SESSION I

OVERVIEW OF NATIONAL AND INTERNATIONAL PROGRAMMES

J.L. Diaz-Diaz (CIEMAT) – Ph. Savelli (OECD/NEA)

RESEARCH AND DEVELOPMENT OF TECHNOLOGIES FOR PARTITIONING AND TRANSMUTATION OF LONG-LIVED NUCLIDES IN JAPAN
– STATUS AND EVALUATION –

Sanae Aoki
Director for Planning,
Radioactive Waste Policy Division, Science and Technology Agency (STA)
2-2-1, Kasumigaseki, Chiyoda-ku ,Tokyo, 100-8966, Japan
E-mail: s3aoki@sta.go.jp

1. Current activities for radioactive waste management

Measures to treat and dispose of radioactive waste are one of the most important issues in the development and application of nuclear energy. The Atomic Energy Commission (AEC) has carefully considered how to classify radioactive waste properly and how to dispose of it according to these classifications.

Japanese basic policy regarding disposal of high-level radioactive waste (HLW) is to solidify it into stabilized form, to store it for 30-50 years to be cooled, and to dispose of it deep to the underground (geological disposal).

In April 1997, the Advisory Committee on Nuclear Fuel Cycle Back-end Policy, AEC, laid down the guidelines on future research and development of the disposal of HLW. In accordance with the report, the Japan Nuclear Cycle Development Institute (JNC released the report on the outcome of R&D activities to elucidate technological reliability of the geological disposal, and to provide technical ground for selecting repository sites and for establishing safety requirement in the form of the second progress report in December 1999, with the co-operation of related institutions, such as the Japan Atomic Energy Research Institute (JAERI), the Central Research Institute (CRIEPI), the Geological Survey of Japan (GSJ), the National Research Institute for Earth Science and Disaster Prevention (NIED), and university researchers.

In parallel with the R&D programme, there has also been an effort to make a system for implementing HLW disposal. In the Special Committee on High-Level Radioactive Waste Disposal, AEC, and in the nuclear sub-committee of the Advisory Committee for Energy, Ministry of International Trade and Industry, various aspects of HLW disposal were considered, including social and economic aspects. A law[1] for implementing geological disposal was passed in the Diet in May 2000. Based on the law, an implementing entity[2] for HLW disposal was established in October 2000. The programme then moves from the generic into the site-specific phase. Thereafter we are looking to start operation of the repository between 2030 and the mid-2040s at the latest.

2. Status of partitioning and transmutation study

At the same time, recognizing the nature of the radioactive nuclides contained in HLW, the aim since the early days of nuclear energy has been to develop technology either to separate useful elements and nuclides in order to re-use them effectively, or to transmute long-lived nuclides into short-lived or stable – i.e. non-radioactive – forms by irradiation.

In Japan, reference to P&T technology for long-lived and other nuclides first appeared in the *Long-term Programme for Nuclear Research, Development and Utilisation* (or "long-term nuclear programme") back in 1972. That programme noted the need for research and development in order to ensure effective processing of radioactive waste.

In a 1976 interim report by the AEC's Technical Advisory Committee on Radioactive Waste, the relationship between P&T technology and the disposal of radioactive waste was specifically pointed out. Specifically, if radioactive nuclides in waste could be appropriately separated into groups, waste management could become more flexible. This is because the amount of radioactive nuclides requiring strict control would be reduced, and treatment and disposal appropriate for the half-life of each group would become possible. In addition, if long-lived nuclides could be transmuted into short-lived ones by nuclear reaction, the burden of long-term waste management could also be reduced.

---

[1] Specified Radioactive Waste Final Disposal Act.

[2] Nuclear Waste Management Organisation of Japan (NUMO).

The long-term nuclear programme issued in 1987 stated that P&T technology was very important from the viewpoint of recycling HLW and enhancing disposal efficiency. It also stated that systematic R&D would be carried out jointly by JAERI, the then Power Reactor and Nuclear Fuel Development Corp. (PNC, now JNC) and others.

Under that programme, in 1988, the AEC's Advisory Committee on Radioactive Waste Measures issued a report entitled, *Long-term Programme for Research and Development on Nuclide Partitioning and Transmutation Technology*[3] This can be considered to have been the first systematic R&D programme on P&T technology in Japan. It presented a plan for R&D that ran from 1988 to 2000 and was divided into two phases**:** Phase I, covering the first four to nine years, which included evaluation of various concepts and R&D on key technologies; and Phase II, covering the next four to nine years, which included engineering experiments on key technologies and demonstrations.

The long-term nuclear programme issued in 1994 stated that each research institute would carry out basic studies on P&T technologies and evaluate each technology at some time in the mid-1990s to determine how to proceed thereafter.

Meanwhile, in 1998, the AEC's Special Committee on the Disposal of High-Level Radioactive Waste released *Basic Concepts in the Disposal of High-level Radioactive Waste*. This stated that, in order to gain public understanding of disposal technology, "research on waste reduction with the aim of achieving safer and more efficient geological disposal, as well as more efficient use of waste, would be carried out on a regular basis". It also said that it was "important to have mechanisms to respond flexibly to any dramatic progress in P&T technology".

Under these circumstances, the AEC's Advisory Committee on Nuclear Fuel Cycle Back-end Policy investigated and considered matters concerning P&T technology for long-lived and other nuclides, based on the evaluation schedule stated in the long-term nuclear programme issued in 1994. The Committee issued a report entitled, *Research and Development of Technologies for Partitioning and Transmutation of Long-lived Nuclide Status and Evaluation Report* in March 2000. The brief summary of this report is as follow.

3. Results to date and analyses of current status

3.1 Elements subject to P&T

Long-lived (i.e. long half-life). In particular**:**

- High radiotoxity due to the emission of rays.
- Fast migration through geological formations via underground water, when disposed of geologically**.**

Relatively short-lived and heat-generating, producing most of the heat in HLW.

Rare and useful elements**.**

[3] Called the "OMEGA Programme" – an acronym for Options Making Extra Gains from Actinides and Fission Products.

3.2 Results to date and analyses of current status

3.2.1 The partitioning process

3.2.1.1 JAERI

JAERI is developing a four-group partitioning process, in which elements in concentrated high-level liquid waste HLLW are separated into four groups: MAs, Tc-platinum group metals, Sr-Cs, and others. Basic experiments using simulated HLLW helped to establish the concept. Test runs with both simulated and actual HLLW on a scale 1/1000 that of an actual plant confirmed the expected capabilities of group partitioning. A recovery rate for MAs of 99.95% or better was achieved.

3.2.1.2 JNC

JNC is developing an improved PUREX process – an advanced version of the conventional reprocessing process – to recover Np. It is also developing a CMPO-TRUEX process to separate MAs from highly concentrated HLLW and an electrolytic extraction method to separate Tc-platinum group and other elements from aqueous reprocessing solutions. In the CMPO-TRUEX process research, it was demonstrated that Am and all nuclides can be recovered to a level of 99.9% or more under standard extraction conditions.

3.2.1.3 CRIEPI

CRIEPI is developing a reductive-extraction process using molten chlorides and liquid metal solvents. Basic data were obtained for the behavior of elements in this type of molten-salt-and-liquid-metal system. Experiments on the separation of recovery of TRUs were carried out using some 10 milligrams of TRUs and some 100 grams of chlorides, which confirmed recovery of more than 99% of the TRUs and adequate separation of TRUs from REs.

3.2.2 The transmutation cycle

JNC and CRIEPI are studying transmutation technology using fast breeder reactors (FBRs). This concept is centered on the use of fast reactors for electricity generation. In this scenario , FBR will take over the role of light-water reactor (LWR) in future, with power generation and the transmutation of MAs and other elements carried out simultaneously by the FBR. In contrast, JAERI's concept is the "double strata fuel cycle", where a dedicated system for transmuting MAs, such as an actinide burner fast reactor (ABR) or an accelerator-driven subcritical system (ADS) is at the centre of the transmutation cycle, allowing a commercial power generation cycle and a transmutation cycle to be developed and optimized independently for their individual purposes.

3.2.3 The fuel production process

3.2.3.1 JAERI

JAERI is developing MA-nitride fuel. The basic data on thermal properties of MA-nitrides necessary to design the fuel, as well as thermal properties of Tc alloys, were obtained. It was confirmed that the MA nitrides could be prepared by means of carbothermic synthesis and uranium nitrides microspheres can be produced via the sol-gel process. In addition, through irradiation tests of U-Pu mixed nitride fuel produced on a trial basis, it was ascertained that the fuel element was intact after a burn-up rate of 5.5% achieved.

3.2.3.2 JNC

JNC is developing fuel in which Np and/or Am is added to the MOX fuel that JNC has developed for FBRs. For the addition of Np to MOX fuel, a vibro-packing process is being developed in a joint international research effort. For the addition of Am to MOX fuel, in addition to irradiation experiments being carried out at the experimental fast reactor "Joyo", remote fuel fabrication facilities, including those to produce pellets and inspect fuel pins, were established and performance tests were carried out.

3.2.3.3 CRIEPI

CRIEPI is developing metallic fuel – an MA-content U-Pu-Zr ternary alloy under the international collaborations. Fuel pins have been made on a trial basis and physical characteristics and other basic data have been obtained. It has been determined that an MA content of about 5% does not affect the characteristics of the fuel, and it is expected that MAs can be mixed homogeneously during fabrication of the fuel.

3.2.4 The transmutation process

3.2.4.1 JAERI

JAERI is developing concepts for ADSs and ABRs. Nuclear data on MA nuclides were obtained through international co-operation and were verified while developing a database, carrying out integral experiments and analysing irradiated MA samples. In the development of a proton accelerator for the ADS, major key technologies were developed, and the highest level performance has been demonstrated.

3.2.4.2 JNC

JNC is developing a MOX-fuelled FBR. The prototype reactor "Monju" already exists – i.e. construction of a "prototype plant" has been achieved – but the development of other key technologies will be required to add MAs to MOX fuel. Nuclear data on MA nuclides were obtained and evaluated via nuclear reactors and accelerators. Design studies were carried out on acceptable amounts of MAs and rare-earth elements, and on actual fuel loading.

3.2.4.3 CRIEPI

CRIEPI is developing the concept of metallic-fuelled FBRs. Regarding nuclear data on MA nuclides, analysis programmes for MA transmutation were developed and analyses were carried out.

3.2.5 Fuel processing

3.2.5.1 JAERI

JAERI is developing a pyrochemical process similar to dry reprocessing. Molten-salt electrolysis of U-nitride, Np-nitride and Pu-nitride on a gram scale were carried out to confirm that transuranic metals can be recovered. For the recovery and recycling of N-15, nitrogen (N_2) release in molten salts was studied, and it was confirmed that almost 100% of the nitrides can be released in the form of N_2.

3.2.5.2 JNC

JNC is considering the same method as for the partitioning process.

3.2.5.3 CRIEPI

CRIEPI is developing molten-salt electrorefining and reductive extraction, which is similar to the partitioning process. Electrorefining forms the main part of the pyro-reprocessing method. Feasibility was confirmed through an in-house study and international joint research, and the process is now at the stage of engineering experiments. Feasibility of the conversion of oxides of spent fuel to metal, and of the spent-salt treatment process, are still to be confirmed.

3.2.6 Conclusion

R&D at the three research institutes has resulted in establishment of processes for P&T technology with the expected performance. The aims of Phase I R&D have thus been achieved. R&D in Phase II has experienced some delays, the primary reasons being that Japan is redefining its entire FBR programme, and facilities to handle MAs and other materials have yet to be constructed. In carrying out further R&D, it is important to promote cooperation with domestic and foreign organizations in order that experimental facilities – including those for engineering experiments – can be used efficiently.

3.3 Technical issues

The implementation of experiments to demonstrate processes using actual HLLW is an issue common to the three organizations. Also common to JAERI and JNC, which are developing aqueous partitioning processes, are development of a method to more efficiently separate MAs and rare-earth elements, and technologies to reduce the volume of secondary waste. At CRIEPI, where dry partitioning is being developed, the main technical issues in the handling of molten chlorides are material development and molten-salt transport technology. Common issues to the three organisations are preparation of a database on fuel irradiation behavior for performance analysis, and development of fuel fabrication technology.

4. Effects and significance of partitioning and transmutation technology

4.1 Radioactive inventory in waste

It is a social imperative to minimise, as far as possible, the generation of hazardous waste produced by industrial activities. Reduction of long-term radioactive inventory through the removal of long-lived nuclides from HLW by P&T technology helps to meet this requirement. If, for example, 99% of MAs contained in spent fuel can be removed, the toxicity of the spent fuel after several hundred years following reprocessing will be equal to the toxicity of the same amount of natural uranium as used in the production of the original fuel.

4.2 Effects on geological disposal

4.2.1 Long-term safety

- Effects on the underground water migration scenario:

  Maximum dose can be reduced by about two orders of magnitude by separating and removing 99% of the ^{135}Cs, and 99% or more of the Np and Am, which are parent nuclides of ^{229}Th.

- Effects on the human intrusion scenario:

  Risks can be reduced by two orders of magnitude by separating and removing 99-99.99% of the actinide elements.

4.2.2 Impact on geological disposal site design

Approximately two-thirds of the heat from HLW is generated by Cs and Sr, and separation and removal of these elements would shorten the required storage period and reduce the size of the site. The HLW storage period could be reduced by separating and removing exothermic nuclides. In addition, disposal site design could be rationalized by, for example, disposing of the HLW in one large cavity rather than in several smaller ones.

4.3 Effective use of resources

Among the materials in HLW, some can be used effectively as resources. For example platinum group elements are widely used as catalysts to reduce nitrogen oxides in vehicle exhaust gases, and so on. However, prior to actual application, clearance level issues are to be solved.

4.4 Reduction of MA and LLFP inventory, and the times required

Even if P&T technology is employed, some MAs and LLFPs will remain in the waste, and final disposal of such waste will eventually be necessary. An oxide-fuelled or metallic-fuelled fast reactor can transmute MAs from more than five or six LWRs every year. While an ADS with one quarter of thermal output of a LWR can transmute MAs from more than ten LWRs (about 250 kg per year).

4.5 Generation of secondary waste

The aqueous partitioning process, like PUREX reprocessing, generates secondary waste. Compared with reprocessing, however, the volume of secondary waste is lower because P&T technology deals with the very limited quantities of HLLW generated by reprocessing.

In the dry-type partitioning process, molten salts and liquid metals are used as solvents, and metallic Li is used as a reducer. These solvents and reducers are less susceptible to degradation by radiation, and may be recycled in the system. But there is almost no experience of using this process on an industrial scale.

To evaluate the secondary waste volume, further investigations and experience using actual materials are needed.

4.6 Short-term increase in radiation dose

When P&T technology is employed in the nuclear fuel cycle, exposure dose could increase in the short term as new processes and facilities are introduced and as the volume of MAs and LLFPs to be dealt with in such processes increases. It will be possible, however, to keep exposure dose for workers and the public below the statutory standard, and as low as reasonably possible, by measures such as enhanced shielding.

4.7 Economy

R&D to date has focused on basic studies to obtain fundamental data for designing processes and systems, and no one is in a position to make a reliable cost estimate for the P&T technology. Nevertheless, very preliminary cost estimates of three organisations indicate a few percent of LWR electricity generation cost for PT implementation.

5. Future research and development

Modern society demands maximum control of hazardous waste produced by industry, as well as recycling to preserve resources and protect the environment. It goes without saying that the nuclear industry, too, must take all effective measures. P&T technology applied to long-lived nuclides can be useful in, for example, reducing the long-term radioactive inventory in nuclear waste, and it is appropriate that R&D should be carried out on an ongoing basis.

5.1 P&T technology and the nuclear fuel cycle

P&T technology is a part of the nuclear fuel cycle. The question of how and in what part of the nuclear fuel cycle P&T technology should be incorporated in order to optimize the cycle, should be considered. The purpose of R&D is to suggest scenarios for introducing P&T systems into the nuclear fuel cycle, and to develop designs and establish key technologies for such systems. Keeping the totality of the fuel cycle in mind, it is necessary to correctly evaluate issues of economy, energy security, and reduction of the radioactive inventory in waste, and to analyse the trade-off among those factors.

5.2 Research on system design and development of key technologies

R&D for P&T technology consists of research on system design with the aim of introducing this technology into the nuclear fuel cycle, and development of the key technologies necessary to realise the system. Development of key technologies takes time and should be carried out in a progressive fashion, while at the same time being properly integrated with research on system design.

5.3 How to proceed R&D in future

P&T technology based on the use of power-generating fast reactors, and P&T technology based on the double-strata fuel-cycle concept, on which R&D is being carried out in Japan, have their own distinctive features. These two concepts also provide new options for the fuel cycle and it is therefore appropriate at this stage to continue the development of both. The objectives of further R&D are to study scenarios, including a possible blending of these two concepts, in order to introduce a feasible P&T technology system into the nuclear fuel cycle, and to develop the necessary technologies. System design and P&T introduction scenarios will continue to be studied. According to the scenarios thus defined, and based on the results of R&D to date, small-scale experiments to demonstrate the feasibility of a series of processes will then be conducted. Following this, systems whose feasibility has been successfully demonstrated will be subjected to engineering tests in order to obtain data on their safety. It will be important at this stage to manage the R&D under a system of checks and reviews, and to update the scenarios on a regular basis.

5.4 Co-operation for R&D

Although there are differences in the concepts, reactor types and systems, many common issues exist in R&D on P&T technology. JAERI, JNC and CRIEPI should work together in an effort to resolve those common issues, strengthening their co-operation through the sharing of their R&D results. At the same time, it is important to carry out the R&D effectively by, for example, cooperating with other domestic organizations and using their existing facilities. In Western nations, the trend is toward international co-operation in various areas of P&T technology R&D, and the three organisations should actively join such cooperation frameworks and make use of research facilities available overseas. They are also encouraged to exchange information through the existing OECD/NEA framework.

5.5 R&D schedule and evaluation

P&T technology is inseparable from the nuclear fuel cycle, and it is therefore appropriate to conduct R&D in this area on a time schedule compatible with nuclear fuel cycle R&D. At present, feasibility study on commercialised FBRs and related fuel cycle system is being carried out under the collaborative efforts of JNC, electric utilities, CRIEPI and JAERI. In this study, R&D scenarios toward commercialization of fast reactor system will be reviewed by about 2005. Thus, around the year 2005 is deemed to be an appropriate time to reconsider all R&D scenarios of PT including the use of FBRs for transmutation together with power generation, and the double-strata fuel cycle. Thereafter, progress, results and R&D policy will be checked and reviewed every five years or so. Evaluations of P&T technology system concepts, and reviews of introduction scenarios, should also be conducted.

6. Concluding remarks

P&T technology belongs to a world quite different from that of ordinary chemical reactions in the sense that, in P&T, materials are transformed at the atomic level. Its potential is not limited simply to transmutation. In addition, its development raises issues that will be difficult to resolve with existing technology alone, overcoming these difficulties could lead to other exciting technological breakthroughs. This, indeed, should be one reason for young engineers scientists to want to become involved in the field. Research on this kind of advanced technology can be expected to make a great contribution to revitalizing nuclear research generally. P&T technology research should be actively promoted in order to nurture the development of human resources in the nuclear field.

In doing this, however, it is important to create an environment in which innovative ideas can be adopted without “interference” from existing systems. P&T technology requires open-minded R&D.

Inspired by Japan’s OMEGA programme, many similar programmes have been established around the world – in France, other European countries, and the United States. It is expected for Japan to play an important on-going role in this area – and to do so as part of her international contribution, while conducting timely evaluation of R&D progress.

Annex 1

R&D scheme for partitioning and transmutation of long-lived radioactive waste in Japan

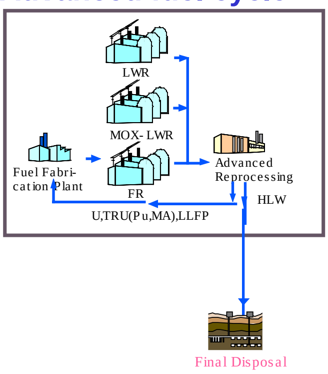
JNC,CRIEPI

- **Advanced fuel cycle**
  - Commercial FR for transmutation
  - Oxide fuel, Metal fuel
  - 2~5% MA content (homogeneous)

JAERI

- **Double-strata fuel cycle concept**
  - Combination of a power reactor fuel cycle & an independent P-T cycle
  - Dedicated systems for P-T
  - Accelerator-Driven System (ADS)

Advanced fuel cycle



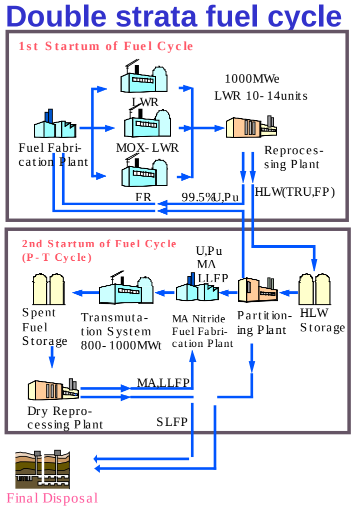
MA ; Minor Actinide
LLFP; Long- lived FP
SLFP; Short- lived FP

Common technologies

R&D items to be developed in collaboration

- Separation chemistry
- Reactor physics
- Fuel basic property
- Irradiation test
- Nuclear data

Double strata fuel cycle



		JAERI	JNC	CRIEPI
Elements subject to P&T	Partitioning	MAs (Np, Am, Cm), Pu, Tc Platinum group (Ru, Rh, Pd), Sr, Cs	MAs (Np, Am, Cm), Pu, Tc Platinum group (Ru, Rh, Pd)	MAs (Np, Am, Cm), Pu
	Transmutation	MAs (Np, Am, Cm), Tc, I	MAs (Np, Am, Cm), Pu, Tc, I	MAs (Np, Am, Cm), Pu
Partitioning process		4-group partitioning process (wet process)	Advanced reprocessing nuclide partitioning system (wet process)	Dry process
	MA separation	DIDPA extraction	CMPOTRUEX process Improved PUREX process	Reductive extraction (molten salt/liquid metal)
	Tc-Platinum group	Precipitation by de-nitration	Electrolytic extraction	–
	Sr-Cs	Column absorption with inorganic ion exchangers	–	–
Transmutation cycle		Double strata fuel cycle	MOX fuelled FBR	Metallic-fuelled FBR
	Fuel type	MA-nitride fuel	MA-MOX fuel	U-Pu-Zr ternary alloy
	Transmutation process	Accelerator driven sub-critical system (ADS) Actinide burner fast reactor(ABR)	FBR	FBR
	Fuel processing	Molten-salt electrolysis (pyroprocess)	Wet process	Molten-salt electro-refining and reductive extraction

Annex 3

Members of the Advisory Committee on Nuclear Fuel Cycle Back-end Policy
Atomic Energy Commission of Japan

Yumi Akimoto	President, Mitsubishi Materials Corporation
Kenkichi Ishigure	Professor, Saitama Institute of Technology
Nobuo Ishizuka	Member of Board and Secretary General, Japan Atomic Industrial Forum, Inc.
Michiko Ichimasa	Professor, Ibaraki University
Yoichiro Ohmomo	Senior Executive Director, Institute for Environmental Sciences
Yoshiaki Oka	Professor, University of Tokyo
Takeki Kawahito	Chairman, Radioactive Waste Management Center
Keiji Kanda	Professor, Kyoto University
Tomoko Kusama	President, Oita University of Nursing and Health Sciences
Nobuaki Kumagai	Professor Emeritus, Osaka University
Keiji Kojima	Representative, Geospace Laboratory
Osamu Konishi	Editor, Nippon Hoso Kyokai (Japan Broadcasting Corporation)
Kisaburo Kodama	Director General, Geological Survey of Japan
Shinzo Saito	Vice President, Japan Atomic Energy Research Institute
Shiro Sasaki	Technical consultant, Japan Nuclear Fuel Limited
Atsuyuki Suzuki	Professor, University of Tokyo
Hiroshi Sekimoto	Professor, Tokyo Institute of Technology
Satoru Tanaka	Professor, University of Tokyo
Yasumasa Tanaka	Professor, Gakushuin University
Akira Tokuyama	President, Fuji Tokoha University
Hiroyuki Torii	Editorial Writer, Nihon Keizai Shimbun, Inc.
Yasuo Nakagami	Executive Vice President, Japan Nuclear Cycle Development Institute
Tadashi Nagakura	Senior Advisor Emeritus, Central Research Institute of the Electrical Power Industry
Kunio Higashi	Professor, Kyoto University
Junsuke Fujioka	Managing Director, Japan Radioisotope Association
Hajimu Maeda	Chairman, Nuclear Task Force, Federation of Electric Power Companies
Miyako Matsuda	Commentator on consumer and environmental affairs (Issues related to waste and recycling)
Hirotake Moriyama	Professor, Kyoto University
Yoshiaki Yamanouchi	Attorney at Law

FRENCH RESEARCH PROGRAMME TO REDUCE THE MASS AND TOXICITY OF LONG-LIVED HIGHLY RADIOACTIVE NUCLEAR WASTE

Jacques Bouchard, Director of Nuclear Energy
Patrice Bernard, Director of Nuclear Development and Innovation
CEA, Nuclear Energy Division
31, rue de la Fédération, 75752 Paris Cedex 15

France has launched a process of optimising waste management by separating and recycling recoverable energy materials, reducing, conditioning and storing final waste. In addition, it has initiated operations to clean up and dismantle older facilities (first-generation reactors, cycle plants, etc.) through the development of related technologies.

French research and industry have developed processes and technologies which ensure downstream management of the fuel cycle and waste (reprocessing of spent fuel, recycling of plutonium, processing and conditioning of waste from nuclear plants and cycle facilities, development of containers and interim storage facilities – clean up and dismantling).

Once operations in the downstream part of the cycle have been completed, long-lived highly radioactive waste (vitrified class C waste) represents the major portion of the waste's total radioactivity, conditioned in a small volume (<180 m^3/year of glass packages).

Research and development are being pursued with two main objectives:

- To minimise the quantity of waste produced by operations at nuclear power plants.
- To develop processes which would make it possible to condition long-lived radioactive materials in order to ensure safe and long-lasting containment in the form of moveable objects, i.e. packages, and also to study interim storage[1] or disposal[2] facilities designed to protect these packages over time.

Research primarily concerns the following areas:

- The control of plutonium, which is both an energy material and the main contributor to long-term radioactivity – studies here target progressive integration into the new fuel cycle so that

[1] Interim storage is a management option under the responsibility of the society, in surface or underground facilities, allowing to protect the packages and to ensure recovery under conditions, which are safe and defined by technical specifications.

[2] Disposal is a solution, which could become definitive in the absence of human intervention, since the geological medium makes it possible to ensure containment on a time scale characteristic of long-lived radioactive elements.

plutonium can be recycled in pressurized water reactors on a recurring basis under economically acceptable conditions.

- Minimising long-lived highly radioactive final waste – studies here concern separation (intensive chemical separation during reprocessing for which new very selective molecules have been developed), transmutation (transformation in industrial or specialized nuclear reactors into non-radioactive elements or with a much shorter life), specific conditioning (incorporation of separated elements, which cannot be transmuted, within the crystalline network of almost unalterable materials on a time scale characteristic of disappearance through radioactive decay) of the main long-lived radionuclides (minor actinides and certain very long-lived fission products abundant in spent fuel and potentially more mobile in the environment[3]) present in highly radioactive waste;

Research is conducted with the goal of establishing by 2006 the scientific feasibility of transmutation in various types of nuclear reactors (PWR, innovative reactors) and the technical feasibility of intensive separation downstream from reprocessing at La Hague, as well as of the specific conditioning of separated long-lived radionuclides.

Studies are conducted in the framework of the French law of December 30, 1991, on the management of long-lived highly radioactive waste, which established a structured research programme with three focuses: separation-transmutation, storage in deep geological formations, conditioning and long-term interim storage.

- Focus 1 studies the various solutions envisaged to ensure a substantial reduction of the mass and toxicity of waste, for the same amount of energy produced, by separating and transmuting the waste.
- Focus 2 studies storage in deep geological formations, a situation which could become definitive in the absence of human intervention, since the geological medium makes it possible to ensure containment on a time scale characteristic of long-lived radionuclides, while maintaining for a certain period an option of reversibility so that our descendants might be able to recover the packages.
- Focus 3 concerns management procedures under the responsibility of the society, in long-term interim storage facilities above or under ground, which make it possible to protect the packages, by having previously conditioned them in a form which ensures long-lasting containment and the possibility to recover the packages under conditions that are safe and defined by technical specifications.

The law defined a calendar which stipulates that a comprehensive report evaluating research will be submitted to the French Parliament in 2006. Public authorities have designated a pilot for each focus: the French Atomic Energy Commission (CEA) for Focuses 1 and 3 and Andra for Focus 2.

This research is conducted in co-operation with partners in the nuclear industry, EdF, COGEMA and FRAMATOME, as well as with CNRS and universities. It benefits from significant co-operation at the European and international level. It is constantly evaluated by the National Evaluation Commission, which draws up and publishes an evaluation report annually.

---

[3] Mainly iodine 129, caesium 125, technetium 99.

The procedure involves identifying a set of complementary scientific and technical solutions, which serve to define open and flexible strategies for the downstream part of the cycle and lay the groundwork for a decision in 2006.

Concerning partitioning research, if studies on uranium and plutonium separation from the other fission products depend on a mature chemical process, intensive separation of minor actinides and these three fission products was not possible using industrial processes. Through studies conducted since 1991, a reference programme was defined for an advanced separation process for the main long-lived radionuclides present in waste:

- Neptunium, iodine and technetium could be separated by adapting the PUREX process used industrially in the reprocessing facilities at La Hague.
- To separate americium, curium and cesium, it was necessary to develop new chemical separation processes by devising very selective molecules capable of separating these elements.

The families of extractors were defined, the principal reference molecules synthesised, and their performances verified experimentally on real radioactive solutions in the ATALANTE facility at CEA-Marcoule, in order to reach the stage of scientific feasibility (2001). The next stage will be that of technical feasibility, moving from the molecule to the overall chemical process, which will be defined and validated in 2005. The existence of the reprocessing industry makes the implementation of these processes a real possibility.

In addition, research conducted in recent years has pointed up the performances of the control of plutonium and of transmutation in different types of electronuclear power plants, showing:

- That it is possible to stabilize over time the quantity of plutonium by consuming it completely with advanced plutonium fuel; an overall balance can thus be reached between the formation and the consumption of plutonium; the amount of final waste is consequently divided by three compared with the open cycle.
- That by separating and multi-recycling the minor actinides in a reactor (in order to transmute them), the mass and toxicity of the waste is divided by 100 on a similar basis, and studies show that the innovative reactors (electricity-producing reactors or those dedicated to transmutation) which present the characteristics adapted to these performances (great capacity to consume plutonium as well as long-lived radionuclides and ability to use to the best advantage the energy contained in the fuel: rapid spectrum, fuel with a very high combustion rate, reactor/integrated cycle, etc.).

Experimental studies on fuel for the transmutation in rapid neutron reactors have been launched, in particular in the PHENIX reactor, whose irradiation programme has focused on this research since 1998 and which has therefore been the object of inspection, renovation and maintenance, in view of a power increase in 2001.

Teams at CEA and CNRS, in cooperation with industrial partners, have provided the technical data for a request for an experimental demonstration model of a hybrid reactor for transmutation, in a European and international framework.

This research is conducted to provide, in particular with reference to the report which must be submitted to Parliament in 2006, the scientific and technical elements which may contribute to the choices and the implementation of management options for radioactive waste based on three guiding principles: the minimization of waste, containment and reversibility.

The strategy targeting the control of plutonium and the minimisation of final waste aims to achieve a significant long-term reduction in the mass and toxicity of waste to be stored and promotes progressive implementation.

- The implementation of the separation-conditioning strategy may be programmed as an extension of existing industrial capability: development, in a reprocessing facility, of complementary processes which would make it possible to carry out the intensive separation of long-lived radioactive elements, then their conditioning in specific matrixes designed to last a very long time.

- The transmutation potential of light water reactors (current and EPR to satisfy the need for new reactors), based on the development of new plutonium fuel, could be used to consume all the plutonium, with the other long-lived elements benefiting from the separation-conditioning strategy; the amount of final waste is thus divided by three compared with the open cycle.

- Future nuclear power production systems, studied in light of objectives of economic competitiveness, optimum utilisation of natural resources in fuel, significant capacity for the consumption of plutonium and long-lived radionuclides, would make it possible to reduce even further the mass and toxicity of waste to be stored.

In addition, research on conditioning, interim storage and long-term storage is conducted, in cooperation with the producers of waste and Andra, in order to develop:

- Processes for processing-conditioning for all types of nuclear waste for which an industrial conditioning process does not exist.
- Containers which are certified for long-term interim storage, compatible with recovery or final repository.
- Knowledge of the characteristics and performances of the long-term behaviour of all the packages.
- Detailed preliminary projects for interim storage facilities, above or under ground, certified for the long-term, and ready to be built if so decided, making it possible to keep spent fuel over time, in particular MOX fuel, in order to preserve the energy content and be able to carry out reprocessing-separation-transmutation operations at a later date.

THE STATUS OF THE US ACCELERATOR TRANSMUTATION OF WASTE PROGRAMME

James C. Bresee[1]**, James J. Laidler**[2]
[1]United States Department of Energy
1000 Independence Avenue, SW, Washington, DC 20585, USA
[2]Argonne National Laboratory (East)
9700 South Cass Avenue, Argonne, Illinois 60439, USA

Abstract

Since the last biannual meeting on partitioning and transmutation, the US accelerator transmutation of waste (ATW) programme has changed significantly. Two years ago, the only effort was the preparation of a research plan for developing ATW technology. Today, a significant research effort in underway, and the US is seeking opportunities to collaborate with other national programmes. Although the US fuel cycle is still based on a "once-through" process, with civilian spent fuel being stored for direct disposal in a geologic repository, the technical feasibility for transmutation is being investigated as a possible future option. Technetium-99, iodine-129 and neptunium-237 may be released from a repository over geologic time periods and are the principle radioisotopes for transmutation studies. Substantial reduction in total fissile materials and generation of useful energy are also possible benefits of ATW. New test facilities are being considered which may be useful for future multinational studies.

1. Introduction

Since the 5th Information Exchange Meeting in Mol, Belgium in November 1998, the US accelerator transmutation of waste (ATW) programme and indeed the US programme for chemical processing of spent fuel has undergone a substantial change. At the time of the Mol meeting, the US Congress had just authorised the preparation of a “roadmap” or programme plan for the development of ATW technology. The background provided by foreign transmutation programmes and commercial spent fuel reprocessing was an important part of the resulting roadmap which was published in late 1999 [1]. Based on that report, the US Congress provided $9 million in Fiscal Year 2000 (October 1, 1999-September 30, 2000) to establish an ATW research and development programme in the Office of Nuclear Energy, Science and Technology. Department of Energy appropriations for the current fiscal year (October 1, 2000 – September 30, 2001) include a substantial increase in ATW funding. The purpose of this paper is to describe the content of that programme and the status of the R&D effort.

2. The US civilian spent fuel management programme

The nuclear fuel cycle in the US is currently a once-through process. Spent fuel from the approximately 100 civilian nuclear power plants is being stored at the reactor sites with the intention of transporting it in the future to a central geologic repository for “permanent” disposal. However, any such repository, under current Nuclear Regulatory Commission requirements, must be designed to allow spent fuel retrieval for at least 50 years. The actual design of a proposed repository at Yucca Mountain, Nevada involves a retrieval capability for at least 100 years. Such retrieval is mainly for safety purposes, in the unlikely event that during performance monitoring, the repository or its contents develop significant problems.

Long term access to the contents of the repository also increases the probability of licensing, since some of the uncertainties about repository safety will be reduced during monitoring. Finally, retrievability offers the possibility that future generations may decide to recover the energy in the spent fuel (principally plutonium-239) and reduce the long half-life radioactivity in the waste through transmutation. Thus, the existence of a US programme for the development of a “once-through” geologic repository while at the same time studying the possibility of nuclear waste transmutation represents a consistent approach and provides technical flexibility. After all of the changes during the twentieth century, an allowance for future technologic advances in nuclear waste management is sound public policy.

The US Yucca Mountain project has reached a critical juncture. In December 2000, the Department of Energy is releasing to the public a Site Recommendation Consideration Report which provides interested parties with essentially all of the information which will provided in June 2001 to the President in a Site Recommendation Report. He will use the final version of the report as a basis for his decision on whether to recommend the Yucca Mountain site to Congress as one he feels meets the strict environmental and safety requirements for a permanent repository. If he does so decide, the Nuclear Waste Policy Act of 1992, as amended, provides an opportunity for the affected state (Nevada, in the case of Yucca Mountain) to object to the President’s decision. Such an objection stands unless overridden by a majority of both the US Senate and the US House of Representatives. The technical content and persuasive arguments of the Site Recommendation Report will strongly influence such a Congressional override.

The Yucca Mountain site is arid. Its annual rainfall is only about 12 centimetres of rain, 95%

of which runs off or is evaporated rather than penetrating the mountain. That which does penetrate moves in unsaturated flow through cemented and uncemented volcanic rock about 300 meters before reaching the waste site and then another 300 meters before reaching saturation. The saturated zone under the proposed repository site then flows slowly toward Death Valley as part of a closed hydrology region. The water eventually evaporates in Death Valley rather than being connected with any regional river system such as the Colorado River. Approximately thirty miles from the Yucca Mountain site, there is some farming in Amargosa Valley which uses irrigation water from the same aquifer flowing toward death Valley. It is the safety of individuals in Amargosa Valley which will determine the acceptability and, if the site is found to be acceptable, the ability to license a possible Yucca Mountain repository.

The most important issues in the decision process will be the containment at the repository site of certain long-lived fission products and heavy elements within the high level nuclear waste. All past performance assessment studies of the Yucca Mountain site as a possible repository, including that reported in the Site Recommendation Consideration Report, have indicated that the dominant mobile radionuclides during the first 10 000 years of the repository life are technetium-99 (213 000 year half-life) and iodine-129 (15.7 million year half-life), both of which may be transported by underground water to points of possible human exposure. After approximately 100 000 years, the dominant isotope is neptunium- 237, with the possibility that plutonium isotopes may also be important if carried by colloids or if plutonium were present in the more soluble VI oxidation state. ^{99}Tc, ^{129}I and ^{237}Np (and other minor actinides) have been the focus of attention in US studies of transmutation. No transmutation evaluations have indicated that a repository programme will not be needed in the future; all such studies have shown that transmutation, if successful, could reduce the hazards of such repositories.

3. The current US transmutation programme

Transmutation R&D in the US initially has been focused on accelerator-driven systems and has involved a series of trade-off studies. In all cases, it has been assumed that uranium remaining in civilian spent fuel elements would be recovered, probably by a modified Purex process called UREX. Initial studies of the UREX process have shown that the uranium product will meet US Class C requirements and could be disposed of as low level waste or be stored for possible future use in a nuclear fuel cycle. The remaining process streams would be chemically separated into transmutation fuel material, long-lived fission product transmutation targets, and a waste stream that can be converted into durable waste forms capable of disposal in a high-level nuclear waste repository.

Various combinations of proton accelerator designs, spallation neutron sources, and transmutation target have been evaluated for technology readiness, and assumed irradiated targets have been studied for the effectiveness of chemical processing to recycle untransmuted long-lived isotopes. These evaluation have resulted in a base-line design which includes a linear proton accelerator (or Linac), a lead-bismuth spallation target, and sodium- cooled metallic or ceramic dispersion transmutation target/blanket non-fertile fuel elements. The initial formation of such non-fertile transmutation targets and their subsequent reprocessing is the subject of a paper to be presented later in this conference [2]. Other alternative designs have included cyclotrons, tungsten spallation targets cooled by sodium, pressurised helium, or water, and nitride transmutation targets.

Another interesting transmutation system design currently being evaluated consists of a "dual strata" approach which would involve a thermal critical reactor within which plutonium and minor actinides would fission and $^{99}Tc/^{129}I$ would be subjected to a thermal neutron flux. Technetium would probably be in metallic form and iodine as an iodide of sodium, silver or other stable cations. The thermal spectrum reactor would be an effective plutonium-239 burner along with other actinides with high thermal fission cross-sections. Higher actinide isotopes would be produced by non-fission neutron capture, and after post-irradiation chemical processing, they would be the primary targets of an accelerator-driven transmutation system. Chemical processing of such targets after irradiation would result in actinide recycle to the ATW unit and $^{99}Tc/^{129}I$ recycle to the thermal reactor. High-level waste streams for repository disposal would be produced by the initial processing of civilian spent fuel, the recycle processing of spent fuel from the thermal reactor, and the ATW recycle process.

Since transmutation produces a net energy gain, it has been of interest to design systems capable of producing electric power to off-set transmutation expenses. One concern has been the current high "trip" rate of present generation accelerators, which may experience several unplanned cut-offs each day. Quite apart from thermal shock safety considerations in the transmutation system, such interrupted power would have much lower value than conventional base-load systems. Early analysis indicates that more than ninety percent of the energy release in the "dual strata" would occur in the thermal reactor, so it may be possible to design the ATW system as a low-temperature actinide burner with much less stringent requirements for accelerator power and stability. Materials and corrosion problems in the ATW system would also be minimised. Studies of the concept are continuing.

4. Advanced accelerator applications

The ATW programme during the current fiscal year involves approximately a doubling of the Fiscal Year-2000 funding. This will allow an expansion of experimental programmes, and DOE's Office Of Nuclear Energy, Science and Technology (NE) is actively seeking opportunities for collaborative research with foreign ADS programmes. Meanwhile, the programme is being reorganised to combine the objectives of the DOE Defense Programme's Accelerator Production of Tritium programme with those of NE's ATW efforts. The combined programme is known as Advanced Accelerator Application, and it will be administered by NE. Congress has requested a report by March 1, 2001 on how the new activity will be carried out. It will be a public document, and it may be of interest to many attending this conference. It will be available on the World Wide Web as well as in hard copy.

One objective of the new programme will be to help strengthen the nuclear science infrastructure in America. To accomplish this, graduate thesis projects related to the programme objectives will be sponsored at many universities. Another objective will be to strengthen nuclear test facilities, and an accelerator driven test facility is under active consideration. The need to make better use of limited test facilities throughout the world is also one of the reasons why DOE will be seeking to increase international ADS/ATW collaboration. The coming years may see a considerable expansion of the international quest for effective transmutation systems.

REFERENCES

[1] *A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology – A Report to Congress*, DOE/RW-0519, October 1999.

[2] James J. Laidler and James C. Bresee, *Pyrochemical Processing of Irradiated Transmutation Fuel*, 6th OECD/NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Madrid, Spain, Dec. 11-13, 2000, EUR 19783 EN, OECD Nuclear Energy Agency, Paris (France), 2001.

IAEA ACTIVITIES IN THE AREA OF EMERGING NUCLEAR ENERGY SYSTEMS

A. Stanculescu
International Atomic Energy Agency
Division of Nuclear Power, Nuclear Power Development Section,
PO Box 100, 1400 Vienna, Austria

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 21^{st} 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 21^{st} 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.

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

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

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

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

ACCELERATOR DRIVEN SUB-CRITICAL SYSTEMS FOR WASTE TRANSMUTATION: CO-OPERATION AND CO-ORDINATION IN EUROPE AND THE ROLE OF THE TECHNICAL WORKING GROUP

M. Salvatores, S. Monti
On Behalf of the European Technical Working Group on ADS

1. Background

In 1998 the Research Ministers of France, Italy and Spain, recognising the potential of accelerator driven systems (ADS) for the transmutation of long lived nuclear waste, decided to set up a Group of Advisors (Ministers' Advisors Group – MAG) to define a common R&D European platform on ADS. In its meeting on May 1998, the MAG recommended an European demonstration programme over a 10-year time scale.

A Technical Working Group (TWG) under the chairmanship of Carlo Rubbia was also established with the task of identifying the critical technical issues in which R&D, in such a demonstration programme, is needed. In October 1998 the TWG issued an Interim Report which, in particular, highlighted a) the need for a demonstration programme, b) the basic components and the different options for the proposed demonstration facility, and c) the R&D directly relevant to the realisation of such a facility.

This report was endorsed by the MAG at its meeting of March 1, 1999. In the same meeting, it was proposed to extend participation beyond the three countries France, Spain, Italy; to consider the role of ADS R&D within the 5th European Framework Programme (FWP); and to recognise an eXperimental ADS (XADS) as an European goal.

As a consequence, a MAG "ad hoc" meeting open to all interested EU member states was held in Rome on April 21, 1999. Representatives of eleven countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Portugal, UK, Spain and Sweden) participated in that meeting which concluded:

It was agreed that neutron induced transmutation represents an attractive approach to radioactive waste management, being complementary to geological disposal.

All participants appreciated the proposal to extend the participation in the initiative to other European countries besides France, Italy and Spain, particularly considering that similar approaches were being undertaken in the USA and Japan.

The interim report of the TWG issued in 1998 was accepted as a good basis for future work to be carried out by an Enlarged Technical Working Group (ETWG), under the chairmanship of Carlo Rubbia.

In September 1999, the ETWG – composed of representatives of Austria, Belgium, Finland, France, Germany, Italy and Spain – issued a second technical report aimed at providing an overview of the different ongoing activities on ADS in various European countries, along with an examination of the proposals to be submitted to the 5th FWP. The report, presented to and endorsed by MAG on its meeting of September 17, 1999, also identified a number of open points and gave recommendations for the future development of the activities. In particular, the ETWG strongly recommended an increased support – in particular by European Commission – and co-ordination of ADS-related activities at multinational level.

At the beginning of 2000 the ETWG (further enlarged to representatives of the JRC, Portugal and Sweden), recognising that the R&D programme on ADS has reached a turning point with regard to programme co-ordination and resource deployment in Europe and taking also into account the substantial recent progress on the subject in the United States and in Japan, issued a so-called "four-page document" on a strategy for the implementation of an ADS programme in Europe. In particular, the document called for the urgent definition of a consensual European "Roadmap" towards demonstration of feasibility of a European waste transmutation facility and recognised its potentially-relevant implications on the 6th European Framework Programme.

The "four-page document" was endorsed by the MAG on its meeting of February 25, 2000 and, consequently, the ETWG started an intensive work aimed at defining the above mentioned European Roadmap. In particular, in order to specifically address some relevant key issues such as accelerator, fuel and fuel processing development, two dedicated sub-groups have been created inside the ETWG and co-ordination with the European ADS system design group has been established.

The roadmap document is expected to be issued at the very beginning of 2001.

In the report, the ETWG will identify the steps necessary to start the construction of an XADS towards the end of the decade. The construction and operation of an XADS at that point in time is considered as an essential prerequisite to assess the safe and efficient behaviour of ADS for a possible large scale deployment of ADS for transmutation purposes in the first half of the century.

The first goal of the roadmap is to propose a technological route to reduce the risks associated with nuclear waste, based on the transmutation of nuclear waste in ADS and to assess the impact of this approach in the reduction of the radiotoxicity of nuclear waste. The report will review historical developments and will identify and review the status of current activities and facilities related to ADS research in the EU and worldwide. A decision to go ahead with the project will require a detailed planning of the technical aspects, a substantially increased budget, together with close synchronisation with the 6th and 7th Framework Programmes. The second and main goal of the roadmap is, therefore, to prepare a detailed technical programme, with cost estimates, which will lead to the demonstration of an experimental ADS (XADS) in 10 years, within the 6th and 7th Framework Programmes. The programme as described in the roadmap will lead to the development of innovative fuels and reprocessing technology, a rationalisation of human resources and experimental facilities, a training ground for young researchers, spin-offs in the fields of accelerators, spallation sources, liquid metal technology, radioisotope production and actinide physics and chemistry. Hence, a final goal of the roadmap is to identify possible synergies and rationalisations that this programme could have within the nuclear community, indicate potential spin-offs, show how competence can be maintained in a currently stagnating field.

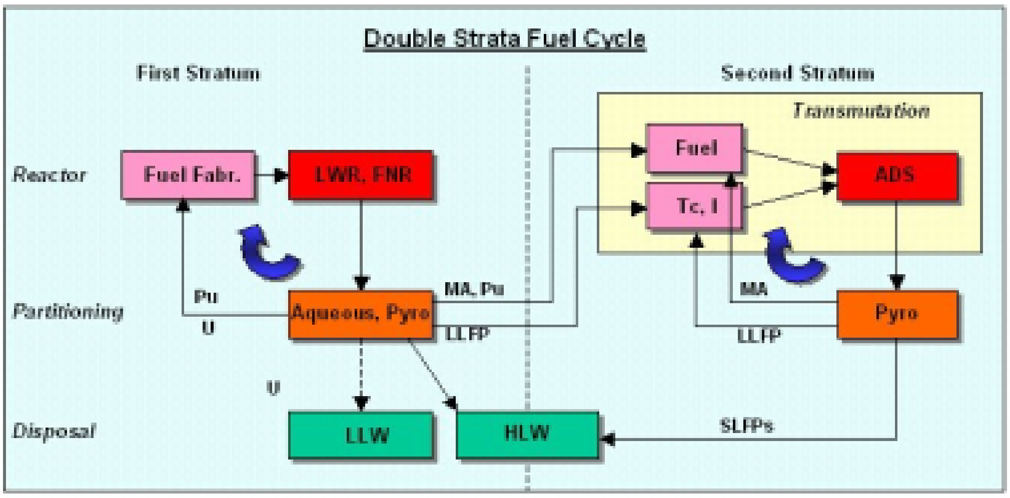
The roadmap will be a result of a mandate given to the ETWG on ADS by the MAG. In the first instance, therefore, the report will be directed at the MAG. The document will be of interest, however, to policy makers throughout Europe, in particular to research ministries in the Member States of the European Union, to members of the European Parliament, and to the relevant Directorates General of the European Union. In addition, the report will be of interest to parties involved with ADS research and development within the EU and worldwide.

2. Motivations for ADS

In contrast to standard critical nuclear reactors in which there are enough neutrons to sustain a chain reaction, sub-critical systems used in ADS need an external source of neutrons to sustain the chain reaction. These "extra" neutrons are provided by the accelerator. More exactly the accelerator produces high-energy protons, which then interact with a spallation source to produce neutrons.

But why go to all this trouble to build an ADS when critical reactors already work? The answer to this lies in the fact that one has more control and flexibility in the design of the sub-critical reactor. This is required when the reactor is being used to transmute large amounts of nuclear waste in the form of minor actinides (MAs). Today it appears that ADS has great potential for waste transmutation and that such systems may go a long way in reducing the amounts of waste and thereby reducing the burden to underground repositories. A schematic description of how an ADS can be used in conjunction with conventional reactors in a "Double Strata" approach is shown in Figure 1.

Figure 1. **Schematic description of the transmutation of nuclear waste by ADS within a Double Strata Fuel Cycle (LLFP: long-lived fission products, SLFP: short-lived fission products, LLW: low level waste, HLW: high level waste)**



The first stratum is based on a conventional fuel cycle and consists of standard light water reactors (LWR) and fast neutron reactors (FNR), fuel fabrication and reprocessing plants. The recovered plutonium is recycled as mixed oxide fuel in the thermal and fast reactors. The remaining plutonium, MAs and long-lived fission products are partitioned from the waste and enter the second stratum where they are transmuted in a dedicated ADS. In the second stratum, devoted primarily to waste reduction, the Pu, MAs, and long-lived fission products are fabricated into fuels and targets for transmutation in dedicated ADS. The use of dry reprocessing in this stratum allows for multiple reprocessing of the fuel. A key advantage of this is that higher levels of radiation can be tolerated in the molten salts, used in this process, and therefore allows reprocessing of spent fuel which has been cooled for periods as short as one month.

Accelerator driven systems therefore open the possibility of "burning" waste material from LWRs in dedicated actinide burners. These actinide burners can burn large quantities of minor actinides per unit (in contrast to critical reactors) safely, and generate heat and electricity in doing so. In addition, schemes have been proposed, in which the long-lived fission products are also destroyed. An advantage of ADS is that, since there is no criticality condition to fulfil, almost any fuel composition can be used in the system.

3. Overall roadmap towards ADT industrial implementation through an ADS demonstration

From now on, taking for granted the potential role of Accelerator Driven Technology (ADT) for radio-toxicity reduction of the ultimate nuclear waste, the main issue is to define a path towards industrial implementation of this very innovative system.

An extended "skeleton" for ADS technology development is given in Figure 2. It consists of three main phases:

- Phase 1: Development/realisation/operation of an XADS/XADT (eXperimental Accelerator Driven System/Transmuter).
- Phase 2: Development/realisation/operation of a PROTO-ADT.
- Phase 3: Industrial application.

In particular, the preparation of the construction of the XADS must be performed in parallel to the development and qualifications of the main components and the basic R&D programme. It starts with a system analysis of different concepts to be performed in 2001 to 2003. Further milestones are:

- A decision on the basic features of the XADS in 2005.
- Start of detailed design work in 2005.
- Final decision and start of construction in 2009.
- Operation of XADS in 2013-2014.

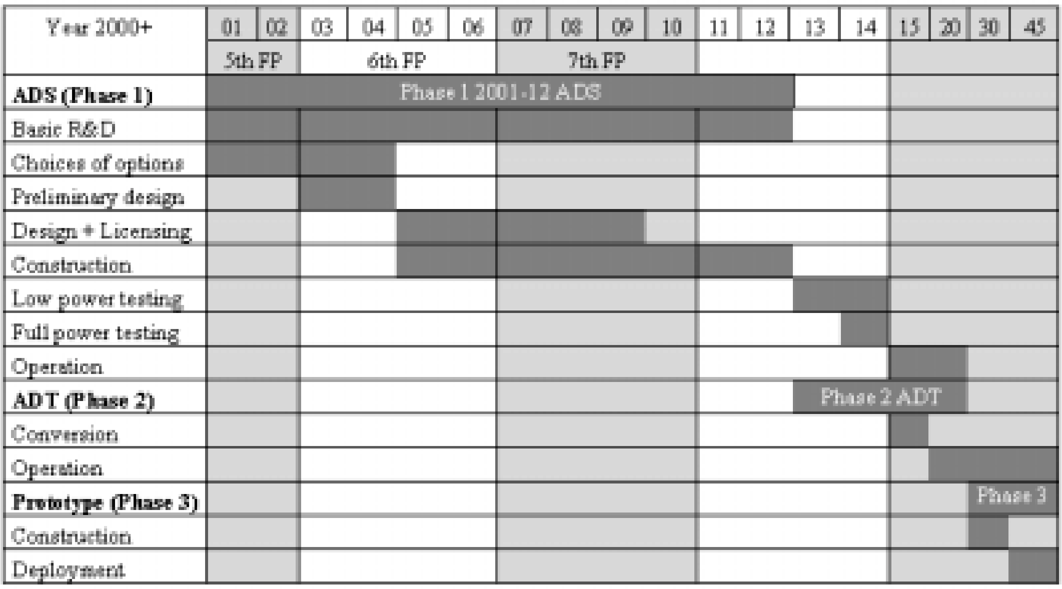
In parallel to the construction of the XADS, which can be considered as the "spallation-fission facility" oriented demonstration, pilot plants have to be built and operated in order to:

- Feed the XADS/XADT – prototype with fuel and targets.
- Get an "As Soon As Possible (ASAP)" operation feedback for further development of industrial scale facilities.

The ADS demonstration phase is characterised, in an ASAP perspective, by the use of available fuel technology, at least in the first sub-phase of the XADS. The two sub-phases currently considered are:

- Sub-Phase 1: which uses available fuel technology and is devoted to the demonstration of the ADS concept and possibly to irradiation purposes (XADS).
- Sub-Phase 2: which is devoted to the transmutation demonstration with a large number of MA-based fuel assemblies. During this phase the XADS will be used more and more as demonstration of a transmuter. In about 2017-2018 a decision has to be made, whether the facility can be modified to a full transmuter (XADT) or whether a new facility would be needed, which possibly should be available in 2025. From 2025 on in any case a full demonstration of accelerator driven transmutation should occur. This requires successful development of the fuel and the fuel cycle facilities till about 2020!

Figure 2. **Time schedule and milestones for the development of an experimental accelerator driven system (ADS) and accelerator driven transmutation (ADT) technology in Europe**



4. TWG sub-group on fuels and fuel processing

As above mentioned, a specific subgroup on "Fuels and Fuel Processing", under the chairmanship of Rudy Konings (ITU-Karlsruhe), has been set up within the TWG. Two status reports have been issued by this sub-group:

- Part I: The Fuel of the ASAP DEMO.
- Part II: Advanced Fuel Cycles.

As far as fuel for XADS, Mixed OXide (MOX) is considered the only "ASAP" fuel option in Europe; indeed, for this fuel:

- Extensive knowledge exists.
- Existing fuel elements or fuel pins (SNR-300 or SPx) are available.
- The required infrastructure for fabrication of new fuel elements is existing.
- Core design has to be adapted (partially) to elements.
- Austenitic cladding of the SNR and SPx elements are compatible with He cooling and can also be used for Pb/Bi coolant, but the oxygen content of the liquid metal should be low.

As far as advanced fuels for transmutation, following the mandate of the TWG, the following boundary conditions were assumed:

- Solid fuel forms.
- High TRU content (up to 50% with MA/(Pu+MA) ratio between 1/5 and 5).

- Fertile support (uranium) is not considered.
- Gas or liquid metal coolant.
- Fast neutron system.

Pros and cons of metal, oxide, nitride, carbide fuel form have been examined. Composite fuels (including coated particle fuels), such as CERCER and CERMET, have been also analysed, as well as fission product targets.

The subgroup also addressed the key issue of fuel reprocessing, concluding that some drawbacks are expected for advanced fuels treated by hydro-chemical reprocessing. On the contrary, pyro-chemical reprocessing is considered a promising technology, given the fact that good fuel solubility can be achieved even for refractory materials. Furthermore, compact facilities and small cooling times are required. Drawbacks of this technology are: aggressive process media, secondary wastes and sophisticated technology which is under development.

The main conclusions of the "fuels and fuel processing subgroup" were the following:

- The European fuel research should be focussed on innovative oxide-based fuels, either as a solid solution or as a composite (CERMET or CERCER), with emphasis on the helium issue.
- Thorium-based fuel should be considered as back-up solution, e.g. $(Th, TRU)O_2$.
- The pyro-chemical reprocessing of these fuel types should be studied.
- In the short term (4-5 years) an out-of-pile testing programme should be performed to establish the properties of MA-based oxide fuels (solid solution, composite).
- In the longer term (8-10 years) a dedicated irradiation programme for these fuels should be performed.
- In parallel a collaboration with Japan and the Russian Federation on nitride fuel must be pursued (U-based nitrides, with limited MA content).

5. TWG Subgroup on accelerators for ADS

A second subgroup devoted to HPPA development for ADS, under the chairmanship of Alex Mueller (CNRS-IN2P3), has been set up within the ETWG. This subgroup has issued a status report on "Accelerators for ADS". The main outcomes of this status report can be summarised as follows.

The orders of magnitude of the characteristics of the accelerator for XADS were defined assuming a 100 MW thermal power for the sub-critical core.

A proton beam of 1 GeV, 10 mA may be obtained both by linac- or cyclotron- type accelerators, although at the very limits of potential performance gains for the latter case.

Concerning the beam structure, the preliminary analysis has not identified principle technical difficulties comparing pulsed or continuous beam operation. However, it seems that the latter option is overall preferred because of a closer similarity to the classical critical reactor.

The accelerator of the XADS has not to be defined only by the needs of the XADS itself, but it should also anticipate the requirements and the technical issues of a future industrial ADS burner. This concerns in particular the reliability, the economical, and the nuclear safety aspects.

A superconducting linac is adapted to a high power industrial ADS burner. Its different components are currently being investigated in several European laboratories. The studies show that a 100 mA proton beam can now be handled.

For comparative cost estimates an energy of 600 MeV has been used: it is the minimum energy (and therefore cost) for a complete ADS demonstration; for this energy band convincing accelerator studies exist for both types of accelerators. The extrapolation to 1 GeV, the energy of best neutron economy, is straightforward for the linac, however delicate for the cyclotron.

The investment cost of a 20 mA, 600 MeV linac, adapted to the XADS needs, including all industrial aspects, is preliminary evaluated to around 200 M €. Its development (R&D and construction) requires around eight years. An extension to 1 GeV would require an additional investment cost of about 100 M €.

A single cyclotron (600 MeV, 5 mA) is adapted to low power applications which is enough for the XADS if coupling of accelerator and reactor are the basic objective. A rough cost evaluation, on a similar base than for the linac, is around 70 M €. Approximately six years are requested for development and construction. If the industrial burner demonstration is a must, the coupling of at least 3 such machines must be demonstrated, of which the global cost is estimated to 240 M €.

6. Harmonisation of industry and R&D proposals for a preliminary design study of an XADS

Nine countries are participating to a 3-years proposal to be submitted to the second call of P&T within the 5th European Framework Programme.

The purpose is to develop conceptual plant configurations to enable definition of the supporting R and D, to perform objective comparisons and to propose reference solutions to be engineered in detail.

- Preliminary design concentrate mainly on three concepts:
  - A small XADS (20-40 MWt) cooled by Pb/Bi (MYRRHA-Belgium).
  - A large Pb/Bi cooled XADS (~80 MWt), developed in Italy.
  - A similar size gas-cooled ADS, developed in France.

Some work will be devoted to a pebble-bed concept developed in Spain.

The work will be carried out in three different phases:

- Phase 1: definition of the main technical specifications of XADS (6 months).
- Phase 2: preliminary engineering design studies (including safety approach, accelerator, core and target, system integration), to consolidate feasibility and cost estimation and to provide essential elements of comparison (2 years).
- Phase 3: comparisons and recommendations to implement the road-mapping towards XADS (6 months).

7. Conclusions

The TWG under the chairmanship of Carlo Rubbia, enlarged from the three initial partners (France, Italy, Spain) to ten partners (Austria, Belgium, Finland, France, Germany, Italy, JRC, Portugal, Spain, Sweden), has worked to identify critical technical issues, R&D needs and a strategy in view of an ADS demonstration programme.

A roadmap document is being prepared, and state of the art reports have been issued in Accelerator and Fuel and Fuel Processing Technologies.

The TWG allows also a monitoring and harmonisation of other European projects, like:

- The MEGAPIE project for the construction and operation of a 1 MWt Pb/Bi target in the SINQ installation in PSI-Switzerland.
- The proposal for a preliminary design study of an XADS.
- Which will be both submitted to the second call of P&T within the 5th European Framework Programme.

PARTITIONING AND TRANSMUTATION IN THE EURATOM FIFTH FRAMEWORK PROGRAMME

Michel Hugon, Ved P. Bhatnagar
European Commission
rue de la Loi, 200, 1049 Brussels, Belgium
E-mail: Michel.Hugon@cec.eu.int

Abstract

Partitioning and Transmutation (P&T) of long-lived radionuclides in nuclear waste is one of the research areas of the EURATOM Fifth Framework Programme (FP5) (1998-2002). The objective of the research work carried out under FP5 is to provide a basis for evaluating the practicability, on an industrial scale, of P&T for reducing the amount of long lived radionuclides to be disposed of. The content and the implementation of the EURATOM FP5 are briefly presented. The research projects on P&T selected for funding after the first call for proposals are then briefly described. They address the chemical separation of long-lived radionuclides and the acquisition of technological and basic data, necessary for the development of an accelerator driven system. Other projects are expected in response to the next call with a deadline in January 2001. International co-operation in P&T should be fostered. Collaboration is being implemented in this field between scientists of the European Union (EU) and the Commonwealth of Independent States (CIS). Finally, a brief outline of the discussions for the preparation of the Sixth Framework Programme (2002-2006) is given.

1. Introduction

The priorities for the European Union's research and development activities for the period 1998-2002 are set out in the Fifth Framework Programme (FP5). These priorities have been identified on the basis of a set of common criteria reflecting the major concerns of increasing industrial competitiveness and the quality of life for European citizens. FP5 has been conceived to help solve problems and to respond to major socio-economic challenges facing Europe. To maximise its impact, it focuses on a limited number of research areas combining technological, industrial, economic, social and cultural aspects.

The Fifth Framework Programme has two distinct parts: the European Community Framework Programme covering research, technological development and demonstration activities; and the EURATOM Framework Programme covering research and training activities (RT) in the nuclear field.

The content and the implementation of the latter are briefly presented in this paper.

Partitioning and Transmutation (P&T) of long-lived radionuclides in nuclear waste is one of the research areas of the EURATOM FP5. This paper briefly recalls the goals of P&T, its position in the framework of nuclear waste management and disposal and its renewed interest worldwide. The research projects on P&T so far selected for funding in FP5 are then briefly described. Co-operation in this field with some countries of the Commonwealth of Independent States (CIS) through the International Science and Technology Centre in Moscow is also outlined.

Finally, some indications are given concerning the European Union's research beyond the Fifth Framework Programme and the "European Research Area".

2. The EURATOM Fifth Framework Programme (FP5) (1998-2002)

The Fifth Framework Programme of the European Atomic Energy Community (EURATOM) has two specific programmes on nuclear energy, one for indirect research and training actions managed by the Research Directorate General (DG RTD) and the other for direct actions under the responsibility of the Joint Research Centre of the European Commission (EC). The strategic goal of the first one, "Research and training programme in the field of nuclear energy", is to help exploit the full potential of nuclear energy in a sustainable manner, by making current technologies even safer and more economical and by exploring promising new concepts [1]. This programme includes a key action on controlled thermonuclear fusion, a key action on nuclear fission, research and technological development (RTD) activities of a generic nature on radiological sciences, support for research infrastructure, training and accompanying measures. The key action on nuclear fission and the RTD activities of a generic nature are being implemented through indirect actions, i.e. research co-sponsored (up to 50% of total costs) and co-ordinated by DG RTD, but carried out by external public and private organisations as multi-partner projects. The total budget available for these indirect actions during FP5 is 191 millions €.

The key action on nuclear fission comprises four areas: (i) operational safety of existing installations; (ii) safety of the fuel cycle; (iii) safety and efficiency of future systems and (iv) radiation protection. The operational safety of existing installations deals with plant life extension and management, severe accident management and evolutionary concepts. In the safety of the fuel cycle, waste and spent fuel management and disposal, and partitioning and transmutation are the two larger activities, as compared to the decommissioning of nuclear installations. The objective of safety and efficiency of future systems is to investigate and assess new or revisited concepts for nuclear energy, that would be more economical, safer and more sustainable in terms of waste management, utilisation of fissile material and safeguards. Radiation protection has four sub-areas: (i) risk assessment and management, (ii) monitoring and assessment of occupational exposure, (iii) off-site emergency management and (iv) restoration and long-term management of contaminated environments.

The implementation of the key action on nuclear fission is made through targeted calls for proposals with fixed deadlines. The generic research on radiological sciences is the subject of a continuously open call, but proposals are evaluated in batches. Following the calls for proposals made in 1999, about 140 proposals covering all areas of the key action and of the generic research have been accepted for a total funding of around 100 million €. Most of the projects have started now. A new call for proposals has been made on 16 October 2000 with a deadline on 22 January 2001 to select proposals for another 50 million €. The 2000 version of the Work Programme is available on the CORDIS website (www.cordis.lu/fp5-euratom). A final call will be made in October 2001.

3. Partitioning and Transmutation (P&T)

Spent fuel and high level waste contain a large number of radionuclides from short-lived to long-lived ones, thus requiring very long time periods to be considered for their geological disposal. The long-lived radionuclides are mainly the actinides and some fission products. Partitioning and Transmutation aims at reducing the inventories of long-lived radionuclides in radioactive waste by transmuting them into radionuclides with a shorter lifetime [2].

Partitioning is the set of chemical and/or metallurgical processes necessary to separate from the high-level waste the long-lived radionuclides to be transmuted. This separation must be very efficient to obtain a high decontamination of the nuclear waste. It should also be very selective to achieve an efficient transmutation of the long-lived radiotoxic elements.

Long-lived radionuclides could be transmuted into stable or short-lived nuclides in dedicated burners. These burners could be critical nuclear reactors and sub-critical reactors coupled to accelerators, the so-called accelerator-driven systems (ADS).

If successfully achieved, P&T will produce waste with a shorter lifetime. However, as the efficiency of P&T is not 100%, some long-lived radionuclides will remain in the waste, which will have to be disposed of in a deep geological repository. P&T is still at the research and development (R&D) stage. Nevertheless, it is generally accepted that the techniques used to implement P&T could alleviate the problems linked to waste disposal.

There has been a renewal of interest in P&T worldwide at the end of the eighties (OMEGA programme in Japan, SPIN programme in France). Meanwhile, sufficient progress has been made in accelerator technology to consider as feasible the use of ADS for waste incineration. Proposals to develop ADS have been made during the nineties by the Los Alamos National Laboratory in the USA with the ATW (Accelerator driven Transmutation of Waste) programme, by CERN in Europe with the Energy Amplifier (EA) [3] and by JAERI in Japan. In addition, there is a number of research activities on ADS going on in several EU countries (Belgium, France, Germany, Italy, Spain, Sweden), Czech Republic, Switzerland, Republic of Korea and Russian Federation.

The interest for P&T in the EU is reflected in the increase of funding in this area over the EURATOM Framework Programmes, 4.8, 5.8 and about 26 million € for the Third, Fourth and Fifth Framework Programmes respectively.

In the EURATOM Fourth Framework Programme (1994-1998), there were research activities on P&T covering three aspects: (i) strategy studies, (ii) partitioning techniques, (iii) transmutation techniques. The progress achieved in the field of partitioning of minor actinides by aqueous processes suggested that, with some additional effort, a one-cycle process for the direct extraction of minor actinides from liquid high-level waste could be demonstrated at the pilot plant scale. The conclusions of the P&T strategy studies concerning critical and sub-critical reactors and the results obtained in the transmutation experiments clearly indicated that the feasibility of ADS should be more thoroughly investigated for transmutation of nuclear waste [4].

4. The research activities on P&T in the EURATOM Fifth Framework Programme

The objective of the research work carried out under FP5 is to provide a basis for evaluating the practicability, on an industrial scale, of partitioning and transmutation for reducing the amount of long lived radionuclides to be disposed of.

After the first call for proposals in 1999, 19 proposals were received in the area of partitioning and transmutation, requesting about 3.8 times more than the available budget. By taking due account of the advice of the evaluators, the Commission services selected 9 proposals for funding at a level lower than requested due to budget limitations. All the projects have already started between August and November 2000.

The selected projects address different scientific and technical aspects of P&T and have therefore been grouped in three clusters. The experimental investigation of efficient hydro-metallurgical and pyrochemical processes for the chemical separation of long-lived radionuclides from liquid high-level waste is carried out in the cluster on partitioning. The work on transmutation is mainly related to the acquisition of data, both technological and basic, necessary for the development of ADS. The cluster on transmutation – technological support – deals with the investigation of radiation damage induced by spallation reactions in materials, of the corrosion of structural materials by lead alloys and of fuels and targets for actinide incineration. In the cluster on transmutation – basic studies, basic nuclear data for transmutation and ADS engineering design are collected and sub-critical neutronics is investigated.

The cluster on partitioning includes three projects, the main characteristics of which are given in Table 1. The first one, **PYROREP**, aims at assessing flow sheets for pyrometallurgical processing of spent fuels and targets. Two methods, salt/metal extraction and electrorefining, will investigate the possibility of separating actinides from lanthanides. Materials compatible with corrosive media at high temperature will be selected and tested. It is worth noting that one of the partners of this project is CRIEPI, the research organisation of the Japanese utilities.

The two other projects are dealing with the development of solvent extraction processes of minor actinides (americium and curium) from the acidic high level liquid waste (HLLW) issuing the reprocessing of spent nuclear fuel. In **PARTNEW**, the minor actinides are extracted in two steps. They are first co-extracted with the lanthanides from HLLW (DIAMEX processes), then separated from the lanthanides (SANEX processes). Basic studies will be performed for both steps, in particular synthesis of new ligands and experimental investigation and modelling of their extraction properties. The radiolytic and hydrolytic degradation of the solvents will be also studied and the processes will be tested with genuine HLLW.

The **CALIXPART** project is dealing with the synthesis of more innovative extractants. Functionalized organic compounds, such as calixarenes, will be synthesised with the aim of achieving the direct extraction of minor actinides from HLLW. The extracting capabilities of the new compounds will be studied together with their stability under irradiation. The structures of the extracted species will be investigated by nuclear magnetic resonance (NMR) spectroscopy and X-ray diffraction to provide an input to the molecular modelling studies carried out to explain the complexation data.

Table 1. **Cluster on partitioning**

Acronym	Subject of research	Co-ordinator (country)	Number of partners	Duration (months)	EC funding (Million €)
PYROREP	Pyrometallurgical processing research	CEA (F)	7	36	1.5
PARTNEW	Solvent extraction processes for minor actinides (MA)	CEA (F)	10	36	2.2
CALIXPART	Selective extraction of MA by organised matrices	CEA (F)	9	36	1.3

The cluster on transmutation-technological support has four projects (see Table 2). The **SPIRE** project addresses the irradiation effects on an ADS spallation target. The effects of spallation products on the mechanical properties and microstructure of selected structural steels (e.g. martensitic steels) will be investigated by ion beam irradiation and neutron irradiation in reactors (HFR in Petten, BR2 in Mol and BOR 60 in Dimitrovgrad). Finally, data representative of mixed proton/neutron irradiation will be obtained from the analysis of the SINQ spallation target at the Paul Scherrer Institute in Villigen.

The objective of **TECLA** is to assess the use of lead alloys both as a spallation target and as a coolant for an ADS. Three main topics are addressed: corrosion of structural materials by lead alloys, protection of structural materials and physico-chemistry and technology of liquid lead alloys. A preliminary assessment of the combined effects of proton/neutron irradiation and liquid metal corrosion will be done. Thermal-hydraulic experiments will be carried out together with numerical computational tool development.

Fuel issues for ADS are addressed in the **CONFIRM** project. Computer simulation of uranium free nitride fuel irradiation up to about 20% burn-up will be made to optimise pin and pellet designs. Other computations will be performed especially concerning the safety evaluation of nitride fuel. Plutonium zirconium nitride [(Pu, Zr)N] and americium zirconium nitride pellets will be fabricated and their thermal conductivity and stability at high temperature will be measured. (Pu, Zr)N pins of optimised design will be fabricated and irradiated in the Studsvik reactor at high linear power (≈70 kW/m) with a target burn-up of about 10%.

The objective of the project **THORIUM CYCLE** is to investigate the irradiation behaviour of thorium/plutonium (Th/Pu) fuel at high burn-up and to perform full core calculations for thorium-based fuel with a view to supplying key data related to plutonium and minor actinide burning. Two irradiation experiments will be carried out: (i) four targets of oxide fuel (Th/Pu, uranium/plutonium, uranium and thorium) will be fabricated, irradiated in HFR in Petten and characterised after irradiation; (ii) one Th/Pu oxide target will be also irradiated in KWO Obrigheim. Though this project was accepted for funding in the area of "safety and efficiency of future systems", it has been grouped with the three previous projects in the cluster on transmutation-technological support for convenience, because it is related to fuel issues.

Table 2. **Cluster on transmutation-technological support**

Acronym	Subject of research	Co-ordinator (country)	Number of partners	Duration (months)	EC funding (Million €)
SPIRE	Effects of neutron and proton irradiation in steels	CEA (F)	10	48	2.3
TECLA	Materials and thermo-hydraulics for lead alloys	ENEA (I)	16	36	2.5
CONFIRM	Uranium free nitride fuel irradiation and modelling	KTH (S)	7	48	1.0
THORIUM CYCLE	Development of thorium cycle for PWR and ADS	NRG (NL)	7	48	1.2

Finally, three projects are grouped in the cluster on transmutation-basic studies (see Table 3). The **MUSE** project aims to provide validated analytical tools for sub-critical neutronics including recommended methods, data and a reference calculation tool for ADS study. The experiments will be carried out by coupling a pulsed neutron generator to the MASURCA facility loaded with different fast neutron multiplying sub-critical configurations. The configurations will have MOX fuel with various coolants (sodium, lead and gas). Cross-comparison of codes and data is foreseen. Experimental reactivity control techniques, related to sub-critical operation, will be developed.

The last two projects are dealing with nuclear data, one at medium and high energy required for the ADS engineering design including the spallation target **(HINDAS)**, and the other encompassing the lower energy in resonance regions required for transmutation **(n-TOF-ND-ADS)**.

The objective of the **HINDAS** project is to collect most of the nuclear data necessary for ADS application. This will be achieved by basic cross section measurements at different European facilities, nuclear model simulations and data evaluations in the 20-200 MeV energy region and beyond. Iron, lead and uranium have been chosen to have a representative coverage of the periodic table, of the different reaction mechanisms and, in the case of iron and lead, of the various materials used for ADS.

The **n-TOF-ND-ADS** project aims at the production, evaluation and dissemination of neutron cross sections for most of the radioisotopes (actinides and long-lived fission products) considered for transmutation in the energy range from 1 eV up to 250 MeV. The project is starting with the design and development of high performance detectors and fast data acquisition systems. Measurements will be carried out at the TOF facility at CERN, at the GELINA facility in Geel and using other neutron sources located at different EU laboratories. Finally, an integrated software environment will be developed at CERN for the storage, retrieval and processing of nuclear data in their various formats.

Table 3. **Cluster on transmutation-basic studies**

Acronym	Subject of research	Co-ordinator (country)	Number of Partners	Duration (months)	EC funding (Million €)
MUSE	Experiments for sub-critical neutronics validation	CEA (F)	13	36	2.0
HINDAS	High and intermediate energy nuclear data for ADS	UCL (B)	16	36	2.1
n-TOF-ND-ADS	ADS nuclear data	CERN	18	36	2.4

The second call for proposals has been published in October 2000 with a deadline in January 2001. This call has been targeted on the areas, which were not sufficiently well covered by the projects selected after the first call, such as preliminary engineering design studies for an ADS demonstrator and technological support. A new item, networking, has been included in this call. But the areas of chemical separation and basic studies are not included, as they were well covered in the first call.

5. ADS related research activities in the framework of the International Science and Technology Centre (ISTC)

The International Science and Technology Centre (ISTC) was established by an international agreement in November 1992 as a non-proliferation programme through science co-operation. It is an intergovernmental organisation grouping the European Union, Japan, the USA, Norway, the Republic of Korea, which are the funding parties, and some countries of the Commonwealth of Independent States (CIS): the Russian Federation, Armenia, Belarus, Georgia, Kazakhstan and Kyrgyzstan. The ISTC finances and monitors science and technology projects to ensure that the CIS scientists, especially those with expertise in developing weapons of mass destruction, are offered the opportunity to use their skills in the civilian fields.

A Contact Expert Group (CEG) on ADS related ISTC projects has been created in January 1998. Its main objectives are to review proposals in this field and to give recommendations for their funding to the ISTC Governing Board, to monitor the funded projects and to promote the possibilities of future or joint research projects through the ISTC. Five topics have been identified for the ADS related projects: (i) accelerator technology, (ii) basic nuclear and material data and neutronics of ADS, (iii) targets and materials, (iv) fuels related to ADS and (v) aqueous separation chemistry. Because the funding parties primarily respond to local scientific/political interests and pressure, it was decided in January 2000 to reorganise the CEG into “local” CEGs (EU, Japan, Republic of Korea and USA) with some inter-co-ordination between them. This inter-co-ordination should foster exchange of information between ISTC projects in the same field, even if they are supported by different funding parties.

The EU CEG should develop co-operation between ISTC and FP5 EU funded projects. In fact, collaboration has already started between EU scientists, not necessarily belonging to the CEG, and CIS research teams both in the preparation of ISTC proposals and in the follow-up of projects in some specific areas. Links with FP5 projects will be established, once the projects have actually started. An area where the co-operation between ISTC and FP5 EU funded projects could be improved is that of basic nuclear data for ADS.

6. Community research for the period 2002-2006

The Commissioner responsible for research in the EC launched the idea of a “European Research Area” in a communication [5] in January 2000. The intention is to contribute to the creation of better overall working conditions for research in Europe. The Communication is applicable to all areas of research. The starting point was that the situation concerning research in Europe is worrying, given the importance of research and development for future prosperity and competitiveness.

In October 2000, the Commission adopted a communication for the future of research in Europe, which sets out guidelines for implementing the “European Research Area” initiative, and more particularly the Research Framework Programme [6]. It is proposed to change the approach for the next Framework Programme, based on the following principles:

- Focusing on areas where Community action can provide the greatest possible “European added value” compared with national action.
- Closer partnership with the Member States, research institutes and companies in Europe by networking the main stakeholders.
- Greater efficiency by channelling resources to bigger projects of longer duration.

The Commission's proposals take account of the results of the evaluation of the previous Framework Programmes carried out by an Independent Expert Panel.

In practical terms, the following arrangements are proposed:

- Networking of national research programmes through support for the mutual opening-up of programmes and EU participation in programmes carried out in a co-ordinated fashion.
- Creation of European networks of excellence by networking existing capacities in the Member States around “joint programmes of activities”.
- Implementation of large targeted research programmes by consortia of companies, universities and research centres on the basis of overall financing plans.
- Greater backing for regional and national efforts in support of innovation and research conducted by small and medium enterprises (SME).
- More diversified action in support of research infrastructures of European interest.
- Increase in and diversification of mobility grants not only for EU researchers but also for researchers from third countries. Measures in respect of human resources in research are proposed, including the “Women and Science” Action Plan.
- Action to strengthen the social dimension of science, in particular in matters concerning ethics, public awareness of science and giving young people a taste for science.

At its meeting in November 2000, the Research Council supported the general approach of the Commission as set out in its communication aiming at the continuation of the implementation of the “European Research Area”. It further noted the importance of the Framework Programmes as strategic tools to achieve the creation of the “European Research Area” and to increase the efficiency of research activities in Europe. Finally, the Council invited the Commission to transmit to it formal proposals concerning the Sixth Framework Programme (FP6) (2002-2006) during the first quarter of 2001.

In view of the future research programme, the EURATOM Scientific and Technical Committee has prepared a report on the strategic issues to be considered in the development of the appropriate nuclear energy research strategies in a 20-50 year perspective [7]. The main message is that “a key R&D objective should be to ensure that future generations have a real selection of available technologies to choose from when they have to decide on the energy supply system that would best suit their needs and acceptance criteria. Therefore, R&D on technical options with a capacity to contribute significantly to base-load electricity supply must be carried out, including the fission and fusion options.” They also stress that, given the increased competition in the deregulated electricity market, public financing will be increasingly needed to ensure that society maintains and develops the scientific and technical infrastructure needed as a basis for long-term industrial development and competitiveness. In the area of nuclear fission, continued support should be given to maintain and develop the competence needed to ensure the safety of existing and future reactors. In addition, support should be given to explore the potential for improving present fission technology from a sustainable development point of view (better use of uranium and other nuclear fuels, whilst reducing the amount of long-lived radioactive waste produced).

The detailed discussions about the content of FP6 have now started.

7. Conclusion

The research activities in the field of partitioning and transmutation under the EURATOM Fifth Framework Programme have now begun. At present, the research projects are addressing the chemical separation of long-lived radionuclides and the acquisition of technological and basic data, necessary for the development of an accelerator-driven system. Other projects are expected for the next call for proposals with a deadline in January 2001. This call is targeted on the areas, which were not sufficiently well covered by the projects selected after the first call, such as preliminary engineering design studies of an ADS demonstrator, technological support and networking. Both, the present projects and those, which will be selected next year, should contribute significantly to providing a basis for evaluating the practicability, on an industrial scale, of partitioning and transmutation for reducing the amount of long lived radionuclides to be disposed of.

Concerning international co-operation, a Japanese research organisation is already participating in one of the FP5 projects without EU funding. The EU Contact Expert Group on ADS is fostering collaboration between EU and CIS research teams by linking FP5 and ISTC EU funded projects, which are related to ADS. It is hoped that co-operation in the field of partitioning and transmutation will be extended to other countries in the near future.

The discussions about the scientific content of the Sixth Framework Programme (FP6) (2002-2006) have just started. FP6 is a strategic tool to achieve the creation of the “European Research Area”, an idea which was launched by the Commissioner responsible for research in January 2000.

REFERENCES

[1] "Council Decision of 25 January 1999 adopting a research and training programme (Euratom) in the field of nuclear energy (1998 to 2002)", *Official Journal of the European Communities*, L 64, March 12th, 1999, p.142, Office for Official Publications of the European Communities, L-2985 Luxembourg.

[2] OECD/NEA, *Actinide and Fission Product Partitioning and Transmutation – Status and Assessment Report*, 1999, OECD Nuclear Energy Agency, Paris, France.

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

[4] M. Hugon, *Overview of the EU Research Projects on Partitioning and Transmutation of Long-lived Radionuclide,* (2000), Report EUR 19614 EN, Office for Official Publications of the European Communities, L-2985 Luxembourg.

[5] *Towards a European Research Area*, Communication from the Commission, COM (2000) 6, 18 January 2000, http://europa.eu.int/comm/research/area.html.

[6] *Making a Reality of the European Research Area: Guidelines for EU Research Activities (2002-2006),* Communication from the Commission, COM (2000) 612, 4 October 2000, http://europa.eu.int/comm/research/area.html.

[7] Scientific and Technical Committee Euratom, *Strategic Issues Related to a 6th Euratom Framework Programme (2002-2006),* (2000), Report EUR 19150 EN, Office for Official Publications of the European Communities, L-2985 Luxembourg, www.cordis.lu/fp5-euratom.

ACTIVITIES OF OECD/NEA IN THE FRAME OF P&T

Luc Van den Durpel, Byung-Chan Na, Claes Nordborg
OECD/Nuclear Energy Agency
Le Seine Saint-Germain, 12, Boulevard des Iles, 92130 Issy-les-Moulineaux, France
E-mail: vddurpel@nea.fr

Abstract

Back in 1989, the OECD/NEA started a comprehensive programme of work in the field of partitioning and transmutation (P&T). This programme was initiated by a request from the Japanese government who was launching a programme on P&T (OMEGA project) and invited the OECD/NEA to co-ordinate an international information exchange programme on P&T.

This OECD/NEA Information Exchange Programme has since then resulted in several activities, among them the Information Exchange Meetings and two state-of-the-art systems studies next to scientific aspects being handled by the Nuclear Science Committee.

The Nuclear Science Committee covers a wide range of scientific aspects of P&T. Aspects ranging from accelerators, nuclear data and integral experiments, chemical partitioning, issues on fuels and materials, and physics and safety of transmutation systems. This paper will overview the activities of the past ten years and will give insight in the ongoing projects, the results, and the perceived future activities.

1. Introduction

Back in 1989, the OECD/NEA started a comprehensive programme of work in the field of partitioning and transmutation (P&T). This programme was initiated by a request from the Japanese government who was launching a programme on P&T (OMEGA project) and invited the OECD/NEA to co-ordinate an international information exchange programme on P&T.

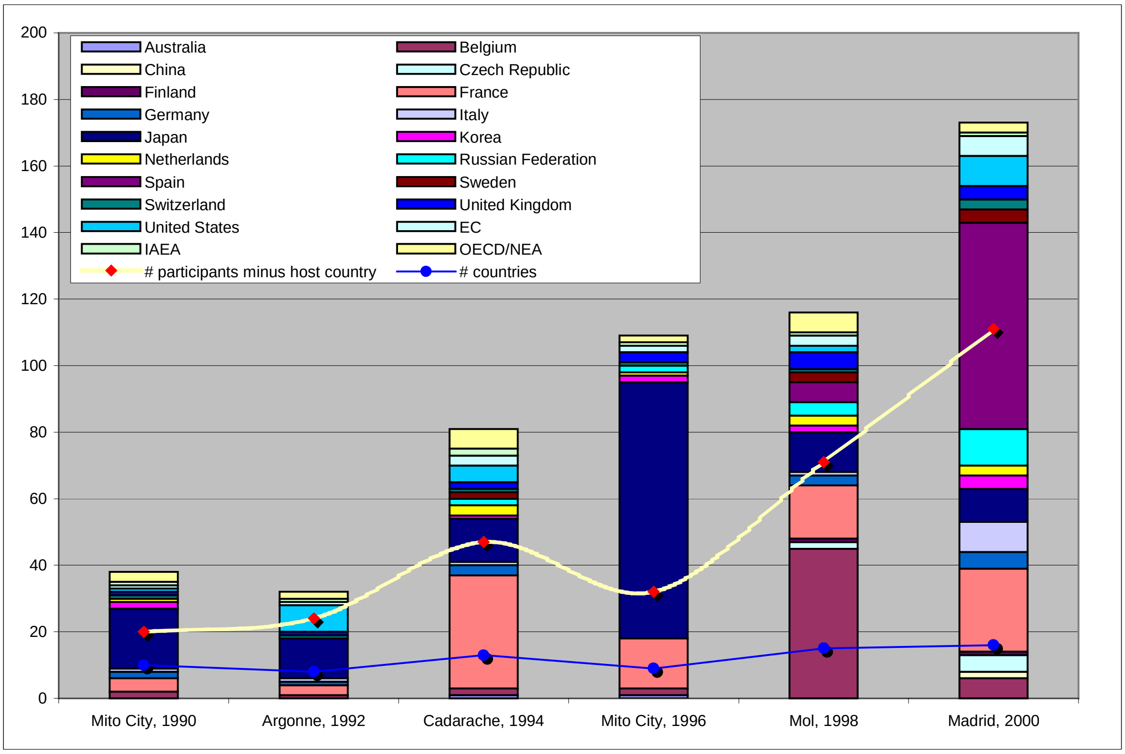
This OECD/NEA Information Exchange Programme has since then emerged in several activities, among them the Information Exchange Meetings and two state-of-the-art systems studies.

Since the NEA was invited to take up this topic in 1988, the interest in it has grown in several of our Member countries. The task is one of long-term scientific research, but it is recognised that certain short- or medium-term benefits could also be derived. There is quite a rich network of bilateral agreements on P&T between OECD Member countries. However, judging from the number of participants who have come a long way to the Information Exchange Meetings and the different workshops, there is a clear view that substantial benefits can be achieved from wider international activities and co-operation.

NEA has recently reorganised the P&T activities as a horizontal project between the Nuclear Development and Nuclear Science Committees and a restructuring of the science programme under the umbrella of a new working party on scientific issues in P&T has recently been started.

Figure 1 shows, for general information, the past increasing interest and participation in the Information Exchange Meetings. The shown trends let us also reflect on the future character of these meetings.

Figure 1. **Historic overview of participation to the OECD/NEA Information Exchange Meetings**



2. The previous 10 years

The activities of OECD/NEA in the field of P&T were initiated in 1989 by the proposal from the Japanese Government to conduct an international Information Exchange Programme under the umbrella of the Nuclear Development Committee. The objective of this OECD/NEA Information Exchange Programme on Actinide and Fission Product Partitioning and Transmutation were defined as to enhance the value of basic research in the subject by facilitating the exchange of information on and discussion of programmes, experimental procedures and results. The Information Exchange Meetings are integral part of this Programme intending to bring a biannual review of the state-of-the-art of P&T and is co-organised by the Secretariat and major laboratories in Member countries. Next to this Information Exchange Programme, other activities under the umbrella of the Nuclear Science Committee are undertaken and will be detailed in following section.

The first Information Exchange Meeting was held at Mito City (Japan) in November 1990 [1]. Various scientific and policy aspects of P&T were addressed and highlighted several disparate approaches which had been taken, covering a variety of aqueous and non-aqueous chemical procedures and a number of different reactor and accelerator based transmutation schemes. As this meeting stressed the need to have some small specialists meetings on suitable topics, OECD/NEA organised two of those specialists meetings. The first one handled on partitioning technologies (Mito City, Japan, November 1991) [2] where the second one focused on the topic of accelerator-based transmutation (PSI, Switzerland, March 1992) [3].

In November 1992, the Argonne National Laboratory hosted the second Information Exchange Meeting [4]. The papers presented indicated that one common thread was the need for some means of taking an integrated view of the expected benefits and possible disadvantages of including P&T in the nuclear fuel cycle. Among other results of such an approach would be guidance on research needs. A number of emerging important issues were identified during the meeting, including the legal background, the incentives and the implications for the whole fuel cycle in different countries. One of the main conclusions was that a comparison of system studies in the field of P&T, some of them already in progress, should form the central part of the P&T activities under the umbrella of the Nuclear Development Committee of the OECD/NEA.

These views were carried forward at the third meeting, hosted by CEA at its Cadarache site in December 1994 [5]. Several participants from 11 countries, together with Russia, the IAEA and the European Commission attended the meeting that primarily focused on P&T strategic systems studies. The meeting provided a solid basis for approaching a more co-ordinated NEA project, which was started in early 1996, on the benefits and penalties of adding P&T to the nuclear fuel cycle. This meeting also concluded that there was a clear need to define objectives against to which to measure the potential benefits of P&T. However, the discussion at the Cadarache meeting indicated that a final set could not yet be established.

The fourth meeting was hosted by STA, JAERI, JNC and CRIEPI and was held again in Mito City, Japan, in September 1996 [6]. The goals for P&T were set clearer during this meeting, i.e. P&T would not replace geological disposal, the potential hazard reduction was mainly associated with TRU elements, and reduction of the dose impact to man would come from mobile fission product radionuclides such as ^{129}I and ^{135}Cs. The main motivation for P&T was considered being based on ethical reasons for the future generations and public claims concerning geological waste disposal sites. The meeting also indicated that there was a need to better define the performance evaluation by the use of criteria. Those criteria would relate to the feasibility and credibility of the achievable reductions in mass and toxicity reduction, the corresponding cut-off period, the best way for industrial implementation and to a reasonable level of extra costs. Achievement of this kind of evaluations would need the continuation of technical studies and of systems and strategic studies including the necessary economical evaluations.

The Fifth Information Exchange Meeting [7], hosted by the Belgian Nuclear Research Centre SCK•CEN and co-organised by the European Commission, was held in November 1998 at Mol (Belgium) with more than 130 participants from 15 countries and 3 international organisations. This meeting could be characterised by two main directions; first of all, a more integrative view on partitioning and transmutation was observed where consensus on the way to perform P&T was achieved but where questions were raised on the added-value of P&T in the nuclear fuel cycle (and the most appropriate way to achieve it). Secondly, the breakthrough in partitioning of minor actinides was achieved on laboratory scale at pre-set performances.

3. Systems studies

In response to the discussions and conclusions of these meetings, two systems studies were conducted by the NDC. Both aiming at a comprehensive authoritative state-of-the-art and assessment report on the role, feasibility and developments of P&T.

The first report, entitled *Status and Assessment Report of Actinide and Fission Product Partitioning and Transmutation*, was published in 1999 [8] and was the result of a two-year's work by an expert group. The report investigates different options to decrease the final radiotoxicity and provides a limited systems analysis of the main options as a step towards clarifying choices among this complex set of possible alternatives. The preliminary systems analysis starts from the present technical state of the art in the fuel cycle and points to some possible developments in P&T technologies which would result in an advanced fuel cycle with an overall reduction of the radiotoxic inventory and a reduced impact on the biosphere. The main general conclusions of this report state:

- Fundamental R&D for the implementation of P&T needs long lead-times and requires large investments in dedicated fast neutron spectrum devices, extension of reprocessing plants, and construction of remotely manipulated fuel and target fabrication plants.
- Partitioning methods for long-lived radiotoxic elements have been developed on a laboratory scale.
- Recycling of plutonium and minor actinides could stabilise the transuranium nuclides inventory of a nuclear power park. Multiple recycling of transuranium nuclides is a long-term venture that may take decades to reach equilibrium of inventories.
- Conditioning of separated long-lived nuclides in appropriate matrices which are much less soluble than glass in geological media, or which could serve as irradiation matrix in a delayed transmutation option, is a possible outcome for future decades.
- P&T will not replace the need for appropriate geological disposal of high level waste, irradiated transuranium concentrates, and residual spent fuel loads from a composite reactor park.

The ongoing systems study on "Comparative Study of ADS and FR in Advanced Nuclear Fuel Cycles" complements this first study by looking to the role of P&T in different nuclear fuel cycle schemes and the specific role of accelerator-driven systems (ADS) versus fast reactors (FR). In addition, the technological status and issues in developing these ADS or FR including the needed developments in the fuel cycle, and finally a cost/benefit analysis and the R&D-issues related to P&T are part of the study's scope. An international expert group has been set-up and will finalise its analysis by mid-2001.

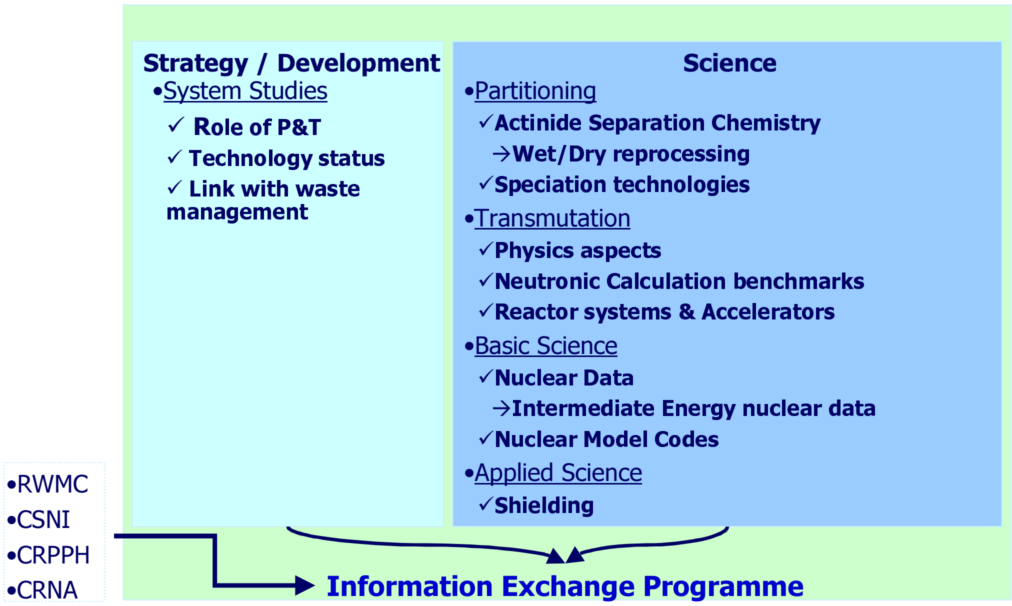
4. Scientific issues of P&T

In parallel with the activities on P&T of the Nuclear Development Division the Nuclear Science Committee (NSC) covers various scientific issues in response to the perceived need expressed during the Information Exchange Meetings.

Where, in principle, the NSC focuses a rather broad field of topics, its initial activities related to P&T were in essence oriented towards two substantial aspects, i.e. the creation of data bases and the organisation of inter laboratory comparison exercises. Later, these activities were expanded to include also other aspects of P&T, e.g. radiochemistry, accelerators, and others.

Today, the programme of work of the NSC in the frame of P&T comprises scientific aspects studied by its working parties and expert groups (or task forces), the NEA Data Bank activities on nuclear data and computer programmes, and finally the organisation of workshops (see Figure 2).

Figure 2. **Overview of today's OECD/NEA's activities within the frame of P&T**



A Task Force to investigate the physics aspects of different transmutation concepts was set-up in the early 1990s. The resulting overview report, published in 1994 [9], described the basic features of a number of different transmutation concepts.

In addition, the Working Party on Evaluation Co-operation (WPEC) worked previously on the High Priority List of Measurements which covers a list of actinides needing further measurement activity, especially in the above 20-MeV part of the neutron energy-range [10]. Co-ordination of differential nuclear data measurements was undertaken as well as an effort was started on intermediate energy nuclear data measurements, evaluation and nuclear model codes development and benchmarking.

In 1996, the NSC Expert Group on Physics Aspects of Different Transmutation Concepts organised a benchmark exercise to investigate the physics of complex fuel cycles involving reprocessing of spent PWR reactor fuel and its subsequent reuse in different reactor types: PWRs, fast reactors and an accelerator-driven system. The results of the comparison of the calculated activities for individual isotopes as a function of time for different plutonium and minor actinide transmutation scenarios in different reactor systems can be found in reference [11].

New activities were launched since 1998 and included workshops on high power accelerators reliability [12]. The first of this kind was held in October 1998 aiming the exchange of information between the accelerator and nuclear community in the light of accelerator driven systems for P&T purposes. The NSC conducted the second workshop on high-reliability accelerators in France at 23-27 November 1999 [13].

A speciation technology workshop was held in 1999 [14] and a workshop on pyrochemistry has recently been organised in October 2000. The NSC also reviewed in 1998 current and developing actinide separation chemistry via a workshop and a report by an expert group [15].

The NSC and Data Bank continue to fulfil their role to provide physics tools and data that enable improved transmutation calculations to be performed. Ongoing activities relate to:

- Nuclear data and benchmark calculations.
  - Activities were conducted in the field of intermediate energy nuclear data. Three studies were completed in the early '90s:
    - ❖ One on the availability of experimental data and nuclear model codes.
    - ❖ A second on the requirements for an evaluated nuclear data file.
    - ❖ The third study was an international comparison of the performance of computer codes used in intermediate energy calculations. The results of this exercise were published in 1994 [16]. It was followed by a specialist's meeting in June 1994 [17], which recommended the systematic compilation of experimental intermediate energy data to assist the theoreticians and evaluators in their work. The Data Bank started to compile these data into the internationally maintained EXFOR database [18].
  - A co-operative project on an evaluated intermediate energy nuclear data file, through its Working Party on International Evaluation Co-operation.
  - Related activities involved a specialist's meeting in 1997 on the optical model dealing with higher energies required in accelerator-driven technologies [19].
  - Benchmark exercises were undertaken and reported in 1997 on the predictive power of nuclear reaction models and codes for calculation of activation yields in the intermediate energy range (up to 5 GeV) [20].
- Shielding aspects of accelerators, targets and irradiation facilities [21].
- Criticality (including sub-criticality) benchmarks.
- A neutronic benchmark of an accelerator-driven minor actinide burner has performed. A summary of the results is presented in this meeting [22] and the final report of the benchmark will be issued in mid-2001

Recently, the NSC meeting of June 2000 endorsed the creation of the Working Party on Scientific Issues in Partitioning and Transmutation (WPPT) in order to guide the P&T-related activities of NSC in the future.

This Working Party will envelop the scientific aspects of P&T and comprises four sub-groups:

- Group on Accelerator Utilisation and Reliability:
  - This group emerges from the previous workshops on Accelerator Utilisation and Reliability, will synthesise the improvements made and draw conclusions from each workshop held and continue to organise such workshops. The group will also deal with target and window performances, for instance, issues on spallation products and thermal stress and radiation damage, respectively.
- Group on Chemical Partitioning:
  - The existing expert group on Pyrochemistry moves under this WPPT where this subgroup will first focus on the drafting of a state-of-the-art report on Pyrochemistry. Despite its name, the group will also look into aqueous processing issues.
- Group on Fuels and Materials, as the new proposed transmutation systems will demand specific materials to be validated or developed for use in more challenging irradiation conditions.
- Group on Physics and Safety of Transmutations Systems:
  - This group will organise theoretical and experiment-based benchmarks to validate nuclear data as well as calculation tools needed for simulating advanced transmutation systems, and investigate safety aspects of transmutation systems such as the beam trip problem of ADS.

5. Other committees

Contacts with the Radioactive Waste Management Committee (RWMC) guarantee that an exchange of resulting information is shared among the related committees. The RWMC issued a statement on P&T in 1992 [23] primarily to emphasise the point that actinide P&T cannot be considered as an alternative to geologic disposal. The RWMC continues general studies related to the development of geologic repositories but there are no activities specifically directed at P&T.

In early 2000, the NEA Steering Committee and Committee of Standing Technical Chairs decided to extend the Information Exchange Programme as a horizontal activity within OECD/NEA, emphasising the multi-disciplinary character of P&T and also responding to a more transparent structure of NEA's activities in this field. Therefore, both the NDC and NSC will co-organise this Programme and input from other committees, especially the Radioactive Waste Management Committee, would be searched for. A new web page has also been launched as a joint activity [24].

6. Possible future activities

Beyond the known NEA activities related to P&T, it is noted that confident decisions or actions regarding a P&T fuel cycle requires significant extensions of existing technology throughout the back-end of the fuel cycle. However, examination of the historical literature reveals a number of important areas of technology that have received relatively little or dispersed attention.

Therefore, while there is continuing need for improved data and analyses on a broad front to provide the basis for governmental decisions, the following areas are perceived as deserving particular attention in the future and appropriate OECD/NEA activities are considered in the future:

- *Repository analysis*: one of the primary benefits of P&T is believed to be a reduction in risk from the geologic repository. Despite this, there have been very few studies to quantify the extent and uncertainty of the risk reduction. Most of the historical studies have used hazard or toxicity indexes that do not properly account for the migration of various radionuclides. The recently published first phase report [9] covered into some extent the impacts of P&T on the long-term repository risk. However, there remains a pressing need to analyse these impacts of P&T on long-term repository risk in all future work and this will again be addressed within the ongoing second phase P&T systems study. Such analysis will request the collaborative effort from RWMC.

- *Fuel cycle impacts*: recycling MAs results in significant changes in the composition of the fuel or targets that contain them. However, the impacts of these changes on the out-of-reactor fuel cycle (e.g. design of facilities and transportation casks, safety impacts) are not yet fully documented and were only partially covered in previous assessment studies. Further detailed studies in this area are needed and are partially included in the second phase study on P&T.

- *Systems analyses*: despite the many studies that have been conducted over decades, the number of systems studies that comprehensively compare the advantages and disadvantages of standard and P&T fuel cycles is small. Such an analysis should be a key component of NEA recommendations to member governments and, as such, constitutes a major need. The first and second phase of NEA's P&T systems studies and the specific NSC-activities have been targeted to cope with this specific demand.

- *Safety of P&T related installations*: the current renewed interest in ADSs and also in FRs for P&T purposes has been evolving such that currently small-scale or demonstration facilities are proposed. Despite the still long-term venture for P&T activities and construction of specific installations, one should already consider basic studies on safety related issues and especially on the ADS related aspects. Some of these aspects have been covered by existing or ongoing systems studies but input of specific expertise could be welcome.

- *Nuclear data*: whilst overall assessment studies are important, the need for basic nuclear data to perform the underlying neutronic calculations are of very high importance. Especially the move to harder neutron spectra in fast reactor systems and accelerator-driven systems, in addition to the specific aspects of spallation neutron spectra and the increasing contents of minor actinides in the fuel, support the need for a continuous and increased need for validated nuclear data files. Specific effort is needed in the intermediate energy domain and NSC-Data Bank has conducted work on this since the early 1990s.

- *Materials science*: the new proposed transmutation systems will demand specific materials to be validated or developed for use in more challenging irradiation conditions. This materials science domain including not only structural materials but also target and fuel materials becomes more dominant in such P&T schemes. Increased effort in experience exchange is needed and has already partially been covered by the NSC International Fuel Performance Experiments (IFPE) database. Activities on a Material Damage Database and a report on the correlation between dpa-calculations and real damage are planned within NSC.

- *Separation chemistry*, being a very important part of any P&T scheme, needs continuous development especially in the light of new developments in aqueous as well as in dry separation methods. NEA's activities cover the follow-up of recent developments and needs.

- *Demonstration Experimental Programme*: while different Member countries study P&T and plan to conduct or are conducting an experimental programme aiming the scientific and technological demonstration of P&T and especially ADS, there is scope for an international co-ordinated joint project in this domain. This joint undertaking would supplement the Information Exchange Programme and aim rationalisation of the different international initiatives in order to support collaborative development in the domain.

7. Conclusions

OECD/NEA has organised a structured programme of work during the past ten years. The two main committees involved in this programme are currently pursuing system studies, nuclear data evaluations and benchmarks, and organise specific workshops on scientific aspects of P&T.

The increasing interest in P&T has brought the OECD/NEA to regroup some of its scientific activities in a new working party WPPT in order to respond better to the perceived needs of the P&T-community and governments.

REFERENCES

[1] OECD/NEA, *Proceedings of the Information Exchange Meeting on Actinide and Fission Product Separation and Transmutation*, Mito City, Japan, 6-8 November 1990, (1991).

[2] OECD/NEA, *Proceedings of the Workshop on Partitioning of Actinides and Fission Products,* Mito City (Japan), 19-21 November 1991, CEA-CONF-11066 (1991).

[3] OECD/NEA. *Proceedings of the Specialists' Meeting on Accelerator-based Transmutation*, PSI-Villigen, Switzerland, 24-26 March 1992, (1992).

[4] OECD/NEA, *Proceedings of the Information Exchange Meeting on Actinide and Fission Product Separation and Transmutation*, Argonne National Laboratory, United-States, 11-13 November 1992, (1993).

[5] OECD/NEA, *Proceedings of the Information Exchange Meeting on Actinide and Fission Product Separation and Transmutation,* Cadarache, France, 12-14 December 1994, (1995).

[6] OECD/NEA, *Proceedings of the 4th Information Exchange Meeting on Actinide and Fission Product Separation and Transmutation*, Mito City, Japan, 11-13 September 1996, (1997).

[7] OECD/NEA, *Proceedings of the 5th Information Exchange Meeting on Actinide and Fission Product Separation and Transmutation*, Mol, Belgium, 25-27 November 1998, EUR 18898 EN, (1999).

[8] OECD/NEA, *Status and Assessment Report on Actinide and Fission Product Partitioning and Transmutation*, Paris, France (1999).

[9] OECD/NEA, *Overview of Physics Aspects of Different Transmutation Concepts*, NEA/NSC/DOC(94)11, (1994).

[10] http://www.nea.fr/html/science/docs/pubs/hprl.pdf.

[11] OECD/NEA, *Calculations of Different Transmutation Concepts – An International Benchmark Exercise*, ISBN 92-64-17368-1, 2000.

[12] OECD/NEA, *Workshop on Utilisation and Reliability of High Power Proton Accelerators*, Mito, Japan, 13-15 October 1998, (1999).

[13] http://www.nea.fr/html/science/hpa2/.

[14] OECD/NEA, *Speciation, Techniques and Facilities for Radioactive Materials at Synchrotron Light Sources* Workshop Proceedings, Grenoble, France, 4-6 October 1998, (1999).

[15] OECD/NEA, *Actinide Separation Chemistry in Nuclear Waste Streams and Materials*, Paris, France, (1997).

[16] OECD/NEA, *International Code Comparison for Intermediate Energy Nuclear Data*, Paris, France, (1993).

[17] OECD/NEA, *Intermediate Energy Nuclear Data: Models and Codes*, Proceedings of a Specialists' Meeting, Paris, France, 30 May-1 June 1994, Paris, France (1994).

[18] http://www.nea.fr/html/dbdata/x4/welcome.html.

[19] OECD/NEA, *Nucleon-Nucleus Optical Model up to 200 MeV*, Proceedings of a Specialists' meeting, Bruyères-le-Chatel, France, 13-15 November 1996, (1997).

[20] OECD/NEA, *International Codes and Model Intercomparison for Intermediate Energy Activation Yields*, NSC/DOC(97)-1, (1997).

[21] OECD/NEA, *SATIF-4 – Shielding Aspects of Accelerators, Targets and Irradiation Facilities. Proceedings of 4th Specialists Meeting*, Knoxville, Tennessee, USA, 17-18 September 1998, (1999).

[22] M. Cometto, B.C. Na and P. Wydler, *OECD/NEA Benchmark Calculations for Accelerator-Driven Systems*, 6th Information Exchange Meeting, Madrid, Spain, 2000, EUR 19783 EN, OECD/NEA (Nuclear Energy Agency), Paris, France, 2001.

[23] OECD/NEA, *Statement by the Bureau of the RWMC on the Partitioning and Transmutation of Actinides*, NEA/SEN/RWM(92)3, (April 1990).

[24] OECD/NEA, P&T web page can be consulted at http://www.nea.fr/html/pt/.