1. INTRODUCTION

Management of radioactive waste (RW) in an environmentally safe manner is an important issue being addressed by all the countries developing a nuclear industry. In many countries it has become a serious political issue attracting intense critical attention of the general public. Therefore, working out of a safe acceptable solution is a technological challenge to international and national nuclear communities. Nuclear spent fuel (NSF) which is the main source of RW contains fissionable isotopes and therefore the issues connected with NSF handling are also proliferation sensitive.

Large scale spent fuel reprocessing has been carried out since the middle fifties by several countries. Countries such as the UK, France, Germany, Japan, India and the Russian Federation have been progressively stepping up their capabilities for spent fuel reprocessing. These countries, after carefully reviewing the various options have recognized that reprocessing of the fuel is the safer way to get rid of the problems associated with the long term storage and disposal of the spent fuel waste, at the same time ensuring augmented energy from a given initial fuel inventory. Several other countries however are storing the spent fuel for the time being and are yet to decide on the final option; the necessity for the decision becomes more urgent as time goes on and spent nuclear fuel continues accumulating on-site and in interim stores, some of them already operating above initially planned capacity.

Geological disposal is considered as the unavoidable final step in any scheme of RW management. But important questions which remain to be answered are:

- Whether the RW, which is usually considered dangerous, can be considered potentially or even presently a valuable commodity?
- What actions if any might be undertaken to turn the RW from nuisance into an asset, into secondary raw material, as it is routinely done in other industries?

Neutron transmutation of long lived radioactive minor actinides (MA - neptunium, americium, curium) by the fission process, producing energy and simultaneously turning them into shorter lived nuclides, is being intensely analysed and discussed as a possible answer to these questions. In the same way, neutron transmutation of selected long lived fission products (LLFP) is being proposed.

The concept of a closed nuclear fuel cycle (NFC) was traditionally considered as transmutation (burning) of only plutonium and recycled uranium, with minor actinides destined for final geological disposal. Now, a new understanding is emerging:

(a) In a long term case (multiple recycling and long total cooling times) plutonium and minor actinides are interconnected and mixed by decays (^{241}Pu into ^{241}Am, ^{242}Cm into ^{238}Pu, ^{244}Cm into ^{240}Pu, etc.).

(b) Plutonium isotopes with small fission to capture ratios are close in their physical properties to minor actinides and degradation of plutonium isotopic composition in multiple recycling is in many ways similar to the admixture of minor actinides (neptunium americium and curium) both in neutronic properties and in the resulting difficulties in fabrication and handling of secondary fuel. Hence the experience gained in MOX fuel fabrication should be useful in the fabrication of fuel with minor actinides.

(c) Production of MA goes up in multiple recycling of plutonium while the mass of plutonium decreases.

(d) Reduction of actinide components would ease requirements for final repositories and make them relatively less expensive.

All this is attracting growing attention to the prospects of neutron transmutation of minor actinides and, also, of some selected fission products (FP). The proposed schemes include burning in advanced reactors, both thermal and fast and in accelerator driven subcritical facilities.

Although initially few nuclides (transuranium elements and ^{99}Tc) have been identified as potential candidates for transmutation, additional ones are under consideration [1]. The extent to which they can be transmuted, is still an open question. Practically any isotopic mixture of minor actinides placed in an intense neutron flux for some time becomes highly radioactive. The period to cool it down to less than its initial radiotoxicity is one of the crucial parameters to be taken into account in planning transmutation schemes.

Several possibilities for the transmutation of long lived nuclides by nuclear reactions have been suggested [2]. In the beginning, the best choice appeared to be the fast breeder reactor [3], because accelerators, light water reactors or even futuristic fusion reactors did not appear economically viable. However, recently there has been a renewed interest in the accelerator driven transmutation (ADT) schemes which seems to show good promise.

The partitioning of nuclides had been seen mainly as an extension of the PUREX process. Technical feasibility studies (mainly in the USA), showed that the cost-benefit ratio for the net radiological risk reduction exceeded by $32,400 per man-rem the US guideline of $1000 per man-rem [4]. Here, the radiological risk reduction considered only minor actinides and not fission products, which, when included in the partitioning scheme, would have considerably reduced the cost per man-rem. Because of their low reaction cross-section, ^{99}Tc, ^{129}I, ^{135}Cs could not be efficiently transmuted in the present nuclear power stations, so that the transmutation of those fission products appeared not to be feasible at this time. Later, it was proposed to use moderated assemblies in the blankets of fast breeder reactors or to employ accelerator driven systems having considerably higher neutron fluxes [5]. In 1982, the French Ministry of Research and Industry [6] encouraged continuation of research in this field, which, in France, led to the SPIN (separation and incineration) Programme where presently several options for partitioning & transmutation (P&T) are being studied. In the nineties the Japanese Government launched a similar initiative and started the Omega Programme that initiated broad research in P&T by several Japanese organizations.

It should be pointed out that technical feasibility, and especially the economic and radiological soundness of transmutation still needs to prove, so the arguments both for and against P&T should be carefully compared and evaluated.

The main arguments in favour of P&T are:

- burning of the actinides considerably reduces the necessary volume and relaxes the longevity requirements for final disposal stores which are very expensive and attract most intense public criticism and objections;
- multiple plutonium recycling which is the essence of a really efficient closed nuclear fuel cycle (NFC) is somewhat more difficult than first Pu recycle. However, additional complications due to the inclusion of MA recycling may not be critical;
- MA may become an additional source of fission energy.

The main arguments against P&T are:

- inclusion of highly radioactive transuranics into the NFC makes fuel refabrication more difficult and hazardous and necessitates the use of remotely controlled operations;
- many materials and technologies involved are proliferation sensitive;
- transmutation reducing the actinide component of high level waste (HLW) increases the total amount of medium level waste (MLW) and low level waste (LLW), but of shorter half-life.

Much stronger and more complicated interdependence of reactor physics on the one hand and the requirements for reprocessing, refabrication and final disposal on the other are characteristic of NFCs involving transmutation. Large variations in recycled fuel composition seem inevitable. Development of a detailed concept of a closed NFC including MA burning in advanced nuclear power systems is not just a multiparametric optimization problem. Some important input data, both in material science and nuclear physics still are not known with the necessary accuracy and should be determined. Various proposed radiochemical processes need further investigations. For accelerator driven nuclear systems new technologies need to be developed.

Strategies of nuclear power development in every country are obviously dependent on historical roots and are strongly individual. The basic reactor types used in national nuclear power industries are quite diverse. Decisions once taken and implemented in each country have determined the path of development for many decades. National approaches to transmutation R&D also reflect this general situation as transmutation technologies are expected to be a logical continuation of the power reactor technologies adopted and proven in a particular country. However innovative approaches should be considered carefully so as not to block the realization of new and promising ideas.

A consistent concept for handling long term HLW must include both general principles, the description of methods chosen for realization of those principles and detailed explanation of the choice. The general points to be considered are:

1. Main strategic options of the nuclear fuel cycle which determine the rate of production, total volume and composition of HLW.
2. Sharing of risk and of responsibility connected with HLW between present, next and future generations.
3. The choice of optimum combination of passive (controlled storage and final disposal) and active (burning up and transmutation) methods in handling HLW.

Further details are related to:

(a) The composition of burnt fuel and the products of its radiochemical processing from presently operating and future plants.
(b) Individual parameters of HLW radionuclides determining the conditions of storage, the need and possibility of transmutation.
(c) The resulting list of the isotopes - candidates for transmutation and optimum storage conditions for the remaining radionuclides.
(d) Critical analyses of proposed transmutation schemes which may fall into the following main categories:
    - high flux reactors with thermal or slightly harder (epithermal, resonance) spectra;
    - fast reactors (FP) (standard power plants or specialized actinide burners);
    - subcritical assemblies and blankets, both thermal and fast, driven by high energy, high current accelerators or by other powerful neutron sources (for example, future fusion reactors).
(e) Using the results of above analyses, to choose the most promising designs and point out both their advantages and the problems to be solved.

There are several international programmes set up to study the P&T option. The OECD/NEA is co-ordinating the R&D activities of its interested Member States. The organization regularly arranges information exchange meetings and has started evaluation of the present activities [7].

In its cost shared action (CSA) programme, the European Union has supported and co-ordinated activities in several fields of partitioning & transmutation. A strategy study is being made to assess the benefits of partitioning & transmutation for the safety of the management and storage of waste. The participating organizations are CEA, Siemens, ECN, AEA Technology and Belgonucléaire. The CEA, FK, ECN, EdF, TUI co-operate together in EFFTRA to develop and jointly test heterogeneous mixed oxide fuels - which are to a large extent in inert matrices - to be irradiated in HFR and PHENIX. In a trilateral co-operation CEA, FK, TUI study mixed oxide fuels under irradiation in HFR, Osiris and PHENIX. In the frame of a CRIEPI commercial contract, the TUI is developing a minor actinide fuel using Zr-based alloys which is being irradiated by CEA in PHENIX (Metaphix).

The ISTC has accepted a research proposal from RIAR to demonstrate a minor actinide fuel cycle based on mixed oxides obtained by electro-deposition from NaCl-2CsCl melt. The oxides are vibro-compacted and will be irradiated in BOR-60. The partners are PNC, BNFL and TUI. Two ISTC grants on transmutation related research were given to IPPE and the largest one ($3.2 million for two years) went to a collaboration, led by IPPE, on ADTT development.

There are considerations which indicate that now it is probably the right time to give further momentum to the research on the subject. First, the next generation of advanced reactors which will start operating in the first decade of the next century will have a lifetime of at least 50 to 60 years. This is long enough to require some flexibility in their fuel cycle options which should be planned now. Secondly, P&T is certainly a long term problem in the early stage of development and definite solutions may be reached only after a considerable amount of R&D work in this area. New facts are being accumulated fast and a lot of new, sometimes radically new, ideas and proposals are being formulated. At the same time, difficulties and contradictions are also being accumulated equally fast. The methods which are proposed to overcome them are often of purely theoretical and even hypothetical nature. Hence there is the necessity for constant analytical work with new information to avoid major mistakes and to correct and optimize plans.

Since there are also R&D activities in this field outside the OECD, the IAEA has taken an initiative to document the research activities in those Member States in order to assist in this programme. For the evaluation of the safety (environmental) and non-proliferation aspects of partitioning & transmutation of actinides and fission products, a co-ordinated research programme has already been set up [8].