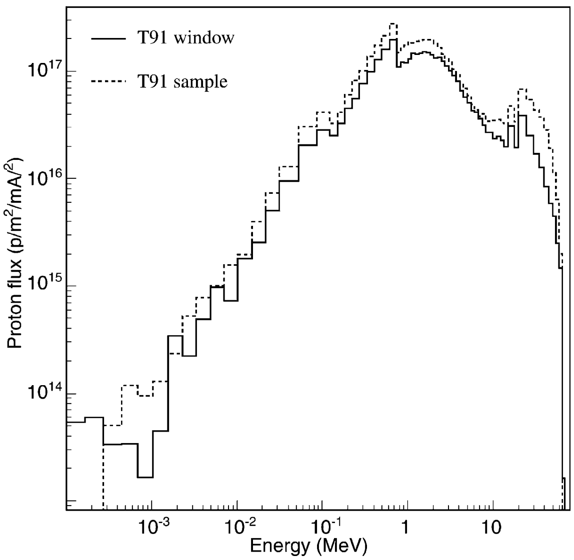

Fig. 9. Neutron energy spectra in the centre of the beam spot on the front part of the test tube (beam window: full line) and in the test specimen (dotted line).

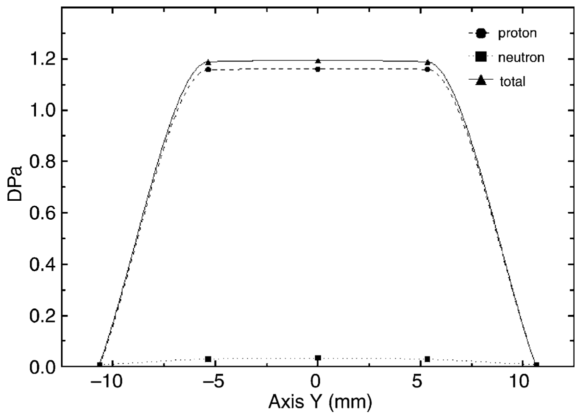

Fig. 10. Vertical ($x = 0$) dpa distribution in the front side of the test tube (dotted line: dpa from the neutrons; dashed line: dpa from protons; full line: total number of dpa).

command system. Fig. 12 represents the drawing of the test section housing with the corresponding equipment (e.g. electrical heaters, cover gas connection,...) and instrumentation (e.g. LBE level meters, thermocouples, LBE leak detector,...).

3.4. The mechanical load machine

To assess the influence of mechanical stress on the properties of the test samples in the liquid metal under

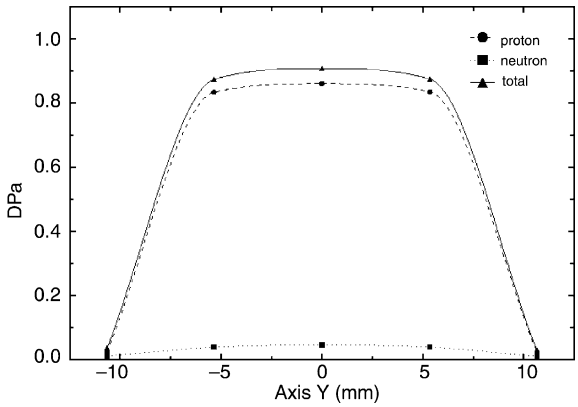

Fig. 11. Vertical ($x = 0$) dpa distribution in the test specimen (dotted line: dpa from the neutrons; dashed line: dpa from protons; full line: total number of dpa).

irradiation a dedicated load machine has been designed to satisfy the following requirements:

- All tests under irradiation have to be performed with a static load being approximately 1/2 to 3/4 of the yield strength of the test specimen.
- The maximum load capacity of the machine has to be 10 kN, which is adapted for 20 mm^2 test specimen cross-section.
- During irradiation, the displacement and load are measured with an extensometer (stroke: 5% of the gauge-length of the sample; accuracy: <5 μm or ±0.5% of the display value) and a load-cell (accuracy: <±0.2% of the load-cell capacity), respectively.

To maintain a static load during the extended irradiation time (min. 20 days) in the presence of the strong radiation environment, a load machine with a pneumatic jack regulated by an electromagnetic pressure valve has been selected.

The load machine is coupled via the hook on the top of the test section to the test specimen as shown in Fig. 13.

3.5. Remote handling of the test section

During the irradiation experiment the test section will be activated. In addition the pipes in the test section (and also in the loop) will be contaminated by LBE after the loop has been drained. This can be due to wetting of the material surface or due to some dead zones where small amounts of LBE remained. The design of the test section has to allow remote manipulation after irradiation and a dedicated remote handling tool has been developed for this purpose.

Technically it was not feasible to extract the irradiated test tube and the test specimen remotely and in-situ

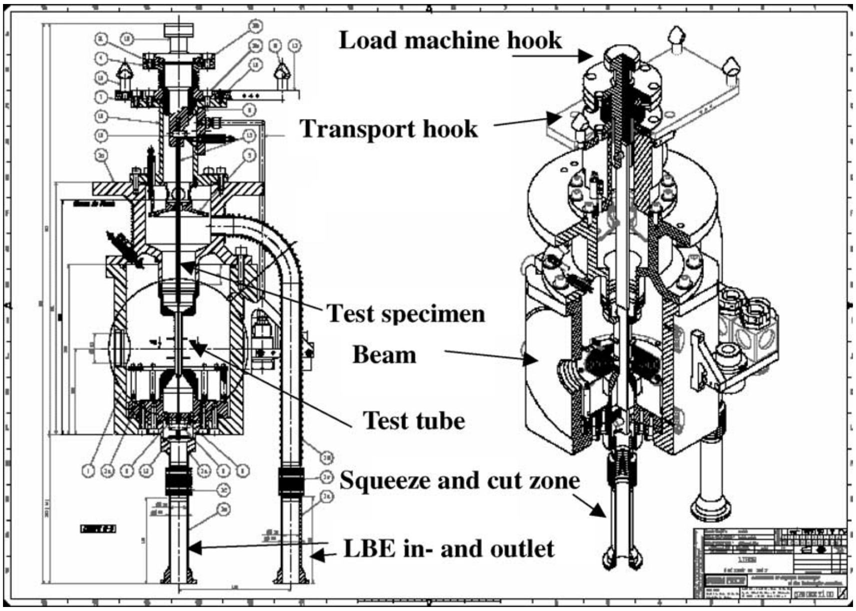

Fig. 12. Drawing of the test section housing.

from the test section housing. The entire test section has to be removed and transferred to the PSI hot cells for accessing the irradiated parts for further post irradiation examination.

After irradiation and the required cool down time of several days the ceiling of the bunker will be opened and the shielded transport flask will be put on the roof at the IP1 access port (see Fig. 2). The mechanical load machine will be detached and removed automatically from the test section.

The disconnection of the test section pipes is schematically shown in Fig. 14. A hydraulic squeeze and cut system (Fig. 15) will be inserted from the top. The straight part of the test section inlet and outlet tube, between the connecting flange and the bellow, will be squeezed with the front part of the hydraulic device. In a second step the tubes are cut. A hook is lowered down from the bunker roof to pick up the test section and raise it up into the shielded transport flask for transport to the PSI hot cells. By lifting up the test section all electrical connectors and the cover gas pipe are disconnected automatically.

For the next experiment a new test section has to be connected to the LBE loop. The remaining parts of the old test section tubes have to be removed by hand. With the hook system, the new test section is inserted into the IP1 bunker and guided by two rails to its final position in the support frame. The weight of the test section is enough to assure an automatic connection of the electrical and gas connectors. Finally the flanges of the inlet and outlet tubes are connected by hand on the LBE loop as shown in Fig. 14.

4. The LiSoR liquid metal loop

The main design constraint for the LiSoR liquid metal (LM) loop comes from the corresponding working environment. The LBE loop has to be located in the very reduced space of the IP1 area and it will be running under the special conditions of a high radiation environment. The loop is designed to provide the specific LM flow rate of 0.2 l/s (linear velocity of 0.9 m/s) and LM temperature in the range from 150 to 350 °C in the test section. The total amount of LBE in the loop is 18 litres in order to minimise the quantity of contaminated liquid metal at the end of the experiment.

The main components of the LBE loop are presented in Fig. 16. They are an electromagnetic induction pump, an electromagnetic induction flow meter, a two stage heat exchanger system (LBEoil and oilwater) for temperature regulation, an expansion tank for the filling and draining procedure, a shielded LBE storage tank, and special fail-safe valves equipped with pneumatic activators. The loop elements are connected with austenitic 316L steel pipes of $\varnothing$ 30 × 2 mm. The LBE is driven by the electromagnetic pump via the heat exchanger and the flow meter into the test section. The outlet of the test section is connected back to the pump. The pipes

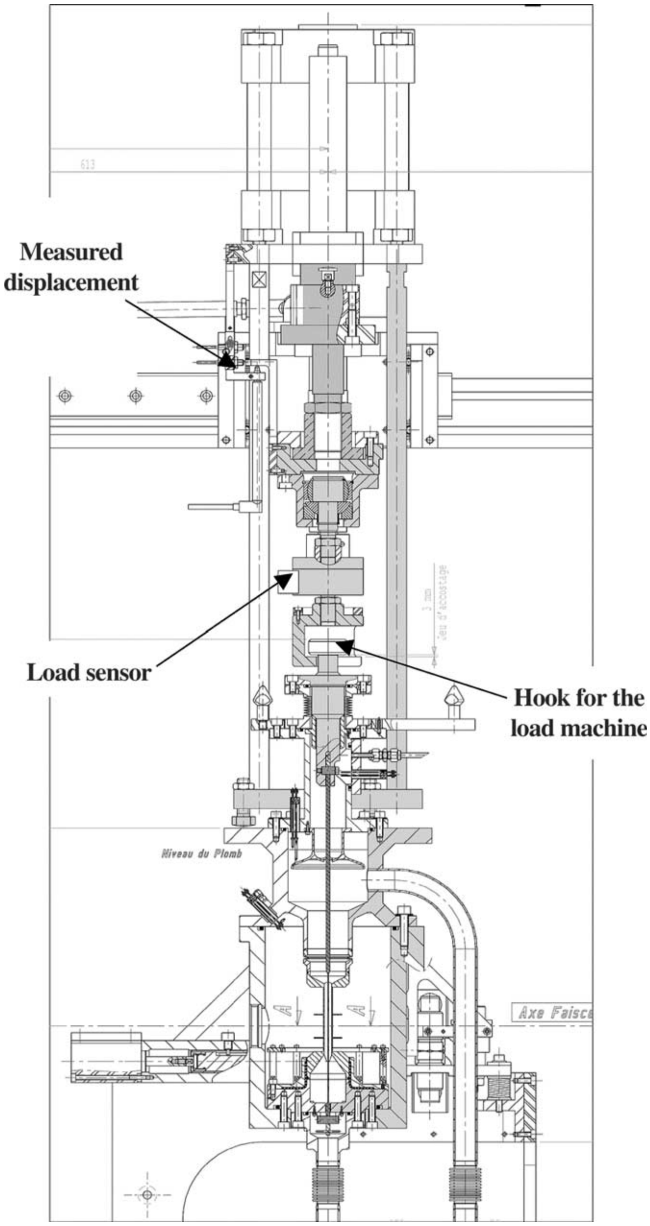

Fig. 13. The mechanical load machine coupled to the test section.

are equipped with flexible heaters to compensate for heat losses. The operating temperature of the LBE on the test specimen is controlled by a powerful 12 kW heater at the inlet of the test section. After the final assembling of the LBE loop all components have been heat-insulated.

In the following two sections the electromagnetic pump and flow meter and the heat exchanger will be presented. More details on the loop components can be found in [7] by Dementjev et al.

4.1. The electromagnetic pump and flow meter

For the electromagnetic induction pump the design was based on the concept of two rotating discs with permanent magnets. The main technical parameters of

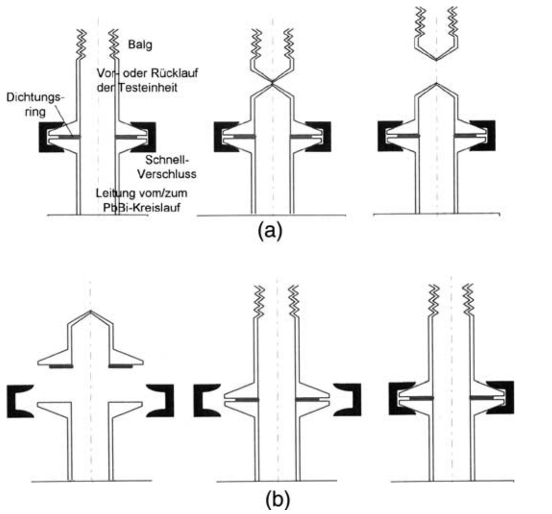

Fig. 14. Schematic view of the LBE pipe disconnection and connection procedure. (a) Extraction of the irradiated test section: squeezing and cutting of the inlet and outlet tube; (b) insertion and connection of the new test section.

Fig. 15. Hydraulic squeeze and cut device for disconnecting the LBE pipes of the test section from the loop. The front part squeezes the pipe and the back part of the device cuts the pipe.

the pump are: working medium LBE; max. temperature 400 °C; pressure from 0.5 to 1.5 bar and a flow rate in the range of 0.1 to 0.3 l/s. The flow rate is controlled by adjusting the rotation speed of the AC motor.

The electromagnetic flow meter measures the LBE flow rate in the steel pipe within a range of 0.05 to 0.5 l/s with a measurement error that does not exceed 2.5%. The calibration characteristics are linear and the indication of the flow meter does not depend significantly on the wetting conditions of the tube wall. The flow meter consists of two flat assemblies located on opposite sides of the pipe. It can be easily positioned on the pipe and dismounted from it. This increases the flow meter's in-service life given the conditions of elevated temperature and radiation.

4.2. The heat exchanger

The distinctive feature of the heat exchanger is the separation of the LBE and water circuits with an intermediate oil loop to prevent direct contact in the case of leakage. The oil loop is filled with two litres of a high-performance heat transfer fluid DIPHYL THT produced by Bayer Ltd for high radiation resistance. The LBE-oil and oil-water heat exchanger have a special design to ensure small size and good heat transfer efficiency considering the relatively high viscosity of the oil at temperatures below 120 °C. The DIPHYL THT oil has also been selected by the MEGAPIE project for extracting the heat from the MEGAPIE target. First results on the operation of this oil in LiSoR will be useful for MEGAPIE.

4.3. Operation of the loop in normal conditions

The working conditions of the LiSoR loop are directly related to the safety requirements in order to assure a safe operation of the loop and a safe handling of the test section after irradiation. Different operation steps characterise the normal working conditions of the loop:

- Standby: The LBE is solidified in the storage tank and the loop disconnected via the valve system from the storage tank, the beam line and the gas exhaust system.
- Filling of the loop: The LBE is melted in the storage tank. The LBE loop and the oil loop are heated to a temperature above the melting point of the LBE. The gas in the loop is evacuated via the exhaust system. With pressure from the cover-gas system, the LBE is pushed into the loop. The LBE level is monitored with the level meter in the expansion vessel and the test section. After the filling process, the expansion vessel is disconnected from the loop to avoid swinging of the LBE free surface in the two expansion volume (expansion vessel and test section). Finally the electromagnetic pump starts the LBE circulation in the loop.
- LiSoR ready for the beam: The loop and the control system are running properly. The shielding is in place and the door of the IP1 area is locked.
- Beam on the test section: Beam position, beam profile and beam wobbling must be optimised. The beam current will be increased to its nominal value and the beam shutter will be opened for the beginning of the irradiation.
- After the irradiation the beam shutter will be closed and the LBE will be drained into the storage tank.

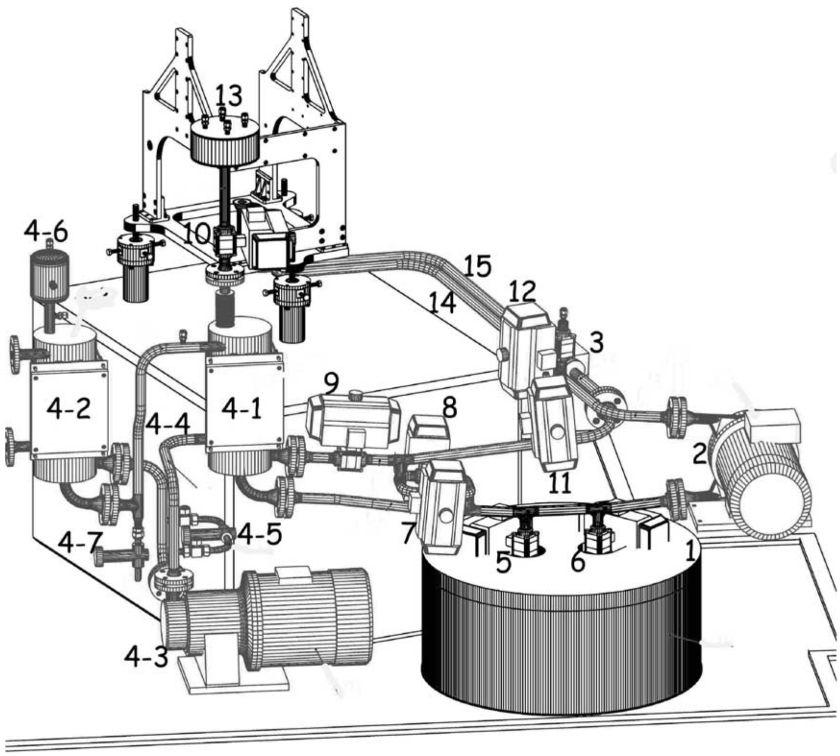

Fig. 16. Schematic of the LBE path: (1) LBE storage tank, (2) induction pump; (3) electromagnetic flow meter; (4) thermostat ((4–1) and (4–2) LBE-DIPHYL and DIPHYL-WATER heat exchangers; (4–3) oil pump; (4–4) Ventury tube; (4–5) bypass; (4–6) oil expansion tank; (4–7) valves for oil loop filling and draining) 5 . . . 12 automatic valves; (13) expansion tank; (14) and (15) inlet and outlet pipe. The pipes 14 and 15 are connected to the test section in- and outlet of the test section (on this figure only the test section support frame is shown).

After a short cool down time (~1–2 days) the irradiated test section can be removed and several days or weeks later a new test section can be installed for the next irradiation experiment.

5. Safety aspects of the LiSoR loop

The construction and operation of the LiSoR facility has to comply with the PSI safety rules based on the Swiss laws on radiation protection and the handling of open radioactive sources. A safety report was required containing: the justification of the experiment, the description of the safety systems, the measures taken to assure the safety of the installation, the organisation responsible for safety and radiation protection and a description of possible accidents and their effect on operation and environment.

The safety report [8] has been submitted to the Swiss licensing authority, the Federal Office for Public Health (BAG). During the licensing phase several meetings were organised to discuss with the authorities particular topics of the safety report and to demonstrate some safety relevant actions on the LiSoR facility (e.g. automatic draining of the LBE in case of a temperature parameter out of range, the squeeze and cut procedure, the remote handling of the test section, . . .).

5.1. Activation of the test section and LBE

For safe handling of the test section and the use of an adequate transport flask for the transport to the PSI hot cells, the gamma activation of the irradiated test section has to be analysed. Fig. 17 shows the evolution of the dose rate after an irradiation of 20 days by a 50 μA beam. The dose rate decreases only very slowly (only a factor of 0.4 from 1 and 10 days). An extended cool down period before the remote extraction of the test section gives no real advantage. The shielding of the transport flask reduces the dose rate from 1 Sv/h at 0.5 m from the source to 80 μSv/h on the surface of the transport container. This value is well below the authorisation limit of 2 mSv/h necessary for the transport.

The estimation of the gamma dose rate of the LBE in normal operation of the loop is relevant in three cases:

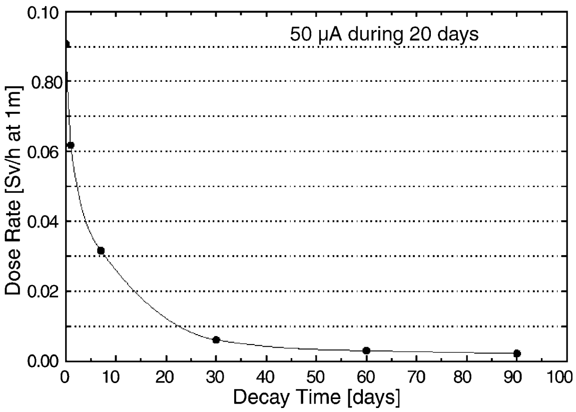

Fig. 17. Decay of the gamma activation of the test section after 20 days of irradiation at 50 μA.

- For the protection of persons that have to enter the IP1 bunker when the LBE is not drained into the storage tank;
- For the protection of persons that have to enter the IP1 bunker with still some remaining LBE in the loop even after draining of the liquid metal into the storage tank;
- For the final decommissioning of the LBE and the loop.

The overall gamma dose rate of the LBE is shown in Fig. 18 for a cumulative irradiation time of 80 days at 50 μA. For installing a new test section an operator enters the bunker to connect the flanges. Assuming that a 0.1 mm thick LBE layer remains at the piping surface (unprotected pipe length of 30 cm), the gamma dose rate from these 27 g of LBE is 100 μSv/h at 1 m after 80 days of irradiation and a decay time of 10 days. This results in a cumulative dose of less than 25 person μSv per change of test section.

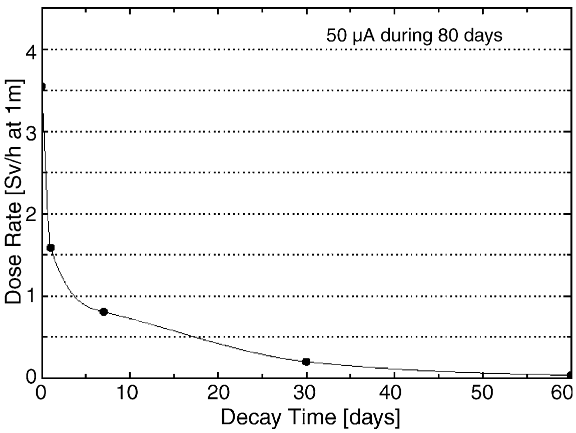

Fig. 18. Decay of the LBE (18 l) gamma dose rate after a cumulative irradiation of 80 days at 50 μA.

Table 4
Production rate of polonium isotopes and related α-activity for 80 days of irradiation at 50 μA

Isotope	Concentration [mol/l] for 80 d, 18 l of LBE	Total activity [Bq at $t = 0$]	α-Activity [Bq at $t = 0$]
Po-202	9.1×10^{-13}	2.8×10^{9}	5.6×10^{7}
Po-203	5.8×10^{-11}	1.9×10^{11}	4.2×10^{8}
Po-204	1.5×10^{-9}	8.8×10^{11}	5.8×10^{9}
Po-205	7.7×10^{-10}	9.7×10^{11}	3.9×10^{8}
Po-206	7.6×10^{-8}	7.5×10^{11}	4.1×10^{10}
Po-207	2.6×10^{-9}	9.2×10^{11}	1.9×10^{8}
Po-208	4.4×10^{-7}	3.6×10^{10}	3.6×10^{10}
Po-209	6.7×10^{-8}	1.5×10^{8}	1.5×10^{8}
Po-210	1.3×10^{-9}	7.9×10^{8}	7.9×10^{8}

5.2. The α-activity of the LBE

The α-activity in the IP1 bunker is relevant only in case of an accident with LBE leaking out of the loop and for the handling of the contaminated parts in the PSI hot cells during the PIE. The α-activity is mainly due to the polonium isotopes produced by nuclear reactions of the protons and neutrons with the LBE (mainly on the bismuth). The polonium production rates calculated with the FLUKA code and related activities are presented in Table 4.

6. Experimental program

After a first successful assembling of the loop in an experimental hall at PSI, first tests without beam and the authorisation of the safety authorities to install the loop on the beam line, the loop has been mounted in the IP1 bunker (see Fig. 19).

In total, five irradiation experiments are foreseen. In the first experiment the sample will be exposed to irradiation only during a short time. In this case the dpa will not be a relevant parameter. The irradiation by the proton beam will just assure the local heat deposition in the sample. The obtained tensile curve will be compared to data performed without irradiation. The temperature of 200 °C is chosen to stay in the range of 100 K above the lead–bismuth eutectic melting temperature (125 °C), which corresponds to the critical region for liquid metal embrittlement.

All other tests are planned at 300 °C. This temperature corresponds to the temperature of the liquid metal at the MEGAPIE window surface. The main parameters that can vary between the different experiments will be the irradiation time, the load condition and the material of the specimen. Table 5 gives an overview of a possible

Fig. 19. Photo of the LiSoR loop installed in the IP1 bunker.

Table 5
Summary of the five irradiation experiments planned with LiSoR

No	Material test section	Material specimen	dpa	Duration	Load conditions	Temperature (°C)
1	MANET	T91	<0.01	short	Tensile test	200
2	T91	T91	1	18 days	50% $R_{p0.2}$ (at 300 °C)	300
3	T91	T91	2	40 days	50% $R_{p0.2}$ (at 300 °C)	300
4	T91	T91 or back-up	1	20 days	$\geqslant$50% $R_{p0.2}$ (at 300 °C)	300
5	T91	T91 or back-up	1	20 days	$\geqslant$50% $R_{p0.2}$ (at 300 °C)	300

experiment matrix for the five irradiation experiments. The feed back of each experiment will determine the final parameter set for the next one. Hence, modifications are possible and a final decision on the type of the back-up material and the load conditions will be made later.

The short test irradiation was planned for June 2002 and the first long-term irradiation was foreseen in July 2002. The post irradiation analysis of the first irradiated samples will be done during summer so that a first feed back from the LiSoR experiment for MEGAPIE can be expected in autumn 2002.

7. Conclusions

An important body of work has been done up to now in designing, building and testing the LiSoR installation. Although the main irradiation experiment still has to be performed, the MEGAPIE project has already benefited from the experience gained during the LiSoR project. This is particularly the case for the work performed on licensing of the facility with liquid metal operating under irradiation and the exchange with the safety authorities.

LiSoR is a unique opportunity to perform material investigations in flowing LBE with a 72 MeV proton beam. Performing test with this proton beam energy is easier because less radioactivity is produced. The LiSoR installation is ready to contribute to the validation of the selected T91 material for the MEGAPIE target window with respect to liquid metal embrittlement, under representative experimental conditions, taking into account the material exposure to irradiation, LBE and mechanical stress.

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