EXECUTIVE SUMMARY

Introduction

Accelerator-driven systems (ADS), i.e. a subcritical system driven by an accelerator in order to sustain a chain reaction, are being considered for their potential use in the transmutation of nuclear waste. The performance of such hybrid nuclear systems depends to a large extent on the specification and reliability of high-power accelerators, as well as on the integration of the accelerator with spallation targets and subcritical systems. Much R&D is still required in order to demonstrate the desired capability as a whole system.

A series of workshops on "Utilisation and Reliability of High Power Proton Accelerators" is thus organised by the Nuclear Science Committee of the OECD Nuclear Energy Agency (NEA). The first meeting in this series was held in Mito, Japan on 13-15 October 1998, and the second and third meetings followed in Aix-en-Provence, France on 22-24 November 1999 and in Santa Fe, New Mexico, USA on 12-16 May 2002, respectively. Accelerator scientists and reactor physicists gathered at the NEA workshops to discuss issues of common interest and to present the most recent achievements in their research.

The present workshop (fourth in the series) took place in Daejeon, Republic of Korea on 16-19 May 2004 and was hosted by the Korea Atomic Energy Research Institute (KAERI).

Topics covered by the workshop

The workshop began with a general session involving 15 invited papers covering large national/ international accelerator programmes and ADS applications. Thirty-eight (38) contributed papers were presented during five technical sessions and three working group discussion sessions were organised. Topics covered by the five technical sessions included:

- accelerator reliability;
- target, window and coolant technology;
- subcritical system design and ADS simulations;
- safety and control of ADS;
- ADS experiments and test facilities.

The three working group discussions covered the following topics:

- accelerators;
- subcritical systems and interface engineering;
- safety and control of ADS.

Summary of the technical sessions

Accelerator reliability

Eleven (11) papers were contributed covering issues on ADS accelerator system designs, subcomponent operation, beam dynamics aspects and SNS commissioning. Regarding the ADS accelerator designs, three out of four designs (European PDS-XADS, Japanese and US SC accelerators, FFAG at Kyoto University) presented at the meeting were based on a superconducting linac solution. As for subcomponent operation, high availability of proton sources, RFQs, PSI beam line operation experimental results and test results with spoke cavities were presented. Aspects of fault tolerance in RF and magnets were discussed. Furthermore, it was reported that analytical and numerical methods can be used to assess sensitivity to fabrication tolerances in such devices as RFQ or periodic beam lines.

Target, window and coolant technology

Nine papers were presented. Recent results were obtained from LBE corrosion loops in Japan and Korea. In the windowless target designs, experimental results of vacuum gas dynamics investigations in the TRASCO programme and those of the vacuum interface compatibility experiment in the MYRRHA programme were reported. Concerning target and beam window designs, the performance of a dual injection tube introduced in KAERI's HYPER target and results of the target and window design study for JAERI's ADS were presented. Two papers from China and Japan were presented on calculation methodologies for spallation isotope yield predictions. Finally, CFD analysis results for an XADS target were reported for both steady state and transient cases from FZK.

Subcritical system design and ADS simulations

Six papers were presented covering research/demo facility designs, conceptual design of a full-scale transmuter, ADS component design and benchmark results on beam trips. Core and/or component design studies from the Kyoto University Critical Assembly (KUCA), the TRADE experiment, the MYRRHA programme, a Cascade Subcritical Molten Salt Reactor (CSMSR) were reported showing a visible convergence for Pb-Bi systems but with a large variety of core designs, fuel options and fuel cycle. Calculation results from the second phase of the NEA ADS beam trip benchmark were presented. These benchmark results included a sensitivity analysis on the main parameters.

Safety and control of ADS

Seven papers were presented. Two papers – very design specific – were presented describing the WP2 results of the PDS-XADS project. The two 80 XADS designs were covered, with the conclusion that a Pb-Bi reactor ADS has significant safety characteristics, particularly if it has a low Δp and a high natural circulation flow rate and if a gas-cooled system has a short period for beam shutoff. Any

pump-driven system will lie between these two. A paper reported that the new Pb-Bi loop can provide neutral circulation, etc., which is useful only for a Pb-Bi system. An interesting paper presented a proposal for dynamic control of an ADS by linking. The use of void boxes with mini cycles was discussed in order to control reactivity swings as well as plans to examine burnable poisons. Finally, a paper compared PDS-ADS Pb-Bi 80 MW and the reactor design considered as part of the EU FUTURE project.

ADS experiments and test facilities

Five papers were presented. JAERI reported the current status of the Transmutation Experimental Facility (TEF) within the framework of J-PARC (Japan Proton Accelerator Research Complex). The TEF consists of TEF-P (transmutation physics experiments with MA nitride fuel) and TEF-T (material irradiation tests). The Czech Republic presented the project SPHINX (spent hot fuel incineration by neutron flux), which is based on a subcritical system with liquid molten fluoride fuel. KAERI presented the HYPER system preliminary design features and the performance analysis for the DUPIC fuel cycle. Numerical comparisons between neutronic characteristics of MUSE4 configurations and XADS-type models with different coolants (Na, Pb/Bi, gas) were reported by PSI. Finally, KAERI presented a paper on the Pb bonding reaction between fuel and cladding, which includes the fabrication process and a thermal stability study on U-Zr fuel.

Summary of the working group discussion sessions

Accelerators

Discussions were held on several topics such as availability, reliability, high intensity and efficiency, etc. After having worked out solutions to some of the key questions (such as *What accelerator type is "best"? → Try SC linac; What are the costs? → First estimates available for prototype machines; What is the energy consumption? → Expected energy efficiency is a maximum of ~50%)*, there are still a few remaining open questions and trying to answer them at present would merely be guesswork. Questions such as *When will what accelerator be fully operational?* and *When will the trip rate reach the desired value?* are still waiting to be answered in the future. The prototypes now under construction will help us in providing answers to these questions and many smaller issues. Details on the discussions can be found in the summary of working group discussion sessions at the end of these proceedings.

Subcritical systems and interface engineering

To understand better the current situation and to identify future R&D needs, six questions were raised: (1) the role of P&T vs. deep geological repository; (2) the role of ADS – only for a transitional period between the present LWRs and the future fast reactor-dominated situation; (3) international co-operation for ADS deployment; (4) window or windowless target – which is the best solution; (5) is there a need for a windowless MEGAPIE experiment; (6) what are the consequences of a window break. Various reactions to each question were discussed and the details can be found in the summary of working group discussion sessions at the end of these proceedings.

Safety and control of ADS

Discussions were held on safety activities, safety guidelines for core melt and design basis accidents, and ADS reactivity control (shutdown, burn-up control). Details on the discussions can be found in the summary of working group discussion sessions at the end of these proceedings. In addition, the working group proposed to the OECD/NEA Nuclear Science Committee a safety-related benchmark as a follow-up activity to the ongoing beam trip benchmarks. The proposed benchmark would consider 800 MW transmuters with Pb-Bi coolant and MA load fuel for both BOC and EOC.

Next workshop

A follow-up workshop has been planned for spring 2006 in Belgium.

TABLE OF CONTENTS

Foreword 3

Executive Summary 11

Welcome 15

D-S. Yoon
Congratulatory Address 17

I-S. Chang
Welcome Address 19

G.H. Marcus
OECD Welcome 21

GENERAL SESSION: ACCELERATOR PROGRAMMES AND APPLICATIONS 23

CHAIRS: B-H. CHOI, R. SHEFFIELD

T. Mukaiyama
Background/Perspective 25

M. Salvatores
Accelerator-driven Systems in Advanced Fuel Cycles 27

S. Noguchi
Present Status of the J-PARC Accelerator Complex 37

H. Takano
R&D of ADS in Japan 45

R.W. Garnett, A.J. Jason
Los Alamos Perspective on High-intensity Accelerators 57

J-M. Lagniel
French Accelerator Research for ADS Developments 69

T-Y. Song, J-E. Cha, C-H. Cho, C-H. Cho, Y. Kim, B-O. Lee, B-S. Lee, W-S. Park, M-J. Shin
Hybrid Power Extraction Reactor (HYPER) Project 81

V.P. Bhatnagar, S. Casalta, M. Hugon
Research and Development on Accelerator-driven Systems in the EURATOM 5th and 6th Framework Programmes 89

S. Monti, L. Picardi, C. Rubbia, M. Salvatores, F. Troiani
Status of the TRADE Experiment 101

P. D'hondt, B. Carluec
The European Project PDS-XADS "Preliminary Design Studies of an Experimental Accelerator-driven System" 113

F. Groeschel, A. Cadiou, C. Fazio, T. Kirchner, G. Laffont, K. Thomsen
Status of the MEGAPIE Project 125

P. Pierini, L. Burgazzi
ADS Accelerator Reliability Activities in Europe 137

W. Gudowski
ADS Neutronics 149

P. Coddington
ADS Safety 151

Y. Cho
Technological Aspects and Challenges for High-power Proton Accelerator-driven System Application 153

TECHNICAL SESSION I: ACCELERATOR RELIABILITY 163

CHAIRS: A. MUELLER, P. PIERINI

D. Vandeplassche, Y. Jongen (for the PDS-XADS Working Package 3 Collaboration)
The PDS-XADS Reference Accelerator 165

N. Ouchi, N. Akaoka, H. Asano, E. Chishiro, Y. Namekawa, H. Suzuki, T. Ueno, S. Noguchi, E. Kako, N. Ohuchi, K. Saito, T. Shishido, K. Tsuchiya, K. Ohkubo, M. Matsuoka, K. Sennyu, T. Murai, T. Ohtani, C. Tsukishima
Development of a Superconducting Proton Linac for ADS 175

C. Miélot
Spoke Cavities: An Asset for the High Reliability of a Superconducting Accelerator; Studies and Test Results of a $\beta = 0.35$, Two-gap Prototype and its Power Coupler at IPN Orsay 185

X.L. Guan, S.N. Fu, B.C. Cui, H.F. Ouyang, Z.H. Zhang, W.W. Xu, T.G. Xu
Chinese Status of HPPA Development 195

J.L. Biarrotte, M. Novati, P. Pierini, H. Safa, D. Uriot
Beam Dynamics Studies for the Fault Tolerance Assessment
of the PDS-XADS Linac 203

P.A. Schmelzbach
High-energy Beat Transport Lines and Delivery System
for Intense Proton Beams 215

M. Tanigaki, K. Mishima, S. Shiroya, Y. Ishi,
S. Fukumoto, S. Machida, Y. Mori, M. Inoue
Construction of a FFAG Complex for ADS Research in KURRI 217

G. Ciavola, L. Celona, S. Gammino, L. Andò, M. Presti,
A. Galatà, F. Chines, S. Passarello, XZh. Zhang, M. Winkler,
R. Gobin, R. Ferdinand, J. Sherman
Improvement of Reliability of the TRASCO
Intense Proton Source (TRIPS) at INFN-LNS 223

R.W. Garnett, F.L. Krawczyk, G.H. Neuschaefer
An Improved Superconducting ADS Driver Linac Design..... 235

A.P. Durkin, I.V. Shumakov, S.V. Vinogradov
Methods and Codes for Estimation of Tolerance
in Reliable Radiation-free High-power Linac 245

S. Henderson
Status of the Spallation Neutron Source Accelerator Complex 257

TECHNICAL SESSION II: TARGET, WINDOW AND COOLANT TECHNOLOGY..... 265

CHAIRS: X. CHENG, T-Y. SONG

Y. Kurata, K. Kikuchi, S. Saito, K. Kamata, T. Kitano, H. Oigawa
Research and Development on Lead-bismuth Technology
for Accelerator-driven Transmutation System at JAERI 267

P. Michelato, E. Bari, E. Cavaliere, L. Monaco, D. Sertore,
A. Bonucci, R. Giannantonio, L. Cinotti, P. Turroni
Vacuum Gas Dynamics Investigation and Experimental Results
on the TRASCO ADS Windowless Interface 279

J-E. Cha, C-H. Cho, T-Y. Song
Corrosion Tests in the Static Condition and Installation
of Corrosion Loop at KAERI for Lead-bismuth Eutectic 291

P. Schuurmans, P. Kupschus, A. Verstrepen, J. Cools, H. Aït Abderrahim
The Vacuum Interface Compatibility Experiment (VICE)
Supporting the MYRRHA Windowless Target Design 301

C-H. Cho, Y. Kim, T-Y. Song
Introduction of a Dual Injection Tube for the Design
of a 20 MW Lead-bismuth Target System 313

H. Oigawa, K. Tsujimoto, K. Kikuchi, Y. Kurata, T. Sasa, M. Umeno, K. Nishihara, S. Saito, M. Mizumoto, H. Takano, K. Nakai, A. Iwata
Design Study Around Beam Window of ADS 325

S. Fan, W. Luo, F. Yan, H. Zhang, Z. Zhao
Primary Isotopic Yields for MSDM Calculations of Spallation
Reactions on ^{280}Pb with Proton Energy of 1 GeV 335

N. Tak, H-J. Neitzel, X. Cheng
CFD Analysis on the Active Part of Window Target Unit
for LBE-cooled XADS 343

T. Sawada, M. Orito, H. Kobayashi, T. Sasa, V. Artisyuk
Optimisation of a Code to Improve Spallation Yield Predictions
in an ADS Target System 355

TECHNICAL SESSION III: SUBCRITICAL SYSTEM DESIGN AND ADS SIMULATIONS 363

CHAIRS: W. GUDOWSKI, H. OIGAWA

T. Misawa, H. Unesaki, C.H. Pyeon, C. Ichihara, S. Shiroya
Research on the Accelerator-driven Subcritical Reactor at the Kyoto
University Critical Assembly (KUCA) with an FFAG Proton Accelerator 365

K. Nishihara, K. Tsujimoto, H. Oigawa
Improvement of Burn-up Swing for an Accelerator-driven System 373

S. Monti, L. Picardi, C. Ronsivalle, C. Rubbia, F. Troiani
Status of the Conceptual Design of an Accelerator
and Beam Transport Line for Trade 383

A.M. Degtyarev, A.K. Kalugin, L.I. Ponomarev
Estimation of some Characteristics of the
Cascade Subcritical Molten Salt Reactor (CSMSR) 393

F. Roelofs, E. Komen, K. Van Tichelen, P. Kupschus, H. Aït Abderrahim
CFD Analysis of the Heavy Liquid Metal Flow Field
in the MYRRHA Pool 401

A. D'Angelo, B. Arien, V. Sobolev, G. Van den Eynde, H. Aït Abderrahim, F. Gabrielli
Results of the Second Phase of Calculations Relevant to
the WPPT Benchmark on Beam Interruptions 411

TECHNICAL SESSION IV: SAFETY AND CONTROL OF ADS 423

CHAIRS: J-M. LAGNIEL, P. CODDINGTON

P. Coddington, K. Mikityuk, M. Schikorr, W. Maschek, R. Sehgal, J. Champigny, L. Mansani, P. Meloni, H. Wider
Safety Analysis of the EU PDS-XADS Designs 425

X-N. Chen, T. Suzuki, A. Rineiski, C. Matzerath-Boccaccini, E. Wiegner, W. Maschek
Comparative Transient Analyses of Accelerator-driven Systems with Mixed Oxide and Advanced Fertile-free Fuels 439

P. Coddington, K. Mikityuk, R. Chawla
Comparative Transient Analysis of Pb/Bi and Gas-cooled XADS Concepts 453

B.R. Sehgal, W.M. Ma, A. Karbojian
Thermal-hydraulic Experiments on the TALL LBE Test Facility 465

K. Nishihara, H. Oigawa
Analysis of Lead-bismuth Eutectic Flowing into Beam Duct 477

P.M. Bokov, D. Ridikas, I.S. Slessarev
On the Supplementary Feedback Effect Specific for Accelerator-coupled Systems (ACS) 485

W. Haeck, H. Aït Abderrahim, C. Wagemans
K_{eff} and K_s Burn-up Swing Compensation in MYRRHA 495

TECHNICAL SESSION V: ADS EXPERIMENTS AND TEST FACILITIES 505

CHAIRS: P. D'HONDT, V. BHATNAGAR

H. Oigawa, T. Sasa, K. Kikuchi, K. Nishihara, Y. Kurata, M. Umeno, K. Tsujimoto, S. Saito, M. Futakawa, M. Mizumoto, H. Takano
Concept of Transmutation Experimental Facility 507

M. Hron, M. Mikisek, I. Peka, P. Hosnedl
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) 519

Y. Kim, T-Y. Song
Application of the HYPER System to the DUPIC Fuel Cycle 529

M. Plaschy, S. Pelloni, P. Coddington, R. Chawla, G. Rimpault, F. Mellier
Numerical Comparisons Between Neutronic Characteristics of MUSE4 Configurations and XADS-type Models 539

B-S. Lee, Y. Kim, J-H. Lee, T-Y. Song
Thermal Stability of the U-Zr Fuel and its Interfacial Reaction with Lead 549

SUMMARIES OF TECHNICAL SESSIONS 557

CHAIRS: R. SHEFFIELD, B-H. CHOI

Chairs: A.C. Mueller, P. Pierini
Summary of Technical Session I: Accelerator Reliability 559

Chairs: X. Cheng, T-Y. Song
Summary of Technical Session II: Target, Window
and Coolant Technology 565

Chairs: W. Gudowski, H. Oigawa
Summary of Technical Session III: Subcritical System Design
and ADS Simulations 571

Chairs: J-M. Lagniel, P. Coddington
Summary of Technical Session IV: Safety and Control of ADS 575

Chairs: P. D'hondt, V. Bhatagnar
Summary of Technical Session V: ADS Experiments and Test Facilities..... 577

SUMMARIES OF WORKING GROUP DISCUSSION SESSIONS 581

CHAIRS: R. SHEFFIELD, B-H. CHOI

Chair: P.K. Sigg
Summary of Working Group Discussion on Accelerators 583

Chair: W. Gudowski
Summary of Working Group Discussion on Subcritical Systems
and Interface Engineering 587

Chair: P. Coddington
Summary of Working Group Discussion on Safety and Control of ADS..... 591

Annex 1: List of workshop organisers 595

Annex 2: List of participants 597