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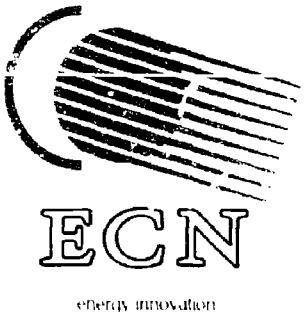

TRANSMUTATION OF LONG-LIVED FISSION PRODUCTS

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K. ABRAHAMS

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TRANSMUTATION of LONG-LIVED FISSION PRODUCTS

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1. MOTIVATION for TRANSMUTATION of LONG-LIVED FISSION PRODUCTS

1.A. ARGUMENTS for and against TRANSMUTATION of NUCLEAR WASTE

Actinides

In literature one finds several arguments in favour of transmutation of nuclear waste [1-4]. Most of these arguments relate to possibilities to reach a more acceptable waste storage strategy, in which the life time of long-lived radioactive components is shortened. One argument in favour of recycling actinides, expresses the wish to utilize the energy content of spent fuel. Thereby one reduces the amount of long lived actinides in the waste stream as well as the risk and cost of mining new uranium per unit of electrical energy generated. Predictions regarding the integrity any disposal site might be falsified by human intrusion, which could become attractive especially after the short-lived fission products have decayed and the waste in the site becomes a more manageable form of partly fissile matter (without recycling up to hundreds of tons of Pu, mixed with long-lived fission product waste).

Fission products

For fission products the argumentation is quite different. In fact long-lived fission products dominate the risk of stored nuclear waste only at very long storage times. Transmutation of these long-lived fission products is motivated by the wish to reduce possible effects of leakage from geological storage in the far future. Most of the reasoning in favour of the transmutation of fission products is expressed by an "As Low as Reasonably Achievable" (ALARA) principle, and stresses the wish to reduce the radiation dose to generations in a far away future. In this way one might simultaneously increase the public acceptance of geological disposal methods, which has been suffering from distrust in very long-term predictions, due to possibilities of either catastrophes or accidental mining activities.

Arguments against transmutation are heard as well. Some argue [5] that the recycling process may also dilute the radiotoxicity and could increase risks due to procedures such as machining or due to spilling of solvents. Further it is not at all clear if and how one can compare the radiological risk of partitioning and transmutation with the dose risk reduction for future generations, and how far in the future one should extend the ALARA principle. Only small additional risks for the present population might be acceptable, and these should be compensated sufficiently by favours to future generations. For scenarios of combined geological disposal and transmutation [5] such favours are hard to estimate. Arguments against transmutation are based on the wish to avoid reprocessing. In the USA for example commercial fuel is not reprocessed at all, in order to restrain the proliferation of the technology of reprocessing highly radioactive fissionable material, and at the same time to reduce costs. Although safeguarding principles do not concern the fission products directly, it is clear that any partitioning process for fission products also involves the actinides.

Criteria to weight the arguments for and against are a key issue in all matters involving transmutation. One criterion might involve the average personal dose in the future due to a possible leakage from repositories. Another possible criterion (especially relevant to

intrusion scenarios) involves any incidental dose above average, as measured by the "Annual Limit of Intake" (ALI) for ingestion or for respiration. A possible third criterion regards safeguarding, and it involves the amount of effort needed to produce a weapon from the waste not only now but also in the far future. Transmutation scenarios should be judged by each of these criteria and possibly by other criteria as well. As each scenario also will have a price, it could also be an approach to see this price expressed for example in the amount of ECU's needed to safe a future human life. Costs should compare favourably with investments that society is willing to make for environmental protection of future generations. For oil and coal the loss of human lives to the present generation due to a constant production of one GW(e) lies between 1 and 10 per year. Casualties are almost an order of magnitude lower for nuclear energy [6], and one could argue that also long term risks due to any integrated collective radiation dose, as might be acquired by distant generations, should be lower than long term risks (CO_2 and pollutants) due to the use of fossil fuel.

1.B. The SITUATION for FISSION PRODUCTS in PARTICULAR

Amount of fission products

It is a fact of nature that the use of fission energy will lead to waste due to fission products and actinides. For the actinides the amount of material formed is highly dependent on the scenario which one might want to use. For the fission products however the amount is rather independent of the scenario and it is roughly equal to 1000 kg for one GWe year. Almost 90% of this amount is either stable or decaying within a few hundred years to stable products. The long-lived remaining part consists for about 35 % of geochemically mobile fission products Tc-99 and I-129. As it is presupposed that certainly for such a relatively short time the integrity and the safeguarding of any disposal site can be guaranteed, the short-lived products are of no concern in the present study. After all in most world scenarios one foresees a few hundred years as a period in which one may safely rely on the knowledge and skills of our descendants to maintain man made barriers.

Conditioning and storage possibilities

In current waste management scenarios the fission products are vitrified or conditioned in some other way in order to make them less mobile. In case that waste disposal sites would not be disturbed, and if the waste remains immobilized satisfactorily, the leakage from these sites would hardly have consequences for the radiation dose to mankind. Numerous studies on consequences of nuclear waste stored in salt domes show virtually no effects to this dose. An example of a natural conditioning of radioactive material is given by the thorium in monazite sand [7]. At some beaches the radiotoxicity of the sand may approach that of highly diluted nuclear waste, but the thorium atoms in the sand just happen to be entirely immobilized. Just like the toxic mercury atoms in our dental fillings, the toxic radionuclides in properly immobilized material apparently are not a problem. For nuclear waste the problem rather is to guarantee that all radiotoxic elements should remain immobilized in the long run. Geologists and chemists take great care to think over possibilities to immobilise all waste elements almost forever, but have not yet convinced everyone. This is especially so for Tc-99 and I-129, as these may remain mobile in the environment for many millennia [8]. Mobile elements may have a large impact on the estimated dose risk integrated over the entire population in the long run even if the amount is marginal. A natural example is the highly mobile radon, a gaseous radiotoxic emanation of radium, the daughter product from the decay of uranium in the soil. This radon dominates the radiation dose to mankind at the moment.

Dose risk of mobile long-lived fission products technetium and iodine.
If one would express the dose risk of the mobile long-lived fission products like technetium and iodine in relation to for example the natural dose risk due to radon from the soil, one encounters some difficulties. In particular for the man-made element technetium there are no well-proven models for its transport (acidity and oxidation potential of the soil play a crucial role) and the methods of conditioning have not been tested over more than decades. A pessimist might therefore take an extreme point of view by assuming that all mobile long-lived material will just leak away within a few thousand years. By taking this point of view, the accumulated collective radiation dose from technetium will approach 9.000 man Sv for a GWe year of nuclear electricity but for iodine this dose seems much smaller (as can be seen from table 1 and ref. [8]). Although these radionuclides live so extremely long the question whether one uses direct storage or conditioned (vitrified) storage, might still be very important, and a more optimistic point of view regarding the mobility of technetium could yield a much lower dose. Table 1 has been extracted from a UK study [8] on deep reposition in granite, and illustrates long-term risks. This table presents, for a normal evolution scenario (without human intrusion) the collective dose in man Sv, due to 30 t of LWR spent fuel. This amount of fuel would arise from the electricity production of a GW(e) light water reactor, during one year of operation. Relevant nuclides are given for directly stored fuel. In table 1 the collective dose is integrated over one million years and over 10^8 years (maxima for individual doses are not considered). From this table it can be concluded that if one does not transmute the waste at all, the integrated collective dose as accumulated over one million year will be less than ten thousand man Sv. If only technetium could be immobilized, one might avoid most of the expected accumulated dose.

TABLE 1: TIME-INTEGRATED LEAKAGE DOSE DUE TO SPENT LWR FUEL (direct storage of spent fuel, due to nuclear generation of one GW(e) year)

Period : Nuclides :	One million years	Hundred million years
Tc-99	98 %	46 %
I -129	2 %	1 %
Cs-135		24 %
U -235		6 %
U -238		14 %
Np-237		5 %
Pu-239		4 %
man Sv	9000 *)	20 000 *)

*) Collective dose for the global population. The average yearly individual dose may be obtained by dividing by the affected number of people and the indicated period.

Although these estimates are based on crude assumptions, it is clear that leakage of radionuclides from the repository will only lead to very small personal yearly dose rates. Apparently the dose of even the most relevant long-lived fission product Tc-99 is only marginal, and it is overshadowed by the natural radon average dose. If one would assume that in due time the Tc will distribute itself evenly in time and space over the world, one would reach a value of 10^{-12} Sv/year as an order of magnitude for the rate of its personal

average dose. Some feeling for the relevance of this number is given by comparison with the "natural" individual dose rate from radon #), which is of the order of 10^{-3} Sv per year.

Only sudden releases of radiotoxic material, caused by human intrusion or catastrophes, could change this picture. Such scenarios, though very unlikely, may finally be the main justification for transmutation of the actinides. For long-lived fission products a word of caution should however be given against any argument with respect to the value of a future human life as if it were a parameter in some mathematical expression, which is valid over many ages. A modest investment in decreasing the radiation dose (for example a reduction in the radon dose) could easily be so rewarding that present comparisons become irrelevant. Moreover it probably is quite incorrect to use a linear dose-response rate without any threshold effects. This would mean that it is not allowed to offer a price of about 100 kECU for each man Sv avoided [1]. Such a high avoidance cost is aimed entirely towards the protection of individual radiological workers from potentially harmful excessive doses.

It has been noted [4] that results of the UK study of ref.[8] rely heavily on assumptions on the effectiveness of vitrification and on geological characteristics of the repository. These may not be quite representative for other repositories, as calculations are based upon site dependent geo-chemical characteristics. If the waste is not in contact with oxygen, the mobility of Tc will be strongly reduced. In clay repositories [10] or in rock salt [11] repositories the I-129 risk could dominate, especially if one would rank the risk not as in table 1 (a collective integrated dose), but rather according to the highest possible individual dose. Any such dose could be caused locally and incidentally, and it would be mainly due to uptake of the iodine in the thyroid (the quantity of iodine in this gland is about 10 mg). It is felt, however, that isotopic dilution with the natural iodine could reduce the highest possible individual dose due to the long lived isotope I-129. If one for example dilutes the I-129 with about a factor 500 with natural iodine, the resulting mixture might have a radiological impact less than that of the small amount of the natural isotope K-40 in food.

Although there are different scenarios for deep geological repositories and different definitions of risk, it nevertheless can be concluded that -at very large storage times- fission products will dominate the collective risk in case of direct storage of spent fuel. As was mentioned above, removal of Tc-99 and I-129 from the waste would reduce the collective one million year dose to negligible amounts (the reduction factor would be close to the decontamination factor in the partitioning process). For the actinides, however, table 1 would hardly give arguments for transmutation or vitrification, still assuming integrity of the site and trusting assumptions regarding mobility, etc. If one wishes to reduce the integrated actinide leakage dose from undisturbed repositories by means of vitrification or transmutation, this would mainly apply to uranium. It can therefore be concluded that reduction of risk by transmutation of long-lived fission products seems only rewarding if one wishes to reduce the collective dose at extended storage times. Actinide transmutation is justified on different grounds, as it reduces the source term rather than the leakage dose of stored waste, already after relatively short storage times (a few hundred years).

#) About 60 t of radium in the soil emanates almost 6 litre of radon each day, which builds up an equilibrium value of about 20 litre of radon in the total biosphere. This tiny amount nevertheless gives about 60 % of the total radiation dose, which averages to about 10^{-3} Sv per person yearly and leads to a collective dose of about $5 * 10^6$ man Sv/year.

2. PARTITIONING and TARGETS

Partitioning of fission products
In the presently used PUREX/TRUEX process the spent fuel is removed from the canning and dissolved in nitric acid. The parts which are not solved are called the "fines" and about one third of the technetium is to be found in these fines. The uranium and the plutonium are extracted from the solution by an organic solvent, tri-n-butyl phosphate (TBP). Later the uranium and the plutonium are again separated by selective reduction of the plutonium (VI) to plutonium (IV), but this has no consequence for the present discussion of the partitioning of the fission products.

Gaseous fission products, such as xenon and krypton and a large part of the iodine are liberated in the process of dissolving the spent fuel, together with the gaseous oxides of nitrogen from the reduction of the acid solvent. Currently noble gases are vented into the air and most of the extracted iodine is gradually diluted into the sea. In order to reduce the dose due to the short lived iodine isotopes, several possibilities exist already to catch the iodine either in alkalic solutions, or in zeolite filters loaded with silver, or in mercury or lead compounds. If one would like to transmute the I-129, these possibilities could be more fully exploited.

The chemistry of technetium in the reprocessing procedures is quite complex. Technetium will be present in 45-70% of the total inventory in the water phase in the form of TcO_4^-, a per-technate ion. For the PUREX process the concentration is about 40 mg/litre. Some small part of the technetium (about 5% of the inventory) is co-extracted in the organic phase because of the formation of complex compounds between the TBP, the uranium oxide, and the nitric acid. A third fraction (25-50%) of the technetium is present in the fines, which do not easily form a solution in acids. It is technically possible to separate the technetium from the watery phase and from the organic phase, but it is more difficult to extract it from the fines. If at any time the transmutation of technetium should become a current practice, it will be necessary to first solve the problem of the technetium in the fines. Present techniques of solvent extraction might either have to be supplemented with pyro-chemical techniques (which involve liquid salts) or quite different solutions should be searched for. Use of the necessary technology on a large scale will need a major effort in the future. Now up to 90% of the technetium could be recovered on a laboratory scale; the large scale recovery losses should be reduced at least to a few percent in order to prevent too large losses of the technetium, which otherwise would be spilled into the waste.

Targets for irradiation (homogeneous versus heterogeneous)
If one wishes to transmute technetium and iodine, the stability of the compounds to be irradiated is of utmost importance. In homogeneous methods one mixes the compounds through the fuel and in heterogeneous methods one physically separates the targets for irradiation. Homogeneous methods are already applied for actinides (MOX) but for fission products it seems more advisable to separate these from the fuel reprocessing cycle. After all, the chemistry of technetium is complex and one does not want to complicate the reprocessing of actinides by admixing substantial amounts of technetium through the fuel. Another possibility would be the application of thin foils of technetium near the cladding of the fuel. At ECN physical and technological aspects of fission product transmutation are studied and demonstrations of irradiations are being prepared for heterogeneous targets [13].

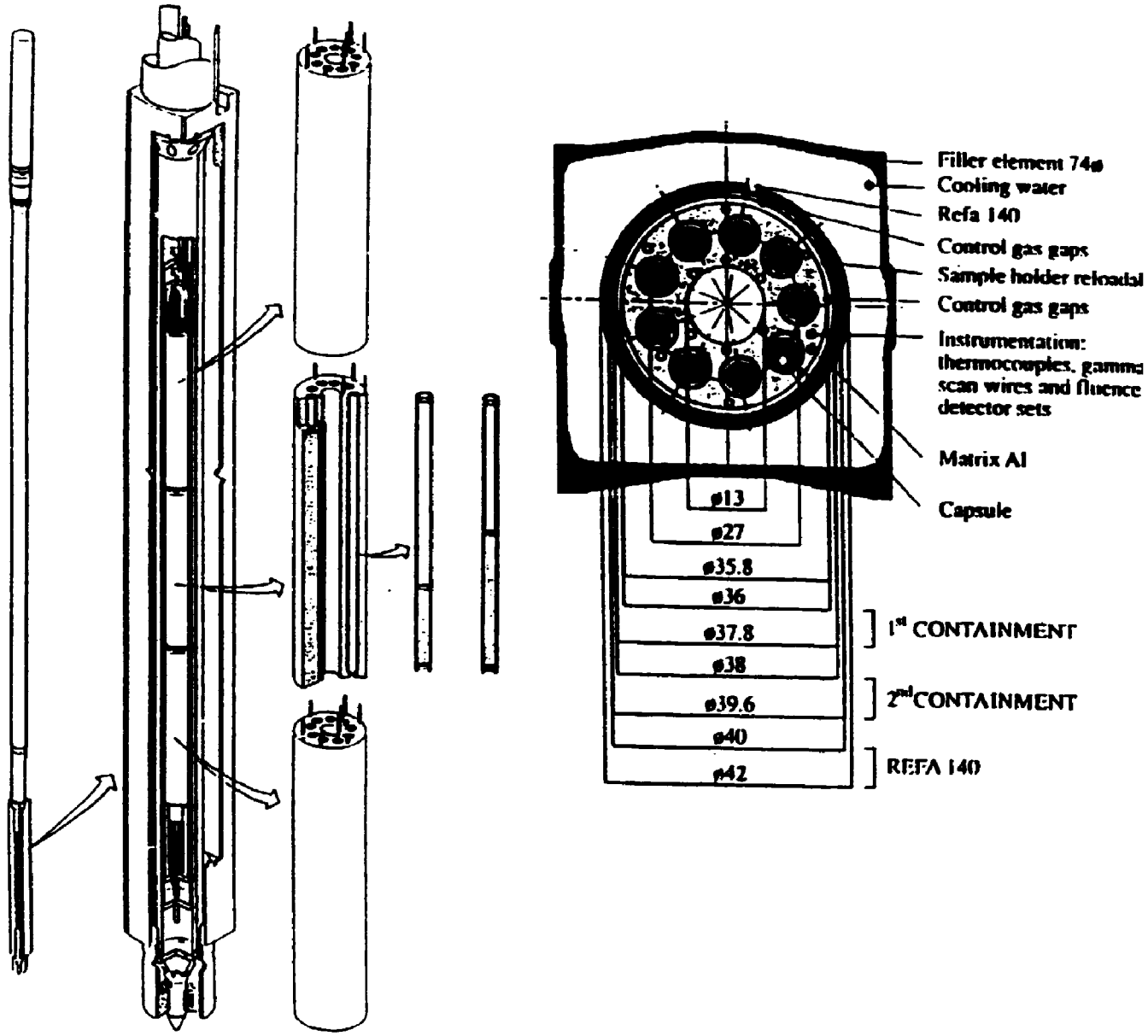

Figure 1 : Schematic drawing of the irradiation facility, with on the right hand side an expanded horizontal cross section of the sample holder

Research and demonstrations
For experimental and technological research on transmutation an European network EFTTRA (Experimental Feasibility of Targets for TRAnsmutation) has been founded. In this network ECN participates together with the French organisations CEA and EdF, with the German KfK and the EC-establishment TUI. In the laboratories of TUI, CEA and ECN, targets are prepared, irradiations will be performed in the Petten HFR by ECN (see fig.1 and ref. [13] for a description of the setup), and later also in the French Phénix reactor. After finishing the irradiations, the targets will be examined to study transmutation efficiency and material aspects. During this work the specific competencies of each of the partners can be exploited optimally. Most of the EFTTRA programme is focused on the irradiation of the actinides (specifically the americium isotopes), but also the fission products iodine and technetium will be studied. Specific problems to be studied first of all are the chemical and material properties of the candidate target materials. Many aspects play a role such as phase transitions in the materials, sensitivity for radiation damage, and the interaction with the cladding. Transmutation of technetium into stable ruthenium is most suitably performed by irradiating it as a metal or an alloy in a thermal neutron field. Demonstrations are relevant because this element does not occur in nature. and therefore chemical and material aspects of technetium are not yet well known. Therefore, also the interaction with the cladding during irradiation is of relevance. Although iodine is a well-known element, research of iodine compounds is needed as well, mainly because iodine is chemically aggressive. An extra complication in the case of transmutation of iodine is due to the fact that transmutation in a thermal neutron field will lead to (stable) xenon gas, which will cause swelling of all solid compounds which are imaginable. Several compounds (metallic iodides) are being tested, and cerium iodides are considered as most promising for xenon retention and stability. However, very recent results obtained at ECN in Petten, indicate that cerium-iodide reacts with the stainless steel cladding [20]. Therefore, other iodides are investigated at present. Another line of research would be the irradiation of liquids such as eutectic compounds of lead, tin and iodine, while removing the gaseous products either on-line or at intervals.

3. TRANSMUTATION DEVICES

For transmutation of fission products thermal neutrons and/or epi-thermal neutrons are needed, and other sources of neutrons might be relevant than those for transmutation of actinides (which in some cases may require fast neutrons to avoid capture and to favour fission). As neutron sources one knows reactors and accelerators. Some possibilities will be shortly reviewed with respect to suitability for transmutation of long-lived fission products. Relevant questions related to the neutron source are: is it intense and economical, is its own polluting effect small enough, and what are the safeguarding aspects of these devices? Material irradiation aspects have been mentioned in the chapter about targets. It is felt that these aspects are the same whatever transmutation device one chooses; this assumption should be tested, however, after a specific choice has been made and after analyzing the demonstrations, which have been mentioned in the previous chapter under "Research and demonstrations".

3.A. TRANSMUTATION IN REACTORS
Nuclear reactors are the most obvious neutron sources as they are abundant in the world, and they may deliver neutrons during the process of energy production. Reactor physics problems are related to the optimization of the flux of excess neutrons in the reactor, and

to the influence of the targets to be irradiated on the safety properties of the reactor.

High flux reactors
From the shielded one-group cross section of the fission products I-129 and Tc-99 (about 12 and 7 b, respectively) in a high flux research reactor such as the Petten HFR, one might conclude that a high transmutation rate of the fission products (50% transmutation within about three years) would be feasible [9]. This 45 MW(th) reactor would however have an amount of excess neutrons which is much too low to cope with amounts of fission product waste from power reactors. Drastic changes in reactor parameters and a high power would be needed for a rapid transmutation of huge amounts of material in any high-flux reactor. Further it is necessary to study material properties of targets under irradiation.

Light water reactors
If one would accept a lower transmutation rate than in the HFR scenario, reactors with a lower neutron flux could also be used. In a regular LWR power reactor the flux would be an order of magnitude lower than in an HFR, and therefore the effective half life for destruction of the fission products would be at least ten times longer then the fuel cycle time. If one wishes to transmute an amount of technetium of the same order as the Tc production of a same LWR, one would require several tons of technetium in the reactor. Because this technetium has to be present during the full life time of the reactor, it should be reprocessed and/or recanned dozens of times before it is entirely transmuted into ruthenium. This would increase the reprocessing cost of the fuel cycle, but it could also have some impact on the radiation dose of the personnel. Similar considerations apply to the transmutation of I-129.

Other reactor types
From the above reasoning it is clear that the choice of reactor type is dominated by the flux of thermal and/or epi-thermal excess neutrons in the reactor. With fast reactors one might produce a high thermal flux by means of moderating material on the spot of the target. High transmutation rates for such irradiation positions are foreseen in studies made at ECN [9] and CEA, and recently by Westinghouse [18]. Also an EC study has been made by Siemens on large scale transmutation possibilities, in the frame of the CEC strategy studies on transmutation of nuclear waste [21]. These possibilities could be attractive, in particular in combination with nuclear incineration of plutonium and minor actinide waste. A heavy water moderated reactor like the CANDU has some advantages as a transmutation device over other reactor types: it combines a high thermal flux with sufficient excess neutrons and flexible loading during reactor operation [12,14].

Summary:
In principle current LWRs could be used for a massive transmutation of Tc and perhaps I, but this would require huge loadings of these materials, additional enrichment and additional reprocessing/ recanning efforts. Fast reactors and HWRs have attractive potential with respect to transmutation in moderated assemblies, but more study is required to assess the optimum technology for transmutation of long-lived fission products on a large scale. HWRs like CANDU have easy refuelling possibilities, which may be an additional advantage in the application of heterogeneous transmutation.

3. B. ACCELERATORS as NEUTRON SOURCES

General aspects of accelerator based transmutation

By means of high energy protons (one GeV or more) neutrons are produced through the spallation process. These neutrons (with an energy of the order of 10-20 MeV) can be either used directly to hit actinide nuclei or they can be moderated to transmute actinides and/or fission products. Each high energy proton might liberate dozens of neutrons (see table 2) in a target of heavy elements.

Table 2: Neutron emission and spallation per proton for a thick target (from ref. [2])

Proton energy GeV	Number of spallations	Number of emitted neutrons per proton in the beam			
		Pb	W	Np	Am
1	3	17	22	33	24
1.5	5	20	28	40	30
2	7	23	34	48	35

By simple reasoning it is easy to show that most fission-product transmutation will take place by capture of the thermal neutrons rather than by any process in which charged particles are involved (these have smaller cross sections due to the Coulomb repulsion). Because thermal neutrons are most relevant for fission product transmutation, one thinks of neutron boosters. These are sub-critical systems with fissionable material in which each neutron from the accelerator-target system might produce again up to ten new fission neutrons. In fact it has been shown that a sub-critical system will be more economical than a system without a booster. The argument is as follows: One 1.5 GeV neutron produces 30 neutrons in a tungsten target without a booster. Suppose the accelerator efficiency is about 50% (a very optimistic statement). In this case the price of one thermal neutron expressed in terms of electrical energy is about 1500/(30*0.5) = 100 MeV. As this electrical energy had to made from thermal energy one would have required about three times as much energy. Because it is extremely optimistic and even unrealistic to assume that each neutron will transmute a technetium nucleus, one will need much more than 300 MeV thermal energy for each technetium nucleus to be transmuted. In case that this 300 MeV would have been generated by means of a nuclear reactor, this would mean that more than one fission in the reactor is needed to transmute one technetium nucleus at the accelerator.

Following this reasoning it seems however that direct transmutation of technetium in a reactor is much more economic in case that also one free neutron might become available for each fission in the reactor itself. The reactor method is clearly more direct, and secondly the 200 MeV, which is generated by fission, can still be used to generate electricity; in the "pure reactor scenario" this electricity is no longer needed to transmute the technetium nucleus with an accelerator. Any combination of an accelerator and a booster seems to approach the economy of the reactor method more closely if the setup is more close to criticality. It has been shown by arguments of mass and energy flows that hybrid systems are not favoured at the moment [12].

Some scenario's:
In the USA, the Los Alamos Laboratory proposed a set of special hybrid accelerator-reactor systems, the so called Accelerator Transmutation of Waste (ATW) systems [15]. In these systems a very high powered (100 MWe) high-energy proton beam plays a key role. Many possible sub-critical reactor systems have been proposed as booster systems. One of the advantages of the high powered proton beam is that one may use a neutron booster with a relatively low value of k_{eff}. As an actinide transmuter this system is supposed to be equiped with either a molten salt reactor or with a graphite moderated lithium-7 cooled system [16]. Arguments in favour of ATW systems are based on relaxation of safety procedures if $k_{eff} < 1$ and this would lead to easier licensing possibilities. An other argument used is that the inventory of radiotoxic material is small while the transmutation rate could be the same as in a reactor. Because of the simple and natural laws of nuclear physics this means that one should work with a very high flux and with diluted fission material inventories. As however the liquid reactor concepts (D_2O moderated slurries or molten salts) suffer from criticality problems due to possible loss of homogeneity, the present designs are solid (graphite moderated) systems, which could even work on thorium in order to relax the problem of actinide waste at the same time [16]. In order to extract a high power from a small system, one should cool with a liquid metal with a low cross section for neutrons, and one selects Li-7 as a coolant. Time obviously will have to learn whether this system could transmute fission products economically, and be competitive. One of the natural facts for any effective incinerator of fissile material is that a large energy flow from the setup should be dealt with, and that the power density at the target should be high. Economy of incineration might require an approach close to $k_{eff}=1$ (a pure reactor) in the end [12].

In the USA (Brookhaven) and in Japan (JAERI), systems have been proposed, which are basically a small (relative to ATW) accelerator with a fast reactor setup as a sub-critical booster [17]. In these PHOENIX and OMEGA proposals one wishes to incinerate the same amount of actinides as in the ATW proposal (the system should be able to compete). Because the accelerator is more modest, the power of the reactor should be high and consequently the value of k_{eff} should be close to one. In fact this is a fast reactor with possibly some improvement of the safety, which is caused by the fact that it is partly regulated by means of an accelerator beam. Because one may trust in possibilities to switch off the beam, one is in a position that a new and very fast "electronic safety rod" has been introduced this way. Although such fast reactor booster systems might have very attractive features (especially if one wishes to fission the minor actinides and the even plutonium isotopes), these systems apparently suffer from a lack of thermal neutrons and are less suited for the transmutation of fission products. Arguments to be followed in order to reach this conclusion proceed along the same line as for fast reactor with a "mechanical safety rod". Likewise accelerator systems with moderated targets are open to consideration.

4. CONCLUSIONS AND RECOMMENDATIONS

Risk reduction and allowable costs of recycling Tc-99.
One of the problems with technetium is that it is an element which does not occur in nature, and that one has little experience how it will behave in the eco system. It has been shown above that total transmutation of technetium could save future mankind some risk due to possible leakage of this radio nuclide at very large storage times. This risk is rather small, but it exceeds the risk of actinides (see table 1). Justification for transmutation of

actinides is mainly based on assumptions of human intrusion or on natural catastrophes. The same argument could to a smaller extend be applied to justify transmutation of technetium. It would be important that costs are kept small with respect to the current fuel cycle costs [4]. This seems possible [12], provided that chemical partitioning and reprocessing costs for Tc are low.

Risk reduction and risk of I-129.
Two points are in disfavour of transmutation of iodine. First of all the amount of man Sv due to a long term global I-129 contamination would be an order of magnitude lower than that from technetium. Secondly iodine is an element which is rather abundant in nature and the technique of isotopic dilution probably can be applied safely. If one for example dilutes the I-129 with about a factor of 500 with natural iodine, the resulting admixture might have a radiological impact smaller than for example the free amount of potassium in the biological cycle of any living creature. Such a small toxicity has never harmed life as far as we know, and the cost and risk of iodine transmutation should be compared with this marginal risk. As these costs and risks would be much higher for iodine than for technetium, the conclusion could be that isotopic dilution could give a solution if it were to receive public acceptance. Meanwhile both partitioning/transmutation as well as isotopic dilution strategies ought to be further evaluated.

Recommendations
For the time being it is recommended to study technetium, its dose consequences and its ecology, as well as its chemical nature especially in the solid state. The time-accumulated dose related to technetium dominates the leakage doses in most scenarios for unperturbed geological disposal. If human intrusion into geologically stable repositories or other disturbances is taken into account, the actinides determine the maximum value of the expected individual dose rates at shorter storage times. Therefore actinides dominate the discussion on transmutation of nuclear waste. Discussions also focus on safeguarding problems related to the whole Partitioning and Transmutation scheme, and the fact that safeguarding procedures should be accounted for, might lead to considerable complications in scenario's for partitioning the actinides from the fission products.

Issues related to public acceptance
Most discussions on nuclear waste, and also the present discussion are based on average quantities such as given in table 1. Any such probabilistic assignments of risk over extremely long periods appear to create suspicion. It seems that public confidence in predictions that range over more than a few thousand years is diminishing. It should be realized that the problem of public acceptance is too complex to be approached in a purely scientific/ technological way. As it nevertheless is necessary to sketch a frame to approach the waste problem, one could start by investigating whether transmutation of fission products is technically feasible or not.

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