MEGAPIE

6^{th} Technical Review Meeting

June 27-29 2005

SCK•CEN Mol

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Programme of the 6th MEGAPIE Technical Review Meeting

Monday, June 27

10:30 Registration
11:45 Lunch

Session 0: "Introduction"

13:00 SCK•CEN: "Welcome"
13:10 C. Latgé: "Introduction to the meeting: agenda, objectives"
13:20 F. Groeschel: "MEGAPIE project overview"

Session 1: "Target design and manufacturing"

13:40 T. Kirchner: "Target design options and final design"
14:00 A. Cadiou: "Target design calculations"
14:20 S. Dementjev: "Electromagnetic pumps system of the MEGAPIE target: test results and manufacturing experience"
14:40 H. Lardenois: "Target manufacturing experience"
15:00 W. Wagner: "Ancillary systems of MEGAPIE: design, commissioning and projected performance"
15:40 Discussion
16:00 Coffee break

Session 2: "System behaviour"

16:20 W. Leung: "Thermalhydraulic system behaviour and the target temperature regulation strategy using RELAP5"
16:50 H. Heyck: "Control system of MEGAPIE: process control, protection functions and SINQ Integration"
17:10 K. Thomsen: "Leak detection in the MEGAPIE target"
17:30 K. Thomsen: "Beam monitoring for MEGAPIE"
17:50 Discussion
18:10 End of day 1

Tuesday, June 28

Session 3: "Thermal hydraulics and structure mechanics"

08:30 T. Dury: "Validation of the CFX-4 CFD code for heat transfer to liquid metal in a curved geometry, and CFD simulation of the MEGAPIE lower target"
08:50 R. Stieglitz: "Turbulent momentum transfer in the MEGAPIE target shell"
09:10 R. Stieglitz: "Turbulent energy transfer in the MEGAPIE target shell"
09:30 J. Patorski: "First results of the KILOPIE-2 pre-experiment"
09:50 B. Smith: "Synthesis, technical assessment"
10:10 Discussion
10:30 Coffee break

Session 4: "Liquid metal technology"

10:50 J. L. Courouau: "Review of the oxygen control for the initial operations and integral tests"
11:10 P. Agostini: "LBE interaction with water"
11:30 P. Agostini: "Synthesis of liquid metal technology"
11:50 Discussion
12:10 Lunch break

Session 5: "Nuclear assessment"

13:20 J. Neuhausen: "Behaviour of nuclear reaction products in MEGAPIE"
13:40 Y. Kurata: "Evaporation behavior of Po and other elements from liquid Pb-Bi"
14:00 L. Zanini: "Nuclear assessment: synthesis, technical assessment "
14:30 Discussion

Session 6: "Irradiated target handling"

14:50 W. Leung: "Control LBE freezing at the end of irradiation test"
15:10 A. Strinning: "Target dismantling and waste disposal"
15:30 Y. Dai: "The optimum and minimum PIE plans of the MEGAPIE target"
15:50 Discussion

16:10 Coffee break

Session 7: "Safety and licensing issues"

16:30 A. Janett: "Safety and licensing issues"
16:50 P. Ming: "MEGAPIE quality assurance system and implementation"
17:10 K. Samec: "LTE design, stress calculations and accident containment"
17:30 F. Groeschel: "Assessment of the reference accident case"
17:50 Discussion
18:10 End of day 2
19:30 TRM2005 Dinner

Wednesday, June 28

Session 8: "Solid-liquid interface"

08:30 A. Terlain: "Corrosion behaviour of T91 and 316L in LBE at MEGAPIE relevant conditions"
08:50 T. Auger: "LME and fatigue of T91 steel in LBE: a review"
09:30 J. Konys: "X7 conclusion"
09:50 Discussion
10:10 Coffeebreak

Session 9: "Materials and radiation damage"

10:30 H. Glasbrenner: "LiSoR experiments: overview and relevant results for MEGAPIE"
11:00 Y. Dai: "Lifetime assessment of structural materials for the MEGAPIE target"
11:30 Y. Dai: "X10 conclusion"
11:50 Discussion

Session 10: "Synthesis"

12:10 All: "Discussion and recommendations"
12:35 C. Latgé: "MEGAPIE TRM2005 synthesis and perspectives"
13:00 End of MEGAPIE TRM2005
13:00 Lunch

Session 0: Introduction

Chaired by W. Wagner

0.1 Welcome (10')

SCK•CEN

0.2 Introduction to the meeting: agenda, objectives (10')

C. Latgé

0.3 MEGAPIE project overview (20')

F. Groeschel

The MEGAPIE project is now running for its 5th year and has definitely passed the design state. The manufacturing of the target and the ancillary components is in the final phase.

The presentation will provide an overview on the status of the project. Starting from the last technical meeting, it will describe the main developments and changes experienced in this period. The following topics will be addressed:

- General Situation of the ADS Research and Position of MEGAPIE within these activities (worldwide and EU framework programs)
- Difficulties and technological evolution of the project since the last meeting
- Evolution of the schedule and financial situation
- Legal situation and licensing process
- Issues solved and still open challenges.
- Outlook on the target implementation and its effect on SINQ operation.

Session 1: Target design and manufacturing

Chaired by G. Bauer

1.1 Target design options and final design (20')

T. Kirchner

The MEGAPIE target design is strongly driven by safety considerations. The main consequence of this is an integrated target design, where all lead-bismuth (LBE) loop components are arranged within the target unit itself, assuring the containment of the irradiated LBE in a double enclosure.

For space limitation reasons the LBE loop was kept as simple as possible. It includes two electromagnetic pumps and a 12 pins counter flow heat exchanger using oil as coolant. In order to improve the heat exchange coefficient on the window a fraction of the LBE main flow is directed towards the center of the target window by a internal by pass. The second enclosure of the target implies also a second beam window for the target and therefore the choice of a cooled window was made in accordance with previous SINQ target experience. The target instrumentation serves for safety and operation purposes using mainly simple and robust thermocouples or derivatives.

For target manufacturing the project organized a very close follow up of the target manufacturing, with the goal to obtain confidence in the manufacturing and also a reliable "as build documentation".

The presentation will recall the purpose of the target and target sub-systems and will explain the actual target and sub-system design.

1.2 Target design calculations (20')

A. Cadiou

The target design included an important amount of mechanical and thermo-mechanical calculations. This presentation will discuss the following topics: norms and standards relevant for the design, computer codes and the calculation tools that were used, list of materials and corresponding material data. Stress analysis, load levels and their consequences on the design will be discussed for some target sub-systems like for example the second target enclosure, the liquid metal container with the beam window, the target head and the target heat exchanger.

1.3 Electromagnetic pumps system of the MEGAPIE target: test results and manufacturing experience (20')

S. Dementjev

The electromagnetic Pumps System for the MEGAPIE target has been developed and built during the recent two years as the result of collaboration between PSI and IPUL. The system operates submerged in lead bismuth eutectic which temperature fluctuates during a beam trip in the range of 240-380°C with rate 5-10°C/s.

The EMPS is responsible for the liquid metal (PbBi eutectic) flow between the target's beam entrance window and heat exchanger to ensure thermal power evacuation. The main pump (EMP1) maintains the flow between the target's proton beam entrance window and heat exchanger (nominal flowrate-4L/s, pressure head- 200mbar). The by-pass pump (EMP2, 0.35L/s, 350mbar) controls flow structure in the beam entrance window to optimize cooling conditions. The both pumps are 2 poles, 18 coils linear cylindrical induction pumps with passive magnetic cores. Active/total power of the EMP1 is 8.2kW/9.8kVA and of the EMP2 - 6.8kW/8.1kVA.

Electromagnetic induction type flowmeters (EMF1 and EMF2) were developed for monitoring of the LBE flowrate in the main and by-pass LBE paths.

The EM pumps and flowmeters are protected from direct contact with LBE by thin-walled austenitic steel 316L protective hull. The hull was designed to withstand 7 bar overpressure without loss of integrity at temperatures up to 380°C and 10.000 fatigue cycles caused by the beam trip. Special bellow units and ceramic heat shield limit the thermal stresses in the protective hull during the LBE temperature transients.

Thermohydraulic and reliability test of the electromagnetic pumps system was carried out October – November 2004 in IPUL. During 590 hours the EMPS operated submerged in liquid PbBi under conditions similar to conditions in MEGAPIE target. The main goals of the test were: EMPS workability and reliability checks as well as experimental verification of the system operating performances.

The test showed that basically the EMPS (electromagnetic pumps and protective hull) meets the technical specification requirements. However the test revealed problems with the electromagnetic flowmeters: although sensitivity of the both flowmeters approximately corresponds to IPUL predictions, leakage electromagnetic flux of the pumps and LBE temperature fluctuations critically affect the flowmeters operation. That reduces accuracy of the flowrate measurements and claims energetic actions from IPUL on the flowmeters electronic circuit and software perfection.

The EMPS has been delivered to ATEA, checked and installed in the MEGAPIE target.

1.4 Target manufacturing experience (20')

H. Lardenois

1 Short presentation of the REEL Group
- 1.1 REEL Worldwide
- 1.2 REEL ATEA in Nantes (France)

2 Quality Assurance Rules
- 2.1 PSI objective
  - 2.1.1 Safety
  - 2.1.2 Reliability
  - 2.1.3 Trust
- 2.2 Quality Assurance System proposed by REEL to reach the PSI objective
  - 2.2.1 Personal Qualification
  - 2.2.2 Documents handling
  - 2.2.3 Design Changes handling
  - 2.2.4 Non Conformances handling

3 Scope of work
- 3.1 Industrial organization
  - 3.1.1 REEL ATEA
  - 3.1.2 Main Suppliers
- 3.2 Procurements
- 3.3 Manufacturing
- 3.4 Assembling & Tests

4 Schedule main steps
- 4.1 Original schedule
- 4.2 Achieved schedule

5 Technical challenges
- 5.1 Procurements
- 5.2 Machining
- 5.3 Welding
- 5.4 Assembling
- 5.5 Testing

6 Feeback experience
- 6.1 Design
- 6.2 Manufacturing
- 6.3 Tests

7 Conclusion

1.5 Ancillary systems of MEGAPIE: design, commissioning and projected performance (40')

W. Wagner

The ancillary systems of MEGAPIE immediately necessary for the target operation comprise the heat removal system (HRS), the cover gas system (CGS), the insulation gas system (IGS) and the fill and drain system (F&D), together with a common control system. Starting from the baseline requirements; during the detailed design phase these systems were subjected to several amendments and adaptations, mostly triggered by more elaborated design criteria, updated data bases and closer specified boundary conditions. Most incisive, for the F&D system the initial requirement for draining the target after irradiation was abandoned in favour of merely inactive draining, imposing the consequence of freezing the target after termination of the experiment.

The paper aims to resume the design phase with special emphasis on design goals and design amendments, commissioning experiences and the projected performance demonstrating their fitness for the experiment.

1.6 Discussion (20')

Session 2: System behaviour

Chaired by G. Bauer

2.1 Thermalhydraulic system behaviour and the target temperature regulation strategy using RELAP5 (30')

W. Leung

A thorough study on the MEGAPIE target cooling system has been conducted with the RELAP5/Mod 3.2.2 code. This target is designed for spallation neutron generation by taking in a powerful proton beam that deposited more than half of a MW of heat into the bottom of the target. Evacuating the heat is the primary function of the cooling system which consists of the target and two cooling loops. The require flows and operating temperatures of all the cooling loops are calculated based on the actual geometries of the manufacturing.

Although this spallation target is run in a continuous mode, there are lots of beam interruptions during a normal operation. The normal transients are the beam trip, beam interrupt and beam start-up, and the nominal steady states are the beam on operation and hot standby. It is necessary to regulate the target cooling in order to maintain a steady temperature in the target in all the operating conditions and heating power. Control scheme has been studied by SIMULINK simulation and implemented in the RELAP5 for studying the thermalhydraulic feedback. It is found that a simple adaptive PI (Proportion, Integrate) scheme is working well in the current system.

To study the off normal transients, hypothetical cases of the failure of a single active component are simulated and those cases are: i. a circulation pump trip, ii, loss of heat sink, and iii, unregulated cooling. Almost all the component failure cases, the duration it takes to reach some critical criteria are long enough for an orderly shut down of the system. The only unknown cases are the main and bypass electromagnetic pump trips, which are the subject of the CFD and structure mechanic studies.

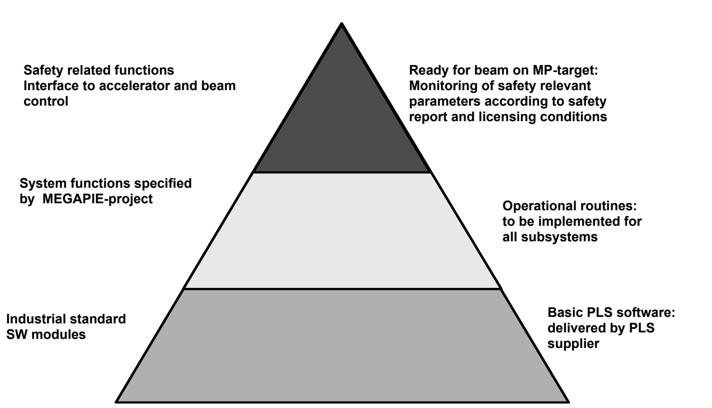
2.2 Control system of MEGAPIE: process control, protection functions and SINQ Integration (20')

H. Heyck

The MEGAPIE control system is reasoned in hierarchical (pyramidal) structure with basic component control functions at the bottom, the system routines and operational system control in the middle, and the alarm- and protection functions combined with the integration to the SINQ control system at the top. The overall requirement is to govern all operation and control processes necessary for a safe operation of the MEGAPIE liquid metal target. The specific requirements are manifold: Triggering and control of individual system components, automatic and/or operator assisted system operation based on operational flow charts, complying with fail-save principles, handling alarms and status messages, managing protection functions, interfacing the SINQ control system and 'ready-for-beam' message. Experimental data recording for off-line evaluation is a further issue.

The paper will resume the hierarchical structure of the sytem, the operational philosophy, operator interfaces, protection functions and the integration into the SINQ control system.

Control Hierarchy



2.3 Leak detection in the MEGAPIE target (20')

K. Thomsen

The integrity of the liquid metal container inside the MEGAPIE target is a mandatory prerequisite for operation and most important during irradiation at SINQ.

The containment of the liquid metal in the proper vessel has to be monitored continuously; a significant leak leads inevitably to the termination of the experiment. The leak detector has to work during all operational conditions of the target when there is liquid LBE in the LMC.

The top level basic requirements for leak detection in the Megapie target are:

- Sensitivity: < ½ Liter of LBE
- Response Time: < 1 Second
- High Reliability:
  - ~100% Detection Probability
  - Very Low False Alarm Rate

Any relevant leak must give a clearly detectable signal. This has to be true for a very wide range of conceivable leaks with very gradually developing slow dripping and "bleeding"on one end of the scale and a "shock leak"due to massive rupture of the LMC on the other. Although the target window is the most critical area any leak must be assumed to possibly occur anywhere along the LMC.

The false alarm rate has to be as low as achievable while staying sensitive enough for real leaks. If the detector does produce a false alarm, i.e. one not caused by actual leaking metal, this is at the most allowed to be of transitory nature only: the system has to be self-resetting or resettable after false alarms. In any case, after switch-off of the beam due to a leak alarm it must be possible to determine indubitably whether a real leak has occurred or not.

Boundary conditions pose very severe limitations on any MEGAPIE leak detector with respect to radiation level, available space and operational temperature. Large temperature variations in the sensors proper are expected due to sharp transients in beam heating, especially when switching from full to zero beam power.

As a result of preliminary development efforts both at Subatech and PSI it has been decided to select the concept of a compound leak detection system comprising:

- Thermocouples (9 individual and independent sensors, 3 of them pre-heated) as the main leak sensor
- Stripe sensors with impedance read-out (3 separate units) as secondary instrumentation

The actual status of the development of the sensors proper and of the dedicated measurement electronics will be reported as well as preliminary experimental results. Further steps planned for the timely qualification and implementation of this redundant and diverse leak detection system will be presented.

2.4 Beam monitoring for MEGAPIE (20')

K. Thomsen

A correct intensity distribution in the incident beam is of highest importance for the MEGAPIE liquid metal spallation target at PSI.

At PSI, the spallation target inside SINQ sits at the far end of the proton beam line. Of special importance for SINQ is Target E, where muons are produced. During normal operation the proton beam is scattered in Target E leading to a wide intensity distribution on the SINQ target with a FWHM in the order of 7 cm. If for any reason the protons were not scattered in Target E their footprint on the SINQ target would shrink to a FWHM of less than 2 cm. Detailed simulations yield a rise in the maximum intensity of the incident beam by a factor of 25. At the corresponding current density of 500 $\mu A/cm^2 mA$ it would take only 170 ms until a hole is burned through both the liquid metal container inside the target and the lower target enclosure, with the liquid metal spilling into the beam line and the catcher vertically below the SINQ target. This constitutes a most severe accident scenario for MEGAPIE.

In order to prevent an insufficiently scattered beam from reaching SINQ three independent safety systems are in place: an improved current monitor, a new collimator and VIMOS. All these systems have to meet the basic requirement to switch off the beam within 100 ms when 10 % of the protons by-pass Target E (corresponding to an increase in peak intensity by a factor of two).

VIMOS is a novel optical system; it will be in the focus of the presentation as it is the most innovative approach implemented. At PSI there already exists a lot of relevant experience concerning collimators and current measurement.
VIMOS works by optically monitoring the glowing of a screen positioned closely in front of the SINQ target. Any local increase of the intensity of the incident protons results in a fast change of the temperature distribution over the foil. Non-scattered protons preferably hit a spot close to the center and heat this strongly, at the same time the intensity towards the rim is reduced. Thus the center glows more brightly while the outer region cools down.
VIMOS hardware comprises a large focusing collecting mirror, a radiation resistant camera, and a dedicated frame grabber sitting inside a powerful PC. Dedicated data acquisition and image analysis software guarantees a timely response while minimizing the false alarm rate.
Among the safety installations which make sure that only properly scattered protons reach the SINQ target and in particular the liquid-metal MEGAPIE target, VIMOS is in a special position. It derives its full right to exist from the fact that it sits closest to the target and watches out for the most relevant quantity: overheating of a spot by the incident beam. VIMOS is equally effective against both technical and human errors. As this system is a very “direct"one, i.e. a simple installation delivers an easy to interpret picture and there are not many complicated measurement devices and data processing steps involved, it is expected to be also very robust.
Already during its commissioning phase VIMOS demonstrated its ability to detect potential harmful distortions in the beam footprint.
Data from the commissioning phase of all three new or upgraded systems (collimator, VIMOS and current monitor, respectively) will be presented.

2.5 Discussion (20')

Session 3: Thermal hydraulics and structure mechanics
Chaired by J. Haines

3.1 Validation of the CFX-4 CFD code for heat transfer to liquid metal in a curved geometry, and CFD simulation of the MEGAPIE lower target (20')
T. Dury

The Accompanying Measures EU Project ASCLIM was carried out during 2002 to assess the present knowledge of thermal hydraulics for liquid metals. A number of experiments were also simulated to validate turbulence models and advection schemes associated with CFD codes. The SINQ HETSS experiment performed at IPUL was one such experiment, and examined the heat transfer process between flowing mercury and a heated surface in a target geometry representative of Megapie. CFD support for the lower region of the Megapie target has so far been assisted by a very limited amount of experimental validation data. Consequently, these SINQ HETSS experiments provide relevant and useful data.

Conclusions have been drawn regarding the best turbulence models to use for Megapie simulations, and the degree of mesh refinement needed, and new calculations have been performed based on a CATIA CAD model of the exact target geometry. The model contains the Fill and Drain tubes, as well as the bypass feed duct. Account has been taken of the change of dimensions resulting from thermal expansion of components during operation.

3.2 Turbulent momentum transfer in the MEGAPIE target shell (20')
R. Stieglitz

The velocity distribution and its stability close to the highly heat loaded region of the beam window in Megapie plays a decisive role in the reliability and operation threshold of the target. Due to the complexity of the geometry, and the limited available HLM velocity measurement technologies, a set of water experiments in similar geometry as that of the Megapie design have been performed, which allows the use of optical and acoustic methods.

Both the Laser Light Sheet imaging and LDA measurements have revealed the presence of complex multi-stream and multi-vortex patterns, especially in the region close to the window. Although the flow is stable and steady in the annular gap, the abrupt change in cross sectional area and flow direction at the lower end of the riser tube causes a one order of magnitude increase in the fluctuation intensities for all velocity components. Additionally, the UDV measurements show that the plane $\phi=90°$ (cross-wise to the line of the guide tube slant) is more affected than the plane $\phi=0°$ (in line with the slant) The introduction of the super-imposed jet flow from the bypass alters the flow pattern only in the immediate vicinity of the window. But, already for z/R=1.9, the differences between both cases is more of a quantitative than qualitative nature.

3.3 Turbulent energy transfer in the MEGAPIE target shell (20')
R. Stieglitz

The heated jet experiment, conducted in the THEADES loop of the KALLA laboratory, was a 1:1 representation of the lower part of the Megapie target, and aimed to study the cooling capability of this specific geometry. A heated jet was injected into the cold main stream at Megapie-relevant flow rate ratios. The resulting temperatures were recorded in the densely instrumented critical lower plenum region. The experiment was accompanied by a three-dimensional turbulent CFD simulation. As well as a detailed study of the reference main/bypass flow combination, other flow rate ratios were investigated, in order to provide estimates of the stable operation limits.

All flow rate ratios investigated exhibited an unstable time-dependent behaviour. The design is highly sensitive to changes of Q_{main}/Q_{jet} and in the scope of this experimental study three completely different flow patterns were identified. Based on this experimental study, it appears that adequate cooling of the Megapie target is only ensured if $Q_{main}/Q_{jet}\leq 11.1$, because for this configuration the jet covers the whole window. Although, compared to the other cases, $Q_{main}/Q_{jet}\leq 11.1$ is more unstable, most of the fluctuations close to the centreline are in the high frequency range (>1Hz), so that they will not lead to severe temperature fluctuations in the window material. Also, good thermal mixing occurred at a height

of 363mm in the riser. As a consequence, for this operational mode, the smallest thermal stresses can be expected for the upper target structures.
For flow rate ratios larger than 11.1, complex flow patterns, consisting of several fluid streaks and vortices, were identified during spatio-temporal analysis of the data. To maintain adequate cooling of the target, such flow rate combinations should be avoided.
Although much effort has been spent in simulating the turbulent flow in the Megapie geometry for a chosen reference case, a comparison of the numerical and experimental data revealed that the geometry is highly sensitive to asymmetries, as well as on events far upstream. Hence, the simulation predicts higher temperatures close to the window than seen in the experiment. Additionally, the mixing behaviour in the riser tube is considerably underestimated by the simulation. A time-dependent solution, as observed in the experiment, could not be achieved.

3.4 First results of the KILOPIE-2 pre-experiment (20')

J. Patorski

The goal of the KILOPIE Experiment series is a determination of absolute values of Heat Transfer Coefficient (HTC) and HTC distribution over the area of the MEGAPIE target proton beam entry window. The first two series of KILOPIE-2 Pre-Experiment have been performed in Mai 2005 at PSI LBE Double-Loop for the initial clarification of some open questions of KILOPIE-1 series (2004). The two new specimen dishes with improved low pressure plasma sprayed (LPPS) ceramic insulation layer and epoxy glued heating foil layer have been used for two different Lead Bismuth Eutectic (LBE) flow geometries. The first series of the KILOPIE-2 Pre-Experiments has used/repeated the KILOPIE-1 reference jet nozzle geometry, i.e. rectangular shape 20x10 mm and outlet tangential to inner hemispherical surface of the target window. The second series of the KILOPIE-2 Pre-Experiment has used the new lifted-up jet nozzle position, with 12 mm free space below the jet outlet axis, the outlet had the same rectangular geometrical shape as in the first series.
The in both series used multi layers “sandwich” wall dishes have been very careful and accurate calibrated related the thermal resistance (TR) for the heat flux through the wall. The knowledge of TR distribution of the heated area of specimen dish has a fundamental relevance in non contact Infrared Thermography (IRT) measured techniques used for two dimensional and dynamic (2-DD) determination of inner surface temperature field of the window, which is consequently necessary for determination of HTC values.
The results obtain for first series with the reference tangential jet nozzle showing the predominant role of the by-pass (BP) jet flow for a good cooling of the window. The central area of the window, even in presence of main pump (MP) driven flow on the low level of 1.0 l/s for the small flow rate of BP=0.1 l/s the HTC amount 15000 W/(Km^2) and for BP=0.4 l/s the HTC amount 25000 W/(Km^2). These values are conforming to results of TC-KILOPIE-1 Experiment, previous experiments with mercury in Institute of Physics of University of Latvia (IPUL) and CFD calculations.
The results obtain for second series with lifted-up jet nozzle are approximately 3 times lower and laying in range from 5000 to 8000 W/(Km^2).
During the KILOPIE-2 Pre-Experiment the absolute value of TR determined in area of a homogenous thickness of glue layer, through thermo couple (TC) temperature measurement of inner surface of the window, has confirmed the laboratory determinate values of TR, which amount in range of 90-120 mm^{2}K/W.
Even not the best homogeneity of the glue layer the 2-D evaluation of the IRT measurement data will allow calculating the distribution field of HTC and the dynamic behaviour of the cooling on approximately 80 % of the dish area..
The works on the high heat flux density specimen dish are continued and the next series of KILOPIE-2 Pre Experiment at PSI LBE Double Loop are foreseen.

3.5 Synthesis, technical assessment (20')

B .Smith

3.6 Discussion (20')

Session 4: Liquid metal technology

Chaired by J. Haines

4.1 Review of the oxygen control for the initial operations and integral tests (20')

J. L. Courouau

The use of liquid metal such as lead alloys is known to require specific procedure and very special care for start-up operation of any facility. The main concern during initial filling, transfer and integral testing operation is related to the presence of an excess of oxygen, eventually leading to solid lead oxides accumulation that may be able to cause hydraulics perturbation and even potentially plugging of the narrowed sections. As no definitive chemistry control systems were available at the time of the design, none will be implemented. However, design and operation was planned to be conducted safely as regards the chemistry control by passive system and efficient operating procedures. As various feedbacks and know-how are available since then, and as the plugging of the target by an unexpected oxide accumulation would be critical to recover from, the review of the operations was launched. Its objective was to detect any potential critical points and to make any recommendation in agreement with the design and construction constraints, in order to increase the overall confidence of the start-up operation.

To that purpose, the analysis of the various pollution sources of the system, identification and rate assessment is first presented and discussed. Then, critical point were identified and analysed in order to ensure the effective management of the operations with the maximum reliability. The analysis led to recommendation at 3 levels: strict operating procedures to limit the pollution source to the minimum achievable (melting, venting-out and transfer), slight component modification or passive system implementation (filters in transfer lines, demister in vessels), and monitoring system implementation for early detection of unexpected events (air inlet).

Only slight modifications were strictly required, which allow considering that the target will be operated safely during the integral tests, and will start the on-beam operation required oxygen specification.

4.2 LBE interaction with water (20')

P. Agostini

The purpose of the code calculations of LBE-water interaction in Megapie, is to analyze the occurrence of steam explosion and/or other sudden pressurizations occurring in the first few seconds. The long time pressurization which could arise after the thermal equalization will be faced by the rupture disk of the target head.

Different boundary conditions are discussed and examined considering that the phenomenon is affected by:

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

The results of calculations by codes which treat complicate mixing conditions among different phases (water, steam, liquid LBE, solid LBE) and the subsequent heat and mass transfers are reported and discussed.

4.3 Synthesis of liquid metal technology (20')

P. Agostini

The MEGAPIE Target for the SINQ Spallation Neutron Source is based on a single material (Lead Bismuth Eutectic) having the double function to generate neutrons when it is hit by accelerated protons and to remove the large amount of thermal energy released in the spallation process. From the neutronic point of view Lead and Bismuth show elevated atomic mass (respectively 207 and 209) which favours the neutron yield. A further advantage is their high transparency to thermal neutrons. From the thermal point of view the combination of low melting temperature and high boiling point allows the designers to have at their disposal a very large range of temperatures for technological applications. Further advantages of LBE are the thermal conductivity, which favours the thermal exchange, and the heat capacity, which contributes to smooth the temperature peaks. Several features of LBE define a limitation to its technological use, therefore they were treated thoroughly in the frame of the MEGAPIE Design Support Groups (X groups). They are mainly:

- Corrosivity (X7)
- Effects of impurities (X8)
- Low Prandtl number which prevents the easy forecast of thermal exchange coefficients (X4-X6)
- Expansion after freezing (X8)
- Production of Po210 and other fission volatile products (X8)

In the present work the issues of X8 including interaction with water, are synthetically described. Special attention is paid to the MEGAPIE operating conditions.

4.4 Discussion (20')

Session 5: Nuclear assessment
Chaired by T. Broome

5.1 Behaviour of nuclear reaction products in MEGAPIE (20')
J. Neuhausen

The behaviour of nuclear reaction products within the MEGAPIE target, including target and construction materials, is discussed from a physicochemical point of view. Special emphasis is given to the behaviour of the volatile elements I, Hg, Tl and Po. Results of both theoretical and experimental investigations are given and conclusions for the release in case of accident scenarios are given. The efficiency of noble metal absorbers for the fixation of mercury within the expansion tank is discussed based on vapour pressure data as well as experimental results.
The stability of binary metal polonides compounds is evaluated using the semi-empirical Miedema model.

Thermodynamic data for polonium and some of its compounds (PbPo, BiPo, H_2Po) are derived in an extrapolative manner based on the periodicity within the chalcogen group. Thermodynamical equilibrium constants for release reactions have been evaluated for the systems Pb/Bi/O/H/X (X=F, Cl, Br, I) and Pb/Bi/H/O/Po. According to these evaluations no large concentrations of radioactive iodine and polonium containing species are expected to occur in the gas phase over liquid LBE under equilibrium conditions. The formation of lead and bismuth polonide as well as polonium hydride is discussed.
Experimental investigations on the temperature dependence of the release of I, Hg, Tl, and the chalcogens Se, Te and Po from liquid LBE under a continuous gas flow are presented. Among these elements, only mercury shows a pronounced tendency to be released from liquid LBE at temperatures relevant for MEGAPIE. However, mercury release is strongly influenced by gas atmosphere. Under an oxygen containing gas atmosphere release is significantly decreased compared to a reducing atmosphere (Ar/H_2). This fact is of importance with respect to accident scenarios.
The expected behaviour of mercury within a closed system such as the expansion tank of the MEGAPIE target is evaluated using vapour pressure data, thermodynamic activity coefficients and Raoult's law. As a result of these evaluations, the vapour pressure of Hg above a highly dilute solution in LBE (mole fraction $\approx 2.5*10^{-5}$ for a proton irradiation of 6.72 Ah) is expected to be very low (about 0.5 Pa). Under these conditions, the functionality of the proposed noble metal absorber is questionable. Indeed, laboratory scale experiments equilibrating suitable amounts of LBE, mercury and noble metals (Ag, Au, Pd, Pt) in evacuated quartz tubes show that most of the mercury is taken up by LBE and not by the noble metal, whereas in samples without the presence of LBE about 99% of the mercury is absorbed in the noble metals.
Formation enthalpies of metal polonides calculated using the Miedema model show that the most stable polonides are formed by alkaline earth and lanthanide metals. However, these metals show an even stronger affinity to oxygen. Therefore, these metals are expected to react with oxygen present in the system as an impurity of LBE or oxide layers of the construction materials rather than forming polonides. Thus, no retention of Po resulting from the formation of such oxides is expected.

5.2 Evaporation behavior of Po and other elements from liquid Pb-Bi (20')
Y. Kurata

Results of evaporation experiments of Po and other elements from liquid Pb-Bi are presented. Firstly, the evaporation experiment of lead-bismuth eutectic(LBE) was performed using the transpiration method to acquire fundamental data of the transfer behavior of LBE from liquid to gas phase. Pure argon was used as a carrier gas and the temperature range of the experiments was from 450°C to 750°C. The evaporation experiment of tellurium in LBE pool was conducted. Furthermore, the evaporation experiment of non-radioactive cesium in LBE pool was conducted because cesium was volatile and one of important elements from a viewpoint of safety estimation. The LBE vapor pressure equation and the gas-liquid equilibrium partition coefficients for tellurium and cesium were obtained from these experiments. In order to perform the evaporation experiments of Po, Po-210 was produced by neutron irradiation of LBE using Japan Materials Testing Reactor(JMTR) at JAERI. Not only polonium contents produced by the irradiation were calculated from neutron fluence and cross section but also measured by the chemical analysis of irradiated samples. The α-liquid scintillation method was employed for measuring Po-210. Good agreement between analyzed and calculated values was obtained and the ratio of analyzed value to calculated one was from 0.86 to 0.93. Po-210, Pb and Bi evaporated during the evaporation experiment of irradiated LBE were collected and analyzed. On the basis of the evaporation experiment the gas-liquid equilibrium partition coefficients for polonium were obtained. Values of the gas-liquid equilibrium partition coefficients for polonium were from 400 to 100 at 450°C to 750°C and an equation describing the temperature dependence was formulated.

5.3 Nuclear assessment: synthesis, technical assessment (30')

L. Zanini

The neutronic and nuclear assessment task took care of essential aspects of the project, including the study of target performance, power deposition, radiation damage, isotope production, shielding design, and calculations for the target disposal. The work consisted mainly in calculations and the main tools used were Monte Carlo codes. A summary of the most relevant achievements is presented. Results from the benchmarks of the Monte Carlo codes performed at the beginning of the project are also discussed.

Experimental work performed in support of the topic of isotope production, and in particular of stable and radioactive volatile elements, is also summarized. This topic was considered on particular importance in the frame of the licensing process. In addition to the other studies presented in the session, an experiment was carried out at CERN-ISOLDE in two separate runs during 2004, consisting in the measurement of the production and release of volatile elements (He, Ne, Ar, Kr, Xe, I, Cd, Hg, Po, At) in a proton irradiated Pb/Bi target. More results with respect to the preliminary ones presented at the Technical Review Meeting in 2004 are shown. These results are in good agreement with the predictions from the Monte Carlo codes FLUKA and MCNPX, and therefore offer an additional validation of these two codes which were used for the calculations in MEGAPIE.

5.4 Discussion (20')

Session 6: Irradiated target handling

Chaired by T. Broome

6.1 Control LBE freezing at the end of irradiation test (20')

W. Leung

The objective of this study is to find a safe way to freeze up the LBE (Lead-Bismuth Eutectic) in the target after the irradiation test in SINQ. It is well known that freshly solidified LBE expanses due to the re-crystallization process. This solid expansion may impose a high stress on the out container. Based on the FEM analysis, the expansion stress is high enough to deform or even rupture the beam window and the lower container. Since the beam window is the focal point of the Post Irradiation Experiment (PIE), it is necessary to find a way to mitigate this expansion stress. It has been found that the expansion stress can be reduced greatly if the cooling rate is kept below 0.02 °C/min. To achieve such a low cooling rate, the heat loss in the lower target must be regulated to ~32 W, but the real heat loss to the safety hull is roughly 1 kW for the cooling heavy water running in nominal conditions (i.e. 2.2 kg/s in 40 °C inlet). Since there is no heating to compensate in the heat loss in the active zone (from the beam window to the start of the central rod), the only way to regulate it is to raise the heavy water temperature in the safety hull. The suggested procedures are as the follows:

- Use the bypass EMP to lower temperature of the target gradually till all flow path is blocked,
- Stop the heavy water flow in the Safety Hull and let the heavy water heated up by the lower target in the mean time,
- Stop the bypass pump, but using the EMP system and the THX to keep the LBE in the upper target in liquid state,
- Low the heavy water temperature in one of these ways:
  - bleed in small amount of cold water periodically, or
  - keep a small flow, i.e. 7~8 ml/s,
- Repeating the previous step till the target reach room temperature.

This step is repeated again and again till the LBE reaches to room temperature.

6.2 Target dismantling and waste disposal (20')

A. Strinning

For the permission to operate the Megapie Target, official licensing of the handling of the activated target is required. The main steps of the works in the post irradiation phase are:

Transfer of the target to the target storage after solidification of the lead bismuth at the end of the operation phase. After a certain cooling time, transport of the target to the hot cells at ZWILAG and at PSI-East, where the inspections, the dismantling, the extraction of samples and finally the conditioning of the activated target will be made. At the end a waste package meeting the requirements of the final repository has to be provided.

The transports on the road (between PSI and ZWILAG) need special grants since a part of the requirements cannot be fulfilled.

An overview of the handlings and a status of the work to achieve a practicable and suitable method for the dismantling and the conditioning of the target are given.

6.3 The optimum and minimum PIE plans of the MEGAPIE target (20')

Y. Dai

MEGAPIE will be the first opportunity to examine a liquid Pb-Bi eutectic (LBE) spallation target of power at 1 MW level. The peak proton fluence at the window will be about 3×10^{25} p/m^2 after six-months of operation at SINQ. With the additional contribution of neutrons, the maximum irradiation damage level in the window material (T91 steel) will be about 12 dpa. The results of the PIE on this heavily irradiated and LBE corroded window are very important to the safety study of the future ADS systems. Of course, the PIE results from other parts of the target which are also in contact with LBE with or without heavy irradiation are essential as well, because these components will be in different irradiation and corrosion conditions which are similar to those of some components in ADS.

The proposed PIE program has an objective to study the irradiation effects and irradiation assisted corrosion and embrittlement effects of LBE in the beam window, flow guide tube and other components, which will be assessed by detailed microstructural examinations, chemical analysis, and mechanical tests. In addition, the PIE program also includes non-destructive-testing (NDT) to inspect the macro damages and dimensional changes in the lower part of the target. In this presentation, as required by project management, options for optimum PIE and minimum PIE plans will be described and the progress in the NDT will be reported.

6.4 Discussion (20')

Session 7: Safety and licensing issues

Chaired by M. Salvatores

7.1 Safety and licensing issues (20')

A. Janett

The formal license of BAG (Swiss Federal Office of Public Health) for the construction and operation of the MEGAPIE target system (dated Oct. 11th 04) contains a total of 52 conditions which have to be fulfilled before starting up the target system with proton irradiation and their implementation has to be accepted from BAG. These conditions – arranged in 5 groups of topics – should guarantee, that a severe accident can be excluded with a high probability and that the reference accident (postulated in condition number 48) do not lead to an exceeding of the dose limit for the population in the vicinity of PSI. The 5 required clearances (milestones) concern

- the HRS
- the CGS
- the decommissioning, transport and disposal of the target system
- the inactive as well as
- the active starting up of the MEGAPIE target system.

We will present the actual state of the dealing with these conditions particularly those that need most effort because of their complexity like

- the reduction of the source term of radioactive release including the sealing of TKE and STK and the inertisation of those or
- the licensing for transportation and safe disposal of radioactive waste in collaboration with ZWILAG (Intermediated Storage Site) and Nagra (National Cooperative for the Disposal of Radioactive Waste).

In addition we would like to remind all the participants of the lessons learned in the past, namely that we can keep the time schedule only if we attach great importance to the

- interface management between the suppliers, the responsible persons of the project and the licensing authorities as well as to the
- Total Quality Management including the updated documents of the FSAR.

7.2 MEGAPIE quality assurance system and implementation (20')

P. Ming

To have an adequate QA system for the project Megapie is a challenge. It has to ensure that all critical systems, most of them never built before, have to meet the overall goal: "Having a safe and functioning liquid metal target in the one Megawatt region". The paper describes the concept of the chosen QA-system and the thinking behind it for the following systems:

- EMP Electromagnetic Pump
- LMT Liquid Metal Target
- CGS Cover Gas System

Furthermore it is shown how the theoretical QA requirements have been transformed into reality, the impact they had to the project and which lessons have been learned for the future.

7.3 LTE design, stress calculations and accident containment (20')

K. Samec

The Megapie target is enclosed within an aluminium containment hull cooled in it's lower half by heavy water.

This Lower Target Enclosure or LTE has been optimised to offer the least resistance to the neutron flux whilst withstanding and containing the effects of an eventual catastrophic failure of the target.

The safety analyses of the LTE are presented in the event of various accident scenarios. Predictions are also made for an upcoming test which will be representative of an accidental leak of LBE into the containment hull. The goal of the test is to validate the design of the hull and also to give full confidence in the analysis tools used to justify the LTE design

7.4 Assessment of the reference accident case (20')

F. Groeschel

For the MEGAPIE experiment, the Swiss authorities have defined an all encompassing reference accident, which postulates

- The breach of the target containers and outflow of the LBE, Diphyl THT oil and cooling water into the beam transport compartment
- The destruction of the moderator tank and outflow of the heavy water
- The ignition of the oil
- The destruction of the target creating a communication between the beam transport and the target enclosure compartments.

Licensing of the experiments will require demonstrating that such an accident can be contained and the dose limits for the public will not be exceeded. The case is aggravated by the assumption that the outer barrier will be breached; e.g. due to a pipe break, since the penetration in this barrier are not protected by automatic shut-off systems. Although the authorities may accept a dose limit of 20 mSv to the public, PSI imposes that a limit of 1 mSv has to be respected as stated in the law.

The assessment of the accident case deals with the

- Risk of oil fire and corresponding countermeasures
- Definition of the source terms for the radioactive gases and volatiles
- Describe the transport of these volatiles to the leak in the outer barrier

Using the standard PSI release code, the dose to the public is calculated.

7.5 Discusssion (20')

Session 8: Solid-liquid interface

Chaired by H. Ravn

8.1 Corrosion behaviour of T91 and 316L in LBE at MEGAPIE relevant conditions (20')

A. Terlain

In this paper, some corrosion results of AISI 316L and T91 steels obtained in flowing lead-bismuth eutectic (LBE) between 400°C and 470°C mainly in the LECOR (**Le**ad **cor**rosion) loop and in CICLAD device (equipped with rotating specimen) with low oxygen activity in LBE are discussed in order to give a statement about the "normal"corrosion behaviour of T91 and 316L in LBE at Megapie relevant conditions.

The results show that, in the presence of Pb-Bi, the austenitic steel AISI 316L is affected by the preferential dissolution of Ni and Cr. The growth of a ferritic layer at the surface is observed.

Under the same conditions the martensitic steel T91 is affected by a uniform corrosion and no preferential dissolution is detected. The limiting step of the T91 dissolution process could be the iron diffusion in the liquid diffusion boundary layer. Therefore, the T91 dissolution rate depends on the hydrodynamics of the Pb-Bi flow.

The test results also show that the corrosion of the steels is very dependent on the native oxide layer which is present at the beginning of the tests.

Based on the experimental results, and assuming a 1 m s^{-1} liquid velocity , the corrosion rate of T91 in MEGAPIE could be between 40 and 130 µm.yr^{-1} depending on the oxygen concentration in the LBE (below or above the oxygen content corresponding to the chromia formation.

However, to ascertain these values, other experimental data would be necessary to take into account the effect of other parameters like the surface state and in particular the presence of an initial oxide layer.

8.2 LME and fatigue of T91 steel in LBE: a review (40')

T. Auger

The MEGAPIE target will operate between 230 and 360°C at low stresses with flowing LBE (flow velocity less than 0.5m.s-1). Liquid Metal Embrittlement (LME) of T91 in LBE has been investigated in order to understand the relevance of this concern with regard to MEGAPIE. This talk will review all the experimental evidences accumulated since the beginning of the project.

The conditions necessary for triggering embrittlement will be presented: the influence of the oxide layer, the influence of metallurgical state and the influence of stress concentration. A comparison will be made with the expected MEGAPIE corrosion behavior in order to derive what could be the detrimental regimes.

Fatigue experiments performed with T91 and 316L in LBE at MEGAPIE relevant temperature will be reviewed. According to the results of low cycle fatigue tests conducted on smooth specimens and to the results of fatigue crack propagation carried out on pre-cracked specimens, it is possible to draw the critical limit of use of T91 from a fatigue point of view. No such critical limit is envisioned for 316L.

The status of rupture mechanics experiments underway at various institutes will be presented.

8.4 X7 conclusion (20')

J. Konys

8.5 Discussion (20')

Session 9: Materials and radiation damage

Chaired by H. Ravn

9.1 LiSoR experiments: Overview and relevant results for MEGAPIE (30')

H. Glasbrenner

Martensitic steel T91 will be used for the liquid lead bismuth eutectic (LBE) container and the beam entrance window of the MEGAPIE target. The irradiation assisted LBE corrosion and embrittlement effects on the behaviours of T91 steel have been studied by performing the LiSoR (liquid-solid reaction under irradiation) experiments, where T91 steel was irradiated with 72 MeV protons to doses up to about 1.0 dpa at temperatures above 300 °C in flowing LBE with or without mechanical stress. Up to now 5 LiSoR test sections have been irradiated. After each irradiation cycle the test section was disconnected from the loop and transported into a hot cell for dissembling and examination. Samples were cut out of the specimen and the tube acting as beam window by EDM wire cutting in a hot cell. SEM/EDX and SIMS analyses were performed on the irradiated area and the area next to it.

The results of the SEM analyses on two samples taken from the LiSoR-3 specimen (irradiated and beside the irradiated zone) did not show any difference. Solidified LBE was detected on some areas of the samples but no wetting of the steel or penetration of LBE into the steel matrix was observed. X-ray mapping revealed oxygen enrichment on top of the surface which is related to a thin oxide layer preventing wetting of the steel. No enrichment or dissolution of steel elements such as Fe and Cr could be detected on the surface near area. The steel surface is still smooth without any indications of corrosion attack. These results are in agreement with the SIMS analyses. Protecting oxide scale is revealed on the steel surface which consists of a magnetite layer on top and an intermediate of iron chromium spinel. The total thickness is between 500 and 600 nm.

Tensile tests on the samples irradiated to 0.2 dpa have been performed in both Ar and LBE environments. The results of the tests in Ar show a slightly hardening and ductility reduction of the material, which should be attributed to irradiation. The irradiation assisted liquid metal embrittlement (LME) due to the exposure to LBE effects is not evident. On the other hand, the tests in LBE (oxygen saturated) indicate a large degradation in ductility which is similar to that observed from unirradiated T91 tested in the same LBE environments. Hence up to now a correlation between irradiation and LME cannot be fully confirmed. The transmission electron microscopy investigations on the irradiated samples demonstrate the typical micro structure of martensitic steels after irradiation, which can well explain the tensile test results.

9.2 Lifetime assessment of structural materials for the MEGAPIE target (30')

Y. Dai

In the MEGAPIE target, basically only three kinds of structural materials will be used for different components: 1) $AlMg_3$ alloy for the safety container; 2) martensitic steel T91 steel for the liquid lead-bismuth eutectic (LBE) container and 3) AISI 316-type stainless steel for almost all the rest components. The performance of these materials is of great concern for a safe operation of the target, particularly that of the T91 steel. In the proton beam entry window area of the LBE container, it will be subjected to intensive proton and neutron irradiation, potential LBE corrosion and embrittlement and mechanical loads. The previous studies [1,2] demonstrate that the LBE corrosion effects will not be a lifetime-limit factor because the corrosion effects are not significant in normal operation condition where the temperature at the inner surface of the window ranges from 230 to about 320°C. The radiation effects can be a lifetime limit factor because the irradiation induced embrittlement effects will be very pronounced and the ductile-brittle transition temperature (DBTT) of the T91 steel will increase to the lowest operation temperature at about 9 dpa [1]. However, a modeling using linear elastic fracture mechanics indicates that the stress intensity at this low stress level (<50 MPa) is only 10 MPa $m^{1/2}$ in such thin structures for an almost penetrating crack [2]. The critical fracture toughness of unirradiated and neutron irradiated T91 steeel is much higher than this value.. But for definite lifetime limit assessment proper toughness data for p/n irradiated and in contact with LBE are needed. In the present report, a definitive assessment will be made based on the new experimental data obtained from the STIP irradiation experiments at PSI and liquid metal embrittlement experiments in other European laboratories. In addition, the behavior of the SS 316L and $AlMg_3$ will be also discussed.

9.3 X10 conclusion (20')

Y. Dai

9.4 Discussion (20')

Session 10: Synthesis

Chaired by F. Groeschel

10.1 Discussion and recommendations (25')

all

10.2 MEGAPIE TRM2005 synthesis and perspectives (25')

C. Latgé

Overview MEGAPIE meetings

	Mo 27/06	Tue 28/06	We 29/06	Th 30/06	Fr 01/07
morning	TRM registration	TRM (audmain)	TRM (audmain)	LBE hndbk (sal1) SC (sal2) TAC (audibas)	LBE hndbk (sal1)
afternoon	TRM (audmain)	TRM (audmain)	TAC (sal2)	LBE hndbk (sal1)	
evening		TRM dinner	SC dinner		

audimain = main auditorium in clubhouse
audibas= smaller auditorium in clubhouse basement
sal1 = salon 1 in clubhouse
sal2 = salon 2 in clubhouse

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