# IAEA ACTIVITIES IN THE AREA OF PARTITIONING AND TRANSMUTATION

**A. Stanculescu**
Division of Nuclear Power Nuclear Power Development Section
International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria

## Abstract

Nuclear power is a mature technology that makes a large contribution to the energy supply world-wide. At the end of 2001, there were 438 nuclear power plants operating in the world representing some 353 GW(e) of generating capacity. According to the projections published by the Inter-governmental Panel on Climate Change (IPCC), the median electricity increase till 2050 will be by a factor of almost 5. It is reasonable to assume that nuclear energy will play a role in meeting this demand growth. However, there are four major challenges facing the long-term development of nuclear energy as a part of the world's energy mix: improvement of the economic competitiveness, meeting increasingly stringent safety requirements, adhering to the criteria of sustainable development, and public acceptability. Meeting the sustainability criteria is the driving force behind the topic of this paper. More specifically, in this context sustainability has two aspects: natural resources and waste management. IAEA's activities in the area of Partitioning and Transmutation (P&T) are mostly in response to the latter. While not involving the large quantities of gaseous products and toxic solid wastes associated with fossil fuels, radioactive waste disposal is today's dominant public acceptance issue. In fact, small waste quantities permit a rigorous confinement strategy, and mined geological disposal is the strategy followed by some countries. Nevertheless, political opposition arguing that this does not yet constitute a safe disposal technology has largely stalled these efforts. One of the primary reasons that are cited is the long life of many of the radioisotopes generated from fission. 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 hybrids. In recent years, in various countries and at an international level, more and more studies have been carried out on advanced waste management strategies (i.e. actinide separation and elimination). In the frame of the Project on *Technology Advances in Fast Reactors and Accelerator-driven Systems for Actinide and Long-lived Fission Product Transmutation*, the IAEA initiated a number of activities on utilisation 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 fission/fusion hybrids.

## Introduction

At the end of 2001, there were 438 nuclear power plants (NPPs) operating worldwide. [1] These NPPs represented some 353 GW(e) of generating capacity. According to IAEA's *Reference Data Series*, [2] the share of nuclear electricity generation in 2000 was 15.9%. At the end of 2001, NPPs represented 10.2% of the global electricity generating capacity. Also at the end of 2001, there were 32 NPPs under construction world-wide, with most current constructions in Asia or in countries with economies in transition.

The most significant trend in recent years has been that of steady increases in NPP availability factors through improvements in operational practices, engineering support, strategic management, fuel supply and spent fuel disposition. These have reduced costs and improved safety. Their cumulative impact has been substantial – since 1990 they have increased availability factors by an amount equivalent to the building of 33 GW(e) of new capacity. [3]

If only to meet the needs of the world's growing population (without considering the expected economic development, particularly in developing countries) which the United Nations estimates will approach 8.5 billion people by the year 2025, world-wide energy use will increase substantially over the next decades, making nuclear energy an indispensable option to meet these needs. According to the projections published by the Intergovernmental Panel on Climate Change (IPCC), by 2050, the global primary energy use will grow by a median factor of 2.5, while electricity demand will grow by a median factor of 4.7 (economic development shifts the demand towards electricity, given its convenience and flexibility). As mentioned earlier, sustainability goals are a major challenge to be met when developing advanced nuclear technology as a long-term option in the world's energy mix. In our context, the sustainability challenge has two aspects: resources and radioactive waste. Looking at the resources aspect, one has to acknowledge that nuclear power production cannot be sustainable if only 0% of the fissile resources in natural uranium are used. That means that ultimately, the fertile reserves (uranium-238, which makes the remaining 99.3% of the natural uranium, and thorium) will have to be tapped. Utilisation of breeding to secure the long-term fuel supply for electricity generation with nuclear power has been the main aim of fast reactor development, and remains the ultimate goal. However, the aims of R&D and fast reactor deployment in the medium term, say during the first decades of this century, are not the same in all countries: West European and North American countries, due to the low growth rate of electricity consumption and the availability of gas, liquid fossil fuel and uranium at stable prices intend to utilise the fast reactor to incinerate and transmute actinides and long-lived fission products. Thus, there is an immediate interest in developing fast reactors (critical and sub-critical) with higher concentrations of actinides and long-lived fission products in the core to enhance the transmutation and incineration rates, and to decrease the contaminated part of the fuel cycle. In Asian countries, on the other hand, particularly China, India, and the Republic of Korea, that have few indigenous gas/oil and uranium reserves, and where significant economic expansion is expected, the governments take a long-term perspective on the need for nuclear power. Near-term financial gains are seen to be less important, and the development of fast reactors is directed at ensuring reliable energy supplies in the long-term. To this end, China and India are now in a position to embark on the construction of experimental and prototype fast reactors.

Thus, in addition to the more long-term "breeder mission" of fast reactors, plutonium recycle (utilisation) in fast reactors, as well as transmutation/incineration of minor actinides (MA) and long-lived fission products (LLFP) (and here we touch upon the second aspect of the sustainability goal) in various types of fission reactors, accelerator-driven systems and molten-salt reactors is under investigation in several Member States. The advantages of some of these concepts (e.g., Accelerator-driven Systems (ADS)) that are put forward are intrinsic low waste production, high transmutation capability, enhanced safety characteristics, and better long-term resources utilisation (e.g., with thorium fuels). Important R&D programmes are being undertaken by various institutions in many IAEA Member States to substantiate these claims and advance the basic knowledge in this innovative area of nuclear energy development. For these groups, as for those focusing more on evolutionary and/or advanced Liquid Metal Reactor development, there is the clearly perceived need for co-ordinating their efforts and also for getting access to information from nationally and internationally co-ordinated activities. Whatever the medium term perspective, the flexibility needed to meet the above mentioned sustainability requirement with regard to natural resources and long-lived radioactive waste management asks for a continuous development of the fast neutron spectrum reactor technology. As a matter of fact, flexibility with regard to breeding or incineration/transmutation is attained only in reactors based on fast neutron cores due to their favourable neutron balance. Moreover, fast spectrum systems are the only ones that provide a high degree of flexibility with regard to isotopic separation (i.e., reprocessing), going as far (at least for sub-critical concepts) as to envisage systems that would both incinerate plutonium, and transmute MA and LLFP without isotopic separation. All these R&D activities, covering the spectrum from evolutionary/advanced fast reactors to hybrid systems (e.g., ADS), have to rely on, firstly, the capability to develop and validate reprocessing technologies for the advanced fuels envisaged (taking into account all criteria and requirements, e.g., non proliferation, and simplification of the fuel cycle), and, secondly, on the availability of a fast neutron spectrum irradiation facility for fuel and material testing.

This paper presents the activities being implemented by the IAEA in this area in support of its Member States' needs for information exchange and collaborative R&D.

## IAEA activities

As in all the other fields of advanced nuclear power technology development, the Agency is relying also in the P&T area on broad, in-depth staff experience and perspective. The framework for all the IAEA activities in the P&T area is the Technical Working Group on Fast Reactors (TWG-FR). In responding to strong common R&D needs in the Member States, the TWG-FR acts as a catalyst for international information exchange and collaborative R&D.

Given the common technical ground between plutonium utilisation R&D activities and the development of technologies for the transmutation of long-lived fission products and actinides, both activities are performed within the framework of a single Agency project: *Technology Advances in Fast Reactors and Accelerator-driven Systems for Actinide and Long-lived Fission Product Transmutation*. [4]

The TWG-FR is a standing working group within the framework of the IAEA. It provides a forum for exchange of non-commercial scientific and technical information, and a forum for international co-operation on generic research and development programmes on advances in fast reactors and fast spectrum accelerator-driven systems. Its present members are the following 14 IAEA Member States: Belarus, Brazil, China, France, Germany, India, Italy, Japan, Kazakhstan, Republic of Korea, Russia, Switzerland, United Kingdom, and United States of America, as well as the OECD/NEA, and the EU (EC). The TWG-FR advises the Deputy Director General-Nuclear Energy on status of and recent results achieved in the national technology development programmes relevant to the TWG-FR's scope, and recommends activities to the Agency that are beneficial for these national programmes. It furthermore assists in the implementation of corresponding Agency activities, and ensures that through continuous consultations with officially nominated representatives of Member States all the project's technical activities performed within the framework of the Nuclear Power Technology Development sub-programme are in line with expressed needs from Member States. The scope of the TWG-FR is broad, covering all technical aspects of fast reactors and ADS research and development, design, deployment, operation, and decommissioning. It includes, in particular: design and technologies for current and advanced fast reactors and ADS; economics, performance and safety of fast reactors and ADS; associated advanced fuel cycles and fuel options for the utilisation and transmutation of actinides and long-lived fission products, including the utilisation of thorium. Given the TWG-FR's broad scope, the coverage will generally be in an integrative sense to ensure that all key technology areas are covered. Many specific technologies are addressed in detail by other projects within the IAEA and in other international organisations. The TWG-FR keeps abreast of such work, avoiding unproductive overlap, and engages in co-operative activities with other projects where appropriate. The TWG-FR thus co-ordinates its activities in interfacing areas with other Agency projects, especially those of the International Working Group on Nuclear Fuel Cycle Options, and the Department of Nuclear Safety, as well as with related activities of other international organisations (OECD/NEA, and EC). The TWG-FR normally meets once per year; the last meeting was hosted in May 2002 by the Forschungszentrum Karlsruhe (FZK), Germany, the next meeting will be hosted in May 2003 in the Republic of Korea by KAERI.

**Recent accomplishments**

***Comparative assessment of thermophysical and thermohydraulic characteristics of lead, lead-bismuth and sodium coolants for fast reactors***

So far, all prototype, demonstration and commercial liquid metal cooled fast reactors have used liquid sodium as a coolant. Sodium-cooled systems, operating at low pressure, are characterised by very large thermal margins relative to the coolant boiling temperature and a very low structural material corrosion rate. In spite of the negligible thermal energy stored in the liquid sodium available for release in case of leakage, there is some safety concern because of its chemical reactivity with respect to air and water. Lead, lead-bismuth or other alloys of lead, appear to eliminate these concerns because the chemical reactivity of these coolants with respect to air and water is very low. Some experts believe that conceptually, these systems could be attractive if high corrosion activity inherent in lead, long term materials compatibility and other problems will be resolved. Extensive research and development work is required to meet this goal. Preliminary studies on lead-bismuth and lead cooled reactors and ADS (in which the coolant can also double as the neutron spallation source that drives the sub-critical core) have been initiated in France, Japan, the United States of America, Italy, and other countries. Considerable experience has been gained in Russia in the course of the development and operation of reactors cooled with lead-bismuth eutectic, in particular propulsion reactors. Apart from being quite rare and hence expensive, bismuth is also a source of the volatile α-emitter $^{210}$Po. Thus, studies on pure lead cooled fast reactors are also under way in Russia. Presently, there is no clear view on the relative advantages and drawbacks of heavy liquid metals vs. sodium, and the preferred options vary considerably from Member State to Member State, sometimes even among various institutions in one Member State. In trying to meet the needs of clarification and exchange of information, the IAEA has published a TECDOC on the review and comparative assessment of the main characteristics of sodium, lead, and lead-bismuth eutectic. [5]

***Co-ordinated research project (CRP) on the "Potential of Thorium-based fuel cycles to constrain plutonium and to reduce the long-term waste toxicity"***

Large stockpiles of civil plutonium have accumulated world-wide from nuclear power programmes in different countries. There is a serious public and political concern in the world about misuse of this plutonium and about accidental release of highly radiotoxic material into the environment. It is therefore necessary to safeguard the plutonium under strong security. One alternative for the management of plutonium is to incinerate it in reactors. However, if the reactors are fuelled with plutonium in the form of U-Pu-mixed oxide (MOX), second-generation plutonium is produced. A possible solution to this problem is to incinerate plutonium in combination with thorium. The thorium cycle produces $^{233}U$ that, from a non-proliferation point of view, is preferable to plutonium for two reasons. Firstly, it is contaminated with $^{232}U$, which decays to give highly active daughter products. This would make handling and diversion difficult. Secondly, in case this is not sufficient a deterrent, the $^{233}U$ could be denatured by adding some $^{238}U$ to the thorium. The quantity of $^{238}U$ could be fine-tuned so as to be sufficient to denature the $^{233}U$, but not so much as to produce a significant quantity of plutonium. The thorium option not only produces electricity, but also replaces the plutonium with denatured $^{233}U$, which can be used in other reactors at a later date. All this can be done in existing reactors.

A CRP on this topic was initiated by IAEA in 1995. The Member States joining into the CRP were: China, Germany, India, Israel, Japan, Republic of Korea, the Netherlands, Russia, and the United States of America. This CRP examined the different fuel cycle options in which plutonium be incinerated by recycling it with thorium. The potential of the thorium-matrix has been examined through computer simulations. Each participant has chosen his own cycle, and the different cycles are compared through certain predefined parameters (e.g., annual reduction of plutonium stockpiles). The radio-toxicity accumulation and the transmutation potential of thorium-based cycles for current, advanced and innovative nuclear power reactors are investigated. The research programme was divided into three stages: Benchmark calculations, studies on the optimisation of the plutonium incineration capability in various reactor types, and assessment of the resulting impact on the waste radio-toxicity. The results of the three stages were presented in [6-8], respectively. The CRP was completed in 2001, and the final IAEA TECDOC will be published shortly.

***Co-ordinated Research Project (CRP) on the "Use of Thorium-based fuel cycles in Accelerator-driven Systems (ADS) to incinerate plutonium and to reduce long-term waste toxicities"***

The IAEA established this CRP in 1996. The Member States and international organisations joining into the CRP were: Belarus, Czech Republic, France, Germany, Italy, Netherlands, Russia, Sweden, Spain, and CERN. The scope of the CRP was to quantify the potential of the ADS in conjunction with thorium-fuel to burn transuranics (TRU) from LWR-MOX discharge, MA from both LWR-MOX and fast reactor fuel discharge, as well as long-lived fission products (LLFP). The specific objective of the CRP was to investigate the neutronics of ADS, and evaluate its TRU incineration and LLFP transmutation capabilities. The CRP addressed the main neutronics issues for both the thorium fuelled and the TRU/MA ADS incinerator concepts. In the first stage of the CRP, benchmark simulations of an Energy Amplifier (EA) [9] like system fuelled with $^{233}U$/thorium were performed. In this stage of the CRP, the principal neutronics features of the EA were inter-compared (i.e., fuel enrichments corresponding to a different sub-criticality levels, sensitivity of sub-criticality levels to fuel burn-up, evolution of proton current requirements, void effect, long-term fuel activity under irradiation. The main goal in this stage was to identify the uncertainties due to the different methodologies, nuclear data and codes used by the various participants. An important achievement of this stage was the clarification of the significant differences in the analytical approach to sub-critical systems (i.e., the full understanding of the importance of the k-source concept, and the limitations of the k-effective approach in the analysis of sub-critical systems). Stage 2 of the benchmark was devoted to the assessment of the neutronics characteristics of a modular fast spectrum ADS for long-lived radiotoxic waste transmutation. The benchmark exercise was based on the simplified modelisation (restricted to the sub-critical reactor part) of an ADS fuelled with TRU or MA ($k_{eff} = 0.96$). In Stage 3, calculations of an existing experimental sub-critical facility have been performed. Using their respective methodologies, the CRP participants have simulated the thermal sub-critical zero power system "YALINA" set up at the Joint Institute for Power and Nuclear Research of the Academy of Sciences of Belarus in Minsk, and the results have been compared with the experimental data. The CRP was completed in 2001, and the final IAEA TECDOC is under preparation. Preliminary results have been presented in. [10]

***International database on ADS related research and development programmes***

Based on the needs for strengthening the international co-operation in the field of the R&D for ADS expressed by Member States, and on the recommendations of various international forums, the IAEA decided to establish a database on existing and planned experimental facilities for ADS related R&D. During the course of the implementation work, it proved practical to include – apart from the experimental facilities – also other ADS and P&T related aspects, e.g., ongoing and planned R&D programmes, studies of conceptual designs, and so forth. The database is WWW-based (http://www-adsdb.iaea.org/index.cfm) and operational. Data collection has started, and all Member States having R&D activities in the ADS and Partitioning and Transmutation (P&T) area are encouraged to contribute to the database (request login information from a.stanculescu@iaea.org).

***"Three-Agency Study"***

The IAEA has contributed to the "Three-Agency Study" on *Innovative Nuclear Reactor Development: Opportunities for International Co-operation*, a joint project among the OECD/IEA, the OECD/NEA and the IAEA. The "Three-Agency Report" is a "first step in examining the scope for enhanced international co-operation in developing nuclear-fission reactor technologies. It shows how new technologies are being developed to address the challenges facing nuclear power today and identifies potential areas for co-operation among technology developers. The focus is on 'innovative' fission reactor technologies, which are those that go well beyond the incremental, evolutionary changes to current technology that have been developed and are the subject of ongoing work". [11]

***Workshop on "Hybrid Nuclear Systems for Energy Production, Utilisation of Actinides and Transmutation of Long-lived Radioactive Waste"***

The main objective of this workshop that was held in Trieste, Italy, from 3-7 September 2001 in collaboration with the International Centre for Theoretical Physics (ICTP) was formation and training. It achieved this objective through lectures, tutorials, and computer exercises. Approximately 50 participants from 26 countries (mostly from Eastern Europe and Asia, but also from Africa, Western Europe, and South America) participated in this week-long workshop. The topics treated ranged from the design of ADS, the simulation methodologies, and the ADS safety to fuel cycle issues. Encouraged by the very positive feedback from the participants, the IAEA has decided to organise another training and formation Workshop in October 2003. [12]

## Ongoing and planned activities

### *Co-ordinated research project (CRP) on "Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste"*

The overall objective of the CRP is to perform R&D tasks contributing towards the proof of practicality for long-lived waste transmutation. In particular, to contribute towards providing the basis for the assessment of both the short and long term benefits – or lack of those – to the nuclear fuel backend of ADS, as compared to other existing, advanced, and innovative concepts. In pursuing this objective, the CRP considers the results and recommendations of the OECD/NEA "Second P&T Expert Group", [13] and concentrates on the assessment of the transient behaviour of various transmutation systems. For a sound assessment of the transient and accident behaviour, the neutron kinetics and dynamics have to be qualified, especially as the margins for the safety relevant neutronics parameters are becoming small in a "dedicated" transmuter. The CRP will integrate benchmarking of transient/accident simulation codes focusing on the phenomena and effects relevant to various critical and sub-critical systems under severe neutron flux changes and rearrangements. The main thrust will be on long (as compared to the neutron lifetime) time-scale effects of transients initiated by strong perturbations of the core and/or the neutron source. Changes of flux-shape and power caused by reactivity perturbations in systems with dedicated fuels and varying MA content will be one focus. For the transient analysis of such transmuters, besides neutronics, thermal-hydraulic and fuel issues are of importance. The behaviour of different transmuter systems under various transient conditions will be assessed. The CRP will investigate future needs both for theoretical means (data, codes), and experimental information related to the various transmutation systems. In a nutshell, the final goals of the CRP are to (a) deepen the understanding of the dynamics of transmutation systems, e.g., the accelerator-driven system, especially systems with deteriorated safety parameters, (b) qualify the available methods and specify their range of validity, and (c) formulate requirements for future theoretical developments.

Should transient experiments be available, the CRP might also pursue experimental benchmarking work. In any case, based on the results, the CRP will conclude on the potential need of transient experiments and make appropriate proposals for experimental programmes. The CRP has received 17 proposals from various R&D institutions in 13 Member States (Belgium, China, Czech Republic, France, Germany, Hungary, India, Japan, Republic of Korea, Netherlands, Poland, Russia, and U.S.A.), and the EC (JRC). Its first research co-ordination meeting, hosted by Forschungszentrum Karlsruhe (FZK), was held from 5-8 November 2002. The CRP is presently scheduled to terminate on 31 December 2005.

### *International conference on "Innovative Technologies for Nuclear Fuel Cycles and Nuclear Power"*

The objective of this conference is to provide a forum for the exchange of information between senior experts and policy makers from developed and developing countries relating to evolving and innovative nuclear technologies that are being considered for future applications. Strategists, decision makers, managers, and technical leaders in public and private institutions are expected to both contribute to and benefit from participation in the conference. The conference will examine the background conditions – social, environmental and economic – in which sustainable nuclear technologies can be expected to be developed in the foreseeable part of this century. The conference will address the requirements set by these expected conditions on technological solutions for the peaceful use of nuclear applications. An awareness of ongoing national and international programmes will be developed within the Member States of the IAEA, and opportunities for developing collaborative work will be made available. The conference will be held in Vienna, from 23-26 June 2002. [14]

### *Coordinated research project (CRP) on "Benchmark Analyses on Data and Calculational Methods for ADS Source-related Neutronics Phenomenology with Experimental Validation"*

This activity has been proposed for implementation in IAEA's 2004-2005 Programme and Budget Cycle. The specific objective of the CRP is to improve the present understanding of the coupling of the ADS spallation source with the multiplicative sub-critical core. As outcome, the CRP aims at advancing the efforts under way in the Member States towards the proof of practicality for ADS based transmutation by providing the information exchange and collaborative research framework needed to ensure that the tools to perform detailed ADS calculations, namely from the high energy proton beam down to thermal neutron energies, are available. The CRP will address all major physics phenomena of the spallation source and its coupling to the sub-critical system. Integrated calculation schemes will be used by the participants to perform computational and experimental benchmark analyses. Considering that the major focus of the CRP will be on the comparison between calculations and experiments, in preparation of the CRP it is intended to convene a (possibly joint NEA/IAEA) technical meeting having the objective of getting a precise status of the world-wide ongoing and planned experimental activities on the coupling of spallation (or other neutron sources) with sub-critical configurations.

### *Planned topical technical meetings*

In 2003, two topical meetings are planned within the framework of the project on *Technology Advances in Fast Reactors and Accelerator-driven Systems for Actinide and Long-lived Fission Product Transmutation*: the first technical meeting will be on Review of Solid and Mobile Fuels for Partitioning and Transmutation, and the second one on Theoretical and experimental Studies on Heavy Liquid Metal Thermo-hydraulics.

## Conclusions

For nuclear energy to remain a long-term option in the world's energy mix, nuclear power technology development must meet sustainability goals with regard to fissile resources and waste management. The utilisation of breeding to secure long-term fuel supply remains the ultimate goal of fast neutron spectrum system. Plutonium recycle in fast reactors, as well as incineration/transmutation of minor actinides and long-lived fission products in various hybrid reactor systems (e.g., ADS) also offer promising waste management options. Several R&D programmes in various Member States are actively pursuing these options, along with the energy production and breeding mission of fast reactor systems.

In line with the statutory objective expressed in Article II: The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, insofar as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose, the IAEA will continue to assist the Member States' activities, also in the area of advanced technology development for utilisation and transmutation of actinides and long-lived fission products, by providing an umbrella for information exchange and collaborative R&D to pool resources and expertise.

## REFERENCES


[1] International Atomic Energy Agency, Power Reactors Information System (PRIS) Database, (http://www.iaea.org/programmes/a2/).

[2] International Atomic Energy Agency, *Reference Data Series No. 1*, Vienna, July 2000 and July 2001.

[3] International Atomic Energy Agency, Nuclear Technology Review 2002.

[4] International Atomic Energy Agency, project on *Technology Advances in Fast Reactors and Accelerator-driven Systems (ADS) for Actinide and Long-lived Fission Product Transmutation*, http://www.iaea.org/inis/aws/fnss/.

[5] International Atomic Energy Agency, IAEA-TECDOC – 1289, *Comparative Assessment of Thermophysical and Thermohydraulic Characteristics of Lead, Lead-bismuth and Sodium Coolants for Fast Reactors*, Vienna, June 2002.

[6] V. Arkhipov, H.J. Rütten, A. Galperin (1998), *Progress Summary of the IAEA Coordinated Research Project on the Potential of Thorium-based Fuel Cycles to Constrain Plutonium and to Reduce the Long-lived Waste Toxicity*, The Ninth International Conference on Emerging Nuclear Energy Systems, ICENES 1998, Tel-Aviv, Israel, June 28-July 2, pp. 647-655.

[7] H.J. Rütten, V. Arkhipov, A. Stanculescu (2000), *Second Progress Report on the IAEA Coordinated Research Project on the Potential of Thorium-based Fuel Cycles to Constrain Plutonium and to Reduce the Long-term Waste Toxicity*, The Tenth International Conference on Emerging Nuclear Energy Systems, ICENES 2000, Petten, the Netherlands, September 24–28, pp. 019.1 – 019.8.

[8] H.J. Rütten, A. Stanculescu (2002), *Final Report on the IAEA Coordinated Research Project on the Potential of Thorium-based Fuel Cycles to Constrain Plutonium and to Reduce the Long-term Waste Radio-Toxicity*, International Conference on the New Frontiers of Nuclear Technology: Reactor Physics, Safety and High-Performance Computing (PHYSOR 2002), Seoul, Republic of Korea, 7-10 October.

[9] C. Rubbia *et al.* (1995), *Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier*, CERN Divisional Report CERN/AT/95-44 (ET), 29th September.

[10] W. Gudowski *et al.* (2001), IAEA Benchmark on Accelerator-driven Systems, American Nuclear Society (ANS) Winter Meeting Embedded Topical Meeting *Accelerator Applications/ Accelerator-driven Transmutation Technology and Applications '01* (AccApp/ADTTA '01), Reno, Nevada, U.S.A., 11-15 November.

[11] International Energy Agency (IEA), OECD Nuclear Energy Agency (NEA), and International Atomic Energy Agency (IAEA) (2002), *Innovative Nuclear Reactor Development: Opportunities for International Co-operation*, Paris, August.

[12] Page http://www.iaea.org/inis/aws/fnss/meetings/index.html#20 on the Web Site of the International Atomic Energy Agency, project on *Technology Advances in Fast Reactors and Accelerator-driven Systems (ADS) for Actinide and Long-lived Fission Product Transmutation.*

[13] OECD Nuclear Energy Agency (2002), *Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles: a Comparative Study*, Paris.

[14] http://www.iaea.org/worldatom/meetings Web Site of the International Conference on *Innovative Technologies for Nuclear Fuel Cycles and Nuclear Power.*

**List of related IAEA publications**

(Most of these publications can be downloaded as pdf files from the Web Site of the project on *Technology Advances in Fast Reactors and Accelerator-driven Systems for Actinide and Long-lived Fission Product Transmutation*: http://www.iaea.org/inis/aws/fnss/).

International Atomic Energy Agency, *Evaluation of Actinide Partitioning and Transmutation*, Technical Report Series No. 214, Vienna, 1982.

International Atomic Energy Agency, *Feasibility of Separation and Utilisation of Ruthenium, Rhodium and Palladium from High-level Wastes*, Technical Report Series No. 308, Vienna, 1989.

International Atomic Energy Agency, *Feasibility of Separation and Utilisation of Cesium and Strontium from High-level Liquid Wastes*, Technical Report Series No. 356, Vienna, 1993.

International Atomic Energy Agency, *Use of Fast Reactors for Actinide Transmutation*, IAEA-TECDOC-693, Vienna, 1993.

International Atomic Energy Agency, *Safety and Environmental Aspects of Partitioning and Transmutation of Actinides and Fission Products*, IAEA-TECDOC-783, Vienna, 1995.

International Atomic Energy Agency, *Advanced Fuels with Reduced Actinide Generation*, IAEA-TECDOC-916, Vienna, 1996.

International Atomic Energy Agency, *Status Report on Actinide and Fission Product Transmutation Studies*, IAEA-TECDOC-948, Vienna, 1997.

International Atomic Energy Agency, *Accelerator-driven Systems: Energy Generation and Transmutation of Nuclear Waste*, IAEA-TECDOC-985, Vienna, 1997.

International Atomic Energy Agency, *Thorium-based Fuel Options for the Generation of Electricity: Developments in the 1990s*, IAEA-TECDOC-1155, Vienna, 2000.

International Atomic Energy Agency, *Comparative Assessment of Thermophysical and Thermohydraulic Characteristics of Lead, Lead-bismuth and Sodium Coolants for Fast Reactors*, IAEA-TECDOC-1289, Vienna, 2002.

International Atomic Energy Agency, *Thorium Fuel Utilisation: Options and Trends*, IAEA-TECDOC-1319, Vienna, 2002.