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IPNO DRE 94-04

TRANSMUTATION OF NUCLEAR WASTES

A working report to Nupecc

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1. Introduction

Almost everywhere in the world, the safe and accepted management of nuclear wastes, produced in nuclear reactors, has become one of the main issue related to the use of nuclear fission for energy production. Attention is mainly focused on the long-term effects on health and environment of nuclear wastes generated at the back end of the nuclear fuel cycle. In fact, these wastes contain highly radioactive and long-lived radionuclei which have been produced inside the reactors through fission, neutron capture, activation and natural decay. Concerning the Light Water Reactor (LWR), table 1 gives the characteristics and the quantities of the most important long-lived nuclei, sequestered in the spent fuels. Most of the actinides (Np-237, Am-241/243 and Pu isotopes), produced by successive neutron

TABLE 1: Production of the most important long-lived nuclei in spent fuels

Nucleus	Half Life (year)	Radiotoxicity[a)] (Bq/l water)	Mass[b)] (g/tHM)	Mass[c)] (kg/TWh)	Mass[d)] (kg/year)
Actinides:					
Np-237	2.14 10^6	0.3	437	1.66	10.15
Pu-238	87.7	0.4	140	0.53	3.25
Pu-239	24110	0.4	5470	20.72	127.05
Pu-240	6550	0.4	2230	8.45	51.80
Pu-241	14.4	20	956	3.62	22.20
Pu-242	3.7 10^5	0.4	486	1.88	11.52
Pu total			9282	35.16	215.60
Am-241	432.6	0.3	296	1.12	6.87
Am-243	737	0.3	84	0.31	1.95
Fission products:					
Tc-99	2.1 10^5	300.	841	3.19	19.53
I-129	1.57 10^7	2.	229	0.87	5.32
Cs-135	2. 10^6	100.	324	1.23	7.53

a): drinking water limits as derived from ICRP-61 [1];

b): in one ton of Heavy Metal (tHM) of spent fuel discharged from a LWR, with a burn-up of 33 000 MWj/t after 5 years cooling;

c): the same, referred to the electricity production of 1 billion of kWh;

d): referred to the annual output of a 1000 MW(e) LWR at a load factor of 70%.

capture and nuclear reactions starting from U-238 and U-235, and decay, have indeed a very long lifetime and an high radiotoxicity. Despite lower radiotoxicity,one has also to consider some long-lived fission, because of their high mobility in the environment. According to the last OECD/NEA evaluation [2], one expects that by the year 2010, about 21% of the electricity will be generated from nuclear plants throughout OECD countries, yielding a cumulative arisings of 180 000 tons of spent fuels. As shown in Tab. 2, one expects very large quantities of long-lived nuclei,especially Plutonium, which may pose a proliferation problem, and Np-237, which presents the highest potential radiological risk (if one does not consider plutonium) in the long-term.

TABLE 2: Spent fuels and long-lived nuclei inventory (in ton) by year 2010

	OECD	Europe	United States	Japan
Spent fuels[a]:	183 000	60 800	63 000	20 550
Actinides:				
Np-237	80	26	27	9
Np-237 (∞)[b]	309	103	106.	35
Pu-total	1700	565	585	191
Am-total	69	23	24	8
Fission products:				
Tc-99	154	51	53	17
I-129	42	14	14	5
Cs-135	59	20	20	7

a): ref. [2].

b): At very long term, Np-237 results from the initial amount and by the three following decay chains of initial nuclei: Am-241 --(α)--> Np-237;
Pu-241 --(β)--> Am-241 --(α)--> Np-237;
Cm-245 --(α)--> Pu-241 --(β)--> Am-241 --(α)--> Np-237.

2. General background

2.1. Present options: Most of the spent fuels unloaded from light water reactors are stored in water-pools, near the reactors, for heat decay. After a certain time, of the order of 5 to 10 years, two options are considered.

The first possibility is to reprocess the spent fuels, in order to separate plutonium and uranium from the remaining inventory, fission products and minor actinides (MA). These high level wastes are vitrified in borosilicate glass, ready for final geological disposal, normally after a long heat decay period, of the order of 50 years.

In the second option, interim storage takes place for a period of time, which can extend to 50-100 years, in dry storage casks. Thereafter, spent fuels are intended to be disposed directly in a deep underground storage site (or eventually reprocessed).

It is worthwhile to point out that the interim storage option without reprocessing is "de facto" adopted throughout the world. Only 20% of the OECD countries spent fuels will be reprocessed between 1990 and 2000 [2]. This is due to the absence of any economical incentive to go in reprocessing, the main goal of which is to remove plutonium. This product can be used either as a substitute for enriched uranium in present reactors (**M**ixed **OX**ide strategy) or in fast breeder reactors, in order to use the total energy content of uranium. For the present time, the very low uranium price (it has fallen from 80 $ per pound in 1980 to 7 $ now) discourages most electrical utilities to enter the reprocessing business which still goes on in France and UK, in accordance with foreign fuel reprocessing contracts which were signed more than 10 years ago.

Moreover, there is a consensus among the national and international nuclear agencies, (Nuclear Agency of OECD, EC, IAEA), that both options ending with the geological disposal of vitrified packages and other α- contaminated wastes or spent fuels, have practically the same level of safety, as far as long-term effects are concerned, and that geological disposal gives large margins of safety at any time in the future. Dose commitments, as deduced from modelized transfer studies, are found at any time in the future to be under the currently accepted level for the public, by at least one order of magnitude [3].

Large efforts are now made in Europe and the United States to select and qualify favorable geological sites. For example, since 1975, the European Community has started an important research program on geological disposal in its laboratories at Ispra and Karlsruhe; it simultaneously supports national programs.

2.2. Status of transmutation

Despite the perceived innocuity of geological disposal, alternative or complementary options are worth examining. For example transmutation, a method to transform long lived nuclei into short lived or less radiotoxic nuclei. For obvious reasons, neutron appears as the ideal particle to induce these transformations, called transmutation or incineration depending on the main route - capture or fission. In this paper, transmutation will be used as a generic name referring to both processes.

The feasibility of transmutation in nuclear reactors has been investigated in the United States by various authors since H.C. Claiborne of Oak Ridge published his first paper in 1972 [4,5,6]. In Europe, two important expert meetings have been jointly organized by the EEC and IAEA at Ispra in 1977 and 1980 [7,8], to evaluate the various transmutation options. At that time transmutation was considered only in thermal or fast neutron spectrum of reactors. The main conclusion of these two meetings was that transmutation was technically possible, but that the gain in terms of long-term safety was uncertain and marginal, all the more as, in the short term, it will probably yield higher dose commitments The following arguments against transmutation were also presented

- Transmutation aims at decreasing the potential radiotoxicity of long lived actinides: however, one has to compare this real risk, which can be reduced through geological disposal, with the long term risk due to uranium tailings (Th-230, Ra-226) which are just left on ground level. There might be no point in transmuting actinides if nothing is done for these tailings. And in the very long term, beyond 100 000 years, tailings dominate the potential radiological risk anyway;
- Transmutation normally implies chemical partitioning and many recycling, during which other types of wastes containing small fractions of actinides are created. Unless high decontamination factors are achieved (one order of magnitude at least compared to present practices), the long—term impact of these wastes might overcome the benefit of transmutation which affects only the high level waste packages.

As a consequence of theses two meetings, the European Community did not give any support to transmutation studies during the 1980-1989 period of the second and third 5-years programs. But meanwhile, and despite these pessimistic conclusions, partitioning of minor actinides was strongly advocated by a task force (the so-called Commission Castaings) set up by the French Government from 1981 to 1985 to review the reprocessing and nuclear wastes policy in France [9]. From 1987 to 1990, strong local opposition appeared against disposal site selection, and a law was voted in December 1991 by the French Parliament specifying that researches on transmutation had to be carried out together with geological studies, before any decision was made in the next 15 years. At the same time, laboratories in United States and Japan proposed new systems to transmute long lived nuclei. In face of this renewed interest for this option, the DGXII of the CEC, in its fourth 5–years program decided to support some evaluation studies carried out by Siemens (Interatome), ECN (Petten) and CEA. On the other hand, the Nuclear Agency of OECD initiated 3 international information exchange meetings in 1990 and 1992 [10,11,12] on the subject of transmutation.

Finally, it might be useful to briefly review the various statements in favor of transmutation [13], some of them being also criticisms against geological disposal:

- there are large uncertainties in the safety evaluation of geological disposal, due to an incomplete knowledge of the various physico-chemical and radio-biological parameters as well as of the mechanisms of radioactivity migration to biosphere. These uncertainties come also from the fact that the list of scenario taken into account in the risk analysis can not be exhaustive (e.g. human intrusion);
- moreover, one cannot avoid that, past a certain time of institutional monitoring, geological disposal will become an irreversible option;
- transmutation could be a response to these drawbacks, provided that wastes would become harmless in a time span, over which institution can keep a look on them. If one is less ambitious, transmutation can be considered as a way to

shorten the time during which the radiotoxicity of high level wastes is greater than the corresponding uranium ore radiotoxicity. Fig1, shows the radiotoxicity decay of high level wastes, when various minor actinides are removed.

-geological disposal is the focus of large public opposition virtually everywhere [14], and in this respect, it is argued that public acceptance of nuclear energy will be largely increased if transmutation is adopted;

- a more recent argument in favor of transmutation, is its possible contribution to the reduction of plutonium stocks (260 tons at the end of 1990), resulting from the nuclear warheads dismantlement undertaken now in Russia and in the United states, as a consequence of START1 and 2 agreements signed in 1991 and 1993 [15,16].

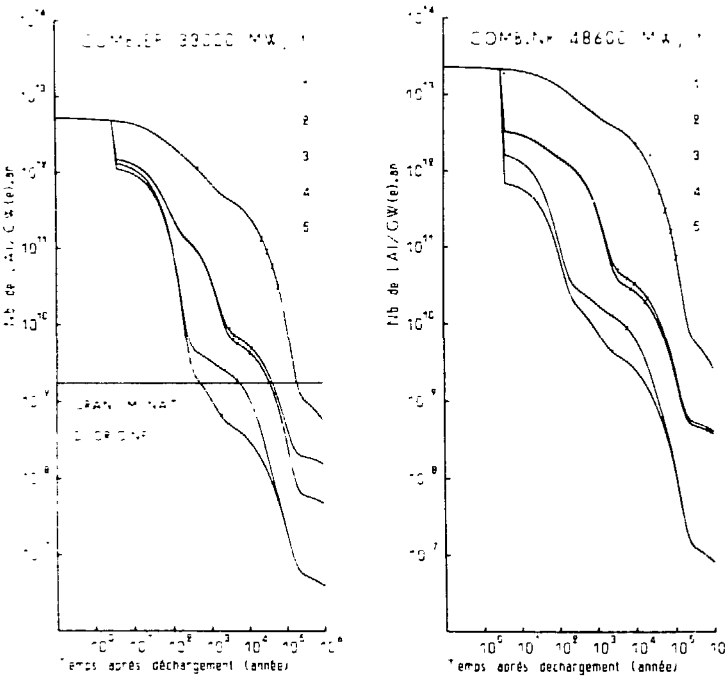

FIGURE 1. Normalized (to GWe.year produced) radiotoxicity by oral intake of high-level wastes from a 33 000 MWd/t LWR and from a 48600 MWd/t FBR, for 5 options [17]. Option 1: spent fuels. Option 2: standard reprocessing. Option 3: Np extracted at 99%. Option 4: Np, Am extracted at 99%. Option 5: Np, Am,Cm extracted at 99%. In the LWR case, the gain in P-T can be measured by the time it takes for the hazard to become equivalent to that of the 175 tons of uranium metal, at equilibrium with its daughter. needed to produce 1 GWe*year: 200 000 years (1), 50 000 years (2,3), 3 300 years (4) and 400 years (5).

3. Technical options for transmutation

In principle, direct transmutation can be induced by a variety of particles. But, due to the large quantities of long-lived nuclei involved (see tables 1 and 2), only neutrons seem usable at present time, mainly for three reasons: being neutral particles, they are not stopped or slowed down like charged particles and can therefore interact with large quantities of nuclei to be transmuted; they can have very large cross-sections, especially in the thermal and epithermal region; finally, by various means, high fluxes, in the range of few 10^{13} - 10^{15} neutrons/sec/cm^2 can be obtained in the large volume of a blanket, and in some instance, thermal energy can be produced from fission. Nevertheless, for the special case of Cs–137 and Sr–90, some authors have looked at the possibility of using photonuclear reactions (10^{18} photons/sec of 20 MeV are needed!) [18] or high energy protons [19].

3.1. Fission reactors

Nuclear reactors have been first considered for transmuting minor actinides, Np-237, Am-241, Am-243, and eventually Cm-244. To be a good transmutation device, a reactor has to have a high neutron flux, large absorption cross-sections and a capture to fission ratio as low as possible. This last requirement, important for neutron economy considerations, usually favors fast neutron reactors over thermal reactors. Moreover, in order to minimize the number of chemical separation processes, and therefore the amount of long-lived contaminated secondary wastes, long irradiation cycles are highly desirable.

There are two ways to introduce minor actinides inside a reactor: either by dilution in normal fuel elements (homogeneous recycle) or by introduction of some minor actinides fuel elements (heterogeneous recycle). Minor actinides concentration is limited by various constraints (heat density, Pu-238 concentration, safety margins like void or Doppler coefficients). In practice, initial concentration cannot exceed a value around 3%, for homogeneous recycle, and in the case of a thermal reactor, the loss of reactivity must be compensated by a higher enrichment. On the contrary, in fast neutron reactors, minor actinides contribute to an increase of reactivity and to energy production. As compared to an open cycle, where the amount of minor actinides sent to the high level wastes increases linearly with the energy production, minor actinides inventories can be stabilized by transmutation, after a certain number of recycles. This stabilized inventory is higher with thermal reactors than with fast neutron reactors (higher production rate), making thermal reactor not a very attractive solution. Due to the value of $\sigma * \Phi$, transmutation appears as a slow process if used in conventional reactors. As an example, a study [13] of minor actinides auto-recycle in a fast reactor, shows that a final stable concentration of 0.5% of minor actinides in the fuels elements is reached after a period of time of the order of 50 years. In that case, the overall transmutation efficiency would be very high, compared to no transmutation at all.

Recently, attention is focused on the civilian and military plutonium. Presently, only a small fraction of plutonium separated from commercial spent fuels is recycled in light water reactors. Although this recycling has no real economical incentive, it could be a way of denaturing military plutonium as well as keeping it safely inside the highly radioactive spent fuels [16]. It has recently been proposed to incinerate plutonium in the core of a fast reactor such as Superphenix, originally designed as a breeder. The CAPRA project studies the possibilities, with taking into account technological, safety and fuel cycle constraint, to reach the theoretical incineration limit of 100 kg per TWh, achieved when all the uranium of the fuel is replaced by an inert matrix [20].

Transmutation in reactor encounters various constraints and limitations: safety margins, concentration limitation, incomplete destruction achieved after a long period of time. Due to this time factor, transmutation in reactor accompanies the energy generation process and is coherent with a large and long-lived nuclear program. Moreover, it needs the construction of a large number of fast neutron reactors (1 for 1 to 3 light water reactors, in the case of the French program [21]). This might be a problem, in view of all the questions raised with fast neutron reactors concerning sodium fires, sudden reactivity variations (as observed on Phenix) and positive void coefficient [22], as well as economical and socio-political issues.

3.2. Hybrid systems

For these reasons,other advanced concepts are now being proposed to speed up the transmutation process and destroy fission products as well. Among these (high flux thermal reactor, actinide burning reactor), we will review hybrid systems coupling an high intensity accelerator to a sub-critical target containing the wastes to be transmuted.

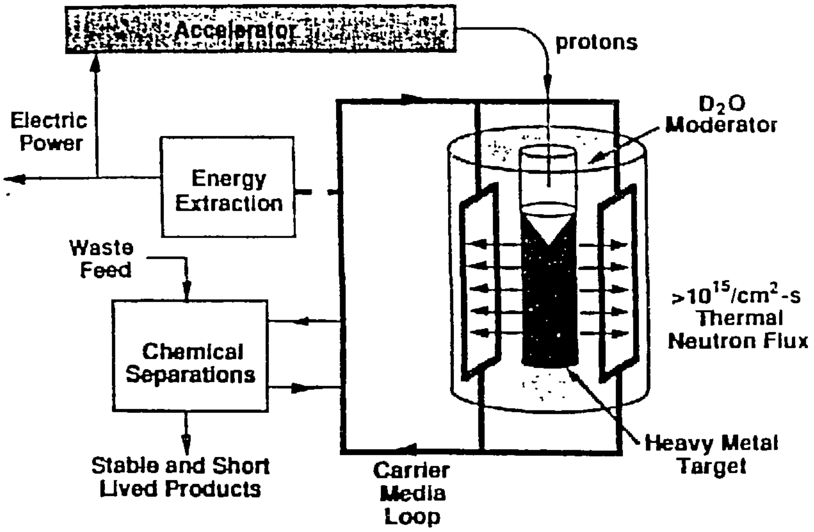

FIGURE 2: Principle of transmutation by accelerator, in the case of ATW [27,28]

The application of accelerator technology to the nuclear fuel cycle has been considered as early as the 50s (see e.g. [17]). At that time the main goal was to breed fissile materials (Pu-239, U-233) from fertile blankets (U-238, Th-232) irradiated by neutrons. These are produced in a thick target by a high intensity proton beam delivered by a 1-2 GeV linear accelerator (linac). Since the 80s, it has been proposed to use this technology for tritium production by Li-6 neutron bombardment [23] and now to transmute minor actinides and some long-lived fission products [24-25]. In these devices, multiple neutron production is induced by a proton beam hitting a target, followed, possibly, by an extra neutron production in some fissile material introduced either in the target itself or in a sub-critical blanket located around the target. Transmutation is then achieved by high neutron fluxes, which can reach values as high as 10^{16} n/cm^2/sec depending on the various projects.

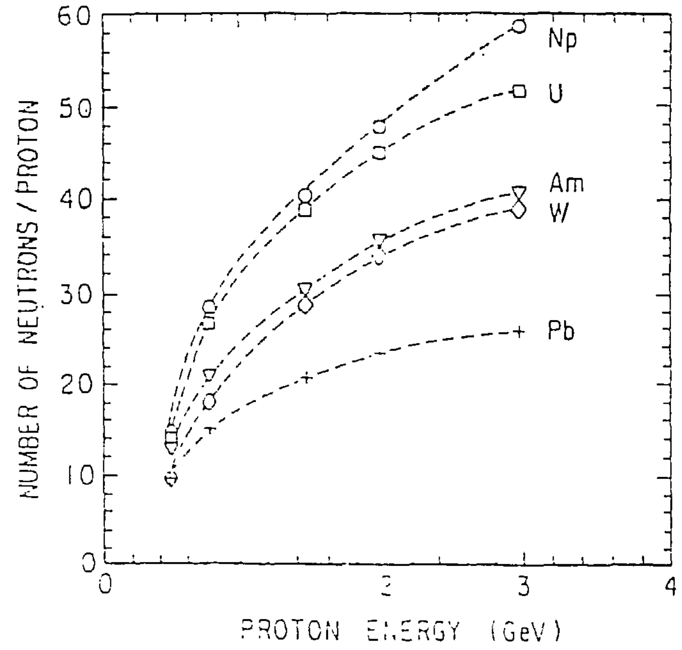

FIGURE 3: Energy dependence on neutrons number generated by spallation [10]

In a thick target, the high energy nucleons produced during the "intra-nuclear cascade" spallation process (see e.g. [29]) can interact with neighboring nuclei, through the so-called "inter-nuclear cascade" during which few more interactions are possible. Large codes, such as HETC [30], based on Monte-Carlo calculations, have been developed to calculate all the relevant quantities. It turns out that one incident proton can produce a large number of neutrons, depending on the incident energy, the atomic mass of the thick target and on its geometry (see fig 3).

Due to their very different origin (spallation, fission, evaporation), the neutron energy spectrum ranges from few keV to the beam energy (in practice approximately 100 MeV). The mean value is slightly under 1 MeV, a value above the mean neutron energy in a fast breeder reactor. Therefore, one expects that these neutrons, if used directly, can achieve a transmutation rate more efficiently than in a fast reactor, because fission dominates now on capture, with a higher cross sections than in a conventional fast neutron spectrum.

Because beam power would be of the order of a few hundred MW(e), it is desirable to have a self-sustained energy system. This is possible in principle, if the subcritical reactor produces enough thermal energy - of the order of 200 MeV per fission - to feed the beam power with an overall efficiency ε. Letting E be the beam energy in MeV, (n/f) the number of neutrons emitted per fission and (n/p) the number of neutrons generated per incident proton inside the target, the system is selfsustainable if the following condition is fulfilled:

$$200\,\varepsilon.(n/p)/(n/f).k/(1-k) \geq E \qquad (1)$$

Equation (1) determines a minimum value for k, the multiplication factor of the fissile configuration of the blanket. Selfsustainability can be achieved with sub criticality as low as $k_{min} = 0.75$, a value which leaves a large safety margin. On the other hand, it is advisable k must not be too close to 1 (say $k<0.95$) to keep the subcriticality in any circumstances and everywhere in the core. It is possible to choose a design with k in between, and in order to reach a certain transmutation rate, directly proportional to the thermal power P of the subcritical reactor, on has to tune the beam intensity according to:

$$P(MW)= 200\,(n/p)/(n/f).k/(1-k).I(A) \qquad (2)$$

In a typical case considered more than 70 mA is necessary to drive a 3000 MWt blanket which could destroy 800 kg of actinides a year, assuming a 70% load factor and no regeneration inside the blanket. The extra electrical power available to the grid increases with k..

Hybrid systems have been recently proposed by various laboratories: Brookhaven (project PHOENIX [25]), Japan (project OMEGA [26]) and Los Alamos (ATW [24,27,28]). In the first two ones, the neutrons are directly used as fast neutrons, and the blanket appears as a classical fast reactor core, cooled with liquid sodium and using solid mixed oxide fuel assemblies.

In the ATW (Accelerator Transmutation of Wastes concept (see fig 2.), the neutrons are thermalized in heavy water, the wastes being circulated in the blanket as a slurry of molten salt. The attractive feature of this design lies in the possibility to destroy fission products (which needs thermal neutrons), mainly Tc-99, while at the same time Np-237 is destroyed directly trough one capture and one fission, due to the intense flux which avoids the normal Pu-238 route taken in the case of a conventional low neutron flux LWR (see fig.4). The Los Alamos group presents the ATW concept as a first step towards a new integrated nuclear energy production system, based on thorium, which would recycle its own actinides and fission products and would make long-term burial unnecessary[28].

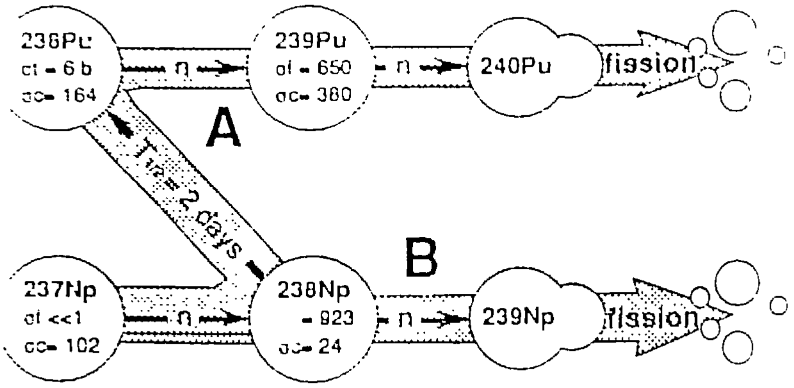

FIGURE 4: The two step fission of Np-237. In a thermal flux below 2. 10^{15} n/cm^2/sec, Np-237 is a nuclear poison, absorbing more neutrons than it generates (route A). In a thermal flux above 2. 10^{15} n/cm^2/sec, Np-237 is a nuclear fuel, generating more neutrons than it absorbs (route B). The key isotope in the Np-237 burn sequence is Np-238, which in a high thermal flux can fission readily instead of decaying to the non fissile isotope Pu-238, which is a poison. Am-241 behaves similarly. The cross-sections (in barn) are averaged over the ATW neutron spectrum [24].

Los Alamos is starting now a new program ADT^2 (**A**ccelerator **D**riven **T**ransmutation **T**echnologies) with four components: weapons plutonium burning; energy production from thorium; commercial waste transmutation; tritium production [31].

On must mention the recent C. Rubbia proposal [32] of an "energy amplifier" coupling a cyclotron (1GeV, ≈few mA) to a subcritical assembly based on the cycle Th-232/U-233 moderated with water. This system differs from those mentioned above, by its output power (in the range of 300 MWth) which needs only low neutron fluxes (≈ 10^{14}/sec/cm^2) and avoids the use of a linac. This machine is intended to produce electricity (100 MWe) and not to transmute actinides and long-lived fission products. It is claimed that such a device - which would be suitable for decentralized energy production in developing countries - produces less radiotoxic wastes on the long term than the usual U-238/Pu-239, and that this energy amplifier is resistant to proliferation.

One of the main advantages of hybrid system is its sub-criticality: neutron flux is completely controlled by the accelerator beam with very short response, making control rods in principle unnecessary. Of course, this advantage is greater if large beam currents are available, which allows a lower k-value (see equation 2). Because, one has not to rely on delayed neutrons to drive such subcritical system, one can in principle achieve a higher MA or plutonium loading than in normal reactors. For the same reason, the practical design of such a system will probably be more easier with respect to safety constraints (Doppler and void coefficients). As far plutonium incineration is concerned, a subcritical design without regeneration due to the presence of uranium, should also be much simpler than with a fast neutron reactor [20].

The second positive feature is the possibility to achieve higher transmutation rates than in conventional reactors, by coupling a high flux with large cross sections (ATW project, MA double capture process) or, on the contrary, with higher fission to capture ratios (Jaeri, Brookhaven projects). It is possible in the case of ATW to simultaneously destroy MA and some long-lived fission products. Because, in the case of ATW, fuel is circulated as a slurry and chemical separation takes place on line, there is a small inventory in the core, a very important feature in terms of safety and afterheat situations.

The main drawback of these systems is technological. On the accelerator side, high intensity linac operating in continuous mode (the greatest linac LAMPF at Los Alamos reaches only 1 mA at 800 MeV) has to be developed (beam handling, RF components...). Such a high intensity accelerator, operating in the range of 250 mA seems technically feasible, according to a review panel of the DOE [33]. On the other hand, one will have to cope with material radiation damages due to high energy neutrons. expected to be much more severe than those encountered in fast neutron reactors or even in fusion reactors. High level activation is also expected, and some chemical isotopes (N–14, Co-59) will probably have to be avoided in some critical parts of the installation. Finally, costs are presently unknown.

4. Inputs on hybrid system and related topics.

Despite, but also because of, these challenges, efforts are being made in various countries, mainly under the auspices of the Nuclear Agency of the OECD [10-12], to evaluate the technical and economical feasibility of this promising way of getting rid of most of the long lived radioactive species generated by nuclear energy. The main projects are those mentioned above (Phoenix, Jaeri and ATW), whereas the related topics are the spallation neutron source presently under construction at PSI [34], the proposals of an European Spallation Source (ESS) between Jülich and Rutherford Laboratory [35] and the energy amplifier [32].

Researches are carried out in various laboratories in Europe, including Russia on the following topics:

-spallation source which is underway at PSI and the ESS project;

-interaction of high energy protons with a thin or thick heavy target (neutron angular and energy distribution, residual nuclei production), both on a theoretical and experimental basis;

-evaluation of the various projects from the point of view of neutronic, safety, thermal aspects, radiation damage, fuel cycle strategies..

The groups involved in such studies are the followings:

a/ France: evaluation studies on the physical aspects, are performed at CEA (Cadarache) [36]. Also an experimental effort started at SATURNE (Saclay) to measure neutron emission from a thin target [37], and to detect the various spallation products [38]. A Los Alamos team [39] is also preparing an integral experiment at SATURNE in order to determine neutron yield with various combinations of beam characteristics (p, d, different incident energies) and target geometries.

b/ Germany: nuclear lay out of the SNQ project (1978-1986) and study of the ESS project at Jülich KFa [40]; general studies on transmutation at Karlsruhe Kfk

c/ The Netherlands: ECN (Petten) is involved in strategy studies, as well as in neutron data needs and evaluation [41]

d/ Italy: ENEA (Casacchia) is studying MA and plutonium burning in relation to ATW , Milano University develops theoretical analysis of MA burning in LWR and JRC at Ispra is collaborating with the Phoenix project [42].

e/ Switzerland: PSI has a collaboration program with Cadarache on theoretical studies for accelerator-based transmutation systems, on experiments at the cyclotron aimed at model validation concerning the direct interaction of protons with MA thin targets and on specific aspects of plutonium burning and actinide transmutation in fast and light water reactors [43].

Some research centers in ex-USSR seem to be (or to have been) engaged in studies on accelerator-based transmutation system both on theoretical and experimental aspects, including accelerator technology: - ITEP (Institute for Theoretical and Experimental Physics), Moscow - FEI (Physical-Energy Institute), Obninsk - IPE (Institute of Power Engineering), Moscow - INP (Institute for Nuclear Power) - MRTI (Moscow Radio-Technical Institute

As stated before, the Nuclear Agency of OCDE has initiated a benchmark study to make an intercomparison of various intra- and internuclear cascade codes. The first part of this exercise (thin target calculations) is now completed, and the results have been presented at the Seattle Conference, september 1993 [44, 45]

5. The specific contribution of the nuclear physics community?

The development of hybrid system needs competencies in various fields: nuclear physics, neutronic. accelerator and reactor technology, materials physics, chemistry ...Some of these competencies are found in Nupecc laboratories, but also outside, mainly in nuclear agencies. As far as Nupecc laboratories are concerned. studies are split throughout many groups and seem to receive very little support; they appear confidential and not well known in the nuclear physics community. They stay basically within groups which have a practice in intense spallation neutron source, although projects of intense neutron sources like ESS, the European Spallation Source, ISiS or the PSI neutron sources, are not intended to be used for transmutation studies.

Nupecc laboratories have at least competencies in two lines of research:

-high intensity accelerator technology;

-relevant nuclear data acquisition related to spallation, and to radiation damage due to high energy neutrons, as suggested by the preliminary results of the OCDE benchmark, which show the necessity of having more reliable simulation tools and data.

To conclude, an european study group would be a useful initiative of Nupecc to bring nuclear physicist together to examine the potentialities of hybrid systems in the domain of energy, including transmutation of wastes, in a long-term perspective which means that it has, at this stage, to be disconnected from well established national or european programs.

References:

[1] L. H. Baetslé, *"Role and influence of partitioning and transmutation on the management of nuclear waste streams"*, OECD/NEA/P&T report n°3, August 1992.

[2] Nuclear Energy data, Nuclear Energy Agency of OECD report, Paris, 1993

[3] Performance Assessment of Geological Isolation Systems for Radioactive Waste, (PAGIS), EUR 12676 FR report, 1990.

[4] H.C. Clairborne, *"Neutron Induced Transmutation of High-Level Radioactive Wasrte"*, ORNL-TM-3964 report, 1972.

[5] A.G. Croff et al., *"A Preliminary Assessement of Partitioning and Transmutation as a Radioactive Waste Management Concept"*, ORNL-TM-5808, 1977.

[6] Jor-Chan Choi, *"Actinide Transmutation in Fission Reactors"*, Ph-D. thesis, University of California, Berkeley, 1981.

[7] First Technical Meeting on the Nuclear Transmutation of Actinides, Ispra, Italy, EUR 5897 report, March 16-18, 1977.

[8] Second Technical Meeting on the Nuclear Transmutation of Actinides, Ispra, Italy, EUR 6929 report, April 21-24, 1980.

[9] Rapport du Groupe de Travail sur la Gestion des Combustibles Irradiés, Ministère de la Recherche et de l'Industrie, Paris, December, 1981 - November, 1982.; Rapport du Groupe de Travail sur les Recherches et Developpements en Matière de Gestion des Déchets Radioactifs, Ministère du Redéploiement Industriel et du Commerce Extérieur, Paris, October, 1983 - October 1984.

[10] Proceedings of the Information Exchange Meeting on Actinide and Fission Product Separation and Transmutation, OCDE/NEA, Mito City, Japan, November 6-8, 1990.

[11] Proceedings of the Specialists' Meeting on Accelerator-Based Transmutation, OCDE/NEA, PSI Villigen, Switzerland, March 24-26, 1992.

[12] Proceedings of the Information Exchange Meeting on Actinide and Fission Product Separation and Transmutation, OCDE/NEA, Argonne National Laboratory, Argonne, United States, November 11-13, 1992.

[13] E. Schmidt, E. Zamorini, W. Hage and S. Guardini, *Assessement Studies on Nuclear Transmutation of By-Product Actinides*, CEC Joint Research Centre Ispra Establishment, S.A./I.05.03.83.13 report.

[14] J.P. Schapira, *Les déchets nucléaires: un problème mondial"*, dossier, Problèmes Politiques et Sociaux, La Documentation Française, n°649, 1er février 1991.

[15] D. Albright, F. Berkhout et W. Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992*, SIPRI, Oxford University Press, 1993.

[16] F. Berkhout et al. dans *Science & Global Security*, 1993, vol.3, 161-213)

[17] J.P. Schapira, *"Long-term nuclear waste management: present status and alternatives"*, Nucl. Inst. and Meth., A280 (1989) 568-582.

[18] T. Matsumoto, *"Calculations of gamma ray incineration of Sr-90 and Cs-137"* Nucl. Inst. and Meth., A268 (1988) 234-243.

[19] P. de Felice et al., *"High Energy interacttions with Sr and Cs: a contribution to the waste transmutation study"*, Nucl. Inst. and Meth., 212 (1983) 359-365.

[20] M. Salvatorès, Consommation Accrue de Plutonium dans les RApides, CAPRA program, private communication.

[21] Le Traitement des Produits de la Fin du Cycle Electronucléaire et la Contribution Possible de Superphénix, report of the Minister of Research and Space to the Prime Minister, Paris, December 17, 1992.

[22] Rapport de la Direction de la Sûreté Nucléaire aux Ministres de l'Environnement et de l'Industrie, Paris, 16 juin 1992.

[23] Accelerator Production of Tritium, Report of the Energy Research Advisory Board to the USDOE, report DOE/S-0074, 1990.

[24] F. Venneri, C. Bowman and R. Jameson, LA-UR-93-752, report, 1993.

[25] G. J. Van Tuyle, H. Takashi, M. Todosow, A. L. Aronson, G. C. Slovik and W. C. Horak, report BNL-52279, 1991.

[26] Proceedings of the Specialists' Meeting on Accelerator-Based Transmutation, OCDE/NEA, PSI Villigen, Switzerland, March 24-26, 1992.

[27] R. A. Jameson, G. P. Lawrence and C. D. Bowman, *Nuclear Instruments and Methods*, **B68** 474 1992.

[28] C. D. Bowman et al. , *Nuclear Instruments and Methods*, **A320** (1992) 336-367 1992.

[29] N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller and G. Friedlander, *Physical Review*, **110** 185 1958.

[30] T. W. Armstrong and K. C. Chandler, ORNL-4744, report, 1972.----

[31] C.D. Bowman, private communication

[32] F. Carminati et al., *"Energy Amplifier for cleaner and inexhaustible nuclear energy production driven bt a particle beam accelerator"*, CERN/ISC 93-37 report.
[33] DOE Energy Research Advisory Board, DOE/S-0074 report, February 1990.
[34] F. Atchison, in ref. [11] page 440.
[35] H. Lengeler et al., *"Study for a European Spallation Source ESS"*, EPS News, October 1993.
[36] M. Salvatores et al., *"A global physics approach to radioactive nuclei transmutation"*, Global'93 conference,Seattle, September 1993.
[37] S. Leray and Y. Patin, *"Etude des neutrons de spallation pour la transmutation des déchets nucléaires à vie longue"*, research proposal at SATURNE, 1993.
[38] R.Michel et al., *"Residual nuclide production relevant for accelerator-based transmutation"*, research proposal at SATURNE, 1993.
[39] G.L. Morgan and T.F. Stratton, *"Composite target experiments for ATW"*, research proposal at SATURNE, 1993.
[40] D. Filges and T. Springer, private communication
[41] A.J. Koning, *"Review of high energy data and model codes for accelerator based transmutation"*, ECN-C-93-005 report, Petten, January 1993.
[42] P.A. Landeyro, private communication
[43] R. Chawla, private communication
[44] P. Nagel, private communication
[45] *"Evaluation de l'ensemble des besoins en matière de données nucléaires"*, Rapport du Secrétariat de l'Agence de l'Energie Nucléaire de l'OCDE, Paris, September 1993.