IAEA ACTIVITIES IN THE AREA OF EMERGING NUCLEAR ENERGY SYSTEMS

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Abstract

Nuclear energy is a proven technology that already makes a large contribution to energy supply worldwide. At the end of 1999, there were 433 nuclear power plants operating in the world with a total capacity of some 349 GW(e). The average annual growth rate of electricity production from nuclear power is estimated to be about 0.6% per year for the period from now to 2015. One of the greatest challenges facing nuclear energy is the highly radioactive waste, which is generated during power production. 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 *Nuclear Systems for Utilisation and Transmutation of Actinides and Long-lived Fission Products* the IAEA initiated a number of activities on utilisation of plutonium and transmutation of waste, accelerator driven systems, thorium fuel option, innovative nuclear reactors and fuel cycles, non-conventional nuclear energy systems, and fission/fusion hybrids.

1. Introduction

In the second half of the 20th century, nuclear power has evolved from an R&D environment to an industry that supplies one sixth of the world's electricity, one fifth of the USA's and almost one third of Western Europe's. At the end of 1999, there were 433 nuclear power plants in operation and 39 under construction. Over nine thousand reactor-years of operating experience had been accumulated.

The turn of the century is a potential turning point also for nuclear power for several reasons:

- Fundamentally solid future prospects due to increasing world energy consumption, nuclear power's contribution to reducing greenhouse gas emissions, nuclear fuel resource sustainability, and improvements in operation of current nuclear power plants.
- Advanced reactor designs that will improve economics and availability, and further enhance safety.
- Continued attention to the key issues of nuclear safety, nuclear waste disposal and non-proliferation of nuclear weapons.

From this perspective, the future prospects for nuclear power and IAEA's role can be summarised as follows:

Nuclear power operates in a growing market segment. Global energy demand is growing due to industrialisation, economic development and increases in world population. It is projected to almost triple by the middle of the 21st century. In developing countries in the next thirty years, energy demand is projected to increase two to three-fold, depending on the economic growth scenario. It is anticipated that most of the world's increase in nuclear capacity will be in Asia. The substantial increase in global energy consumption in the coming decades will be driven principally by the economic growth and industrialisation of developing countries, whose three quarters of the world's inhabitants consume only one quarter of the global energy. North America has a per capita consumption more than twice that of Europe and almost eight times greater than that of South East Asia and the Far East. Strong economic growth in many developing countries is already leading to sharp increases in per capita energy consumption. Consumption will continue to rise, driven also by the projected two-fold expansion in world population during the 21st century that will occur overwhelmingly in the developing regions. Globally, fossil fuels provide 87% of commercial primary energy. Nuclear power and hydroelectric each contributes 6%. The non-hydroelectric renewables, solar, wind, geothermal and biomass, constitute less than 1% of the energy supply. One third of commercial primary energy is consumed in electricity generation.

Nuclear power reduces greenhouse gas emissions. Currently, nuclear power avoids annually about 8% of global CO_2 emissions from energy production, or more than 600 million tonnes of carbon (or 2 300 million tonnes of CO_2). As more and more people become convinced of the potential consequences of global warming, and realise that the solutions are not going to be easy, the potential for nuclear power to play an important role in the future energy mix in various regions must inevitably become more widely recognised. The years since the Rio conference have solidified the international consensus that increasing greenhouse gas emissions will have serious global consequences.

Nuclear power can compete with other energy sources. Despite the prevailing relatively low fossil-fuel prices, the generating cost of nuclear electricity continues to be competitive with fossil fuel for base-load electricity generation in many countries. Although the large capital investment required for nuclear power plants is a disadvantage, especially in developing countries, the nuclear fuel cost is relatively low. Moreover, the prices of fossil fuels are likely to increase over the long term (and have actually started to do so) because the resource is limited and also if pressures are applied – policy or financial instruments, to discourage use. On the other hand, there is still scope in the nuclear industry for rationalisation, standardisation, modular construction, shorter construction periods, higher burn-up and simplification, resulting in better performance and lower electricity generation costs. Nuclear power can thus be expected to be more competitive with fossil-fired plants in many areas of the world in the long run.

In the early years of the next century, however, nuclear utilities will experience an operating environment in which nuclear power plants will face increased competition, in an open energy market, with other suppliers of electricity. In the face of this competitive pressure, nuclear power plants worldwide are already showing a steady increase in the energy availability. The IAEA emphasises improving the performance and reliability of nuclear power plants through the sharing of information and experience world-wide, provides the PRIS database, as an authoritative source of information for statistical analysis of nuclear power plant performance indicators, and conducts projects in nuclear power plant performance assessment.

Moreover, nuclear power programs in Member States are making significant investments in technology development and designs for the next century, focusing on substantial evolutionary improvements of reactor systems to further enhance their economics, reliability and safety. To support these programmes, the IAEA promotes technical information exchange and co-operation between Member States, provides a source of balanced, objective information on developments in advanced reactor technology, and publishes reports available to all Member States interested in the current status of reactor development. These activities are conducted within the frames of technical working groups for the major reactor lines: light water reactors, heavy water reactors, fast reactors, and gas cooled reactors.

The global nuclear safety culture is extensively addressed by regulators in the Member States, and by operators who have the prime responsibility for nuclear safety. The IAEA contributes to the global nuclear safety culture through the introduction of binding conventions and recommended standards, the provision of advisory services and the exchange of experience and information.

Nuclear waste disposal is often seen as the Achilles heel of the nuclear industry. Extensive research and development in many countries has led to the general conclusion that final disposal is technically feasible, but it still needs to be demonstrated convincingly to the public. That this has not been done is largely attributable to public scepticism or opposition and lack of the necessary political support. Presently, high level wastes are being stored above or below ground, awaiting policy decisions on their long-term disposal.

The IAEA plays a major role in facilitating *safe management of radioactive wastes*. Support is given to the collection, assessment and exchange of information on waste management strategies and technologies for nuclear power plants, fuel cycle facilities, radioisotope applications, research activities, and waste site restoration. The IAEA provides general technical guidance, assistance in technology transfer and promotes international collaboration in optimising the development and establishment of technical waste management infrastructures and programmes in Member States.

The IAEA plays a vital role in operating the *international safeguards system* that serves the overall objective of non-proliferation of nuclear weapons. It also provides services designed to strengthen the physical protection of nuclear materials and to combat the threat of illicit trafficking in such materials. The safeguards system of the IAEA has been strengthened, *via* the so-called 93 + 2 programme, with requirements for more information and for allowing safeguards inspectors greater access to installations, even to undeclared nuclear facilities. Through a co-operative activity between the IAEA Departments of Nuclear Energy and of Safeguards, guidelines for design measures to facilitate the implementation of safeguards for future water cooled nuclear power plants have been prepared.

To facilitate energy policy decision-making by Member States, the IAEA's *comparative assessment programme* is aimed at defining optimal strategies for the development of the energy sector, consistent with the aims of sustainable development. This program focuses on developing and disseminating databases and methodologies for comparative assessment of nuclear power and other energy sources in terms of their economic, health and environment impacts; ensuring that the results of IAEA-supported assessments are made available to relevant national and international forums (such as the Intergovernmental Panel on Climate Change and the United Nations Framework Convention on Climate Change); and on enhancing the capability of Member States to incorporate health and environmental considerations in the decision making process for the energy sector.

In summary, as an international forum for exchange of scientific and technical information, the IAEA plays a role in bringing together experts for a worldwide exchange of information about national programmes, trends in safety and user requirements, the impact of safety objectives on plant design, and the co-ordination of research programmes in advanced reactor technology. To support its information exchange function, and to provide balanced and objective information to all Member States on advances in reactor technology, the IAEA periodically prepares status reports on advances in technology for each major reactor line.

3. IAEA activities in the area of Emerging Nuclear Energy Systems

The IAEA convened two meetings (The senior expert group and the external experts review group) to review the Agency's major programs. Both groups endorsed the Agency's activities geared towards the development and introduction of proliferation-resistant, long-lived radionuclides incinerating/transmuting fuel cycles and innovative reactor designs in the small and medium sized category.

During the 42nd General Conference in September 1998, representatives from the United States (Mr. Bill Richardson, Secretary of the US DOE), and the Russian Federation (Mr. E.O. Adamov of Minatom, RF) promoted international R&D co-operation regarding research into the potential of nuclear reactors and fuel cycles based on innovative technologies.

3.1 Innovative reactors and fuel cycles

Several experts' groups at its meetings held in Vienna in 1998-2000 stated that "In response to the new realities, it is important that nuclear technology be economically competitive, manage its waste in a publicly acceptable manner, and contribute to sustainable utilisation of the earth's resources. As with other globally important technologies the nuclear community should mobilise the intellectual and technical potential to produce innovative reactors and fuel cycles".

In this context an IAEA initiative on innovative reactors and fuel cycles is timely and in accordance with the interests of Member States, who are currently reviewing and discussing options for the future direction of nuclear energy. Accordingly, the IAEA in co-operation with other relevant international organisations, including OECD/NEA and IEA, is recommended "to provide an international forum for discussion of innovative reactors and fuel cycles and to consider a possible international R&D project". In compliance with these findings, IAEA activities aiming at the establishment of an international R&D project on innovative reactors and fuel cycles are now in progress.

3.2 *Non-conventional Nuclear Energy Systems*

As mentioned, the civilian nuclear energy enterprise is presently at a crossroads, the installed nuclear energy market penetration having levelled off at only about 6% of the global total primary energy consumption. This share will possibly even decrease in the near term since new nuclear power plant construction is not likely to compensate for the decommissioning of existing ones. Underlying this malaise are deeply held public apprehensions on issues such as reactor operational safety, long-term spent fuel safety, and fissile material proliferation safety.

While researchers continue to investigate narrow aspects of nuclear reactor processes and components, there exists little understanding of the integrated effect, which such investigations may have on actual public acceptance of an entire operating nuclear energy system. It follows, therefore, that there exists a need for the development of a complementary, client oriented "system performance framework" to help focus nuclear energy research and development activities.

For the near term, small, factory-fabricated, modular plants which are delivered turnkey, are supported by front end (fuel production) and back end (reprocessing and/or waste disposal) services by the supplier, and which are offered for delivery under favourable financing might be favourable received. They could accommodate the client's situation of scarce financing, spare infrastructure, and need for only small to medium sized increments in capacity. If the product mix produced by the plant were diverse as well (producing potable water, electricity, and process heat), this would further enhance their attractiveness to a developing country having natural resources but unskilled labour and a need to manufacture value-added products based on their indigenous natural resources.

The process heat applications and enabling technologies to support them could lead in a natural way to the longer term (second half of the 21st century) nuclear power architecture which must be based on fast spectrum systems which couple to modern energy converters such as gas turbines and fuel cells. Technologies which support high core outlet temperature (850°C) and hydrogen production via water cracking will be needed. The near-term developments to support process heat applications in developing countries (such as coal reforming, heavy oil hydrogenization) will offer opportunities for symbiosis with nuclear's competitors for primary energy fuel supply – by helping to make fossil more environmentally attractive – and thereby would provide incentive to large industrial groups (coal, oil) to support innovations in nuclear technology.

3.3 *Fission/fusion co-operation on technology aspects*

Along with the ongoing efforts to establish fusion as an energy source, there is renewed interest in fusion neutron source applications. In addition to fundamental neutron research, fusion R&D activities are becoming of interest to nuclear fission power development. Indeed, for nuclear power development to become sustainable as a long-term energy option, innovative fuel cycle and reactor technologies will have to be developed to solve the problems of resource utilisation and long-lived radioactive waste management. Both the fusion and fission communities are currently investigating the potential of innovative reactor and fuel cycle strategies that include a fusion/fission hybrid. The attention is mainly focused on substantiating the potential advantages of such hybrid systems: utilisation and transmutation of actinides and long-lived fission products, intrinsic safety features, enhanced proliferation resistance, and fuel breeding capabilities. An important aspect of the ongoing activities is comparison with the accelerator driven sub-critical system (spallation neutron source), which is the other main option for producing excess neutrons. A consultancy held in Moscow in July of this year initiated the preparation of a background report on the use of fusion/fission hybrids for utilisation and transmutation of actinides and long-lived fission products, identifying the needs of the R&D groups involved, and thus providing justifications and incentives for the Agency's future initiatives in this area.

3.4 The Three Agency study

"R&D on Innovative Nuclear Reactors – Status and Prospects" has been launched in 1999. The three Agencies co-operating on the study are OECD/NEA, IAE and the IAEA. The objectives of the study are: to trace possible paths to the future availability of nuclear technologies that are sufficiently improved in safety, environmental performance and economics that they could conceivably be commercially ordered in competitive energy markets within about 20 years, and to identify where current research and development are feeding into such paths. Future nuclear technology R&D needs will be identified and discussed in the context of decreasing public and private energy technology R&D budgets. Particular attention will be paid to the potential role of international co-operation in facilitating R&D and enhancing its cost effectiveness.

3.5 ADS and transmutation

In recent years, an old idea has re-surfaced and is gaining attention in nuclear technology: the sub-critical, spallation neutron source driven nuclear system, or hybrid system. In this concept, a powerful proton accelerator produces a spallation neutron source that drives a sub-critical core to a relatively high fission power. Accelerator driven spallation targets and their proposed applications are hybrid technologies, coupling the fields of accelerator design, particle beam physics, spallation target design, and nuclear as well as reactor physics and the related engineering disciplines.

Particle accelerator and nuclear reactor technologies have developed for several decades along parallel paths, with an important similarity being the capacity to produce large numbers of neutrons, via fission (reactors) or spallation. Because of the improvements in particle accelerator technology and economics, several large-scale applications of accelerator driven systems have been proposed. One of the earliest proposed hybrid applications involved using spallation neutrons to supplement the fission process in accelerator driven breeder reactors. More recently, a wider range of applications for hybrid technologies was proposed to incinerate/transmute materials produced in nuclear reactors. These applications rely on the larger availability of neutrons from hybrid systems and on their operation flexibility as compared to critical nuclear reactors. Specifically, these applications include spallation neutron sources, accelerator driven transmutation of waste, and accelerator driven power production.

Nuclear waste contains large quantities of plutonium, other fissionable actinides, and long-lived fission products that pose challenges for long-term storage of waste and that are potential proliferation concerns. If one assumes the same level of global nuclear power generation as exists today, then in the year 2015 there will be more than 2 000 tons of plutonium in the spent fuel worldwide.

Different strategies for dealing with nuclear waste are being followed by various countries because of their geologic situations and their views on nuclear energy, reprocessing and non-proliferation. The current United States policy is to store unprocessed spent reactor fuel in a geologic repository. Other countries are opting for treatment of nuclear waste, including partial utilisation of the fissile material contained in the spent fuel, prior to geologic storage.

The accelerator driven transmutation of waste (ATW) concept offers potential alternative paths that would essentially eliminate plutonium, higher actinides, and environmentally hazardous fission products from the waste stream destined for permanent storage. ATW does not threaten but instead enhances the viability of permanent waste repositories. As such, ATW has increasingly become of worldwide interest and could be an important component of strategies to deal with international nuclear materials management requirements.

Accelerator driven systems: energy generation and transmutation of nuclear waste (Status report). Participants of the special scientific programme on “Use of High Energy Accelerators for Transmutation of Actinides and Power Production” held in Vienna, in 1994 in conjunction with the 38th IAEA general conference recommended the IAEA to prepare a status report on accelerator driven systems (ADS). The general purpose of the status report was to provide an overview of ongoing development activities, different concepts being developed and their status, as well as typical development trends in this area and to evaluate the potential of this system for power production, Pu burning and transmutation of minor actinides and fission products. This document includes the individual contributions by the experts from six countries and two international organisations, as well as executive summaries in many different areas of the ADS technology. The document was published and more than 500 copies were distributed by the IAEA in 1997 (IAEA-TECDOC-985).

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 is now in progress. The participating countries and international organisations in the CRP are Belarus, Czech Republic, France, Germany, Italy, the Netherlands, Russian Federation, Sweden, CERN and Spain (as an observer). The purpose of the CRP is to assess the uncertainties of the calculated neutronic parameters of a simple model of thorium or uranium fuelled ADS, in order to get a consensus on the calculational methods and associated nuclear data. Participants identified a number of issues, which should be considered to get a better understanding of the ADS and agreed that some points, such as comparison of the different approaches and tools used by the different groups, should be reviewed.

Three research co-ordination meetings (RCM) were held: in 1997 in Bologna, Italy, in 1998 in Petten, Netherlands, and in 1999 in Vienna. Detailed papers on the results of these RCMs were reported to several international meetings, e.g. the technical committee meeting on *Feasibility and Motivation for Hybrid Concepts for Nuclear Energy Generation and Transmutation* (Madrid, Spain, September 1997), and the *Third International Conference on Accelerator Driven Transmutation Technologies and Applications* (Prague, Czech Republic, June 1999). As agreed at the consultancy in Minsk, Belarus, in July of this year, the present stage of the CRP will be based on the YALINA set-up, a well-defined and refined experiment considered by the experts as having the potential to resolve some of the existing discrepancies in simulation of sub-critical systems and to give an indication on the quality of widely used evaluated nuclear data libraries. Moreover, the present stage of the CRP gives an opportunity to widen international participation in benchmarking and validation activities and lays the ground for future activities in this area. The participants had committed themselves to perform in advance “blind” test simulations of the first experiments. Already the preliminary results and comparisons presented during the consultancy are of the great interest for the participating parties.

Technical committee meeting on Feasibility and Motivation for Hybrid Concepts for Nuclear Energy Generation and Transmutation. The purpose of this TCM was to assess the advantages and disadvantages of hybrid concepts for nuclear energy generation and transmutation of minor actinides and their potential role relative to the current nuclear power programmes and potential future direction to promote these concepts worldwide. The TCM was hosted by CIEMAT (Centro de Investigaciones Energeticas Medicamentales y Tecnologicas) and held at its headquarters in Madrid, Spain, on

17-19 September 1997. Several major programmes/concepts on ADS development were presented, i.e. the CERN ADS concept, the OMEGA Program and Neutron Science Project for Developing Accelerator Hybrid Systems at JAERI, the Los Alamos ATW Program, and the Hybrid Systems For Nuclear Waste Transmutation Project in France.

The most salient observations resulting from the TCM were:

- Several accelerator systems and source concepts can be developed for ADS.
- Importance to have a very reliable neutron source coupled with the reactor system.
- The associated sub-critical reactor will likely be liquid lead (or lead-bismuth) cooled, with efforts to use natural convection for coolant circulation.
- Effort to develop neutronic benchmarks and codes for ADS should be pursued at the international level under the aegis of the Agency.
- Even if ADS is tentatively presented by some as a way to solve all nuclear waste issues, ADS is not an alternative to geological disposal. However, ADS has the potential to drastically reduce the waste toxicity, thanks to their capacity to burn minor actinides and fission products. As a reprocessing stage will be required, non-proliferation concerns should be addressed.
- Further development of ADS requires the building of a demonstration device with a thermal power, in the 100-300 MW range. Efforts should be co-ordinated at international level on this matter.
- This pre-industrial test should provide input on the feasibility of the industrial deployment of ADS, including fuel cycle requirements, and a better understanding of the safety issues to be addressed. The proceedings of this TCM were published by CIEMAT and distributed recently by IAEA.

Database of experimental facilities and computer codes for ADS related R&D. The needs for strengthening international co-operation in the field of the R&D for accelerator driven systems was emphasised at several international forums, e.g.:

- Scientific program on “Use of High Energy Accelerators for Transmutation of Actinides and Power Production”, Vienna, 21 September 1994 (in conjunction with the 38th IAEA General Conference).
- The Second International Conference on Accelerator Driven Transmutation Technologies and Applications, Kalmar, Sweden, 3-7 June 1996.
- The 8th International Conference on Emerging Nuclear Energy Systems (ICENES’96), Obninsk, Russian Federation, 24-28 June 1996.

The consultancy on Hybrid Concepts for Nuclear Energy Generation and Transmutation held in Vienna, in December 1996 noted that an increasing number of groups are entering this field of research, many of these groups are not embedded in wider national activities, for these groups there is a need for co-ordinating their efforts and jointly funding projects as also for getting access to information from nationally or internationally co-ordinated activities.

Discussing organisational aspects of a possible IAEA involvement, the consultants came to the conclusion that an effective co-ordination would necessitate the creation of an information document on existing and planned experimental facilities which can be used for ADS related R&D. To substantiate this recommendation, several consultancies were organised in 1997-2000 to work out and finalise the format of the document.

In June 1998, a draft of the database was distributed by the Agency to all contributors in the form of working material. Presently an "electronic" version of the database is available on CD-ROM and will be publicly accessible on the Internet very soon.

Advisory Group Meeting (AGM) on Review of National Accelerator Driven System (ADS) Programs. This AGM was hosted by KAERI in Taejon, Republic of Korea, from 1-4 November 1999. Its purpose was to review the current R&D programs in the Member States, and to assess the progress in the development of hybrid concepts, as well as their potential role relative to both the current status and the future direction of nuclear power worldwide. Further, the AGM participants provided advice and guidance for the IAEA activities in the ADS area.

Technical Committee Meeting (TCM) on Core Physics and Engineering Aspects of Emerging Nuclear Energy Systems for Energy Generation and Transmutation. This TCM was hosted by the Argonne National Laboratory in Argonne, Illinois, USA, from 28 November-1 December 2000. Its objective was to review the status of R&D activities in the area of hybrid systems for energy generation and transmutation, to discuss in depth specific scientific and technical issues covering the different R&D topics of these systems, and to recommend to the IAEA activities that would be specifically targeted to the needs of the Member States performing R&D in this field.

Co-ordinated Research Project (CRP) on Safety, Environmental and Non-proliferation Aspects of Partitioning and Transmutation (P&T) of Actinides and Fission Products. The overall objectives of the CRP were to study the possibility of reduction of the long-term hazard arising from the disposal of high level waste. More specifically, the CRP aimed to identify the critical nuclides to be considered in a P&T strategy, to quantify their radiological importance in a global nuclear fuel cycle analysis and to establish a priority list of radionuclides according the hazard definition. In the framework of the CRP the radionuclides hazard was studied in order to identify the critical nuclides to be considered in a P&T strategy and to quantify their radiological importance in a global nuclear fuel cycle analysis.

4. Thorium fuel option

Since the start of nuclear power development, thorium was considered to be the nuclear fuel to follow uranium. The technology to utilise thorium in nuclear reactors was sought to be similar to that of uranium, thorium resources to be larger than those of uranium, and the neutron yield of ^{233}U in thermal and epithermal regions is higher than that for ^{239}Pu in the U/Pu fuel cycle. In more detail the major reasons for the introduction of the thorium-based nuclear fuel cycles are: enlargement of fissile resources by breeding ^{233}U; large thorium deposits in some countries, coupled with a lack of uranium deposits in those countries; potential reduction in fuel cycle cost; reduction in ^{235}U enrichment requirements; safer reactor operation because of lower core excess reactivity requirements; safe and more reliable operation of thorium oxide fuel at high burn-up as compared to uranium oxide, due to the higher irradiation and corrosion resistance of the former.

However, thorium has some disadvantages when compared with uranium, and this was also recognised right from the beginning: thorium is more radioactive than uranium, making its handling in the fabrication stage more challenging; the nuclear reactions induced by neutron absorption in thorium and the decay schemes of the resulting nuclides are complicated, and the time for spent fuel storage in water is longer due to the higher residual heat; potential difficulties in the back-end of the fuel cycle.

In spite of the above-mentioned disadvantages, R&D efforts on the thorium/uranium fuel cycle and thorium-fuelled reactor programmes started in the early 50s in several countries.

A series of three meetings was organised by IAEA in the period 1997-1999 on the thorium fuel options: (1) Advisory group meeting on Thorium Fuel Cycle Perspectives, Vienna, Austria, 16-18 April 1997, (2) Advisory group meeting on Thorium Fuel Utilisation: Options and Trends, Vienna, Austria, 28-30 September 1998, and (3) Technical committee meeting on Utilisation of Thorium Fuel: Options in Emerging Nuclear Energy Systems, Vienna, Austria, 15-17 November 1999. The meetings were organised jointly by the Nuclear Power Technology Development Section of the Division of Nuclear Power and by the Nuclear Fuel Cycle & Materials Section of the Division of Nuclear Fuel Cycle and Waste Technology. The purpose of the meetings was to assess the advantages, shortcomings, and options of the thorium fuel under current conditions, with the aim of identifying new research areas and fields of possible co-operation within the framework of the IAEA "Programme on Emerging Nuclear Energy Systems". Apart from current commercial reactors, the scope of the meetings covered all types of evolutionary and innovative nuclear reactors, including molten salt reactors and hybrid systems.

Preparations for publication of the proceedings (IAEA-TECDOC) of the above mentioned meetings is under way. Contributions to these meetings in the form of working material were distributed to the participants.

Status report on Thorium-based Fuel Options. Within the framework of IAEA activities, the Agency has maintained an interest in the thorium fuel cycle and its utilisation worldwide. Its periodic reviews have assessed the current status of this fuel cycle, its applications worldwide, its economic benefits, and its perceived advantages *vis-à-vis* other nuclear fuel cycles. Since 1994 the IAEA has convened a number of technical meetings on the thorium fuel cycle and related issues. Between 1995-1997 individual contributions also were solicited from experts of France, Germany, India, Japan, Russia and the United States of America, in many different areas of the thorium fuel cycle. They included evaluations of the current status of the thorium fuel cycle worldwide, evaluation of new incentives for using thorium as a result of the large stockpiles of plutonium produced in nuclear reactors, new reactor concepts that can utilise thorium, strategies for thorium use, and an evaluation of the toxicity of thorium fuel cycle waste as compared to other fuel cycles. The results of this updated evaluation are summarised in the present publication "Thorium based fuel options for the generation of electricity: developments in the 1990s", IAEA-TECDOC-1155. Additionally, this document is a contribution to the important task of preserving a large amount of past experience.

Co-ordinated research programme (CRP) on the Potential of Thorium-based Fuel Cycles to Constrain Plutonium and to Reduce the Long-term Waste Toxicity. At the consultancy on "Important Consideration on the Status of Thorium" held in Vienna from 29 November to 1 December 1994, participants recommended the IAEA to organise a CRP on thorium-based fuel cycle issue. In 1995, the Agency approved the topic for the CRP: "Potential of Thorium-based Fuel Cycles to Constrain Plutonium and to Reduce Long-term Waste Toxicity". The scope of this CRP was discussed and agreed upon by the participants of the consultancy on "Thorium-based Fuel Cycles", held from 6 to 9 June 1995 at the Agency's Headquarters in Vienna. The participating countries in the CRP are: China, Germany, India, Israel, Japan, Republic of Korea, the Netherlands, Russian Federation and the United States of America.

This CRP examines the different fuel cycle options in which plutonium can be recycled with thorium to incinerate plutonium. 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 on the basis of certain predefined parameters (e.g. annual reduction of plutonium stockpiles). The toxicity accumulation and the transmutation potential of thorium-based cycles for current, advanced and innovative nuclear power reactors are investigated. The research program has been divided into three stages: (1) benchmark calculations, (2) optimisation of the incineration of plutonium in various reactor types, and (3) assessment of the resulting impact on the waste toxicity.

The results of stage 1 were presented at ICENES 98. As agreed at the last RCM in Taejon (Republic of Korea), in October 1999, the paper reporting the results of stage 2 was submitted to this conference.

5. Efforts pursued jointly with other international organisations

Apart from the already mentioned “Three Agencies Study,” a collaborative effort with OECD/NEA and IAE, two more salient recent examples of collaboration between the Agency and other international organisations are worthwhile mentioning. The first one is the joint benchmark program set up by the IAEA and the European Commission (EC) to assess the potential of reducing the sodium void reactivity effect in innovative fast reactor designs and to perform comparative assessments of the consequences of severe accident scenarios on such advanced fast reactor designs with near-zero sodium void reactivity effect (this joint benchmark program has resulted in IAEA-TECDOC-731, and IAEA-TECDOC-1139). The second example is the Agency’s participation in OECD/NEA’s Expert Group on “Comparative Study of ADS and FR in Advanced Nuclear Fuel Cycles” whose objective is to assess whether ADS deliver distinctive benefits in an advanced fuel cycle that includes P&T, as compared to fast reactors.

6. Conclusions

The expansion of nuclear energy has been dampened in the past decade by a number of factors. However, the prospects for the long term are positive. The global energy market is expanding and nuclear energy has the potential to increase market share by diversification into non-electric use of energy. Nuclear energy has two fundamental competitive advantages: long-term security of supply and the potential for reduction of the emission of greenhouse gases. Significant investments are being made in advanced nuclear reactor designs and technologies with the goal of having the technology ready for the 21st century. Continued safe operation of current reactors, implementation of nuclear waste disposal technology, and an improved safeguards regime should reduce concerns about nuclear power. Nuclear power can be expected to make an important contribution to global energy needs and to the abatement of greenhouse gases in the next century and beyond.

For the last four decades, the IAEA has fulfilled the objective expressed in Article II of the Agency’s Statute: “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”. Accordingly, the IAEA’s role is to provide all Member States with an international source of balanced and objective information on advances in nuclear technology, and to provide an international forum for information exchange and co-operative research. We see our role in continuing to support joint efforts in emerging nuclear energy systems development. The IAEA will continue to play a major role as the nuclear industry faces the challenges and opportunities of the 21st century.

LIST OF IAEA PUBLICATIONS

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

2. 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.

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

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

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

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