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INTRODUCTION

Enrico Fermi, one of the great nuclear pioneers, already at the dawn of nuclear era in 1940 anticipated that management of radioactive materials and nuclear waste could become a technical and sociological problem in the future [1]. He was also convinced, together with other constructors of the first nuclear reactor, E. Wigner and A. Weinberg, that in a long term only breeder reactors could ensure nuclear energy supply based on a fission process. Fermi was definitely right in the first case, the second one is more questionable and controversial today than it was before. There is a number of arguments why we should develop nuclear energy and at least equally many arguments why we should not do that. An attempt to address and reasonably answer most of important questions concerning future of nuclear energy would significantly excess a scope of a paper for particle and nuclei interaction conference. Instead, this paper is focused on transmutation technology, particularly accelerator-driven transmutation technology. Transmutation technology can solve some of the problems of nuclear energy, which are considered of significant importance. Moreover, transmutation technology can offer a reasonable solution for both, mentioned above problems, which worried the nuclear pioneers.

Criticality concerns, decay heat management and radioactive waste handling are perceived as the primary, unsatisfactorily resolved technological problems of nuclear reactors. They all originate from very specific features of a fission phenomenon: self-sustained chain reaction in fissile materials, very strong radioactivity of fission products and very long half-life of some of the radioactive fission and activation products.

Self-sustained chain reaction is the very principle of nuclear reactor operation but it also creates non-negligible hazards of so called, criticality excursion, i.e. a possible (even if very unlikely) reactor run-away accident. A reactor run-away (or reactor excursion) accident can lead to unmanageable power raise and to a disruption of the reactor vessel integrity ending with a release of otherwise contained radioactivity. The control of self-sustained chain reaction, called alos criticality control, relies on the small fraction of delayed neutrons emitted from the fission products a ”long time” (a “long time” compare to the life time of neutrons in a reactor core) after the fission event itself. This small fraction of delayed neutrons determines the criticality safety margins and puts some serious constraints on the fissile fuel composition, e.g. reactors can not operate on purely minor actinide fuel, because of a very low fraction of delayed neutrons.

Few percents of energy released in fission emerges as delayed gamma and beta radiation with very different decay constants, giving rise to decay heat problems in nuclear reactors. It implies that reactors have to have ensured cooling even long time after shutting down of the self-sustained chain reaction. For many hours after shutting down of a typical Light Water Reactor (LWR) of 1 GW_{el} power there are still many Megawatts to be cooled away to avoid a reactor-core meltdown. A long time component of decay heat remains a problem even in a long time scale – as a heat source in nuclear waste management.

Decay heat and radioactivity of spent fuel are very generic consequences of the natural laws governing a fission process and a specific design of reactor fuel. Decay heat requiring extensive cooling in a shutdown reactor is simply originated from short-lived radioactive fission products and can hardly be solved by other measures than an apprioprate, dedicated core design.

Radioactivity of spent fuel is a combined effect of some fission product decay constant and a buildup of radioactive elements in neutron absorption processes in a reactor core. Neutron absorption processes can be divided into simple activation, like buildup of ^{93}Zr isotope (natural Zr is a main component in fuel cladding in LWRs) and a chain of transuranic isotope buildup originated from neutron capture in ^{238}U and in a lesser extent in ^{235}U.

Radioactivity itself is not a good measure of hazards or noxiousness of radioactive wastes, therefore radiotoxicity, in most cases the ingestion radiotoxicity, is used as a measure of the biological consequences of radioactivity. The ingestion radiotoxicity of an element is a measure of the biological consequences of its ingestion, assuming that this element stays forever in a human body. The radiotoxocity is related to radioactivity in a very simple relation:

$R(Sv)=F_d\ (Sv/Bq)\ A(Bq)$

where R(Sv) is the radioxicity in Sievert per mass unit, $F_d(Sv/Bq)$, is the dose factor in Sievert per Becquerel activity and A(Bq) is the mass specific activity. The value of the dose factor Fd for every radioactive isotope is based on evaluation given by International Commission on Radiation Protection [2]. It has to be noted that evaluation of ingestion radiotoxicity hazards for nuclear waste deposited in an underground storage is a very complicated process of simulation of a long time transport of each isotope from a repository bed into the biosphere. Final results strongly depend on the assumptions, specific models and extrapolations used in the calculations, therefore **reduction of source radiotoxicity of the nuclear waste** seems to be the least controversial reference goal for transmutation of eadioactive waste.

Spent nuclear fuel contains almost the whole Periodic System of Elements, however, it can be hardly called a ***Mendeleyev Garbage-Can,*** only very few isotopes determine the radiotoxicity of spent fuel, and consequently its hazardness. In a short time perspective, like 100 years, spent fuel hazards is dominated by fission products ^{90}Sr and ^{137}Cs and Pu – isotopes, as presented on Fig. 1. ^{90}Sr and ^{137}Cs belong to short-lived fission products, being of big concern in a case of nuclear accident, can however, be readily retained in storage facilities for reasonable periods to minimize their threat to the human environment. In the long time, comparable with life-time of containers in geological

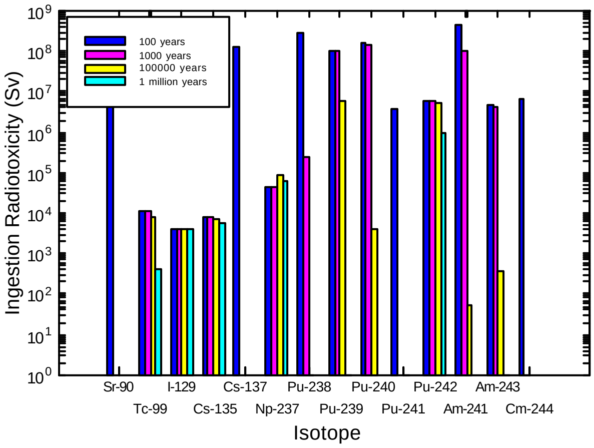

Figure 0. Radiotoxicity of the isotopes determining total radiotoxicity of LWR wastes for different time

repositories, the radiotoxicity is determined by transuranic elements: ^{239}Pu (up to 100 000 years), ^{242}Pu, ^{237}Np and long-lived fission products ^{129}I, ^{135}Cs and ^{99}Tc. Plutonium and other actinides have a very low mobility in geological environment, so they do not easily enter the biosphere. On the contrary Iodine, Caesium and Technetium, being much more mobile can leak the geological repository. Proliferation concerns is another strong argument for transmutation of actinides, parti-culary Plutonium. Increa-sing a worldwide stockpile of Plutonium in spent reactor fuel must be of concern, above all in few hundred year perspective when a “protective” barrier of radioactivity of short-lived fission product will decay out. Fortunately, as it will be shown later most of the isotopes can be effectively transmuted.

TRANSMUTATION PROCESSES

Transmutation can be defined as the transformation of one isotope into another isotope by changing its nuclear structure. The most effective nuclear process that can be used for transmutation of radiotoxic isotopes is a neutron absorption. Virtaully every transuranic elements, Np, Pu, Am and Cm can be fissioned by one or few successive neutron absorptions with, in many cases, energy surplus and neutron gain. All transuranic isotopes are netto neutron producers in fissions induced by fast neutrons (so called fast spectrum fissions). In thermal neutron spectrum corresponding to Light Water Reactors only ^{239}Pu, ^{241}Pu and Cm-isotopes are “unconditional” neutron producers, other transuranic isotopes like ^{237}Np, ^{238}Pu and ^{241}Am may become neutron producers in a very high neutron flux. In these cases beta-decay of the intermediate neutron capture products competes with a fission probability. In the case of ^{237}Np and a thermal spectrum, the lowest neutron flux converting ^{237}Np from neutron consumer into neutron producer is expressed by

$$F_{lim} = \frac{ln\,2}{s_{\mathrm{f}} \times \mathrm{T}^{b}_{1/2}}$$

where s_{f} is a fission cross section for ^{238}Np, $\mathrm{T}^{b}_{1/2}$ is a half-life of beta-decay of ^{238}Np. For a well thermalised system, like a molten-salt system, this limiting flux is about 2-3×10^{15} n/cm^{2}s

Transmutation of fission products through neutron absorption is also possible for the long-lived radiotoxic isotopes like ^{99}Tc and ^{129}I, converting them into stable Ru and Xe, respectively. However, transmutation of fission products, in contrary to transmutation of transuranic isotopes, is a purely neutron consuming process and requires plentifulness of neutrons. This surplus of neutrons can be obtained in different ways:

- In crtical reactors, which can be designed as “burners”, in order to use all available neutrons for transmutation processes. This implies use of reactors with an excellent neutron economy, which limits the choice to fast reactors with the hardest possible spectrum , possibly revival of heavy water moderated reactors or use of highly enriched fuel in standard LWRs. Neither of these choices is very probable today. Moreover, criticality conditions, dependence of safe reactor

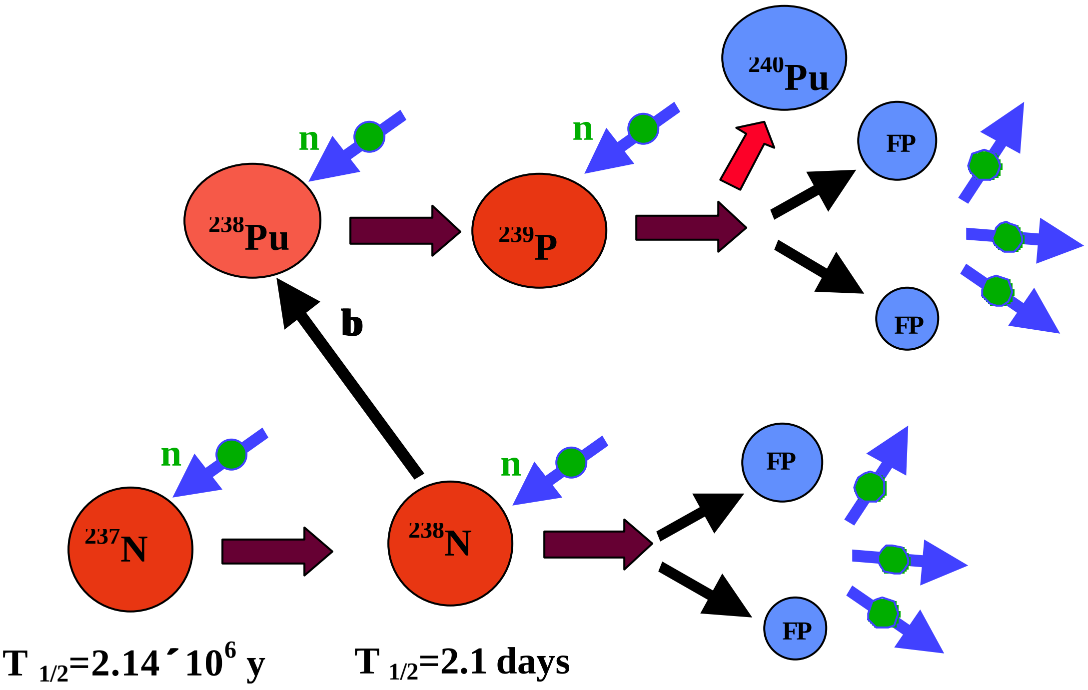

Figure 2. Neutron induced transmutation of ^{237}Np. In fast neutron spectrum ^{237}Np fissions directly as in the lower part of this figure. In the thermal neutron spectrum fission competes with β-decay of ^{238}Np

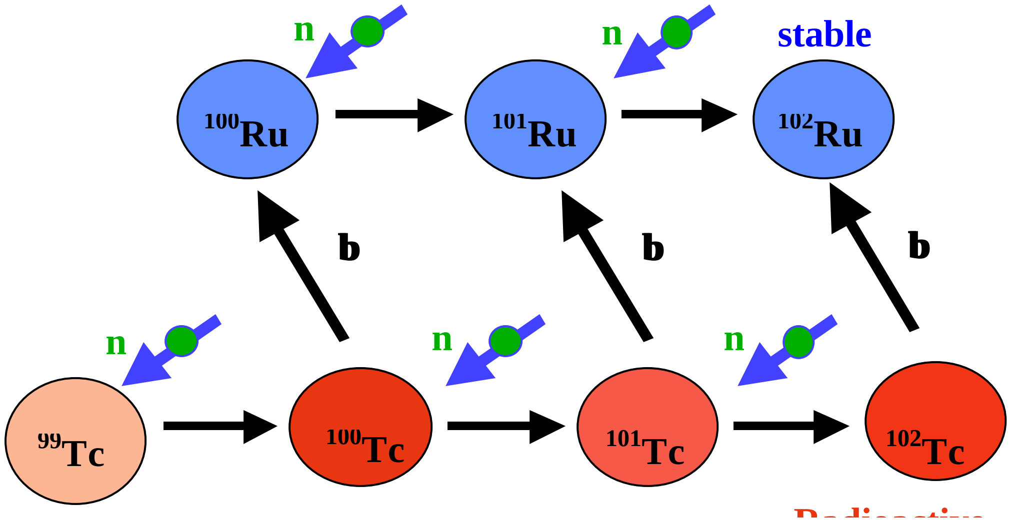

Figure 3. Neutron induced transmutation of ^{99}Tc. All isotopes of Ru, products of different paths of Tc transmutation, are stable.

operation on delayed neutron fraction and negative temperature feedbacks put severe constraints on the possible use of crtical reactors.

- In subcrtical systems driven by an intense external source of neutrons – so called Accelerator-Driven System (ADS). An external neutron source and subcritical operation open new possibilities for transmutation.

ACCELERATOR-DRIVEN TRANSMUTATION

The idea of combining powerful accelerators - with a subcritical reactor for transmutation purposes is not a new one. Nuclear transmutation itself was demonstrated for the first time by Rutherford in 1919, who transmuted ^{14}N to ^{17}O using energetic α-particles [3]. I. Curie and F. Joliot produced the first artificial radioactivity in 1933 using α-particles from naturally radioactive isotopes to transmute Boron and Aluminum into radioactive Nitrogen and Oxygen [4]. It was not possible to extend this type of transmutation to heavier elements as long as the only available charged particles were the α-particles from natural radioactivity, since the Coulomb barriers surrounding heavy nuclei are too great to permit the entry of such particles into atomic nuclei. The invention of the cyclotron by E.O. Lawrence [5] removed this barrier and opened new frontiers. When coupled with the spallation process, high power accelerators can be used to produce large numbers of neutrons, thus providing an alternative method to the use of nuclear reactors for this purpose. Spallation offers exciting possibilities for generating intense neutron fluxes for a variety of purposes.

To use only the spallation neutrons generated in a proton target, the fission products would be placed around the target. For the highest efficiency, depending on the material to be transmuted, either the fast neutrons would be used as they are emitted from the

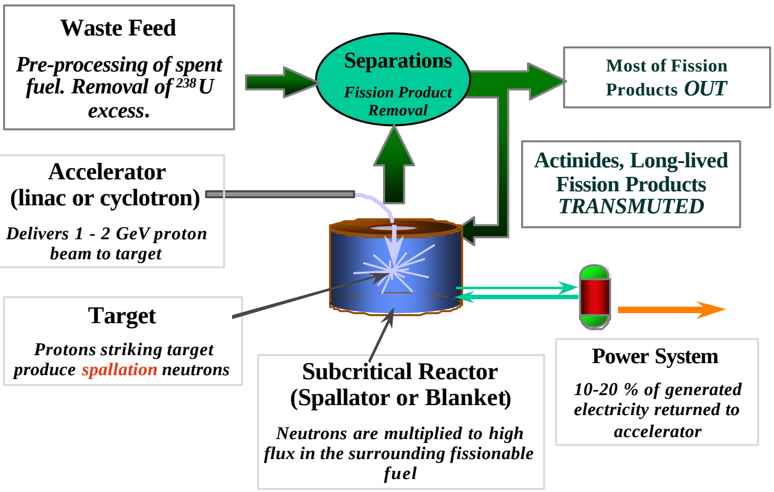

Figure 4. A schematic view of an Accelerator-Driven Transmutation system (courtesy F. Venneri)

target or they would be slowed down by moderators to energies with higher transmutation cross-sections, for example, the resonance or the thermal region. To improve the transmutation efficiency even more and to combine it with an effective energy generation it is desirable to surround the spallation target with a subcritical reactor core (most often called blanket) - an idea which has been materialized in hybrid systems proposed for different purposes in the last few years (in its very general design is presented on Figure 4.

The main components of ADS are a high-intensity accelerator delivering a particle beam of 5 to 40 MW power, a transmuter - a sub-critical reactor with spallation source, and chemical reprocessing.

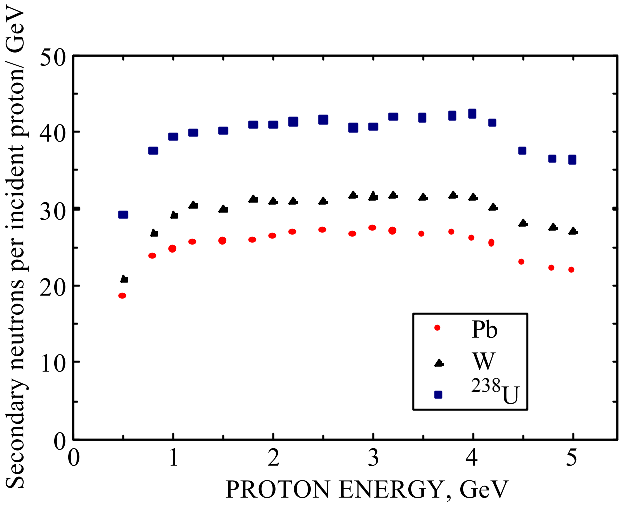

Figure 5. Number of neutrons per incident proton and its energy (GeV) produced in a spallation processes in different thick targets.

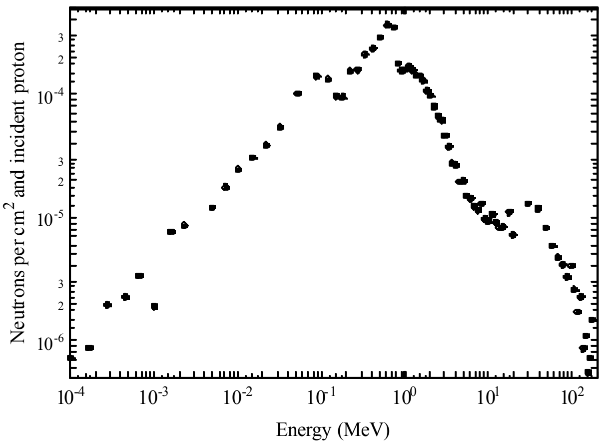

Figure 6. Energy spectrum of spallation neutrons

When a particle beam (in most designs - protons) from accelerator hits a thick target of heavy elements, large quantities of neutrons and charged particles are obtained, largely through spallation of the atomic nuclei in the target. Most of the charged particles are slowed down and stopped inside the target or in its vicinity as an effect of Coulomb interaction, while the neutrons penetrate the target and surrounding subcritical core. Typically, several tens of neutrons will be produced from each proton colliding with the target. This means that a reasonable beam of protons (for example 20 mA at 1 GeV of proton energy) can produce a large number of neutrons per unit of time - see Figure 5 [6]. If the spallation target is placed in the center of a subcritical core, the latter can act as a neutron multiplier even if it would not otherwise be self-sustaining. This is due to the fact that losses of neutrons can be compensated for through the supply of new neutrons from the spallation target. Through the fissions that occur in the core during neutron multiplication, more energy can be generated than is consumed to produce the proton beam. This therefore results in another type of self-sustaining system. The conversion of heat from the core into electricity in the conventional manner, via steam generators, turbines and generators produces electrical energy which is more than sufficient to operate the accelerator. In turn, this produces the protons which, after conversion into neutrons in the target, sustain the production of energy in the core. The spallation neutrons play the same role as delayed neutrons in conventional nuclear reactors – sustaining the desired fission power level, the system is driven by neutrons originated from accelerated protons.

The neutrons emerging from both the target and the fuel in the subcritical core originally have high energies as shown on spallation neutron spectrum in Figure 6. By introducing a moderator, the neutron energy can be reduced (neutrons can be moderated) in the same way as in a thermal reactor. The advantage of this is that most reaction cross-sections are greater at low neutron energies than at high energies. Thus, less fissile material is needed for a given reaction rate at low neutron energies than at high neutron energies, that is for a given energy: In principle, considerably higher neutron fluxes can be achieved in this type of system than in a thermal self sustaining reactor.

Water and graphite normally require encapsulated solid fuel and are therefore less suitable as moderators in accelerator-driven systems due to the large gradients in power density etc. Consequently, ”thermal” molten salts, where actinides are dissolved in different types of fluoride salts have been considered to be a better combination of fuel and moderator. The homogenization of the fuel and subcriticality of the system mean that a substantial neutron flux is obtained close to the target, with a high transmutation rate, while most of the core has a considerably lower neutron flux. This can not be compensated for by increasing the supply from the accelerator-driven target, since material damage on the accelerator window, above all on the wall between the target and core, will be unacceptable at high proton and neutron fluxes [7]. More sophisticated solution can be applied, like multiple target system, in which subcritical core surround 3-5 target modules fed by splitted proton beam or even fed by separate accelerators (in this case only use of cheap cyclotrons makes economical sense) [8]. Acceptable fission power distribution in the core can be obtained in this way but the technical complexity of this system increases considerably. Moreover one has to cope with a very significant reactivity swings requiring either sophisticated fuel feeding procedures or very flexible accelerator working with current varying almost by a factor of 5 [8].

Using fast neutron spectrum it is easier to design a suitable neutron multiplying blanket/core for a subcritical system than for a critical fast reactor, since the spallation source can deliver neutron flux of very high intensity. Also longer neutron free flow path in the fast systems makes the power peaking problem much less severe than in the thermal systems and consequently makes possible use of solid, reactor like fuel rods.

The heat generated by fission processes in ADS can of course be used to produce electrical energy. Some of this heat is used up to feed the accelerator. In a fast accelerator-driven system, this share is typically on the order of 4-8%, and comparable to the energy which is used for secondary needs in a critical reactor.

COMPONENTS OF DIFFERENT ADS-DESIGNS.

Accelerator

Two acceleartors types are being proposed to drive an Accelerator-driven System – linear accelerator or cyclotron. The final choice will depend on an interdependent and complex optimisation of the whole ADS including economical constraints and probably also local traditions of research groups, which will succeed to build the first demonstration facility. Both accelerator types have different advantages (and disadvantages), however the optimal final parameters of the accelerator are relatively easy to estimate: proton energy should be around 1 – 1.5 GeV (see Fig. 5 – there is no significant gain in number of neutrons per proton energy over 1 GeV) and proton current would depend on desired beam power, which for a demonstartion facility would be in the limit of 5 – 10 MW, corresponding to 5 – 10 mA of protons. Two most powerful accelerators today, are representing both accelartors types: linac at Los Alamos National Laboratory, running at 800 MeV and 1 – 1.5 mA proton beam, and cyclotron at Paul Scherer Institute, having a 1.5 mA proton beam with 590 MeV energy. Both accelerator types require intensive development in order to match the requirements that are common for nuclear power systems. The reliability and availability of the accelerator in accelerator driven systems is an important issue. Taking into account the fact that proton beams from existing high power proton accelerators trip very frequently, it is indispensable to understand the effect of such beam trips on different subsystems, especially a subcritical reactor. Temperature fluctuation caused by power change in the accelerator beam enforces thermal transients to reactor structures and beam window, where thermal fatigue or creep-fatigue damage will be accumulated during life time. When large number of severe thermal stress cycles are enforced, there is a possibility of crack initiation and propagation at structural walls. Figure 7 [9] presents the number of trips of Los Alamos accelerator (LANSCE) during a 2870 hours operational period in 1997, as a function of a beam trip duration. (Beam trip is defined as a particle current drop below 50% of nominal/scheduled value). The average value is about 1.6 trips/hour. Incidently PSI – cyclotron has about the same trip frequency [10].

One of the most important question concerning accelerator performance is: What beam trip rate is the maximum acceptable limit for a high power subcritical reactor? The beam trip frequency should be compared with actual number of unscheduled shutdowns in existing nuclear plants (LWRs), which are in the region of 0.3-3.5 shutdowns/year. For instance, if a beam trip rate of the same level as the actual unscheduled reactor shutdown is required, the necessary improvement is tremendous and it seems to be very ambitious. On the other hand, if the maximum acceptable trip rate can be relaxed to 10-100 trips/year, the goal seems to be more realistic. Although, the beam trip rate for short beam trips (<1 min) is very high, one should keep in mind that short trips is not as serious as long trips in terms of thermal shock to structure material. The temperature swing in the reactor caused by a short beam trip is small due to the thermal inertia of the system, for example, it takes certain amount of time for the coolant to recycle the reactor [11].

A linear accelerator is a preffered option for Los Alamos ATW group [12], taking advantage of accelerator development work done in the frame of Accelerator-Production of Tritium (APT). Down-sized ATP accelerator for ADS would be a a 45 MW (1GeV energy

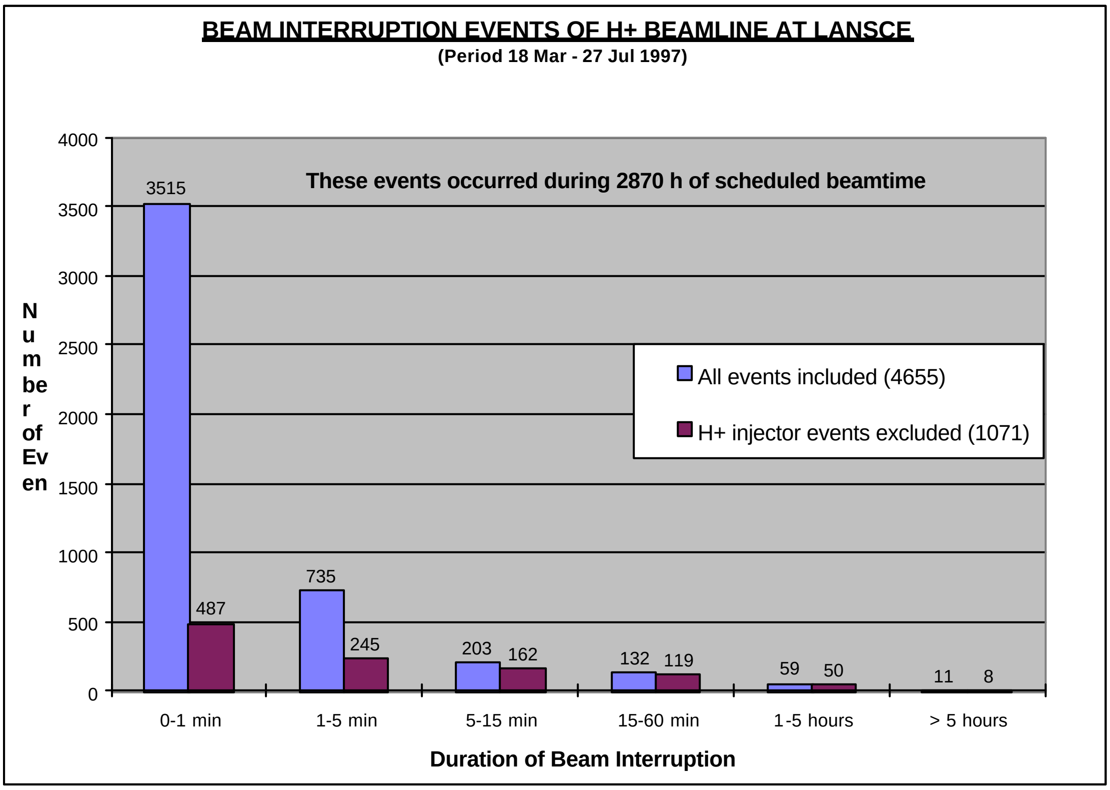

Figure 7. Beam failure statistics of the LANSCE accelerator facility

and 45 mA current) superconducting linac driving several transmuters through a sophisticated system of beam splitters.

Most of the European groups are focused on advantages of cyclotron, proposing to overcome the technological limit of cyclotron current of about 10-15 mA, thruogh use of multiple cyclotrons. Multiple cyclotrons, if cheap enough would be a good option to improve the reliability of ADS-facility.

Even if there are no obvious show-stoppers for improvemnet of accelerators, an intensive research work should focus on:

for linacs:

- Improved reliability and trip-free performance
- Extensive use of superconductors(development of lower-beta superconducting cavities and cryomodules)
- Increase of electrical field gradients leading to reducing the size
- Increase of current and possibly beam splitting/sharing to share accelerators in development stage;

for cyclotrons:

- Improved reliability and trip-free performance
- Increase of beam current - novel concepts highly desired, space charge challenges
- Cost reduction through compactness and robust constructions

Target

Two different technical solution can be envisaged for an ADS spallation target: a solid tungsten target clad in stainless steel and cooled by sodium and a liquid metal target, in which target fluid is also used as the primary cooling loop. The solid tungsten target design was developed in details in the APT project, however this solution is not very attarctive for ADS. The preferable target for ADS would be a liquid metal target; for most cases liquid lead-bismuth eutectic (LBE) has been proposed. Other possible metals are liquid lead.magnesium eutectic and mercury. Mercury target seems to be a preferred option for spallation neutron scattering facilities, like American Spallation Neutron Source (SNS) [12] project and European Spallation Source (ESS)[10].

The great advanatages of LBE are chemical inertia, high boiling temperature, relatively low melting temperature (123.5°C), good heat conductivity and no immediate volume expansion upon solidification (however slow volume expansion in a solid state due to recristallization requires some precautions). Moreover there are 70 reactor-year experiences from LBE-reactors developed in Russia. A significant disadvantage of the LBE spallation target is generation of ^{210}Po, a short-lived hazardous alpha emitter formed by neutron irradiation of Bismuth.

The key technological problem for the target desiign is a design of a target window which can withstand radiation damages of proton beam and backscattered neutrons, thermal stresses caused by accelerator trips and corrosion in LBE environment. Effects of spallation products on LBE corrosion control is one of the key problems to be investigated.

Some important questions concerning the technical details of the ADS spallation target will be answered in a collaborative project between Institute of Physics and Power Engineering (IPPE) in Obninsk – Los Alamos National Laboratory – Royal Institute of Technology in Stockholm and CEA Cadarache on manufacturing and testing of 1 MW LBE spallation target. This target is now under manufacturing process in Russia, funded by International Science and Technology Centre (ISTC), and will be irradiated next year at Los Alamos accelerator. A sketch of a target design is presented on Fig. 8

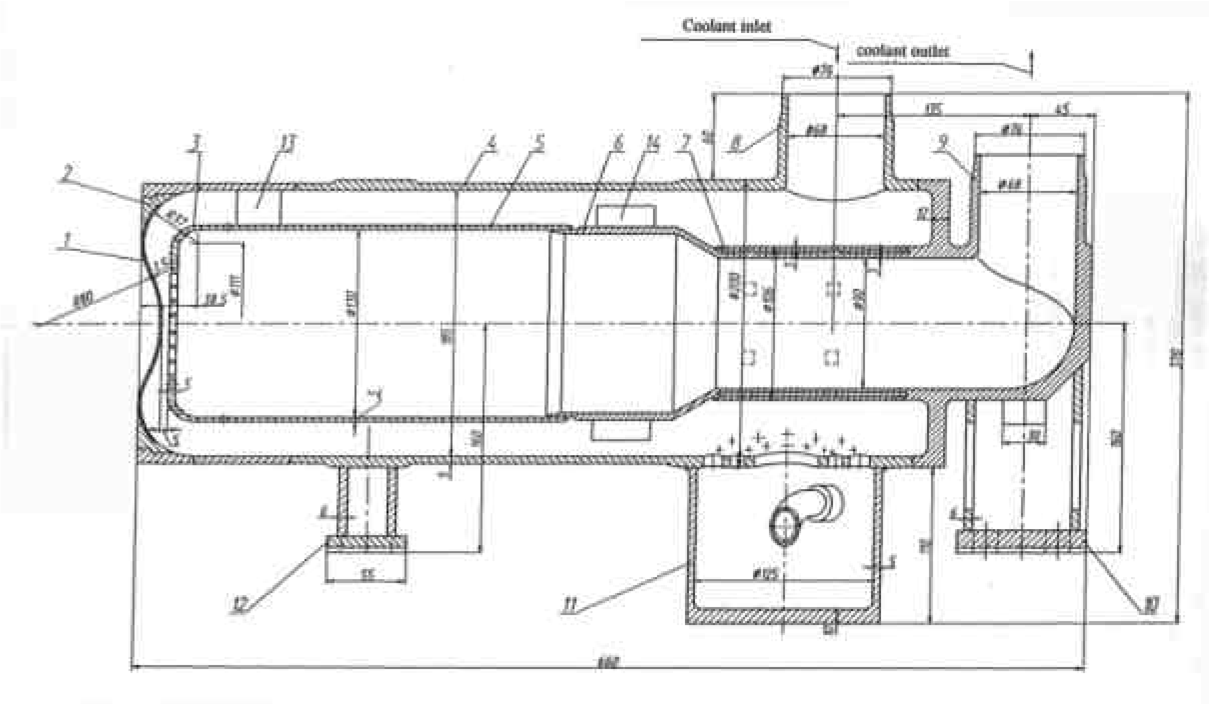

Figure 8. The spallation LBE-target developed in ISTC-project 559. Main components of the target: 1 - window, 2 - window support, 3 - diffuser plate, 4 - target hull, 5 - inner channel.

Subcrtical core: coolant/fuel system

Differtent conceptual design have been proposed for the coolant/fuel systems in the last few years. The very common feature for most of them is use of liquid Lead or LBE as a coolant. In Europe several options of fuel have been proposed and the first option for a planned demonstration facility would be solid oxide fuel e.g. (Pu+MA) oxide, taking advantage of an existing reprocessing technology in Europe. A system which this fuel-coolant combination and 130 MW_{th} power at k_{eff}~0.97 would be capable to burn about 100kg Pu + MA , 30 kg of ^{99}Tc and ¨20 kg of ^{129}I per TWh_{el} . In the longer time perspective Th-based fuel cycle is considered as an option of further reduction of ADS waste radiotoxicity. Thorium based fuel cycle, having worse neutron economy than U fuel cycle would additionally benefit from the external neuron source. Some extensive engineering studies was already done by Italian Ansaldo based on the conceptual design of C. Rubbia [14] .

For a solid fuel system cooled by LBE there is an open question of spallation target integration into a subcritical core. Having the same coolant, the spallation target could be integrated into the core cooling system having the same first cooling circuit. It would definitely simplify the construction of the ADS, however the price would be a contamination of the whole primary liquid metal loop with the spallation products. So for the first demonstartion solution it will probably be preferable to have a spallation target with a separated cooling circle, to contain the spallation products into the minimal volume.

As a backup ADS option it is now considered in Europe an advanced gas-cooled (He) ADS with LBE spallation target and MOX or more advanced fuel. Other very novel systems are also under considerations, like thermal neutron ADS cooled with liquid lead solution of Pu and PuMA, or liquid lead suspension of Pu and/or PuMA oxides. Conceptual design of thisADS, called Jülicher Transmuter, has been developed in IABAT-project [8].

In USA the ADS of a primary interest is based on LBE cooling and metallic, Uranium free-fuel, array of metal fuel pins - blend of actinides and Zirconium. This metallic fuel provides the high rates of heat transfer required. Use of a metal fuel makes pyrometallurgical processing attractive for recovery and recycle of the discharged ATW fuel. However, Uranium (or Thorium) free fuel implies a rapid drop of k_{eff} with burnup of the fuel. To compensate reactivity drop and to keep a constant power level, accelerator has to deliver particle current varying by a factor of 3-4 during a single irradiation period, moreover such a core has to be reloaded about 3 times a year.

An alternative, thermal neutron accelerator-driven transmutation system - Tier - has been proposed in USA by Ch. Bowman [15]. Tier 1 (k_{eff} = 0.96, neutron flux 2×10^{14}n/cm^{2}s) is a graphite assembly with circulating molten salt ($NaF\text{-}ZrF_4$) fuel and liquid Lead spallation target. This ADS-system with 750 MWth power generated by fission of 300kg/y of Pu and MA corresponding to annual PWR production of these elements would be a once-through transmuter with 80% efficiency. Tier 2 (keff=0.95, neutron flux 4×10^{14}n/cm^{2}s) system would be then a back-end option transmuting the spent fuel from 4 Tier 1 units. The choice of $NaF\text{-}ZrF_4$ salt in favour of $LiF\text{-}BeF_2$, which had been proposed in earlier molten salt system is determined partially by economy the once-through performance of Tier system, in which no salt recovery is foreseen.

ADS system under consideration in Japan are to support 10 LWRs with MA transmutation []. Following options are investigated:

Solid fuels system:

- Nitride fuel core with enriched ^{15}N
- Tungsten target and sodium cooling

  or
- Pb-Bi target-cooling system.

Molten- salt system:

- Chloride salt as target, fuel and coolant with on-line processing.

Taking advantage of subcriticality of ADS fuel for these systems can be purely MA-fuel without ^{238}U. Such type of fuel is unacceptable in critical reactor due to their small delayed neutron fraction-β and small Doppler effects so it is considered that ADS can play a significant role as ”Transmuter” in the back-end of fuel cycle.

Reprocessing chemistry

Accelerator driven transmutation implies, and depend very strongly on the chemical processes, which are commonly called reprocessing chemistry. This chemical processes are inevitably necessary to perform effective transmutation, and can be briefly divided into three different steps: chemistry which process LWR spent fuel and produce primary fuel for the first step of transmutation, i.e. first cycle in ADS; chemistry which makes possibly recirculation of the in ADS and finally, processes of conditioning the final outcome from ADS, i.e. final waste and tailings.

To produce the primary fuel for the first cycle of the waste in ADS, aqueous separations can be used, which is a well-developed technology in countries like France, UK and Belgium and can be relatively easily adopted for ADS. This step would primarily remove the excess of 238U and some fission products from LWR wastes, without a necessity of separation Pu or other transuranium elements. For the second stage of ADS fuel cycle - recirculation of the fuel in ADS, aqueous chemistry can not be used, because one would like to recicurculate this fuel without too long cooling time. Chemical reprocessing technology not sensitive for high radioactivity, must be applied. Pyrometallurgical separation provides this capabilities and is considered to be more proliferation resistant. Pyroprocesses withstand the high heat and radiation anticipated during the processing of fuel that has been irradiated in the ADS transmuter. All separations, either aqueous or pyro-based, should be modularized and constructed close to the transmuter, thereby limiting materials transport to either spent fuel from current nuclear power reactors or waste forms from ADS.

CONCLUSIONS

Accelerator-Driven Systems open new possibilities to perform transmutation of nuclear waste on a safe and effective way. Figure 9 summarizes a transmutation potential of different reactors and ADS in a coordinate system of TRU-consumption and TRU consumption over discharge. The right-upper corner of the plot represents an ideal transmutation system [for details see reference 8]. It can be concluded that ADS may play an important role in a nuclear fuel cycle as an effective way to transmute most cumbersome isotopes. To develop these transmutation systems an extensive research program of interdisciplinary dimension has to be started- This program covers nuclear physics, nuclear technology including high intensity, medium energy accelerators, reactor physics, material sciences, chemistry and nuclear chemistry, radioactive waste treatment technologies etc. In many countries the synergy between neutron science, accelerator technology, nuclear physics and transmutation research has been already recognized and common research and development programmes have been formulated and launched.

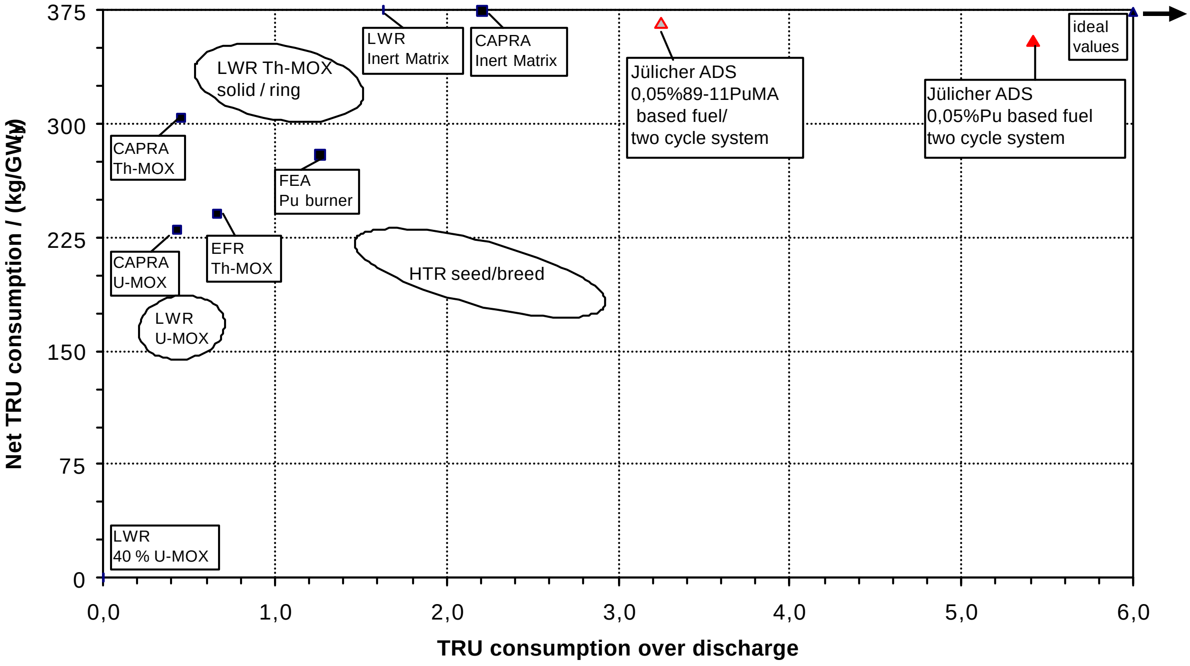

Figure 9. Transmutation potential of different reactors and Accelerator-Driven Systems.

Nuclear and particle physics has an important role in development of ADS, particularly:

- Development of nuclear models, creating nuclear data bases, improving and designing new computer codes for particle interactions in the medium energy range (up to 300 MeV)
- Development and optimization of high current accelerators with exceptionally high reliability and low beam losses
- Development of spallation neutron targets
- Material irradiation studies and development of theoretical and computer models for irradiation induced material damages
- New approaches to a nuclear fuel cycle.

This list of important topics is open and will cover more and more topics emerging from experimental work, which will hopefully start soon.

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