IAEA ACTIVITIES IN THE AREA OF PROTON ACCELERATOR APPLICATIONS

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The IAEA accelerator related activities address nuclear science and nuclear energy topics, and are implemented as a joint effort between the Departments of Nuclear Applications and Nuclear Energy. The IAEA is pursuing efforts on utilizing accelerators to support the research, development and deployment of materials of nuclear interest and concomitantly, the training and qualification of a highly educated nuclear workforce. Ageing studies on materials of nuclear interest to predict their in-service behavior is an area of topical interest in nuclear science with the IAEA and its Member States, and in which accelerators can play a key role in analytical applications and in simulating radiation damage at fast fission and fusion relevant conditions. At the back end of the nuclear fuel cycle, environmental concerns linked with the long half-life radioisotopes generated from nuclear fission have led to increased R&D efforts to develop a technology aimed at reducing the amount of radioactive waste through transmutation in either fast fission reactors or accelerator driven systems. In the framework of the project on Technology Advances in Fast Reactors and Accelerator Driven Systems, the IAEA has implemented a number of initiatives on utilization of plutonium and transmutation of long-lived radioactive waste, accelerator driven systems, thorium fuel options, innovative nuclear reactors and fuel cycles, non-conventional nuclear energy systems, and fusion/fission hybrids. This paper gives an overview of IAEA's accelerator related activities in nuclear science for materials development, and partitioning and transmutation of nuclear waste.

I. INTRODUCTION

Accelerators can provide some of the best analytical techniques and applications in a diverse range of fields such as materials science, environmental science, cultural heritage and the biosciences. The effective utilization of accelerators is being promoted through participation in knowledge building activities, the development and application of innovative nuclear science, and the development of innovative nuclear energy systems. These areas offer a broad spectrum of activities for the development, and new applications of accelerators and accelerator based techniques.

The IAEA's activities based under the subprogramme "Utilization of Accelerators and Instrumentation" have been described in a previous paper[1]. Some main topics were the application of low-energy accelerators and the new world survey of accelerator based analytical techniques. A dedicated report on the "international collaboration of the IAEA in utilization of accelerator-based analytical facilities" will be given during the conference[2] and will not be part of this report.

This report will describe the latest developments as supported by the IAEA in the field of low-energy accelerators, especially the use for cultural heritage, for medium energy accelerators and their use for the effective production of neutrons. The main emphasis of the work of the IAEA is on training and education. In the field of education the IAEA is working together with the Abdus Salam International Center of Theoretical Physics (ICTP), Trieste, Italy. The new requirements on structural materials for fission and fusion request the use of accelerators and new modelling efforts. The IAEA has coordinated research projects on this topic, but would like to increase their efforts, on request by the Member States.

II. ADVANCED MATERIALS IN NUCLEAR SCIENCE AND APPLICATIONS

II.A. Low Energy Accelerators

Low energy accelerators are mainly used for applied research and industrial applications today. In view of this, but taking into account the needs for developing countries to be part of the latest developments in this field, the IAEA has Coordinated Research Projects (CRPs) on nuclear microprobe techniques, accelerator mass spectrometry, and ion beam analysis. Additionally the IAEA established a Particle Induced X-ray Emission/ Rutherford Backscattering Spectrometry (PIXE/RBS) beamline in Zagreb.[1] A new development as supported by the IAEA is the use of accelerators in conservation of cultural heritage.

Nuclear analytical techniques are more and more used in the fields of art and archaeology. "Curators at top museums in Europe and the United States have long reached for the instruments of nuclear science to hit treasures of art with invisible rays,” the *New York Times* feature reports. “The resulting clues have helped answer vexing questions of provenance, age and authenticity.” The methods include neutron activation analysis, proton-induced X-ray emission, accelerator mass spectrometry and X-ray fluorescence spectrometry. Art and archaeological objects offer some unique challenges for researchers. First, they are almost always extraordinarily inhomogeneous across individual pieces and across types. Second, they are often valuable and delicate so sampling is discouraged. Finally, in most cases, each piece is unique, thus the data is also unique and is of greatest value when incorporated into the overall understanding of the object or of the culture of the artisan. Ion Beam Analysis (IBA) solves many of these problems. With IBA, it is possible to avoid sampling by using an external beam setup or by manipulating small objects in a vacuum. The technique is largely non-destructive, allowing for multiple data points to be taken across an object. The X-ray yields are from deeper in the sample than those of other techniques and using RBS one can attain bulk concentrations from microns into the sample. And finally, the resulting X-ray spectra is easily interpreted and understood by many conservators and curators, while PIXE maps are a wonderful visual record of the results of the analysis.

The IAEA has initiated multiple coordinated research projects in this field, using neutron, IBA, or XRF techniques[3].

II.B. Medium Energy

Materials science and biomedical research are driving developments of accelerators, novel analytical techniques, and improved nuclear instrumentation. In the medium to high energy regime, synchrotron light sources are in increasing demand by large user communities. The IAEA is supporting the synchrotron light source in the Middle East (SESAME), see Chapter III.B., mainly through fellowships. Visits and fellowships to other synchrotron sources like Diamond in United Kingdom, Soleil in France, and Australian Synchrotron are supported by the IAEA too. Support to experimental research is provided through a coordinated research project on improving the neutron flux at spallation sources.

II.B.1. Efficient Moderators at Spallation Sources

For over 50 years research reactors have supported developments in neutron beam research, new materials, and component integrity testing, and are expected to continue to do so in the coming decades. The scientific and technological problems being addressed using neutron beams are becoming increasingly large and complex that research reactors alone will not be able to cater to all the requirements. They will need to be complemented by neutron beams from spallation neutron sources, where the extremely high peak neutron fluxes and time structure of the pulsed neutron beam opens up numerous new experimental opportunities. Higher intensity spallation sources have become operational in 2006; SNS in USA and SINQ with the Megapie target in Switzerland. Conceptual designs for extremely high current machines are in an advanced stage and await sufficient investments to emerge.

However, providing a worldwide access to these techniques cannot be accomplished by the few high-energy spallation neutron sources alone. A broad network of low-medium energy facilities is needed to render accessibility, availability to a wider community, to allow the development of new techniques and applications, and to train new users and operators. Such a network will enhance the impact of the major facilities, for many emerging economies and the developing nations have a keen interest to expand opportunities in education, research, and industrial applications, using nuclear technology, but they do not always have sufficient resources, technology, or trained manpower to establish facilities suitable for these tasks.

The IAEA has initiated a CRP on *Improved production and utilization of short pulsed, cold neutrons at low-medium energy spallation neutron sources* to enhance the utilization possibilities of low and medium energy spallation neutron sources for research and development in neutron science and applications, by increasing neutron supply at sources and by improving optimum use of neutron techniques in interested Member States.

III. EDUCATION AND TRAINING

The enhancement of nuclear science education and training in all of the IAEA’s Member States, but in particular the developing countries, is of interest to the IAEA since many of these countries are building up their scientific infrastructures but are lacking in sufficient numbers of highly educated and well qualified persons. This may arise from amongst other things, a lack of upcoming candidates who would qualify to receive specialized training, a lack of institutions available to train nuclear science technologists and specialists i.e. those institutions with an established programme of research, and the potential loss of valuable knowledge due to ageing of the current nuclear work force.

III.A. Schools on Accelerators and Applications

Recognizing a need to enhance educational and research opportunities for young nuclear professionals, the IAEA in collaboration with the ICTP holds a number of specialist educational schools and training workshops annually. Recently held schools at ICTP include *School on Pulsed Neutron Sources: Enhancing the Capacity for*

Materials Science (17-28 October 2005), *Technology and Applications of Accelerator Driven Systems (ADS)* (17-28 October 2005) and *School of Ion Beam Analysis and Accelerator Applications* (13-24 March 2006). Lecture notes from these, and other ICTP events, are freely available to the wider scientific community and accessible online via ICTP's web page http://www.ictp.it/pages/events/calendar.html.

Related forthcoming events in 2007-2008 are *School on Pulsed Neutrons: Characterization of Materials* (15-26 October 2007), *School on Physics, Technology and Applications of Accelerator Driven Systems* (19-30 November 2007), *Advanced Workshop on Model Codes for Spallation Reactions* (4-8 February 2008), *Workshop on Nuclear Reaction Data for Advanced Reactor Technologies* (19-30 May 2008) and *Workshop on the Training in Basic Radiation Materials Science and its Applications to Radiation Effect Studies and Development of Advanced Radiation Resistant Materials* (10-21 November 2008).

The Schools on Accelerator Driven Systems, like other courses, offer to graduate level students a curriculum comprising the theoretical foundation of all ADS design aspects (i.e. high-power accelerator, spallation target, and sub-critical blanket), modern theoretical models used to predict nuclear reaction cross sections, principles of data libraries evaluation methodology, and system simulation codes. Lectures and computer simulation exercises are combined to offer as much as possible a "hands-on" experience.

III.B. Support to Evolving Institutions and Networks

History has shown that establishing well-supported programs of scientific research is a very effective means of developing and stimulating talented researchers and knowledgeable educators. Many Member States are thus increasing investments in new enabling technologies that boost their research and manpower capabilities. Such national developments can also support a longer-term objective to develop a knowledge base from which to engage and increase participation in activities at advanced nuclear facilities such as include high flux research reactors, synchrotron light sources, spallation neutron sources, and ion beam accelerators.

It is widely recognized that solutions for many of today's pressing problems require a multidisciplinary approach using a variety of complementary analytical techniques. Member States desire mechanisms whereby researchers can increase their knowledge and utilization in advanced nuclear technologies much beyond what could be acquired using national facilities alone. Strong and nationally available research facilities, in combination with regionally and internationally facilitated access to major nuclear research facilities, can provide Member States with the best of experimental conditions to support their own research programs. This effective utilization of global resources can prove beneficial for Member States geographically or scientifically isolated from major research facilities, as is often the case for many developing countries.

In 2006, a joint IAEA-ICTP initiative helped form a new scientific network, termed the Accelerators for Sustainable Development in Africa (ASDA) Network. Its main role is to address a strong demand for knowledge and technology transfer related to accelerator applications and accelerator-based analytical techniques in the Sub-Saharan region of Africa. Network activities will be implemented through regional workshops, seminars, and scientific collaborations. Its membership in 2007 comprises 16 interested parties from 6 countries (Egypt, Ghana, Mozambique, Nigeria, South Africa, and Sudan).

SESAME (Synchrotron-light for Experimental Science and Applications in the Middle East) and the IAEA share the goal of promoting regional and international cooperation through the peaceful use of science. An inter-regional project entitled *Support for Human Capacity Building in the Utilization and Operation of SESAME* is under implementation since January 2007 and will go on for a period of 4 years. It will essentially support training of fellows and the provision of expert advice.

IV. STRUCTURAL MATERIALS AND FUEL DEVELOPMENT

The core structural materials of fission reactors have to retain their functionality for maintaining integrity of the fuel (rods and assemblies) and preventing radioactivity release to the coolant. Materials behavior under irradiation has been studied for more than 50 years, but still the major experience belongs to the area of "thermal reactor materials" (Fig. 1) where core structural materials are subject to temperatures up to 400ºC and damages up to 20 dpa (for a typical LWR fuel cladding at a burnup of 40 GWd/tU).

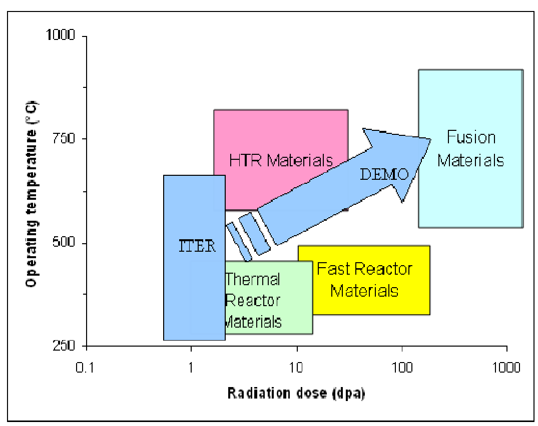

Fig. 1. Growing operational requirements for thermal and future innovative nuclear systems.

ITER will experience 100–300ºC and damages of about 3 dpa from 14 MeV neutrons. In the prototype fusion power reactor DEMO the operating temperatures are expected to be in the range of 500–1000ºC and damage will reach ~150 dpa at the end of five years of full power operation, while radiation doses in future commercial fusion power reactors can be several times higher.

The cost and duration of direct irradiation testing of new radiation resistant materials for these innovative nuclear systems are raising accordingly that makes such experiments practically impossible and requires alternative development of accelerator simulation tools and theoretical models of radiation damage for prediction of material behavior in real operational conditions. That is why it was agreed between the IAEA Departments of Nuclear Energy and Nuclear Sciences and Applications to launch in 2008, a CRP on *Accelerator Simulation and Theoretical Modeling of Radiation Effects* aimed at improvement of irradiation tools and methods, joint experimental studies of perspective structural materials and development of theoretical models of radiation damage. By now the project is mostly targeting the improvement, development and testing of core structural materials for higher burnups in light water reactors and for applications in advanced fast reactors. Depending on demands from the Member States fusion-oriented tasks can be easily integrated due to the common nature of the material-related problems in advanced fission and fusion reactors.

For the sake of knowledge preservation and transfer the IAEA has been carrying out a number of expert reviews on properties and radiation behavior of nuclear structural materials including both traditional (“thermal”) materials like zirconium and new reduced activation ferritic-martensitic and oxide dispersion strengthened (ODS) steels, which are considered for both advanced fission (“fast”) and future ADS and fusion reactors.

V. ACCELERATOR DRIVEN SYSTEMS (ADS)

Based on projections like those made by the Intergovernmental Panel on Climate Change (IPCC) asserting that the median electricity increase till 2050 will be by a factor of almost 5, it can be expected that nuclear energy will play a role in meeting this demand growth. Long-term development of nuclear energy, however, faces four major challenges: improvement of the economic competitiveness, meeting increasingly stringent safety requirements, adhering to the criteria of sustainable development, and public acceptability. Of interest here are the sustainability criteria, and, more to the point, its two aspects, i.e. resources and waste management. IAEA’s activities in the area of Partitioning and Transmutation (P&T) are in response to the latter point[4]. One of the primary reasons for the poor public acceptance of nuclear energy is the perception that, because of the long life of many of the radioisotopes generated from fission, waste disposal was an unsolved issue. This concern has led to increased R&D efforts to develop a technology aimed at reducing the amount of long lived radioactive waste through transmutation in fission reactors or accelerator driven (hybrid) systems (ADS). IAEA’s activities in this field are implemented within the framework of the Technical Working Group on Fast Reactors (TWG-FR), which is providing advice and marshalling the necessary scientific and technical support for IAEA’s information exchange and collaborative research and development activities.

V.A. Information Exchange

The IAEA has published a Technical Report on Heavy Liquid Metals (HLM) Thermal Hydraulics[5]. The detailed knowledge of the basic thermal hydraulics phenomena associated with the use of HLM is a necessary step for the development of the Computational Fluid Dynamic (CFD) codes to be used in R&D studies, as well as in the engineering design of HLM components. This is of considerable relevance in the case of high power particle beam targets and in the case of the cooling of accelerator driven sub-critical cores. The publication reviews the status of CFD codes addressing modeling, material property data, numerical problems, as well as code performance and usability. Turbulence phenomena, two-phase and free-surface flows phenomena, as well as experiments and measurement techniques are identified as being the key areas requiring additional theoretical and experimental development work.

One of the important tasks performed within the framework of the TWG-FR is to periodically publish status reports on various aspects of fast neutron systems research and technology development. Currently, the ADS status report[6] is being updated. The publication will provide a comprehensive overview of the most important ADS concepts under development, of the state of the art of the associated research and technology development, and of the main national and international development programs. Also serving Member States’ information exchange needs is the *ADS Research and Development* Database[7]. The database provides information about ADS related R&D programs, existing and planned experimental facilities as well as programs, methods and data development efforts, design studies, and so forth.

With regard to collaborative R&D in the area of transmutation systems technology development, the IAEA is implementing two CRPs: the first one on *Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste*[8], and the second one on *Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems (ADS)*[9]. The overall objective of the first CRP, initiated in 2003 and ending this year, is to increase the capability of Member States in developing and applying advanced technologies in the area of long-lived radioactive waste utilization and transmutation. Twenty institutions from 15 Member States and one international organization are participating in this CRP. The CRP concentrates on the assessment of the dynamic behavior of various transmutation systems. The reactor systems that are investigated comprise critical reactors, sub-critical accelerator driven systems with heavy liquid metal and gas cooling, critical molten salt systems, and hybrid fusion/fission systems. Both fertile and fertile-free fuel options are being investigated. Apart from the benchmarking of steady state core configurations (including the investigation of transmutation potential, burn-up behavior and decay heat of minor actinides bearing fuels), the CRP participants determine the safety coefficients for the individual systems and are performing transient analyses which reflect the generic safety related behavior of the various transmutation systems. The objective of the second CRP, initiated in December 2005, is to improve the understanding of the physics of the coupling of external neutron sources with sub-critical cores. Currently, 27 institutions in 18 Member States and two international organizations are actively participating in this CRP. The participants are applying integrated calculation schemes to perform computational and experimental benchmark analyses. ADS constitute the main thrust of the CRP. For these systems, the CRP is addressing all major physics phenomena of the spallation source and its coupling to the sub-critical core. In the case of detailed ADS calculations, these analyses extend from the simulation of the high-energy proton beam down to thermal neutron energies in the sub-critical core. However, transmutation concepts based on sub-critical cores driven by non-spallation neutron sources are also considered, making good use of results coming out from experimental demonstration projects using non spallation targets [e.g. (D,D) or (D,T) neutron sources, and photon-neutron sources based on electron accelerators].

VI. CONCLUSIONS

The IAEA's programme reflects the urgent needs of the Member States in application and research using accelerators. This includes use of low, medium and high energy accelerators for many applications. The IAEA has no programme on the very high energy part of accelerator research, but is interested in providing fellowships to young scientists from developing countries, if they can gain knowledge at these facilities.

Three main efforts should be highlighted: the training and qualification of a highly educated nuclear workforce using accelerators, the use of accelerators for materials research, and the development of innovative nuclear energy systems utilizing accelerators.

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