

OECD/NEA

**Fourth International Workshop on Utilisation and
Reliability of High Power Proton Accelerators**

Programme & Abstracts

16-19 May 2004

**International Nuclear Training and Education Center (INTEC)
KAERI, Daejeon, Republic of Korea**

**Hosted by
Korea Atomic Energy Research Institute
under the auspices of the
OECD/NEA Nuclear Science Committee**

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Fourth International Workshop on Utilisation and
Reliability of High Power Proton Accelerators
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KAERI, Daejeon, Republic of Korea

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Final Programme

Sunday, 16 May 2004

Spapia Hotel

14:00 – 18:00 **Registration**
16:20 – 18:00 **Cocktail reception**

Monday, 17 May 2004

INTECT, KAERI

8:00 – 8:30 **Registration**

Welcome addresses

Woonam Auditorium

Chair: B. H. Choi (KAERI, Korea)

8:30 – 8:40 Dr. Chung-Won Cho (Director-General, Atomic Energy Bureau, Ministry of Science and Technology, Korea)

8:40 – 8:50 Dr. In-Soon Chang (President, KAERI, Korea)

8:50 – 9:00 Dr. Gail H. Marcus (Deputy Director-General, OECD/NEA)

General session: Accelerator programmes and applications

Woonam Auditorium

Chairs: B. H. Choi (KAERI, Korea) and R. Sheffield (LANL, USA)

9:00 – 9:30 Background/Perspective, T. Mukaiyama (JAIF, Japan)

9:30 – 10:00 ADS in Advanced Fuel Cycles, M. Salvatores (ANL-CEA, USA-France)

10:00 – 10:20 **Break**

10:20 – 10:50 Present Status of J-PARC Construction, S. Noguchi (KEK, Japan)

10:50 – 11:20 R&D of ADS in Japan, H. Takano (JAERI, Japan)

11:20 – 11:50 Los Alamos Perspective on High-Intensity Accelerators, R. W. Garnett (LANL, USA)

11:50 – 12:20 French Accelerator Research for ADS Development, J-M. Lagniel (CEA, France)

12:20 – 14:00 **Luncheon**

KAERI Guest Restaurant

General session: Accelerator programmes and applications (continued)

Woonam Auditorium

Chairs: B. H. Choi (KAERI, Korea) and R. Sheffield (LANL, USA)

14:00 – 14:30 HYPER Project, T. Y. Song (KAERI, Korea)

14:30 – 15:00 R&D on ADS in the EURATOM Fifth and Sixth Framework Programmes, V. Bhatnagar (EC)

15:00 – 15:30 Status of the TRADE Experiment, S. Monti (ENEA, Italy)

15:30 – 16:00 European XADS-PDS, P. D'hondt (SCK-CEN, Belgium)

16:00 – 16:20 **Break**

16:20 – 16:50 Status of the MEGAPIE Experiment, F. Groeschel (PSI, Switzerland)

16:50 – 17:20 ADS Reliability Activities in Europe, P. Pierini (INFN, Italy)

17:20 – 17:50 ADS Neutronics, W. Gudowski (RIT, Sweden)

17:50 – 18:20 ADS Safety, P. Coddington (PSI, Switzerland)

18:20 – 18:50 Technological aspects and challenges of HPPA for ADS application, Y. L. Cho (ANL, USA)

Tuesday, 18 May 2004

INTECT, KAERI

Technical Session I: Accelerator reliability

Woonam Auditorium

Chairs: A. Mueller (CNRS, France) and P. Pierini (INFN, Italy)

- 8:00 – 8:40 The PDS-XADS reference accelerator, D. Vandeplassche, et al. (IBA, Belgium)
- 8:40 – 9:00 Development of Superconducting Proton Linac for ADS, N. Ouchi, et al. (JAERI, KEK, MHI, MELCO, Japan)
- 9:00 – 9:20 Spoke cavities: an asset for high reliability of superconducting accelerator. Studies and test results of a $b=0.35$, 2 gap prototype and its power coupler at IPN Orsay, C. Miélot (IPN, France)
- 9:20 – 9:40 The Current Status of HPPA accelerator in China, X-L Guan (CIAE, China)
- 9:40 – 10:00 Beam Dynamics Studies for the Fault Tolerance Assessment of the PDS-XADS Linac Design, J. L. Biarrotte, et al. (IPN, CEA, France, INFN, Italy)
- 10:00 – 10:20 **Break**
- 10:20 – 10:40 High energy beam transport lines and delivery systems for intense proton beams, P. A. Schmelzbach, et al. (PSI, Switzerland)
- 10:40 – 11:00 Construction of FFAG Accelerator Complex for ADS Research in KURRI, M. Tanigaki, et al. (Kyoto Univ., Japan)
- 11:00 – 11:20 Improvement of reliability of the TRASCO intense proton source (TRIPS) at INFN-LNS, G. Ciavola, et al. (INFN, Italy)
- 11:20 – 11:40 An Improved Superconducting ADS Driver Linac Design, R. W. Garnett, et al. (LANL, USA)
- 11:40 – 12:00 Methods and Codes for Estimation of Tolerance in Reliable Radiation-Free High-Power Linac, A. P. Durkin, et al. (MRAS, Russia)
- 12:00 – 12:20 Status of the Spallation Neutron Source Accelerator Complex, S. Henderson (ORNL, SNS, USA)
- 12:00 – 12:20 **Luncheon** **KAERI Guest Restaurant**

Technical Session II: Target, window and coolant technology

Lecture Room 1

Chairs: X. Cheng (FZK, Germany) and T. Y. Song (KAERI, Korea)

- 8:00 – 8:20 Research and Development on Lead-Bismuth Technology for Accelerator Driven Transmutation System in JAERI, Y. Kurata, et al. (JAERI, Japan)
- 8:20 – 8:40 Vacuum gas dynamics investigation and experimental results on the TRASCO ADS windowless interface, P. Michelato, et al. (INFN, SAES, ENEA, ANSALDO, Italy)
- 8:40 – 9:00 Corrosion Tests in the Static Condition and Installation of Corrosion Loop at KAERI for Lead-Bismuth Eutectic, J. E. Cha, et al. (KAERI, Korea)
- 9:00 – 9:20 The Vacuum Interface Compatibility Experiment (VICE) Supporting the MYRRHA Windowless Target Design, P. Schuurmans, et al. (SCK-CEN, Belgium)
- 9:20 – 9:40 The Introduction of a Double-Annular Guide Tube for the Design of 20MW Lead-Bismuth Target System, C. H. Cho, et al. (KAERI, Korea)
- 10:00 – 10:20 **Break**
- 10:20 – 10:40 Design Study around Beam Window of ADS, H. Oigawa, et al. (JAERI, Japan)
- 10:40 – 11:00 MSDM Calculations of Primary Isotopic Yields From Proton-Induced Reaction on ^{208}Pb at Energy of 1 GeV, F. Sheng, et al. (CIAE, China)
- 11:00 – 11:20 CFD Analysis on the Active Part of Window Target Unit for LBE cooled XADS, N. I. Tak, et al. (FZK, Germany)
- 11:20 – 11:40 Optimization of a code to improve spallation yields predictions in a ADS target system, T. Sawada, et al. (TIT, Japan)
- 12:20 – 14:00 **Luncheon** **KAERI Guest Restaurant**

Tuesday, 18 May 2004

INTECT, KAERI

Technical Session III: *Sub-critical system design and ADS simulations*

Woonam Auditorium

Chairs: W. Gudowski (RIT, Sweden) and H. Oigawa (JAERI, Japan)

- 14:00 – 14:20 Research on Accelerator Driven Subcritical System at Kyoto University Critical Assembly (KUCA) with the FFAG Proton Accelerator, T. Misawa, et al. (Kyoto Univ., Japan)
- 14:20 – 14:40 Improvement of Burn-Up Swing for Accelerator-Driven System, K. Nishihara, et al. (JAERI, Japan)
- 14:40 – 15:00 Status of the conceptual design of accelerator and beam transport line for TRADE, L. Picardi, et al. (ENEA, Italy)
- 15:00 – 15:20 Estimation of some characteristics of cascade subcritical molten salt reactor (CSMSR), A. M. Degtyarev, et al. (KI, Russia)
- 15:20 – 15:40 CFD Analysis of the Heavy Liquid Metal Flow Field in the MYRRHA Pool, F. Roelofs, et al. (NRG, Netherlands, SCK-CEN, Belgium)
- 15:40 – 16:00 Results of the second phase of calculations relevant to the WPPT benchmark on beam interruptions, A. D'Angelo et al. (ENEA, Italy)
- 16:00 – 16:20 **Break**

Working Group Discussion on Accelerators

Woonam Auditorium

Chair: P. Sigg (PSI, Switzerland)

- 16:20 – 18:00 Discussion results to be reported at the Closing session

Tuesday, 18 May 2004

KAERI Guest restaurant

- 18:30 – 21:00 Banquet

Wednesday, 19 May 2004

INTECT, KAERI

Technical Session IV: *Safety and control of ADS*

Woonam Auditorium

Chairs: J-M. Lagniel (CEA, France) and P. Coddington (PSI, Switzerland)

- 8:00 – 8:20 Safety analysis of the EU-PDS-XADS designs, P. Coddington (PSI, Switzerland)
- 8:20 – 8:40 Comparative Transient Analyses of ADS with Conventional Fast Reactor Fuel and ADT with Advanced Fertile Free Fuel, X.-N. Chen, et al. (FZK, Germany)
- 8:40 – 9:00 Comparative transient analysis of Pb/Bi and Gas cooled XADS concepts, P. Coddington (PSI, Switzerland)
- 9:00 – 9:20 TALL Test Facility and Experimental Progress, B. R. Sehgal, et al. (RIT, Sweden)
- 9:20 – 9:40 Analysis of Lead-Bismuth Eutectic Flowing into Beam Duct, K. Nishihara, et al. (JAERI, Japan)
- 9:40 – 10:00 On the Supplementary Feedback Effect Specific for Accelerator Coupled Systems (ACS), P. Bokov, et al. (CEA, France)
- 10:00 – 10:20 k_{eff} and k_s burn up swing compensation in MYRRHA, W. Haeck, et al. (SCK-CEN, Belgium)
- 10:20 – 10:40 **Break**

Wednesday, 19 May 2004

INTECT, KAERI

Technical Session V: ADS experiments and test facilities

Woonam Auditorium

Chairs: P. D'hondt (SCK-CEN, Belgium) and V. Bhatnagar (EC)

- 10:40 – 11:00 Concept of Transmutation Experimental Facility, H. Oigawa, et al. (JAERI, Japan)
11:00 – 11:20 Core neutronics assessment for TRADE experiments, D. G. Naberezhnev, et al. (ANL, USA)
11:20 – 11:40 Application of the HYPER System to the DUPIC Fuel Cycle, Y. H. Kim, et al. (KAERI, Korea)
11:40 – 12:00 Numerical comparisons between neutronic characteristics of MUSE4 configurations and XADS-type models, M. Plaschy, et al. (PSI, Switzerland)
12:00 – 12:20 Reaction of Pb Bonding between Fuel and Cladding, B-S. Lee, et al. (KAERI, Korea)
12:20 – 12:40 Experimental Verification of Selected Transmutation Technology and Materials for Basic Components of a Demonstration Transmuter with Liquid Fuel based on Molten Fluorides, M. Hron, et al. (NRI, Czech Rep.)
12:40 – 14:20 **Luncheon**

KAERI Guest Restaurant

Working Group Discussion on Sub-critical Systems and Interface Engineering

Woonam Auditorium

Chair: W. Gudowski (RIT, Sweden)

- 14:20 – 16:00 Discussion results to be reported at the Closing session
16:00 – 16:20 **Break**

Working Group Discussion on Safety and Control of ADS

Lecture Room 1

Chair: P. Coddington (PSI, Switzerland)

- 14:20 – 16:00 Discussion results to be reported at the Closing session
16:00 – 16:20 **Break**

Closing Session: Technical session summary and Working group discussion summary

Woonam Auditorium

Chairs: R. Sheffield (LANL, USA) and B. H. Choi (KAERI, Korea)

- 16:20 – 18:00 Presentations of the chairs

Adjourn

General session:
Accelerator programmes and applications

Chairs: B.H. Choi (KAERI, Korea) and R. Sheffield (LANL, USA)

- *Background/Perspective*, T. Mukaiyama (JAIF, Japan)
- *ADS in Advanced Fuel Cycles*, M. Salvatores (ANL-CEA, USA-France)
- *Present Status of J-PARC Construction*, S. Noguchi (KEK, Japan)
- *R&D of ADS in Japan*, H. Takano (JAERI, Japan)
- *Los Alamos Perspective on High-Intensity Accelerators*, R. W. Garnett (LANL, USA)
- *French Accelerator Research for ADS Development*, J-M. Lagniel (CEA, France)
- *HYPER Project*, T. Y. Song (KAERI, Korea)
- *R&D on ADS in the EURATOM Fifth and Sixth Framework Programmes*, V. Bhatnagar (EC)
- *Status of the TRADE Experiment*, S. Monti (ENEA, Italy)
- *European XADS-PDS*, P. D'hondt (SCK-CEN, Belgium)
- *Status of the MEGAPIE Experiment*, F. Groeschel (PSI, Switzerland)
- *ADS Reliability Activities in Europe*, P. Pierini (INFN, Italy)
- *ADS Neutronics*, W. Gudowski (RIT, Sweden)
- *ADS Safety*, P. Coddington (PSI, Switzerland)
- *Technological aspects and challenges of HPPA for ADS application*, Y. L. Cho (ANL, USA)

Technical Session I:
Accelerator reliability

Chairs: A. Mueller (CNRS, France) and P. Pierini (INFN, Italy)

The PDS-XADS reference accelerator

Dirk Vandeplassche, Yves Jongen
for the PDS-XADS Working Package 3 Collaboration
Ion Beam Applications SA, Chemin du Cyclotron 3, B – 1348 Louvain-la-Neuve (Belgium)

The PDS-XADS accelerator is specified as a 600 MeV, 10 mA CW proton accelerator associated with its specific beam transport line. There is obviously a very strong emphasis on an extremely high reliability of the beam delivery, with a requirement of less than 5 unwanted beam trips per year lasting longer than 1 s.

The PDS-XADS project is supported by the European Commission within its 5th R&D Framework Programme. Working Package 3 is a collaboration between Belgium (IBA), France (CEA, CNRS, Framatome ANP), Germany (U. Frankfurt, FZ Juelich, Framatome ANP GmbH), Italy (INFN, ENEA, Ansaldo) and Portugal (ITN). WP3 is working out technical answers to the accelerator requirements, applying proven principles in an innovative way and continuously considering the highest reliability as a top priority.

The study has led to a reference design based on a linear superconducting accelerator which is rendered intrinsically fault tolerant. The linac consists of an injector (source and RFQ), a medium energy section which has the lowest possible initial energy, and a high energy section starting around 100 MeV and going up to final energy. Superconducting cavities will be used from as low an energy as achievable onwards (“spoke” cavities in the medium energy section, “elliptical” cavities in the high energy section). Taking advantage of a superconducting linac's modular build-up, the fault tolerance is obtained by the combination of proper beam-optical properties with novel high speed digital feed-back systems in the low level RF control. This allows a single module to fail without bringing the beam out of its specifications. In the low energy range and in that part of the medium energy range where this principle cannot be realised, fault tolerance is obtained by a full time hot spare.

The accelerator is connected to a doubly achromatic beam delivery line in order to obtain the maximum stability on target.

Besides by its intrinsic fault tolerance, the linac obtains a high reliability by using components well below their nominal ratings (increasing Mean Time Between Failures), and by a "repair-friendly" approach (reducing Mean Time To Repair). The latter involves both design principles (power converters, building layout) and radioprotection issues.

This design study is presently being pursued, and also its industrial realisation and its extrapolation towards higher performances are examined. The needs for the subsequent R&D program are identified.

Development of Superconducting Proton Linac for ADS

N. Ouchi, N. Akaoka, H. Asano, E. Chishiro, Y. Namekawa, H. Suzuki, T. Ueno, *JAERI*
S. Noguchi, E. Kako, N. Ohuchi, K. Saito, T. Shishido, K. Tsuchiya, *KEK*
K. Ohkubo, M. Matsuoka, K. Sennyu, *MHI*
T. Murai, T. Ohtani, C. Tsukishima, *MELCO*

ADS require a high intensity proton accelerator of which energy and beam power are about 1 GeV and 20-30 MW, respectively. JAERI, KEK, MHI and MELCO have conducted a program for the development of superconducting proton linac for the ADS since 2002. This program, which is based on the achievement of the J-PARC design work, consists of two parts, development of a 972MHz cryomodule and system design of a superconducting proton linac in the energy range between 0.1 and 1 GeV.

In the development work of the 972MHz cryomodule, a prototype cryomodule is in fabrication now. The cryomodule includes two 9-cell cavities of $\beta=0.725$ of which operating temperature is designed to be 2K. The goal of this work is stable operation in the horizontal tests at the surface peak field at 30 MV/m, which corresponds to the accelerating gradient of 10 MV/m. The cavities and the RF power couplers for the cryomodule have been already fabricated. Surface treatments and vertical tests of the cavities progress now. High power test of the power couplers will be done soon. The cryomodule will be assembled at JAERI until next February and horizontal test will be performed in 2004.

In the system design work, the beam dynamics design is in proceeding now in the energy range between 0.1 to 1 GeV. The conditions of the design are frequency of 972MHz, 9-cell elliptical cavity, 2 cavities in a cryomodule, room temperature focusing magnet between cryomodules, synchronous phase angle of -30 deg. and the phase slip in the cavity is less than ± 30 deg. In the preliminary design results, the number of beta family of the cavity is 3, total number of the cavity is about 200 and the total length of the superconducting linac is about 500m.

More details for the prototype cryomodule development and the beam dynamics design will be presented at the workshop.

**Spoke cavities : an asset for high reliability of superconducting accelerator.
Studies and test results of a $\beta=0.35$, 2 gap prototype and its power coupler at IPN Orsay**

C. Miélot
IPN, France

The spoke cavity tested at IPN Orsay, has been realized in the framework of 2 European projects : the EURISOL project (European Isotope On Line facility) and the XADS preliminary design study (eXperimental Accelerator Driven System). The XADS will be made of a high power proton accelerator linked to a sub-critical nuclear reactor through a spallation target. One of the main challenge concerning the accelerator requirements is the very high reliability needed. To meet this goal, superconducting spoke cavities are especially foreseen in the intermediate energy part of the accelerator. As they can be fed by separated power sources and so, as it is possible for the whole accelerator to compensate the breakdown of one cavity, they can make the superconducting accelerator completely fault tolerant.

One prototype of $\beta=0.35$ spoke cavity (named AMANDA) has been designed and tested in a vertical cryostat at IPN Orsay and fabricated by CERCA. The very encouraging results (i.e. accelerating field =12.5 MV/m) are far beyond the project requirements and give safety margins.

On the other hand, numerical simulations have been done on the cavity and on the power coupler. The main goals of these studies are to find the correct position of the coupling port, to do thermal calculations and to design the ceramic window of the coupler.

Then, as a conclusion, we will talk about the future development of this study in our laboratory, the future test of AMANDA already scheduled in December 2003 and the fabrication of a $\beta=0.15$ prototype.

The Current Status of HPPA accelerator in China

Guan Xialing

China Institute of Atomic Energy

A 3.5MeV RFQ accelerator for the China Accelerator driven sub-critical reactor system (ADS) is currently under construction at China in last two years, which is a 75keV/3.5MeV 352.2MHz 50mA four vanes type RFQ. In this paper the characteristics of the machine are described, which including the 3.5MeV-RFQ Physical Parameters RF characteristics; Thermal & Structure Analysis⁴. Cold Model Measurements; RF Power System; Fabrication Test of Technology Model and it's Assistant Facilities. In this paper the microwave ion source and the LEBT also are described.

Beam Dynamics Studies for the Fault Tolerance Assessment of the PDS-XADS Linac Design

J.L. Biarrotte^a, M. Novati^b, P. Pierini^b, D. Uriot^c
^aIPN/IN2P3 Saclay, ^bINFN Milano LASA, ^cCEA Saclay

In order to meet the high availability/reliability required by the PDS-XADS design the accelerator needs to implement, to the maximum possible extent, a fault tolerance strategy that would allow beam operation in the presence of most of the envisaged faults that could occur in its beamline components.

In this work we report the results of beam dynamics simulations performed to characterize the effects of the faults of the main linac components (cavities, deflecting and focusing magnets, ...) on the beam parameters. The outcome of this activity is the definition of the possible corrective and preventive actions that could be conceived (and implemented in the system) in order to guarantee the fault tolerance characteristics of the accelerator.

The PDS-XADS Program is funded by the EC 5th Framework Program, under contract FIKW-CT-2001-00179.

High Energy Beam Transport Lines and Delivery Systems for Intense Proton Beams

P.A. Schmelzbach, H. Frei, G. Heidenreich, I. Jirousek, L. Rezzonico,
E. Steiner, U. Rohrer, C. Tschalär, E. Wagner
Paul Scherrer Institute, CH-5432 Villigen PSI, Switzerland

The transport of intense proton beams in high energy beam transport (HEBT) lines and beam delivery systems (BDS) set very severe requirements on the design of the components exposed to high levels of radiation. While in the low-loss sections a conventional approach might be adequate and “hands on” maintenance can be considered, repairs of beam line components in the vicinity of the targets could be very time consuming and much critical in respect to personal safety. The concept applied at PSI for the design of such systems is presented, with emphasis on reliability and maintainability aspects. The requirements on a run-permit system allowing for a safe operation of the facility will also be stressed.

Construction of FFAG Accelerator Complex for ADS Research in KURRI

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Yoshihiro Ishi, Shintaro Fukumoto
Mitsubishi Electric Company
Yoshiharu Mori
High Energy Accelerator Research Organization
Koichi Nakayama
Isogo Engineering Center, Toshiba Corporation
Kazuo Hiramoto
Hitachi Ltd.

KART (Kumatori Accelerator-driven Reactor Test facility) project, which intends to perform basic studies on accelerator-driven subcritical system (ADS), has started in Research Reactor Institute, Kyoto University (KURRI) from fiscal year 2002 with the grant by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). The purpose of this project is to demonstrate the basic feasibility of ADS, studying the effect of incident neutron energy on the effective multiplication factor of the subcritical nuclear fuel system. For this purpose, an accelerator system suitable for ADS will be constructed and coupled with the Kyoto University Critical Assembly (KUCA). A variable-energy FFAG (Fixed Field Alternating Gradient) synchrotron is regarded as a major candidate for such purpose because of its features such as a large acceptance, a much faster repetition rate (up to ~ 1 kHz) than those for conventional synchrotrons (~ 1 Hz). Furthermore, recent studies on FFAG synchrotron in the High Energy Accelerator Research Organization (KEK) have shown the solution for technical difficulties in realizing a heavy ion FFAG synchrotron, such as a wide band RF cavities.

We are now constructing an FFAG proton accelerator complex, consisting of one FFAG betatron and two FFAG synchrotrons as the source of proton beam for our project. Our system aims to attain $1 \mu\text{A}$ proton beam with energy range from 20 to 150 MeV with a repetition rate of 120 Hz. Primary acceleration is performed by the spiral sector FFAG betatron up to 2.5 MeV for the injection to the booster ring. The injected beam is accelerated up to 20 MeV in the booster ring and finally in the main ring up to 150 MeV. Both booster and main rings are radial sector type FFAG synchrotrons, which are different in the production of the magnetic field with a certain magnetic field index. For the booster ring, such a field is realized by using trim coils with flat magnetic poles, while the pole shape itself is formed to achieve such field.

First beam from our FFAG complex is expected to be available by the end of March, 2005, and the experiment on ADS with KUCA and the FFAG complex will start in 2005.

Improvement of reliability of the TRASCO intense proton source (TRIPS) at INFN-LNS

G. Ciavola, L. Celona, S. Gammino, L. Andò, S. Passarello, X.Zh. Zhang,
F. Consoli, A. Galatà, F. Chines
INFN-LNS, Catania, Italy
M. Winkler
University of Giessen and GSI, Darmstadt, Germany

The aim of improved reliability of a source for High Power Proton Accelerator has been pursued during last two years at INFN-LNS.

Reliability tests have been carried out and the results, featuring an almost satisfactory behaviour, are here described.

In addition, a full set of measurements of the magnetic field has been carried out to define a different design of the TRIPS magnetic system, based on permanent magnets, in order to further increase the Mean Time between Failure (MTBF) of such source which needs high MTBF for ADS purpose.

The OPERA-3D package was used to simulate the magnetic field and a new magnetic system was designed as a combination of three rings of NdFeB magnets and soft iron. The high voltage insulation has been completely modified, in order to avoid any electronics at 80 kV voltage.

The description of the magnetic measurements and the comparison with the simulations are presented, along with the mechanical design of the new version PM-TRIPS and the new design of the extraction system.

Finally the modification of the low energy beam transfer line (LEBT), which now includes a 30° bending magnet, will be outlined, with a special regard to the accelerator availability improvement which can be obtained with the installation of two PM-TRIPS sources or more on a switching magnet that may be the first element of the LEBT.

An Improved Superconducting ADS Driver Linac Design

R. W. Garnett, F. L. Krawczyk, G. H. Neuschaefter
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

In this paper we discuss recent work to further improve our superconducting (SC) ADS driver linac design. Our design assumes use of the 6.7-MeV LEDA RFQ as an injector to the SC driver linac. We have examined the feasibility of accelerating a 20-mA cw beam to 600 MeV using only 350-MHz SC multi-spoke resonator cavities operating at 4°K. Replacing the 2°K, 700-MHz SC elliptical cavity sections with spoke resonators has several advantages including reduced cryo-plant operating cost and an improved real-estate accelerating gradient due to the longer active lengths of the 350-MHz cavities. We discuss the details of the new design layout and beam dynamics simulations, including beam matching, and effects due to operational and alignment errors. Preliminary cavity modeling results for the proposed 5-gap spoke resonators to be used in the high-energy section of the linac are also discussed. This accelerator design would be appropriate as a driver linac for applications such as waste transmutation, fusion materials testing, etc. This work is supported by the U. S. Department of Energy Contract W-7405-ENG-36.

Methods and Codes for Estimation of Tolerance in Reliable Radiation-Free High-Power Linac

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Successful development of a reliable and normal hands-on maintainable high-power linac requires minimization of beam losses along accelerator. High sensitivity of high-power linac focusing channel to random perturbation causes the designers to concentrate their attention on tolerances estimation problem. Beam parameters degradation including transverse size and emittance growths is caused by channel and beam parameter perturbations. Calculation of channel sensitivity permits to estimate each perturbing factor influences on beam parameters and determine the main source of perturbation, to find perturbing factors compensation possibilities and to determine required factors guaranteed the beam passing throughout the real channel without losses. Methods for estimation of tolerance in high-power linac accelerating-focusing channel are consider in presented paper. Realization of these methods in LIDOS code package is presented. Monte-Carlo simulation results for various types of accelerating channels are discussed.

Status of the Spallation Neutron Source Accelerator Complex*

S. Henderson, for the SNS collaboration

The Spallation Neutron Source accelerator systems will provide a 1 GeV, 1.44 MW proton beam to a liquid mercury target for neutron production. The accelerator complex consists of an H⁻ injector capable of producing 38 mA peak current, a 1 GeV linear accelerator, an accumulator ring and associated transport lines. The linear accelerator consists of a Drift Tube Linac, a Coupled-Cavity Linac and a Superconducting Linac which provide 1.5 mA average current to the accumulator ring. The design of the accelerator systems is complete; installation of the accelerator components is in progress; and staged beam commissioning is proceeding as installation progresses. The installation and final commissioning of the project is on-schedule for completion in early 2006. The status of the project design, installation and commissioning will be presented.

* SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy. SNS is a partnership of six national laboratories: Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos and Oak Ridge.

Technical Session II :
Target, window and coolant technology

Chairs: X. Cheng (FZK, Germany) and T. Y. Song (KAERI, Korea)

Research and Development on Lead-Bismuth Technology for Accelerator Driven Transmutation System in JAERI

Y. Kurata, et al.
JAERI

Research and Development on Lead-Bismuth Technology for Accelerator Driven Transmutation System (ADS) have been conducted in JAERI to reduce the radiotoxicity and the amount of the high-level radioactive waste. Lead-bismuth eutectic (LBE) is a potential candidate of target and coolant of the ADS. Technical issues are described in using LBE as spallation target and coolant. A target design of LBE is introduced with thermo-fluid dynamics. LBE technologies and data on material corrosion under flowing LBE have been obtained through operation of the LBE loop. The first 3000h test at JAERI showed decrease in flow rate of LBE and the corrosion depth of 100 μ m at high-temperature specimen. It was found that the decrease in flow rate was caused by deposition of Fe-Cr crystals and PbO. Elements of Fe, Cr and Ni dissolved into LBE at the high temperature parts and Fe-Cr crystals deposited at the low temperature parts of the loop. Characteristic of the electro-magnetic flow meter was also measured. The modification of the loop system such as adoption of metallic filters and a wide flow channel in the electro-magnetic pump system, and the use of an inner-polished specimen tube brought about a good effect on operation of the loop. Characteristic of oxygen sensors with solid electrolyte was measured. The on-line monitoring and controlling system of oxygen concentration in liquid LBE has been developed. For the purpose of understanding the basic corrosion mechanism in LBE and finding better corrosion resistant alloys, static corrosion tests have been conducted. From the experiments in oxygen-saturated LBE, it was found that the corrosion depth of steels decreased at 450°C with increasing Cr content in steels. The thick ferrite layer was formed at 550°C near the surface of austenitic stainless steels containing Ni. Concentrations of Ni and Cr decreased at the ferrite layer and penetration of Pb and Bi occurred. A Si-added austenitic stainless steel showed good corrosion resistance at 550°C because of formation of a protective oxide film.

Vacuum gas dynamics investigation and experimental results on the TRASCO ADS windowless interface

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TRASCO – ADS is a program aiming at the design of an accelerator driven subcritical system in which INFN, ENEA and Italian firms work on preliminary studies and on the design of the high intensity proton linac accelerator and on the windowless interface between the accelerator and the reactor.

The accelerator UHV and the spallation target vacuum are divided only by a suitable pumping and trapping system for the gases and the vapors out coming from the molten LBE. In order to design a pumping system for interface accelerator-reactor region, vacuum gas dynamics theoretical considerations and experimental evaluations are needed to understand the vapors and gases behaviour in the target region. For the same purpose the literature data and experimental results on the radioactive gases and vapours, produced by the spallation process, must be investigated.

From the vacuum gas dynamics point of view, a numerical method, based on angular coefficients, has been validated to estimate the net flux of the LBE vapors and the gases coming from the spallation process, the oxidation control and the tube outgassing.

From the safety point of view, preliminary experiments are under way, for an estimation of net flux of high activity gases as mercury and polonium (using tellurium as a polonium simulator) with the purpose to evaluate the radioactivity in the beam tube.

All these data, compared with the literature ones and the experimental results, give an improvement towards a suitable design of the pumping system for an ADS windowless interface according to technological and nuclear safety constrains.

Corrosion Tests in the Static Condition and Installation of Corrosion Loop at KAERI for Lead-Bismuth Eutectic

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Lead-Bismuth Eutectic (LBE) has been widely studied as a core coolant and target material of ADS (accelerator driven transmutation system) in various countries. Since 1997, Korea Atomic Energy Research Institute (KAERI) has also conducted systematic studies to develop the ADS system, called HYPER (**HY**brid **P**ower **E**xtraction **R**eactor). LBE corrosion has been considered as an important design factor to limit the temperature and velocity of the ADS system. For the corrosion study, KAERI finished the setup of the LBE static corrosion facility and also finished the preliminary design of a dynamic corrosion loop and started a setup-process to construct the loop by summer of 2004. KAERI recently finished a preliminary test during 500hr under a reduced condition to check the performance of the static facility. We also have a long-term plan to build a proton irradiation test loop. In this paper, we described the results of the preliminary static test under a reduced condition and a status-of-art for the installation of the corrosion loop at KAERI.

The Vacuum Interface Compatibility Experiment (VICE) Supporting the MYRRHA Windowless Target Design

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Because of the high proton current density, in excess of $150 \mu\text{A}/\text{cm}^2$, enforced by the required neutron flux performance of the subcritical core of the accelerator driven system (ADS) MYRRHA that is under development in Mol, Belgium, a windowless liquid Pb-Bi eutectic (LBE) spallation target is foreseen in the design. Liquid target material that is circulated around in a loop allows the use of forced convection to evacuate the 1.4 MW of beam power deposited into a target volume of 0.5 l. The lack of a physical separation between the spallation target and the beam line implies that both share the same vacuum. As initial outgassing, liquid metal evaporation and emanation of volatile spallation products from the target surface take place, the beam-gas interaction causes the formation of plasma that could be the source of sputtering on the inner walls of the beam line. Eventually a plasma formation run-away may take place leading to damage on the beam tube or even, in extreme cases, to beam clogging. The amount of plasma formation critically depends on the competition between the outgassing rate and the vacuum pumping capacity that is limited due to spatial considerations. The combination of the vacuum requirements and oxygen control to inhibit corrosion and PbO precipitation necessitates careful conditioning of the LBE and thorough investigation in realistic geometrical and operational conditions..

To assess the issues sketched above, the VICE set-up was built. It consists of two ultra high vacuum (UHV) vessels, each designed to contain about 100 kg of liquid Pb-Bi. In the first stage of the experimental programme coarse outgassing in combination with procedures for the initial cleaning and control of the oxygen content for purposes of corrosion inhibition of the Pb-Bi eutectic are studied. For this, a barrel-shaped UHV-pressure preconditioning vessel was designed and built to be used at pressures between 10^{-7} and 10^6 Pa and temperatures up to 500°C . Besides vacuum pumping and pressure gauging equipment it carries plasma cleaning, gas cleaning and oxygen monitoring systems and a set of induction coils for magneto-hydrodynamic stirring of the melt. When the first stage of Pb-Bi outgassing and cleaning is completed the liquid eutectic is transferred to a second UHV vessel. This apparatus is a 5 m high, largely one-to-one scale model of the vacuum conductance geometry of the lower part of the beam line connecting to the MYRRHA spallation target area. It therefore avoids the need to extrapolate the results which would otherwise not easily scale in all respects. In this device the initial and long-term outgassing of the target material and the gas transport properties of the proton beam line is investigated in controlled pressure, temperature and pumping speed conditions using a three-stage quadrupole mass spectrometer in combination with gas flow differential calibration. In the present paper the principal scheme, the first experiences with the set-up and initial results on the PbBi outgassing and conditions experiments will be presented.

The Introduction of a Double-Annular Guide Tube for the Design of 20MW Lead-Bismuth Target System

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In an ADS, a high energy proton beam is impinged on a heavy metal target to produce spallation neutrons that are multiplied in a sub-critical blanket. Therefore, the spallation target is one of the most important units of an ADS.

The key issue in the target design is how to design an appropriate beam window and LBE flow so that the system can sustain thermal and mechanical loads as well as radiation damage. Recently there have been some intensive studies on the design of LBE spallation targets.[1][2] However, they are mainly focused on spallation neutron sources or experimental scales of ADS targets. It is well known that a proton beam power of 15-25 MW is inevitable for the practical size (about 1000 MWth power) of the ADS.[3] The design of a 20 MW spallation target is very challenging because more than 60% of the beam power is deposited as heat in the window and a small volume on the target system.

The main objective of the present paper is to show the possibility of designing a 20 MW LBE spallation target with a beam window.

In a previous study, we designed a 20MW LBE target for HYPER. However, it was found that the LBE flow rate was too high, almost 10% of the total coolant flow rate, and also the average LBE temperature rise in the target is too low, compared to the LBE heat up in the core. Thus, there is a big necessity to reduce the LBE flow rate in the target channel, without hampering the target performance.

For this purpose, we introduce an LBE guide tube, which controls the LBE velocity distribution at the target inlet. Sensibility studies for the guide tube have been performed for the HYPER target system and the results are provided in this paper.

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Design Study around Beam Window of ADS

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The reference design of the ADS in JAERI is the 800MWth, Pb-Bi cooled, tank-type subcritical reactor loaded with (MA+Pu) nitride fuel which aims at the effective transmutation of MA. To keep thermal power of 800MW at $k_{eff} = 0.95$, 20MW proton beam having 600MeV-1.5GeV is necessary. The present study discusses the design of ADS especially around the beam window from viewpoints of the proton beam profile, thermal-hydraulics and structural strength.

In JAERI's reference design, "ductless type" fuel assemblies are adopted to reduce neutron capture reactions by structural material and to enhance cooling capability of decay heat during fabrication, transportation and storage. In the design around the beam window and the core, the Pb-Bi is distributed to the target region and the core region at the bottom of the core. Preliminary analysis for thermal-hydraulic behavior showed that the cross-flow of Pb-Bi between the spallation target and the ductless-type fuel assemblies will occur, if there is no partition wall between them. This cross-flow may deteriorate the flow speed of Pb-Bi around the innermost fuel, and hence the cooling performance of the hot-spot fuel pins will be seriously affected. The installation of the partition wall around the spallation target is, therefore, presently under consideration, though it may worsen the neutron economy and increase activated waste.

Structural analysis for the engineering feasibility of the beam window was also attempted. The preliminary results showed that the beam profile of the high-intensity proton is quite important. If the beam has sharply peaked profile, the maximum temperature will exceed the allowable limit temperature. The beam expansion mechanism, therefore, will become important to ensure the viable design of the beam window. To cool the beam window effectively, a guide tube to lead Pb-Bi to the hot spot on the window is under consideration.

The irradiation effect by protons and neutrons are also to be taken into account. Preliminary analysis shows that about 20DPA irradiation by high energy proton and neutron is expected during one-year operation as well as 70DPA irradiation by fission neutrons from the subcritical core.

MSDM Calculations of Primary Isotopic Yields From Proton-Induced Reaction on ^{208}Pb at Energy of 1 GeV

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The simple Fermi-gas level density is replaced by Ignatyuk formula at Many Stage Dynamical Model (MSDM). The MSDM code has been being used to study the isotopic cross sections from proton induced spallation reaction on ^{208}Pb at the energy of 1 GeV for the elements from manganese to lead. The MSDM simulations of charge and mass distributions are compared with the experimental data measured by Yu E Titarenko at ITEP and T Enqvist at GSI. The comparisons of the MSDM calculations for the charge and mass distributions with simulated by LAHET code, INCL4+KHSv3p model and R Silberberg's semi-empirical method- YIELDX, respectively. The good agreements are shown between the MSDM calculation and experimental data. The deviations mainly show up between the results of LAHET code, INCL4+KHSv3p model and R Silberberg's semi-empirical method- YIELDX and measured data. The good agreements are given between the MSDM calculations and experimental data for the isotopic products too.

CFD Analysis on the Active Part of Window Target Unit for LBE cooled XADS

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The window target unit for the LBE cooled primary core is one of the promising options considered in the framework of the preliminary design study of experimental accelerator driven system (PDS-XADS). In the present work, numerical design study using CFX 5.6 has been performed for the active part of this option with special attentions to the coolability of the window.

The target unit in the center of the XADS core is composed of an evacuated central beam tube inside a shell forming the physical boundary to the surrounding core assemblies and reactor coolant. The proton beam enters the beam tube at the upper end, penetrates the beam window at the lower end and impinges on the upward flowing target LBE. This accompanies high thermal load to the window as well as LBE. Heat is removed from the target in a heat exchanger at the upper end inside the target unit. A LBE fluid flows around the target unit by natural convection force. The design of the heat exchanger and the secondary system assures a stable natural circulation in the target unit during operations.

Axi-symmetrical 2D computational domain was chosen due to symmetry. Normal steady-state performance as well as transient dynamic behaviour has been investigated. As a form of boundary conditions, the CFX model is interfaced with a Monte Carlo code (MCNPX), which provides the heat source distribution produced by the spallation process, and with a one-dimensional system code (HERETA), which provides inlet LBE conditions and outer wall conditions of the target shell.

The results of CFX calculations for normal steady-state operation conditions with the reference design parameters and the maximum proton beam current of 6 mA show that the maximum LBE velocity is well below the design limit 2 m/s. But the maximum temperature of the window exceeds the design limit 525 °C. Therefore, a series of parametric studies varying the window and funnel geometries to reduce the window temperature have been made and show that the window temperature can be reduced by the reasonable amount with a slight modification of the reference design. In addition, it is found that short periods of beam trips less than 1 second could also be crucial to the integrity of the window by transient simulations of the CFX code.

Optimization of a code to improve spallation yields predictions in an ADS target system

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Spallation neutron source is made with an intense beam of high energy particles hitting a thick target made of heavy nuclei in accelerator driven nuclear transmutation system. As a by-product of this, a lot of spallation isotopes are produced. The produced spallation isotopes show extensive distribution about the number of mass and their life-time. It become understood that there are some spallation products which has the radioactivity comparable with Po that has been used to pay attention in usual Pb-Bi cooling system. In this regard, the amount of spallation yields must be evaluated in good accuracy.

We have developed the code to search a set of optimum parameters that is prepared in the evaluation code to the compared experiment. This optimization code has combined with the evaluation code in order to increase the accuracy of the prediction of the spallation yields

We show that combined the optimization system with the Particle and Heavy Ion Transport code system (PHITS) for the evaluation improve the accuracy of prediction of each spallation product yields.

Adopted evaluation code for spallation process is PHITS which is extended version of NMTC/JAM originated from NMTC/JEAR197 [1]. The parameter prepared in PHITS is optimized to the experiment data which are recently carried out by GSI [2].

Adopted parameters to optimise are the parameter for the calculation model choice of 14 which takes the discrete values and the 5 continuous parameters. Degree of freedom is 256 for 276 experimental data we use. We use maximal likelihood method to optimise these parameters using likelihood function made of the production cross section for each spallation produced isotopes. In order to search global maxima for the likelihood function, DIRECT algorithm is used, which is known to be very efficient method for optimisation. Among provided experimental data, we use selected data of isotopes which was produced with high production cross section, because the calculated statistical error grow for the isotopes which were produced with small production cross section. Figure 1 show the comparison of experiment with the predicted production cross section of PHITS with optimum parameters.

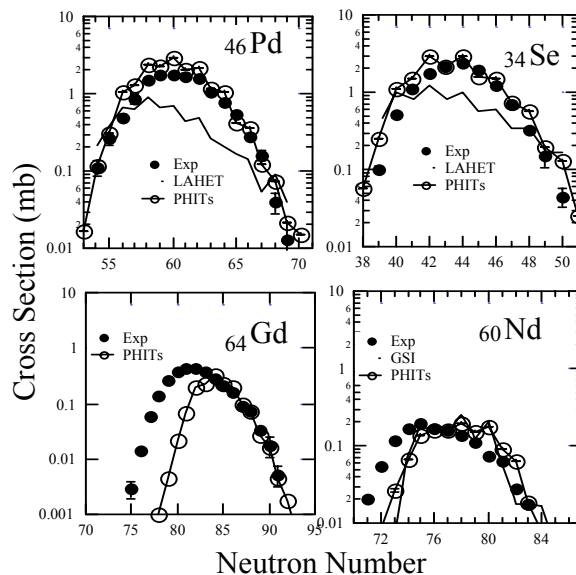


Fig. 1 Comparison of predicted cross section with experiments

The predicted cross section for the low mass isotopes are in good agreement with experiment data. On the other hand, The discrepancy for high mass isotopes are relative large.

We found from this study that predicted cross section are sensitive to the parameters which determine the energy at which adopted intra-nuclear cascade model has been changed or at which evaporation model has begun to adopt.

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Technical Session III:
Sub-critical system design and ADS simulations

Chairs: W. Gudowski (RIT, Sweden) and H. Oigawa (JAERI, Japan)

Research on Accelerator Driven Subcritical System at Kyoto University Critical Assembly (KUCA) with the FFAG Proton Accelerator

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At Kyoto University Research Reactor Institute (KURRI), a new project for research on the accelerator driven subcritical system (ADS) has been started from 2002. In this project, a new ring type accelerator based on the up-to-date FFAG (Fixed Field Alternating Gradient) technology that can produce proton beam of about 1 microampere current with arbitrary energy up to 150 MeV will be constructed. The proton beam from this accelerator will be introduced into a core of Kyoto University Critical Assembly (KUCA) to generate high-energy neutron by collision with heavy metal such as tungsten. Note that KUCA has a core that uses highly enriched uranium fuel plates and a solid material such as polyethylene or graphite as moderator and reflector and whose core configuration or neutron spectrum (moderator to fuel ratio) can be easily changed depending on the purpose of experiments. Subcriticality of the core is altered by control rod operation or number of loaded fuel assemblies. The accelerator building and its system are now under construction and new experiments at KUCA combined with the FFAG accelerator will be started from 2005, and the design analysis of this project has been carried out with MCNPX Monte Carlo code.

Before starting this experiment, basic research on ADSR has been performed at the KUCA combining with a Cockcroft-Walton type accelerator that was already equipped inside the KUCA building. This accelerator can accelerate the deuteron beam up to around 350 keV and the beam is led to a tritium target located adjacent to the KUCA core to generate 14 MeV pulsed neutrons. The peak current of deuteron beam was around 2 mA and the pulse frequency was in the range from around 20 Hz to 1 kHz depending on the purpose of experiment.

The following experiments has been carried out so far: (1) subcriticality measurement by pulsed neutron method or modified source multiplication method, (2) neutron flux distribution measurement by using optical fiber detectors or by foil irradiation method in subcritical core, (3) neutron noise analysis such as new variance to mean ration method with pulsed neutron source to measure subcriticality and core properties, and so on. The results of experiments were analyzed with a deterministic method using an SN transport code and Monte Carlo code such as MCNP and MVP.

From these experiments using the current accelerator, experimental techniques for research on ADSR have been developed, which will be utilized after installation of the FFAG accelerator.

Improvement of Burn-Up Swing for Accelerator-Driven System

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JAERI has been developed the accelerator-driven subcritical system (ADS) for transmutation of minor actinides (MA). The key parameter of the ADS is criticality (k_{eff}). The higher k_{eff} brings many benefits such as the lower power of the proton accelerator, the lower damages to the beam window and the lower power peak in the MA fuel region. On the other hand, the higher k_{eff} has a wrong influence to the safety. Ideally, k_{eff} should be a high constant value during all burn-up term as not to be critical. The goal of the present study is to decrease the change of k_{eff} , that is, burn-up swing, near the maximum k_{eff} during the all cycles.

The supposed ADS is the tank type reactor cooled by Lead-Bismuth eutectic (LBE). The target is also LBE. The proton energy is 1.5GeV and the power is about 14 to 30 MW. The fuel consists of MA nitride (MAN), plutonium nitride (PuN) and zirconium nitride (ZrN). Although PuN is not preferable from the viewpoint of MA transmutation; it is necessary only in the first cycle to elevate k_{eff} in early cycles. ZrN has a role to attenuate the actinide fuel, that is, to decrease k_{eff} . Values to be adjusted in the present study are the PuN ratio in the first cycle and ZrN ratio in each cycle.

First of all, the maximum k_{eff} is determined from reactivity of power defect, accident, measurement uncertainty and calculation uncertainty. As the result of calculation, the maximum was set to 0.97. The minimum k_{eff} is 0.925 in 3rd cycle, which corresponds to proton power of 38.3 MW. In the equilibrium cycle, the k_{eff} falls from 0.97 to 0.953, which correspond to proton power of 14.7 MW and 23.6 MW, respectively.

Next, k_{eff} in the beginning of each cycle is improved by adjusting ZrN ratio. The minimum of k_{eff} is improved to 0.933, which corresponds to the proton power of 34.1 MW. The total proton power during 10 cycles is decreased by 18% from the original case.

Finally, the k_{eff} in the end of each cycle is elevated by introduction of burn-up rods consisting of B₄C. At the beginning of each cycle, k_{eff} is adjusted to 0.97 with full insertion of the burn-up rods. The burn-up rods are pulled up during each cycle so as to keep k_{eff} 0.97 as possible. The 3 or 4 burn-up rods are loaded to the MA fuel region and supply k_{eff} of 0.018 from the beginning to the end of each cycle. The minimum k_{eff} is elevated to 0.951, which corresponds to the proton power of 24.5 MW. The total proton power is decreased by 37% from the original case.

As mentioned above, the power of the proton accelerator and the total power can be saved by the improvement of burn-up swing. The power peaking in the MA fuel will be also improved. In the presentation, the calculation result will be shown about the adjustment of ZrN ratio, the position of burn-up rods and the improvement to the burn-up swing.

Status of the conceptual design of accelerator and beam transport line for TRADE

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The TRADE (TRIGA Accelerator Driven Experiment) accelerator characteristics have been changed since the beginning of the study. At present a 300 MeV Separated Sector Cyclotron is foreseen to be used that will be able to extract also a lower energy beam in the case of target or radioprotection problems. The cyclotron will deliver a 300 uA max beam to TRADE, but it will be designed for a maximum current higher than 2 mA. A 30 m long beam transfer line will transfer the beam from the cyclotron vault through a locally shielded channel to the top of the TRIGA reactor pool and will direct it through an achromatic bend to the target placed in the central thimble of the reactor. The original design has been modified to include a vertical translation within the cyclotron vault, in order to lower the losses in the TRIGA building. To expand the beam onto the target, both techniques of defocusing the beam by means of quadrupoles and beam raster scanning or wobbling will be available.

The two final bending 45° dipoles will be immersed in reactor water for beam line shielding. As they will be hanging on the reactor core, their gap will be designed as small as possible in order to limit the magnet weight within 1 ton each.

This work has been performed in the frame of an International Working Group on the TRADE experiment. The original membership - ENEA (Italy), CEA (France), CERN (Switzerland) and ANSALDO (Italy) - is extended to FZK (Germany), DOE (USA), CIEMAT (Spain), CNRS (France), JRC-ITU (EU), PSI (Switzerland), SCK•CEN (Belgium), AAA (France), AIMA (France) and IBA (Belgium)

Estimation of some characteristics of cascade subcritical molten salt reactor (CSMSR)

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The ADS-burner of Minor actinides (MA) was considered taking into account the following assumption:

- Proton accelerator as a driver with energy 1 GeV and current 10 mA;
- Two core cascade reactor with $\Delta k_{\text{eff}} \approx 0.05$ consisting of zone of cascade amplification (ZCA) and transmutation zone (TZ).
- Homogeneous molten salt NaF-ZrF₄ as a coolant and the nuclear fuel in TZ.

In our consideration we used technical solutions verified by real experience or close to them.

Reactor has a form of cylinder with diameter 3.4 m and height 2.3 m with three zones of cascade amplification (ZCA) with diameter 37 cm. ZCA consist of four concentric elements: central target, two layers of fuel lattices with plutonium and neptunium fuel and buffer zone. Pb-Bi eutectic is used simultaneously as the neutron production target, coolant and spectrum ventile between ZCA and TZ.

There were calculated neutron generation in the ZCA target and the main neutron-physics characteristics of reactor including reactor power and power distribution, reactivity effects, actinides burnup, thermo-hydraulics of ZCA fuel elements, etc.

The following reactor parameters are obtained:

- power 800 MWth with distribution between ZCA and TZ as 19:81;
- cascade amplification factor (CAF) is ~ 3 ;
- average energy release at TZ is 30 Wth/cm³, neutron flux $\sim 5 \cdot 10^{14}$ n/cm³c;
- power distribution and reactivity effects are satisfactory.

Effectiveness of our model of CSMSR as incinerator of MA was estimated for VVER fuel in the open fuel cycle as 51 kg/year, i.e. RW amount of 1.6 VVER reactors.

CFD Analysis of the Heavy Liquid Metal Flow Field in the MYRRHA Pool

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SCK•CEN, the Belgian Nuclear Research Centre at Mol, is designing a Accelerator Driven System (ADS) – MYRRHA – aiming to serve as a basis for the European experimental ADS and providing protons and neutrons for various R&D applications. It consists of a proton accelerator delivering a 350 MeV * 5 mA proton beam to a liquid Pb-Bi spallation target, which – in its turn – couples to a Pb-Bi eutectic cooled, sub-critical fast-spectrum core in a pool type configuration.

The core pool is separated in a lower cold part and an upper hot part by a diaphragm, which is fixed ultimately to the rim of the double-wall vessel. It contains a fast-spectrum core with hexagonal fuel assemblies and could house several islands with thermal spectrum regions located in in-pile sections. Three central hexagons are left free for housing the spallation module. The pool also contains the four units of liquid metal main pumps and the heat exchangers using water as secondary fluid and the two fuel handling robots.

The liquid metal flow pattern in the lower vessel part of MYRRHA needs to be investigated in order to:

1. Assess the further details of flow eddies and dead-water zones

The knowledge of possible occurrence of slow eddies and dead-water zones is important to the MYRRHA team. It allows them to judge that there occurs neither physico-chemical effects of deviations from the correct oxygen level for corrosion control nor sludge formation by lead oxide nor precipitation of fractionally condensed components of Pb-Bi.

In view of this, first an isothermal case with symmetrical flow from all four pump units is investigated; then asymmetric variations (unequal flow rates and tripping of unit(s)) are studied.

2. Assess the scaling of the flow down to a model which can be handled experimentally

Under the MYRRHA R&D program, the possibility of an experiment with Pb-Bi is investigated in a model with a true volume of about 1 m³ or less as compared to the ~ 30 m³ of the full size MYRRHA.

In view of this, different strategies of downscaling (Reynolds, time and velocity-based), are investigated with the final aim of having dimensionless residence times and velocities in the model similar to the full size situation.

For these purposes, Computational Fluid Dynamics calculations have been performed by NRG and SCK•CEN. The paper will elaborate the methodology of the calculations and the main findings.

Results of the Second Phase of Calculations Relevant to the WPPT Benchmark on Beam Interruptions

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(on behalf of benchmark participants)

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The results of the second phase of calculations relevant to the OECD/NEA WPPT benchmark on Beam Interruptions in a Lead-Bismuth cooled and MOX fuelled Accelerator-Driven Systems are presented and analysed in this paper. It can be worthwhile to shortly remind that a previous first phase of calculations /1/ was devoted to a particularly clean comparative assessment of the different computation methods used to evaluate power and temperature transients induced by beam interruptions of different duration. This second phase of beam interruption investigation /2/ has been extended also to cases that are characterised by larger fuel power densities. In particular, the beam interruption investigation is no more limited to the Ansaldo-XADS, but extended to average and hottest fuel pin cases relevant to the MYRRHA experimental ADS. Moreover, to evaluate the uncertainty of the calculated results, the benchmark has been also extended to sensitivity analyses of the main results to assumptions (on models and data) different from those recommended in the benchmark specification. Practically, the participants have evaluated also the impact on the benchmark results of any assumption they thought to be a valid alternative or an improvement upon the recommendations given in the benchmark specifications.

Benchmark Participants

Table I lists the benchmark participants and the codes they used to obtain their solutions.

Participant	From	Code used
A: D'Angelo and F. Gabrielli	ENEA Casaccia Italy	TIESTE-MINOSSE
Gert Van den Eynde and Baudouin Arien	SCK-CEN Mol-Belgium	SITHER-PKS
Kazafumi Tsujimoto	JAERI Tokai-Japan	EXCURS-M
Marcus Eriksson	Royal Institute of Technology, Stockholm-Swiden	SASSYS/SAS4A
Michael Schikorr	FZK Karlsruhe-Germany	SIM-ADS
Paul Coddington and Konstantin Mikityuk (1 st solution)	PSI Switzerland	TRAC-M/AAA
Paul Coddington and Konstantin Mikityuk (2 nd solution)	PSI Switzerland	LOOP2
Pieter Wakker and Jim Kuijper	NRG Petten-the Netherlands	TRAC MOD
Ron Dagan and Cornelis Broeders	FZK Karlsruhe-Germany	SAS4ADS
Yonghee Kim	KAERI Daejeon-Republic of Korea	DESINUR

Results

The sensitivity analysis of the results allows to quantify larger fuel temperature relative uncertainties relevant to cases that are characterised by larger fuel power densities (i.e. larger heat fluxes through the fuel pin materials and interfaces). This conclusion agrees (even quantitatively) with the larger dispersions of the corresponding reference results, obtained by the different participants and codes. Practically, larger sensitivities amplify any effect on the fuel temperature due to different assumptions on models or data. Larger sensitivities mean also larger effects of any slightly different assumption that participants did unintentionally by utilising their codes, although they have tried to reproduce as well as possible the benchmark recommendations. On the contrary, reference calculations of the outlet core coolant temperature and temperature trends give particularly precise

results. Also in this case, the sensitivity analysis confirms the information coming from the dispersion of the reference calculation results. In fact, all the investigated variations of calculation assumptions lead to negligible or relatively limited effects on the calculated coolant temperatures: no more than 3% for a variation of 10% in the coolant specific heat.

Conclusions

The results of the benchmark second phase of calculations allow to evaluate fuel and core outlet coolant temperature trends induced by 1s and 6s beam interruptions in the XADS and MYRRHA experimental ADS, together with the corresponding uncertainties. Results and uncertainties generally depend on the different fuel power density conditions relevant to the XADS or MYRRHA cases.

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Technical Session IV:
Safety and control of ADS

Chairs: J-M. Lagniel (CEA, France) and P. Coddington (PSI, Switzerland)

Safety analysis of the EU-PDS-XADS designs

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Within the Fifth Frame Work Program of the E.U., the PDS-XADS Project is focused on the design studies of an eXperimental Accelerator driven reactor System (ADS). Two basic design options are being studied in detail, an ADS with a lead bismuth eutectic (LBE) – cooled core and another with a gas (Helium) – cooled core.

The one of the work packages of the PDS-XADS project is concerned with the assessment of the safety of these designs with the following main objectives to:

Develop an integrated safety approach common to both the LBE- and the gas-cooled concepts.
Identify the main safety issues in an XADS with their phenomenology and develop an evaluation methodology for both alternatives.

Perform transient analyses with the aim of producing safety analysis reports with the identification of the design features required to meet the XADS safety objectives.

The rationale for the integrated safety approach is quite similar to that practiced for the current LWR plants i.e. defense in depth, single failure criterion, specified safety goals. The PDS-XADS is a subcritical fast reactor, and is cooled either with LBE or gas; thus it has the inherent advantage that reactivity – initiated accidents (RIAs), which were the bane of fast reactors may be prevented by an appropriate choice of the subcriticality level. The safety evaluation approach required the specification of the design-basis conditions (DBC) and the design-extension conditions (DEC) for both the LBE-cooled and the gas-cooled designs. Again, guidance in their specification was derived from the safety regulations for the LWRs and for the fast reactors.

For the LBE-cooled XADS designed by ANSALDO/ENEA a total of 26 transient initiators were identified for detailed analysis, categorized into Operational Transients (3), Protected Transients (11), and Unprotected Transients (12). For the gas-cooled XADS designed by FANP and NNC/CEA a total of 31 transient initiators were identified, categorized into Operational transients (3), Protected Transients (17), and Unprotected Transients (11). Many of the transient initiators are common to both designs, eg spurious beam trip, protected/unprotected loss of flow – loss of heat sink, unprotected sub-assembly blockage etc., while some of the initiators are specific to one particular concept, including loss-of-coolant accidents and water/steam ingress into the reactor core for the gas cooled design.

In order to perform the analysis a review was made of the codes systems available to the project partners, which could be adapted to the analysis of the PDS-XADS DBC and DEC transients. These include: (i) The SIM-ADS code, (ii) the RELAP-5 code modified for LBE by ANSALDO, and RELAP-5 – PARCS coupled code (with gas-cooled subcritical system kinetics models added by ENEA), (iii) the TRAC-M code of USNRC, modified for LBE and gas coolants by the Los Alamos National Laboratory, (iv) the code EAC (European Accident Code) developed at the JRC-Petten, (v) the SAS-4, SASS-SYS codes modified to include LBE, (vi) the SIMMER code, which can model fast reactor hypothetical core disruption accidents (HCDA) and the STAR-CD code. The availability of a number of different codes able to analyse the same transients offers the capability of performing code-to-code comparisons, which is very important when analysing new reactor systems in the absence of extensive experimental validation studies.

In the paper representative results of the transient analyses performed using the different code systems for the different designs, including the code-to-code comparisons will be presented and discussed. These results show for the LBE-cooled XADS that this design exhibits a very wide safety margin (for both protected and unprotected transients) as a consequence of very favorable safety characteristics, including; excellent heat transfer properties and high boiling point of the coolant, favorable in-vessel and secondary system coolant

natural circulation flow characteristics, and the large thermal inertia within the primary system as a result of the large coolant mass (pool design). For the gas-cooled XADS the results demonstrate the adequacy of the decay heat removal system for protected depressurization and loss of flow transients, and help to define the limited time window for backup proton beam shutdown systems in the event of an unprotected transient.

Comparative Transient Analyses of ADS with Conventional Fast Reactor Fuel and ADT with Advanced Fertile Free Fuel

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Within the 5th Framework Program (FP) of the European Union, several projects on Accelerator Driven Systems (ADS) are running in parallel. One is the Preliminary Design Studies of an Experimental Accelerator-Driven System (PDS-XADS) of the 80 MWth power class with MOX fuel, while another is FUTURE on fuels. The main goal for PDS-XADS is to demonstrate the feasibility of ADS. For FUTURE an 800 MWth accelerator driven transmuter (ADT) has been designed and investigated. The core contains advanced fertile free fuels CERCER and CERMET.

Comparative safety analyses and investigations have been performed for both XADS and ADT Pb/Bi cooled designs. The analyses cover both perturbations of the source, as e.g. unprotected transient over current (UTO) and beam interruptions and perturbations on the core, such as protected and unprotected transient over power (P/UTOP) reactivity additions, unprotected loss of flow (ULOF) and blockage accidents. Investigations of these advanced composite fuels reveal that especially for severe transients new phenomena and scenarios have to be expected and modeled, e.g. because of the different melting points of the constituents, the high He content from Am+Cm decay. The analyses are mainly performed with the SIMMER-III code, a 2D multiphase, multi-component multi-field code coupled with space-time kinetics, using transport theory for the flux-shape calculation.

For the small scale PDS-XADS with good safety coefficients (negative void worth, large Doppler) the analyses reveal a benign behavior under design basis conditions (DBC) and strong resistance against severe transients. The calculations of beam over current (UTO) show that no severe fuel melting problems are encountered even for 100% increase of the source strength. In the DEC calculations, e.g. the ULOF simulation shows that the remaining natural convection flow after the pump trip is sufficient to prevent any clad and fuel melting. Even under hypothetical conditions of core degradation and melting (DEC-design extension conditions), defined with ad-hoc assumptions no severe accident scenario develops.

For the ADT with deteriorated safety parameters work has been started to get a first picture of its behavior. For transients within the design basis the fertile free cores show virtually no stabilizing feedback from Doppler, but might reveal a positive feedback from coolant expansion. Thus via the beam or control rods the stability has to be managed. A high thermal conductivity shows to be essential for providing the necessary margin for the power to melt ratio. In first analyses of the DEC behavior show the importance of the clad worth of these cores, as steel melting advances any Pb/Bi boiling. Voiding could add reactivity via the blow-down of He and fission gases. This in consequence leads to un-clad pin-stubs, which disrupt and may involve sweep-out scenarios, depending on the timing and amount of clad removal.

Comparative transient analysis of Pb/Bi and Gas cooled XADS concepts

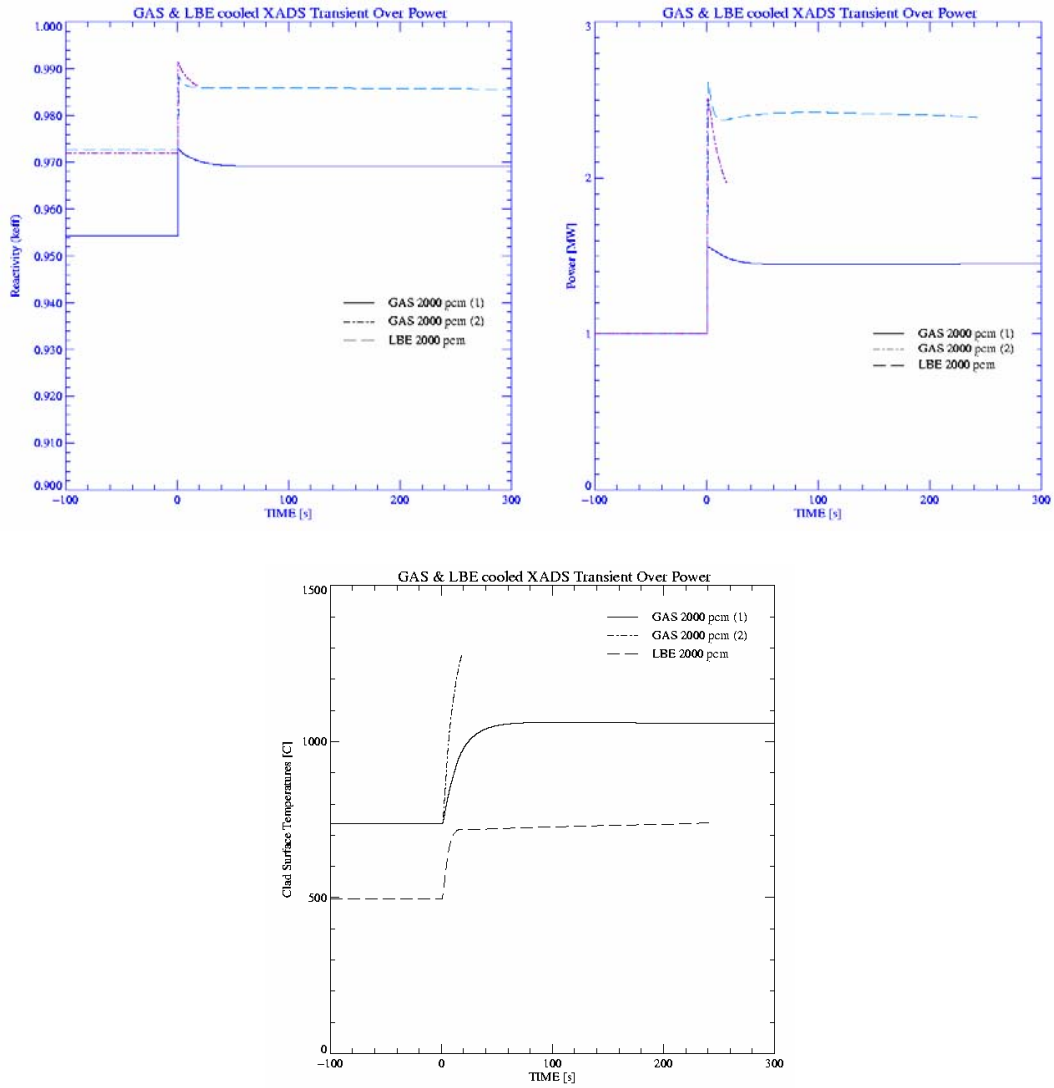
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In the field of waste management incorporating a transmutation option, accelerator-driven systems (ADSs) represent an important alternative to conventional reactors due to their higher safety level when minor actinides such as neptunium and americium are loaded into the core such that, within the European Union 5th Framework Program (FP), several ADS-related projects are being performed, one of which is the Preliminary Design Study of an Experimental Accelerator-Driven System (PDS-XADS). The main goal of PDS-XADS is to demonstrate the feasibility of an ADS and compare different coolant (Pb/Bi and Gas) and power (50 to 80 MWth) options. All options use MOX fuel.

Comparative safety analyses have been performed using an adapted version of the TRAC-M/AAA code for both the 80 MWth Pb/Bi and gas cooled designs. The analyses cover perturbations of the source, e.g. transient over current and beam interruptions, perturbations of the core, eg reactivity increase and transients coming from faults in the primary and secondary coolant systems, eg loss of flow, loss of coolant etc.

A detailed evaluation of the reactor safety depends upon a wide range of considerations including possible initiating events, response of the reactor core, the reactor coolant, mitigating effects eg shutdown mechanisms, decay heat removal etc. Many of these features are design specific, so that a simple one-to-one comparison between the two systems is very difficult. For example, the safety of a given XADS concept is a mixture of the response of the plant system (which would be similar to that in the corresponding critical reactor case and so is unrelated to the subcritical nature of the ADS) and the response of the reactor core (where the individual core design and level of subcriticality are important). This will be highlighted by comparing both system and core initiated transients for the two XADS concepts.

As an example, we show the results obtained for an unprotected transient over-power accident (addition of 2000 pcm of reactivity) in subcritical gas and lead bismuth cooled reactors. The results (curves (1) for gas) show comparative calculations for the two systems beginning from the same sub-criticality level of ~ 0.97 , which is that chosen for the lead bismuth cooled system. The power jump to approximately 2.5 x nominal is the same in both systems. However, because of the higher power rating in the gas cooled system and the low thermal inertia of the coolant, the clad and fuel temperatures increase to much higher values; in fact for this transient the calculation terminates as soon as fuel melting occurs. Curves (2) for the gas cooled system show that this transient is mitigated when the initial (operating) reactivity level is reduced. In this calculation the nominal value of about 0.954 for the gas cooled design was used.



Relative reactivity, power and peak clad temperature for LBE and gas cooled XADS in an Unprotected Transient Over Power (UTOP) accident.

TALL Test Facility and Experimental Progress

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Royal Institute of Technology (KTH) is participating in two specific research projects of the EURATOM Fifth Framework Programme, one named as TECLA and the other as PDS-XADS, both on Accelerator-driven Transmutation of Waste (ATW) using lead-bismuth eutectic (LBE) as spallation target as well as coolant in a subcritical reactor which is driven by an accelerator.

According to the work-package profiles of TECLA and PDS-XADS, the Thermal-hydraulic ADS Lead-bismuth Loop (TALL) was designed and erected at KTH to investigate the heat transfer performance of different heat exchangers, and the thermal-hydraulic characteristics of natural circulation and forced circulation flow under steady and transient conditions.

The specifications of TALL are chosen to simulate prototypic thermal hydraulic conditions of an ADS reactor, with well-conditioned flow and controllable power for thermal-hydraulic tests. The facility is 6.8m tall and the placement of heaters and heat exchangers allows natural convection flows as should occur in the prototypic vessel. The LBE loop is of full height and has been scaled for prototypic (power/volume) ratio to represent all the components whose LBE volume, pressure drops, flow velocity and heating rates correspond to one tube of the heat exchanger design chosen. The loop is re-configurable for thermal-hydraulic experiments with steady and transient conditions. Sections of the loop allow for easy replacement.

The facility has come into operation since September 2003, and investigations on LBE flow and heat transfer characteristics have been carried out for straight-tube heat exchanger and U-tube heat exchanger, respectively.

Transient experiments with the test facility will be investigated with reference to safety issues of ADS. While simulating decay heat in the core tank, the temperature and flowrate transient characteristics are measured during the following conditions,

- a) loss of heat sink (switch off the pump of the secondary loop);
- b) loss of external driving head (switch off the pump of the primary loop)--- completely passive mode of LBE loop operation;
- c) switch on and off the heater to simulate accelerator trips;
- d) blockage in pipes; and
- e) Sudden increase in power.

The above experiments will provide valuable data for the safety evaluations of ADS design since the data can be employed for validation of safety analysis codes particular to an LBE-cooled reactor.

Analysis of Lead-Bismuth Eutectic Flowing into Beam Duct

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Beam wind breakage is one of the most considerable accidents in the operation of an accelerator-driven subcritical system (ADS). After the beam window breaks, the target material, which is supposed to be Lead-Bismuth eutectic (LBE), flows into the beam duct in liquid and gaseous phases. The inlet speed of the liquid LBE and the pressure of gaseous LBE in the duct were analyzed.

The depth of the beam window is supposed to be 6.5m from LBE surface around the beam duct. The diameter of the duct is 0.4m and 0.05m at beam expansion part and upstream duct, respectively. The length of the beam expansion part is 10m. Temperature of LBE is 430-centigrade degrees.

The window breakage is considered in two cases; one is large fracture and the other is small fracture. In the case of large fracture, the diameter of the fracture area is supposed as 0.1m to 0.4m. As the result for 0.4m, the LBE flows up to 14m over the surface at 2.6 second after the breakage. The pressure in the duct increases twice at 0.5 sec after the breakage, when the level of LBE is almost same as the surface around the duct.

In the case for the small fracture, the proton beam evaporates LBE flowing into the duct, and the amount of evaporated LBE balances with the inlet to the duct. The gaseous LBE distributes in the duct according to the evaporate pressure for temperature at each position.

The detection of fracture by pressure gauge is not difficult for the case of large fracture. After the detection, the valve can be closed within 0.01 to 0.02 sec. For the case of small fracture, on the other hand, the detection will be difficult, because the evaporate pressure at position of the pressure gauge is 6.3×10^{-8} Pa according to the ENEA evaluation formula*.

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On the Supplementary Feedback Effect Specific for Accelerator Coupled Systems (ACS)

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In general, nuclear systems, devoted to the nuclear waste transmutation, may suffer from the significant degradation of safety characteristics. In particular, such important parameter as delayed neutron fraction can decrease by several times compared to presently implemented fuel cycles. Another serious problem, arising in such systems, is the reduction of Doppler effect - the fastest and the most important temperature feedback effect in reactor's core. This degradation of safety properties makes the control of such systems rather delicate or in some cases even dangerous.

An innovative solution, aiming to handle the above problem, has been proposed and consisted of the artificial enhancement of neutron balance of the system. In practice, an external neutron source added to the system permits the core to operate in a sub-critical mode (so-called hybrid nuclear systems). In Accelerator Driven Systems (ADS), where a sub-critical core serves only to amplify the incident beam energy, a large sub-criticality margin ($k_{\text{eff}} \sim 0.95-0.97$) mitigates the negative consequences of safety parameters degradation [1]. However, this significant sub-criticality level requires powerful and expensive particle accelerator. Another way to deal with the problem is to employ the concept of the Accelerator Coupled System (ACS) [2]. In this system an external neutron source, coupled directly to the core power and artificially or naturally delayed, can compensate decreased fraction of delayed neutrons. On the other hand, the ACS inherits some properties of a critical nuclear system. In some cases, the degradation of feedback effects, like Doppler effect, makes possible power and temperature excursions in the case of unprotected reactivity insertion.

Here we propose a new approach to the realization of ACS, where a significant improvement of the feedback effect is achieved, thanks to the particularities of the neutron production in a spallation target. Our major goal is to get an auto-regulating behavior of the ensemble "accelerator – sub-critical core" in terms of deterministic safety. A proposed system would have the kinetics of a critical system with artificial group of delayed neutrons as in the case of "standard" ACS. In addition, its external neutron production would contain the additional feedback, able to stabilize the installation's power in its nominal state. Our preliminary results show that according to the new concept, the power (and temperature) excursion would be less important than in the "standard" ACS [3]. It seems that qualitative improvement of the safety can be reached already at the sub-criticality level of the order of 300-400pcm. Therefore, even low power accelerators could be used to provide an external neutron source (and inherent safety at the same time) in these particular cases.

In this study we explain the principle of new system's operation, discuss advantages and disadvantages of the proposed concept. The quantitative analysis of the system's functioning is based on generalized point kinetics model. In the frame of this simplified model, we give some restrictions on neutron production parameters, necessary for realization of a proposed system. Some optimization on the geometry of spallation target, which helps to strengthen the feedback of the system, is suggested and discussed in detail. We use the MCNPX code for these quantitative estimates related to the neutron production.

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k_{eff} and k_s burn up swing compensation in MYRRHA

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MYRRHA is an Accelerator Driven System (ADS) under development at Mol in Belgium and aiming to serve as a basis for the European experimental ADS to provide protons and neutrons for various R&D applications. It consists of a proton accelerator delivering a 350 MeV*5 mA proton beam to a liquid Pb-Bi spallation target that in turn couples to a Pb-Bi cooled, sub critical fast core.

The effective multiplication factor k_{eff} and consequently the source multiplication factor k_s , describe the performance of any ADS system. Due to the effect of burn up, these multiplication factors decrease in time. In the case of MYRRHA (initial k_{eff} of 0.95 with a 5 mA 350 MeV proton beam), we are considering to operate the facility with cycles of 90 days at nominal proton beam current. The source multiplication factor k_s drops by about 1000 pcm over 90 days due to the burn up swing. As a result the source multiplication M_s (the total number of fission neutrons to the number of source neutrons) decreases from 22.52 to 18.25, which is a drop of about 20 %. The flux in the system will show a similar effect. The thermal power of the system also decreases by 20 %. This situation is clearly not dramatic in MYRRHA because this system is designed as an experimental machine to provide high flux. Nevertheless, such a situation is not desirable for an industrial ADS especially when considering a longer operation cycle.

A number of possible techniques have already been proposed and studied to minimize this burn up swing such as proton current variation, use of burnable poisons, use of negative void coefficient, or multi-batch core operation. As we foresee MYRRHA as one of the very first ADS to be put in operation, we are excluding to use the proton beam variation to avoid the risk of unprotected incidents such as the abrupt increase of proton current when not needed. We can even accept the performance drop by 20% on average on the duration of the 90 days cycle but we decided to study the possibilities to compensate the k_s drop in MYRRHA if such a need would become a necessity. Among the possible techniques we are analyzing for use in MYRRHA we can cite the use of burnable absorber (possible candidates would be natural boron, enriched ^{10}B , Hf, ...), and the possible use of the negative void coefficient of LBE by introducing voided boxes in the periphery of the sub critical core. The purpose of this paper is to make an initial assessment of the applicability and effects of all these different techniques to the MYRRHA case. Finally, we will propose a concept of a realistic operational cycle in which voided boxes and/or burnable absorber (with different levels of enrichment) are used to minimize the burn up swing in the MYRRHA case.

Technical Session V :
ADS experiments and test facilities

Chairs: P. D'hont (SCK-CEN, Belgium) and V. Bhatnagar (EC)

Concept of Transmutation Experimental Facility

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The Japan Atomic Energy Research Institute (JAERI) is conducting a research and development program on the Accelerator Driven System (ADS) to transmute minor actinides (MAs) contained in the high-level radioactive waste. However, there exist several technical issues to be solved for the ADS in the fields of subcritical reactor physics coupled with a spallation neutron source, nuclear data of MA, controllability of hybrid system, feasibility of beam window from view points of corrosion / erosion by Pb-Bi, heat stress and irradiation effect, operation of high power spallation target, and so on. To overcome these difficulties, JAERI proposes the Transmutation Experimental Facility (TEF) in the framework of J-PARC (Japan Proton Accelerator Research Complex). The TEF consists of two satellite facilities: the Transmutation Physics Experimental Facility (TEF-P) and the ADS Target Test Facility (TEF-T). The TEF-P is a critical facility where 600MeV-10W proton beam can be introduced. The TEF-T is a material irradiation facility using 600MeV-200kW proton beam, where Pb-Bi target is installed, but neutron multiplication by nuclear fuel will not be attempted. In the TEF-P, many kinds of reactor physics experiments regarding the interaction between a spallation neutron source and a fast-neutron subcritical core are planned including the operation test of the subcritical core and the mock-up experiments with using MA fuel. The TEF-P can be operated also at the critical state without introducing the proton beam, which enables us to make precise measurements of reactivity effect. In the TEF-T, material irradiations by protons and neutrons are planned in the flowing Pb-Bi under various conditions of temperature. As the irradiation facility dedicated to the target development for the ADS, the TEF-T will produce lots of valuable data which are indispensable to the construction of next-step large-scale ADS.

Core neutronics assessment for TRADE experiments

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TRADE (TRIGA Reactor Accelerator Driven Experiment) will be a demonstration of the coupling of a real spallation source with a sub-critical reactor. A primary objective of the TRADE experiment is to validate the coupling of the different components of an ADS at power operating conditions using an existing critical reactor. In particular, one is interested in addressing the following issues:

- validation of the dynamic behaviour of an ADS at power with different levels of sub-criticality including start-up and shut-down procedures;
- validation of experimental methods for measurements of sub-criticality at power; assessment of external neutron source importance, search for an optimal sub-criticality level of operation;
- study of the relation between reactor power and proton current in the accelerator, and means to control reactivity of the system;
- compensation of power effect of the reactivity swing with control rods movements or with proton current variation.

The TRIGA core is a cylindrical structure immersed in water, which serves as primary coolant. The core forms an annulus with seven coaxial cylindrical rings of fuel elements. These rings are named by letters from A (central) to G (outer) ring and contain 127 possible locations. The numbering order starts with B-1 fuel element and is clockwise. There are three control rods: SH1 and SH2 (positions C10 and C7 respectively), and security rod SEC (position C4). In addition a regulation rod REG is situated at the position F1. The reactor core (~56.5 cm in diameter and ~72 cm high) is surrounded by graphite reflector and is immersed in a water tank.

Argonne National Laboratory (ANL) provides experimental, analytical, and calculational support for neutronics of the TRIGA reactor core. A number of neutronic codes with appropriate modeling of different reactor configurations are used for the core analysis. Monte Carlo approach (MCNP code) is primarily used for the purpose of benchmarking. A deterministic hexagonal model of the TRIGA core was created for DIF3D and ERANOS codes. This was done in order to fully exploit all features of modular ERANOS code. The group constants are generated with the WIMS-ANL lattice code. The DRAGON lattice code was also used for comparison.

In this study we mainly focus on the validation of experimental methods for measurements of sub-criticality (second bullet in the list of TRADE objectives above). In particular, ANL leads the experimental work at TRIGA for the assessment of physics characteristics of the core and provides calculation of MSM (Modified Source Method) factors needed to correct the value of measured subcritical reactivities.

At present time, several recent experimental configurations of the ENEA TRIGA reactor are available for the neutronic analysis. The first series of experiments was conducted in fall 2002 for several core configurations in order to: a) validate numerical tools; b) prepare the testing of sub-criticality measurements techniques. In total four critical configurations of the reactor were studied. Table 1 describes the four critical configurations. We analyzed all four configurations with Monte Carlo with real geometry (MCNP code) of the reactor and deterministic approaches with hexagonal geometry (ERANOS code) in order to prepare calculation scheme for the MSM factor calculation. The results are shown in Table 2 and display a consistency between both calculations.

CONTROL RODS POSITIONS				
	SH1 (C10)	SH2 (C7)	SEC (C4)	REG
CRITICAL 1	UP	UP	UP	751/800
Critical 1 notes	1) 2 assemblies (positions B1 and B5) are voided starting at the lower graphite section of a fuel pin up to 40 cm above the core with void diameter of 2.54 cm 2) 2 assemblies (positions B2 and B4) are filled with water			
CRITICAL 2	UP	DOWN	UP	402/800
Critical 2 notes	1 assembly (position B5) is voided up to 40 cm above the core			
CRITICAL 3	481/800	DOWN	UP	UP
Critical 3 notes	Core restored to normal			
CRITICAL 4	665/800	DOWN	UP	DOWN
Critical 4 notes	A graphite element (G19) is removed and the position is filled with water			

Table 1 Description of the recent critical configurations of the TRIGA reactor.

	MCNP (real geometry)	ERANOS (hexagonal geometry, diffusion)
CRITICAL 1	1.03206 ± 0.10%	1.03188
CRITICAL 2	1.02435 ± 0.11%	1.02972
CRITICAL 3	1.02371 ± 0.11%	1.02749
CRITICAL 4	1.02521 ± 0.10%	1.02744

Table 2 Results of the analysis of the four TRIGA critical configurations with MCNP and ERANOS codes.

The calculated k_{eff} are higher than measured criticality by ~2.5-3%. It is believed that this is related to the uncertainties in the fuel compositions, in particular to the absence of fission product in the fuel composition used in the calculations. A more detailed burn-up analysis is needed in order to assess this issue.

In the MSM approach the reactivity in a sub-critical system is measured according to the expression:

$$\rho = \rho_1 \frac{T_{d1} \varepsilon s}{T_d \varepsilon_1 s_1},$$

where $\text{MSM} = (\varepsilon/\varepsilon_1)(s/s_1)$, and ρ is reactivity, T_d is detector count rate, ε is detector efficiency, and s is external neutron source. The subscript 1 refers to a known (reference) sub-critical configuration, while quantities without subscript 1 refer to a studied configuration. Thus, the value of measured reactivity depends on the ratio of weighted reaction rates. Provided that the correction needed to eliminate fuel composition uncertainty does not produce significant local flux gradients at detector locations, one can adjust the fission spectrum in all four critical calculations in order to achieve sub-criticality and consequently calculate MSM factors. To make the system subcritical in all four configurations, we adjust the fission spectrum by the highest k_{eff} value as given by a transport calculation. The adjustment factor was calculated to be 0.96. With this adjustment we calculate the MSM factors.

In the full paper we will give the diagram of the core with corresponding values of MSM factor. Finally, we will present the analysis of the recent (October 2003) measurements. This time the experiment team has completed the reference MSM measures. There are 6 different core configurations, with 11 sub-critical and 1 critical measures, depending on regulation rod (REG) rod position.

Application of the HYPER System to the DUPIC Fuel Cycle

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In Korea, a lead-bismuth eutectic (LBE)-cooled accelerator-driven system (ADS), which is called HYPER (Hybrid Power Extraction Reactor) and rated at 1000 MWth output, is currently under development for the transmutation of TRUs (Transuranics) and LLFPs (Long-Lived Fission Products). Up to now, the HYPER system has been based on a simple PWR-HYPER fuel cycle, where the PWR spent fuels are directly transmuted in HYPER. In this paper, the HYPER system is applied to the DUPIC (Direct Use of PWR spent fuel in CANDU) fuel cycle, where PWR spent fuels are used in CANDU reactors and the spent fuel of CANDU is transmuted by the HYPER system.

A PWR-CANDU tandem cycle has been studied in Korea to improve the fuel cycle cost and to minimize the spent fuel volume of the CANDU reactors. It has been found that a PWR spent fuel can be directly reutilized in CANDU after a very simple fuel re-fabrication process, which is considered highly proliferation-resistant. The DUPIC process leads to a significantly reduced amount of spent fuel, compared with the conventional CANDU fuel cycle based on the natural uranium fuel.

The objective of this study is to investigate the TRU and LLFP transmutation potential of the HYPER core for the DUPIC fuel cycle. A DUPIC spent fuel is reprocessed with a simple proliferation-resistant pyroprocessing which was previously adopted in the HYPER fuel cycle. All the previously-developed HYPER design concepts were applied to the new core design except that the fuel is composed of TRUs from the DUPIC spent fuel. The core characteristics of HYPER are analyzed with the REBUS-3/DIF3D code system.

Numerical comparisons between neutronic characteristics of MUSE4 configurations and XADS-type models

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In the field of waste management incorporating a transmutation option, accelerator driven systems (ADSs) represent an important alternative to conventional reactors due to their higher safety level when minor actinides such as neptunium and americium are loaded into the core. It has accordingly become necessary to extend the validation domain of calculational methods for critical fast reactors to the analysis of source-driven subcritical configurations.

To reach this goal, an experimental programme has been established at the MASURCA facility at CEA-Cadarache (France), called MUSE. In particular, the MUSE4 phase consists of the coupling of the PuO₂/UO₂+Na core with an external neutron source of high intensity. This has been achieved by employing a specially constructed neutron pulsed generator, called GENEPI, which produces monoenergetic neutrons via either a D(d,n)He³ or a T(d,n)He⁴ reaction. More generally, these measurements constitute an important experimental database to be used in validating the calculational methods and data employed in the analysis of the neutron coupling in ADS-type configurations.

In this context, specific investigations have been performed to study the representativity of MUSE4 configurations with respect to alternative ADS concepts (XADS). In other words, analysis has been conducted to quantify the possible contribution of the MUSE4 project to access to a validated numerical code, which could then be used to design an ADS demonstrator.

The first step of this work has been to define simplified RZ models for different XADS types, related to the more heterogeneous systems currently being considered. These models are:

RZ-XADS model with MOX fuel and sodium coolant

RZ-XADS model with MOX fuel and a lead/bismuth coolant

RZ-XADS model with MOX fuel and a gas coolant

To compare these systems with the MUSE4 RZ-models, it has been chosen to use the ERANOS deterministic calculational scheme and to define the spallation source for the XADS models, where the external source input (energy of neutrons lower than 20 MeV) has been obtained from recent MCNPX calculations. The parameters studied are primarily the multiplication factor (k_{eff}), the effectiveness of the source (φ^*), and some spectral indices at different core locations. For each parameter and for each system, sensitivity and uncertainty calculations (due to the nuclear data) have been performed.

To summarise the findings, the representativity of the MUSE4 configurations is, in general, quite satisfactory with respect to XADS-Na and XADS-gas. However, in the case of the XADS-Pb/Bi system, effects of the significant uncertainties associated with the nuclear data of lead and bismuth have been clearly highlighted. In this context, the present study has indicated the desirability of new, more specific experiments for XADS-Pb/Bi validation.

Reaction of Pb Bonding between Fuel and Cladding

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The blanket fuel assembly for HYPER(Hybrid Powder Extraction Reactor) contains a bundle of pins arrayed in a triangular pitch which has a hexagonal bundle structure. The reference blanket fuel pin consists of the fuel slug of the TRU-xZr(x=50-60wt%) alloy and it is immersed in lead for thermal bonding with the cladding HT9.

In this study, U-55wt%Zr alloy fuel was fabricated instead of the actual TRU-Zr fuel and HT9 is used for the cladding material. In order to clarify reaction and diffusion characteristics of Pb bonding between fuel and cladding, a series of experiment has been executed with fuel and cladding in Pb melt at 650, 700 and 750°C for 100 to 500hrs. The composition of diffusion layers and reaction products, and the diffusion depth were analyzed by using SEM/EDS.

**Experimental Verification of Selected Transmutation Technology and Materials for Basic Components of a Demonstration Transmuter with Liquid Fuel based on Molten Fluorides
(Development of New technologies for Nuclear Incineration of PWR Spent Fuel in the Czech Republic)**

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The development of the project SPHINX (Spent Hot fuel Incineration by Neutron fluX) of transmutation technology in the Czech Republic is based on the utilization of a subcritical system with liquid fuel based on molten fluorides. For an experimental testing of the system and individual technological components as well as new developed materials which should be resistant in the environment of molten fluorides at the operational temperatures the own existing experimental facilities, long term experience and know-how have been used, to which the following belongs in particular:

- Experimental reactors LR-0 and VR-1 with inserted zones for the investigation of neutronic characteristics of transmuter blanket cores.
- Research reactor LVR-15 with instrumented probes for transmuter blanket samples testing in high neutron flux conditions.
- Experimental loops with molten fluoride salts for an investigation of transmuter systems operational conditions.
- Know-how in the field of fluorine technology gained in the frame of a long-term R&D activity in spent fuel reprocessing by a dry method.

The whole project is based upon the activity of the national consortium TRANSMUTAION having been established in November 1996 by four leading institutions in nuclear research:

Nuclear Research Institute Rez plc, Nuclear Physics Institute of Academy of Sciences, SKODA Nuclear Machinery Ltd. and Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague to whom Technical University in Brno has associated in the year 2000.

After successful finishing of the first stage (1998-2000) of the project which represented an R&D program for elaboration of complex input for designing of an experimental transmutation system on zero power level, the second stage (which will focus on an experimental verification of selected transmutation technology for a design development of basic components of a demonstration transmuter on the power level of 10 MW) has been approved for the period of 2000 up to 2003 and necessary funding was provided by governmental authorities of the Czech Republic as well as the future utilities of the developed technology like the Radwaste Repository Agency, Czech Electricity Generating Board, SKODA Works comp. and others.

The substantial part of the project has been incorporated in suitable forms of international collaboration:

1. the project MOST (Molten Salt Technology) of the European Commission 5th Framework Program,
 2. a bilateral contract with the Kurchatov Institute in Moscow
- might be supposed the most useful ones in particular. The individual parts of the project as well as the whole complex are being proposed into another convenient forms of a multinational co/operation, too.

There are some of the experimental and test facilities described in the paper and some of the latest results of the experiments a tests performed will be introduced there as well.

Closing Session:
*Technical session summary and Working group discussion
summary*

Chairs: R. Sheffield (LANL, USA) and B.H. Choi (KAERI, Korea)

Map of the INTEC meeting rooms

To be provided at the registration

Map to the KAERI Guest Restaurant

To be provided at the registration