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Accelerator-driven Transmutation Projects. The Importance of Nuclear Physics Research for Waste Transmutation.

Waclaw Gudowski[a]

[a]Royal Institute of Technology, Stockholm, Sweden

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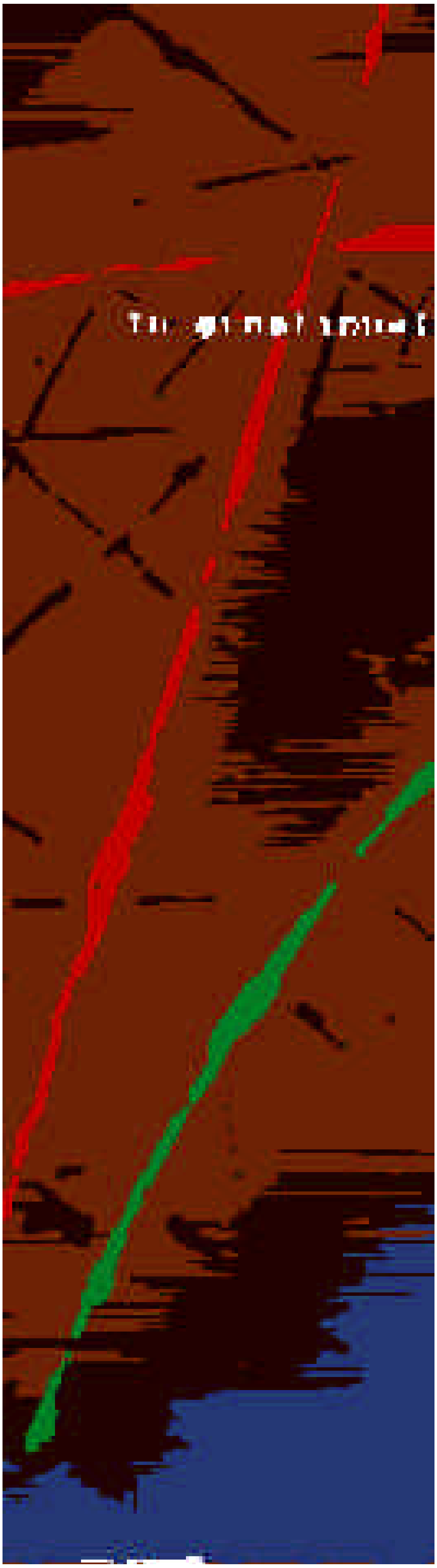

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The Importance of Nuclear Physics Research for Waste Transmutation.

Waclaw Gudowski
Royal Institute of Technology
Stockholm, Sweden

1. INTRODUCTION

After unprecedented development of physics and particularly nuclear physics in the first half of our century it was expected that fission and fusion processes could ultimately ensure practically inexhaustible energy supply for the growing population of Earth. Unfortunately, the reality turned out to be much more complicated. Commercial fusion reactors are today as distant in time as they were almost 50 years ago, still facing enormous technological challenges. Fission reactors - after spectacular development in fifties and sixties, that resulted in deployment of over 400 power reactors - are wrestling today more with public acceptance than with unresolvable technological problems. In a whole spectrum of reasons which resulted in today´s opposition against nuclear power few of them are very relevant for the nuclear physics community and they arose from the fact that development of nuclear power had been handed over to the nuclear engineers and technicians with some generically unresolved problems, which should have been solved properly by nuclear scientists.

What are these major problems of nuclear power today? In a certain degree of simplification one can say, that most of the problems originate from very specific features of a fission phenomenon: self-sustained chain reaction in fissile materials and very strong radioactivity of fission products and very long half-life of some of the fission and activation products. And just this enormous concentration of radioactive fission products in the reactor core is the main problem of managing nuclear reactors: it requires unconditional guarantee for the reactor core integrity in order to avoid radioactive contamination of the environment; it creates problems to handle decay heat in the reactor core and finally it makes handling and/or disposal of spent fuel almost a philosophical issue, due to unimaginable long time scales of radioactive decay of some isotopes.

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 potentially possible 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 release of otherwise contained radioactivity. The Chernobyl catastrophe was just an example of a such accident. The control of self-sustained chain reaction, or what we prefer to call - criticality control, relies on the small fraction of delayed neutrons emitted from the fission products ”long time” after the fission event itself. This small fraction of delayed neutrons determines the criticality safety margins, which puts some serious constraints on the fissile fuel composition, e.g. reactors can not operate on purely minor actinide fuel, because of the very low fraction of delayed neutrons.

The serious question is, what can be done to eliminate or further minimize these concerns. On stake is a future of nuclear power, which currently generates about 17 percent of the world’s electricity. If this electricity were generated instead by coal, world carbon dioxide emissions from fossil fuel consumption would be almost 10 percent larger than they currently are [1].

A lot can be done to improve the design of well known conventional nuclear reactors; new, better reactors can be designed but it seems today very improbable to expect any radical change in the public perception of conventional nuclear power. In this context a lot of hopes and expectations have been expressed for novel systems called Accelerator-Driven Systems (ADS), Accelerator-Driven Transmutation of Waste (ATW) or just Hybrid Reactors. All these names are used for description of the same nuclear system combining a powerful particle accelerator with a subcritical reactor.

The idea of combining powerful accelerators - with a subcritical reactor for transmutation purposes is not a very new one. Nuclear transmutation itself was demonstrated for the first time by Rutherford in 1919, who transmuted ^{14N} to ^{17}O using energetic α-particles [2]. 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 [3]. 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 [4] removed this barrier and opened quite new possibilities. 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.

Transmutation processes in a bigger scale can be realized using different particles, as shown on Figure 1, like neutrons, charged particles and even γ-rays. However neutrons offer the best and most efficient way of transmutation due to lack of Coulomb barrier and favourable cross-

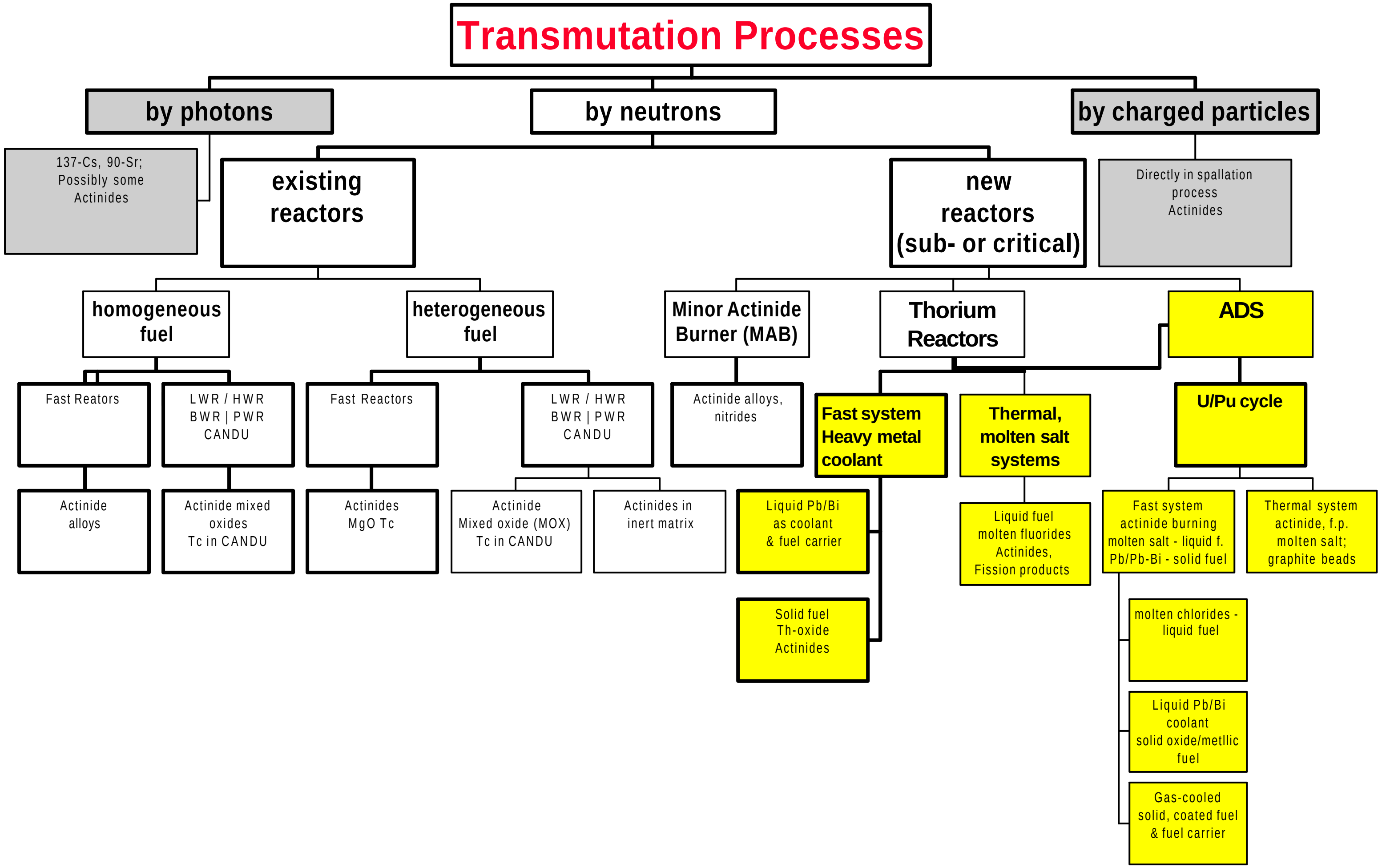

Figure 1. Different transmutation options with existing and new nuclear systems.

sections. As depicted on the Figure 1 existing nuclear reactors can be also used to a certain degree to perform transmutation, as well as new critical reactors can be designed for transmutations but assessment of transmutation potential of critical reactors would be far beyond the scope of this paper, which is focused on accelerator-driven transmutation.

The first practical attempts to promote accelerators to generate potential neutron sources were made in the late 1940's by E.O. Lawrence in the United States, and W.N. Semenov in the USSR. The first such application for the production of fissile material was the MTA project at the Lawrence Livermore Radiation Laboratory. This project was abandoned in 1952 when high grade Uranium ores were discovered in the United States.

In 1960's Brookhaven National Laboratory presented several proposals for accelerator breeders such as the Na-cooled fast reactor target, the Molten Salt target, the He-gas-cooled target, as well as the LWR fuel regenerator [5]. This concept of the accelerator breeder has also been studied by Russian scientists. Under the guidance of V.I. Goldanski, R.G. Vassylkov [6] made a neutron yield experiment in depleted Uranium blocks using the accelerator at Dubna.

The original idea of exploiting the spallation process to transmute actinide and fission products directly was soon abandoned.The proton beam currents required were much larger than the most optimistic theoretical designs that an accelerator could achieve, which are around 300 mA. Indeed, it was shown that the yearly transmutation rate of a 300 mA proton accelerator would correspond only to a fraction of the waste generated annually by a LWR of 1 GWe.

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 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 it is desirable to surround the spallation target with a subcritical nuclear 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 2). ADS on fast neutrons for the incineration of higher actinides was proposed at Brookhaven National Laboratory (PHOENIX-project) and is now carried out in Japan as a part of OMEGA-programme [7]. Los Alamos National Laboratory has developed several ideas to use the hybrid system on thermal neutrons with a linear accelerator for incineration of Plutonium and higher actinides, for transmutation of some fission products in order to effectively reduce long-term radioactivity of nuclear waste as well as for producing energy based

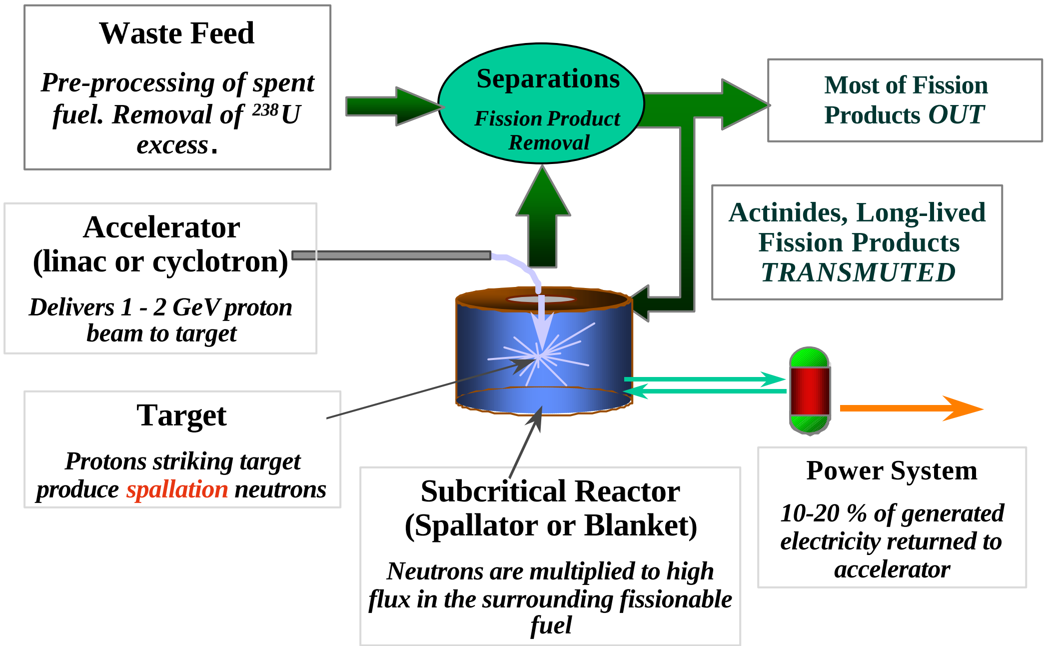

Figure 2. A schematic view of an Accelerator-Driven Transmutation system (courtesy F. Venneri)

on the Thorium fuel cycle [8,9]. In 1993 Carlo Rubbia and his European group at CERN [10,11] proposed a cyclotron based hybrid system to produce nuclear energy based on the Thorium fuel cycle. It revived significantly a scientific interest for a Thorium fuel cycle in spite of the fact that the main interest in conceptual designs of ADS has focused much more on the transmutation of existing nuclear waste from Light Water Reactors. More detailed description of the existing research projects will be given in the next sections.

Figure 3 shows an overview over transmutation systems proposed in the last years. The criterion for classification is a proposed neutron spectrum, type of fuel and target-coolant system, purpose of the system (type of transmuted elements, energy production etc.) and accelerator type. As it is pointed out in this paper most of the projects are converging now into solid fuel, heavy metal cooled, fast neutron systems - as presented on the left hand side of the Figure 3.

As mentioned before since the end of the 1980´s research in transmutation, particularly Accelerator-Driven Transmutation of long-lived and radiotoxic nuclides has increased all over the world. In particular, interest in accelerator-driven systems for transmutation of nuclear waste (and possibly weapon-grade Pu) and, in somewhat lesser extent, energy production has increased over the past few years. Different reasons

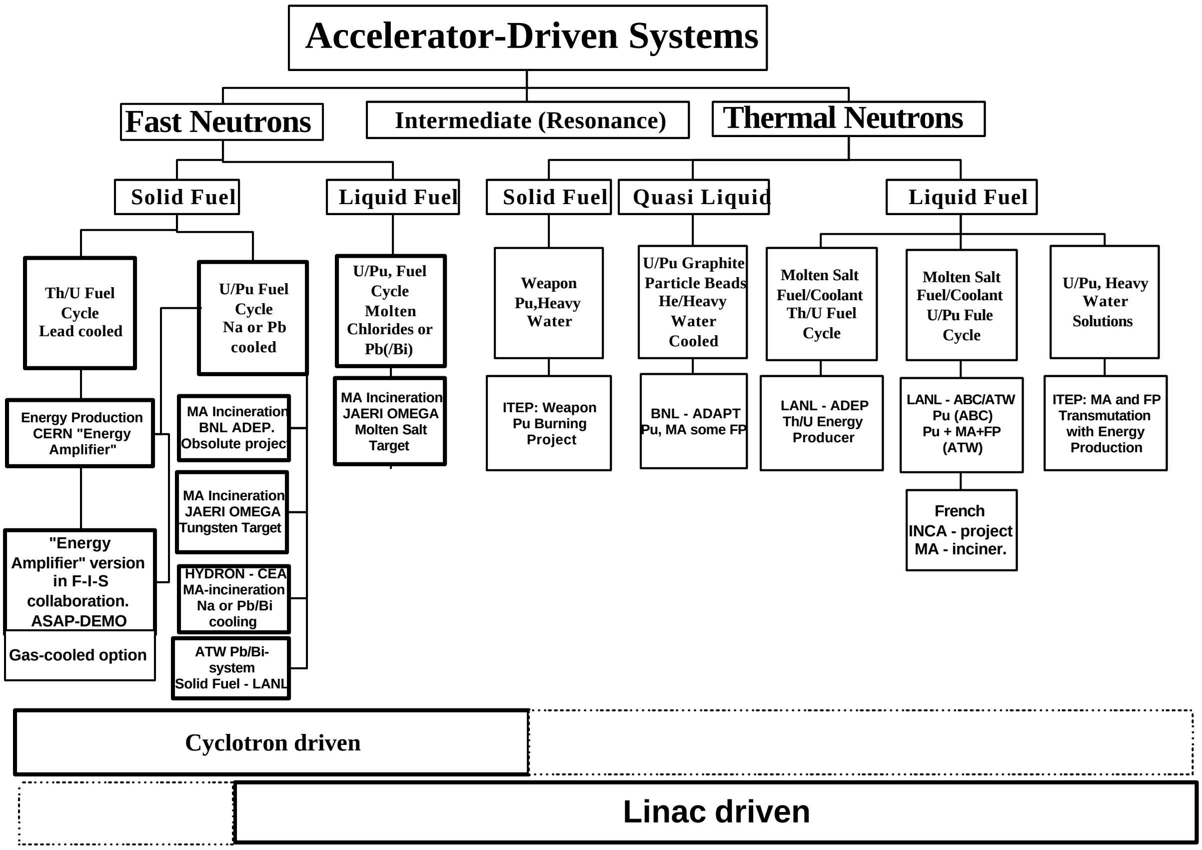

Figure 3. Classification (with a historical insight) of Accelerator-Driven Systems in terms of neutron energy, type of fuel and coolant. Acronyms used in this figure correspond to the project names or institute names and are explained in the text.

stimulate these research activities in many countries having very different fuel cycle policy from countries like France, Japan or Russia having ”reprocessing” fuel cycle policy for Pu recirculation, through the countries which adopted once-through fuel cycle (like USA or Sweden) and ending on the countries without nuclear power at all (Italy, Poland). In France and Japan, where for a decade, active research programmes on transmutation have been carried on, new problems concerning future of fast breeder reactors have stimulated greater interest in Accelerator-Driven Systems. ADS are considered as an viable option for minor actinides transmutation. In USA a road-mapping activity have just been started to formulate a DOE programme on Accelerator-Driven Transmutation of Wastes and to define a place for this technology in a US waste management policy. In Russia, few hundreds former weapon researchers are currently involved in transmutation related projects, financed mainly by the USA, EU, Japan and Sweden through the International Science and Technology Centré (ISTC). Countries like Italy and Spain has recently started well defined research programmes ADS, while other countries have allocated additional funds to existing programmes (Belgium, India, Sweden, South Korea, Czech Republic etc.) Part of the European research activities has been conducted with the financial support of in the 4th Framework Research Programme of European Union [12].

2. ACCELERATOR-DRIVEN TRANSMUTATION

A schematic picture of an accelerator-driven transmutation system is presented on Figure 2. The core components of ADS are a high-intensity accelerator delivering a particle beam of 5 to 40 MW power, a sub-critical reactor with spallation source, and supporting chemical processing.

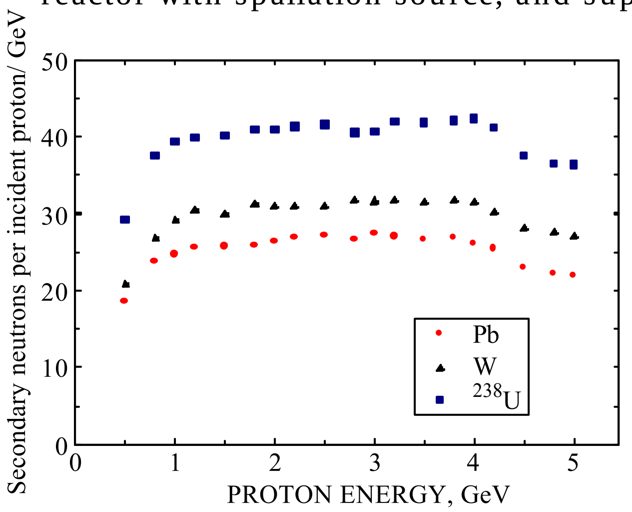

Figure 4. Number of neutrons per incident proton and its energy (GeV) produced in a spallation processes in different thick targets.

When a particle beam (in most designs - protons) from accelerator hits a thick target of heavy elements, large quantities of neutrons are obtained, largely through spallation of the atomic nuclei in the target. 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 4 [13]. If the spallation target is placed in the center of a reactor 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 neutrons emerging from both the target and the fuel in the reactor core originally have high energies. By introducing a moderator, the energy level can be reduced in the same way as in a thermal reactor (see thermal neutron branch on Figure 3). 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. However; a slower reduction in the speed of the neutrons is obtained in these systems than in self sustaining water-moderated reactors. Consequently, the cross sections for fission are somewhat lower than for systems where the neutron energies are reduced faster. Furthermore, 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 [14]. 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 [15].

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 reaction heat 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 4-5%, and comparable to the energy which is used for secondary needs in a self sustaining reactor.

Systematic studies (see Figure 3) and research conducted in last few years in many countries have lead to some degree of converegence with respect to some important objectives and potentials of accelerator-driven transmutation:

- Transmutation of of nuclear waste will not eliminate or replace geological disposal but could be a complement leading to a considerable reduction in the quantity of long-lived isotopes which must be deposited in such a repository. Possible reduction factors vary from 10 to 100 times.
- Most of the system studies converged now on fast neutron systems, which have good neutron economy and favorable fission/capture ratio for most of the isotopes. However, the thermal neutron systems can still be interesting as a final ”transmuter” of remnants.

- Liquid heavy metal coolants (Pb or Pb/Bi - Lead-Bismuth Eutectic - LBE) are the best candidates for ADS, due to the chemical and thermodynamical features: chemical inertia, high boiling temperature, relatively low melting temperature, heat conductivity etc. Circulation of a molten metal would facilitate heat removal and offer the possibility of operations at sufficiently high temperatures to provide power production at a high thermal efficiency. Neither molten Lead nor LBE are reactive to air and moisture as is sodium, the traditional coolant for fast reactors. LBE with a melting point of 123.5^{o} C would offer certain operating advantages compared with Lead (melting point, 327^{o} C), but that advantage is somewhat offset by the presence of ^{210}Po, a short-lived hazardous alpha emitter formed by neutron irradiation of Bismuth. Sodium coolant is still considered an option, but less feasible due to the concerns raised for fast, sodium cooled reactors in Japan and France. Also gas cooling is now investigated as as a possible option.
- Either molten Lead or Lead/Bismuth eutectic are also considered to be the most suitable as a spallation target. The backup options are solid target of Tungsten or Mercury liquid target.
- Pyrochemical partitioning should be well integrated into in-site ADS concept, in order to improve the overall economy and efficiency, as well as to avoid transportation of fissile and hazardous materials.

3. ON-GOING PROJECTS IN ACCELERATOR-DRIVEN SYSTEMS

3.1. USA

Several different strategies for the transmutation of nuclear waste have been presented in the USA in past years. The waste treatment aspect of ATW was compared with treatment by thermal and fast reactors in an extensive study performed for DOE by the National Research Council (NRC) and published in 1996 [16]. This report, has determined to a large extent the official American policy in this respect .

The principal conclusions of the NRC report were [17]:

- Separation and transmutation (S&T) of transuranics and certain long-lived radioisotopes in spent reactor fuel is technically feasible and potentially beneficial to repository performance,
- A system to treat U.S. spent fuel would be very expensive and require many decades to implement,
- While thermal and fast reactors applied to S&T would be based on considerable technologic experience, ATW would require extensive development before even technical feasibility could be realistically assessed,

- No S&T system offers sufficient promise to abandon the current once-through fuel cycle in the U.S. nor to delay the opening of the first nuclear waste repository,
- Even with a successful S&T system, a geologic repository would still be required, and
- S&T may be able to delay or eliminate the need for a second repository, but there are legislative and less expensive technical ways to increase the first repository capacity by an equivalent amount.

Because of significant advances in technology and different technical selections for the ATW building blocks, a review of the Los Alamos National Laboratory ATW technical approach was provided by Massachuset Institute of Technology (MIT) in January 1998. It was concluded that presented ATW technology have ”no insurmountable issues or show stoppers. While the proposed technologies are in several instances extrapolations of existing experience to untested conditions, they represent reasonable targets for development over the next 5 to 10 years." The review acknowledged also ” that ATW has the potential to provide added flexibility to the design of the high level waste repository and to reduce the uncertainties about its performance." Figure 5 presents the potential impact of ATW on US waste management. Moreover it was pointed out that "...the main technologies to be develop are all worthwhile technologies for other applications beside the transmutation of wastes.

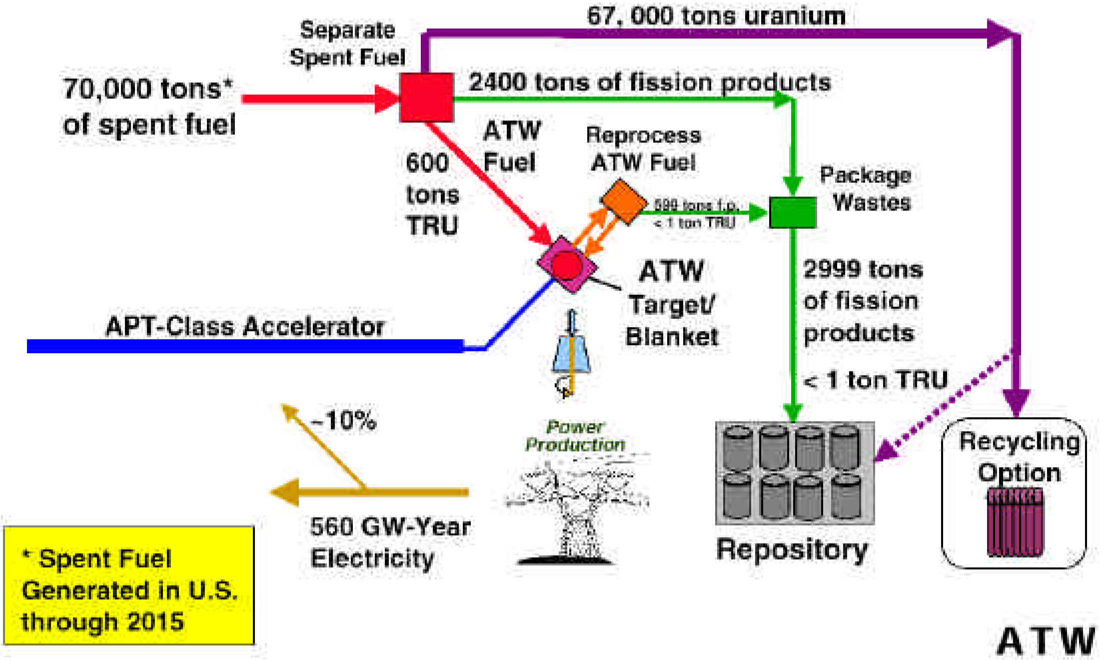

Figure 5. Potential impact of ATW on US waste management.

We see the spin-offs from the development efforts as equally important reasons for the undertaking of the proposed development program in the next few years."

The development of the Accelerator-Driven Transmutation System in Los Alamos National Laboratory has been focused for last 2 years on the fast neutron option for Pu and MA transmutation with following components:

*Accelerator***.** A linear accelerator with beam power in the 5 MW to 40 MW range taking advantage of a development achieved in the frame of the Accelerator Production of Tritium - project.

Subcritical core. A design based on liquid Pb/Bi reactors developed in Russia with Pb/Bi cooled array of metal fuel pins - blend of actinides and Zirconium. The design work includes development of natural circulation heat removal and controlling of Pb/Bi ”corrosive” chemistry. Also the qualification of materials compatible with liquid Pb/Bi is to be included in R&D plans.

Spallation target. Liquid Pb/Bi target which is under development in the frame of International Science and Technology Centre collaboration between Institute of Physics and Power Engineering (Obninsk,Russia) - Los Alamos National Laboratory - Centre d´Etudes Cadarache - Royal Institute of Technology.

Separation and Partitioning technology. It is considered that one of the most serious ATW challenges would be the demonstration at a commercial level of highly efficient chemical separations processes with which to isolate and recycle Plutonium, minor Actinides (predominantly Neptunium, Americium and Curium) and long-lived fission products (principally ^{99}Tc and ^{129}I). Accelerator-driven transmutation will require multiple recycle, and minimizing between-cycle waste accumulation will require relatively short cooling times, perhaps as short as 120 days. The resulting intense radioactivity will require pyroprocessing, developed at a bench-scale for fast reactor use but requiring modifications and scale-up for ATW use. ATW´s pyroprocessing scheme proposed by Los Alamos National Laboratory is shown on Figure 6 [18].

An alternative, thermal neutron accelerator-driven transmutation system - Tier - has been proposed in USA by Ch. Bowman [19]. Tier 1 (k_{eff} = 0.96, neutron flux 2×10^{14}n/cm^{2}s) is a graphite assembly with circulating molten salt (NaF-ZrF_4) fuel and liquid Lead spallation target. This ATW-system with 750 MWth power generated by fission of 300kg/y of Pu and MA corresponding to annual PWR production od these elements would be a once-trough 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-ZrF_4 salt in favour of LiF-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.

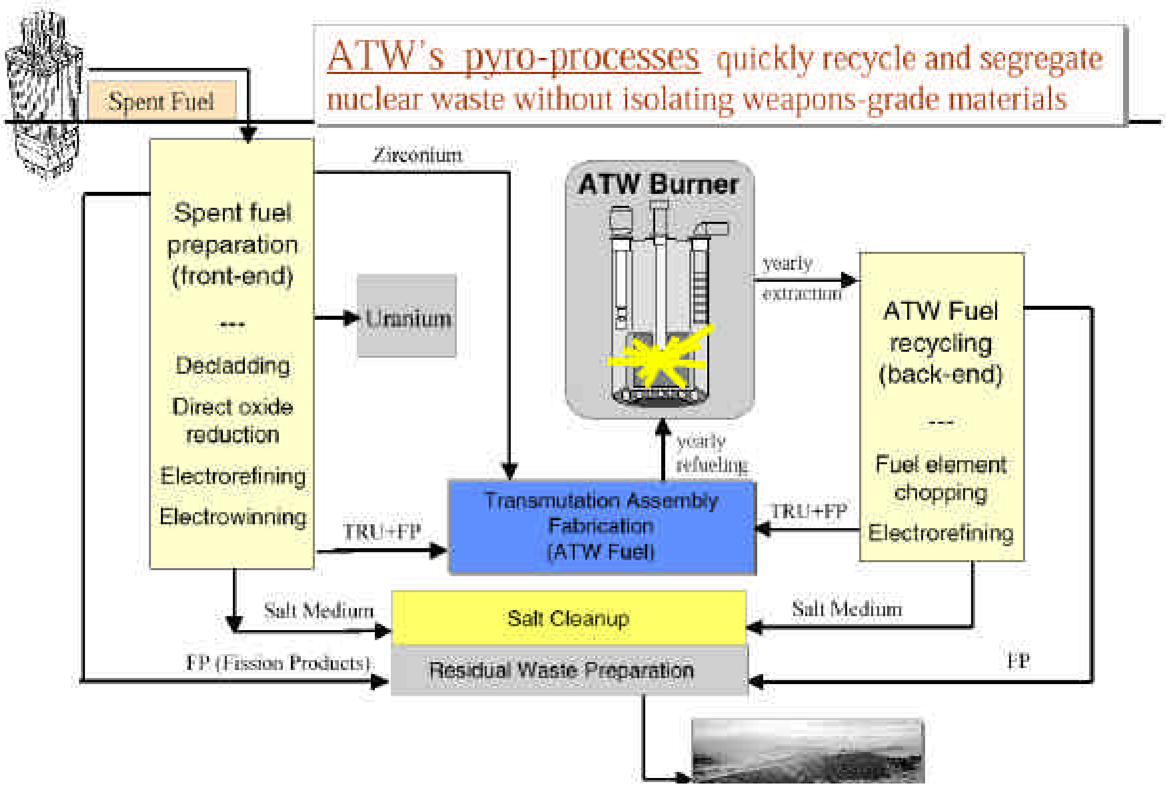

Figure 6. Pyrochemistry propsed for ATW in USA.

3.2. CERN-initiative and French-Italian-Spanish ADS collaboration

An important initiative to demonstrate ADS technology on the basis of Energy-Amplifier design has been taken by C. Rubbia in collaboration with France, Italy and Spain [20]. The research Ministers of these countries have decided to set up a group of advisors to define a common R&D European platform on Accelerator-Driven Sub-critical systems. This group have evaluated few design options including liquid Pb/Bi cooled system with U and Pu MOX fuel and a back-up option - He-gas cooled system with advanced coated fuel particles as future fuel and classical FBR fuel as a short term fuel option.

The assessment of ADS technology and ADS impact on nuclear power done by this group concluded:

1. "The concept of Accelerator-Driven Subcritical systems seems to possess remarkable potentialities, notably for what concerns the transmutation of the long lived waste, as to warrant a serious industrial effort.
2. The construction of a demonstrator facility of significant power in the order of 100 MWth on a 10 years time schedule, is a necessary step for the development of the industrial strategies which will eventually lead to the actual exploitation of the concept. The facility will be in itself an important part of the R&D effort.

3. To reach such an objective a serious R&D effort is required, for which a coordinated joint action of governmental research agencies and of industrial bodies is called for, with ad hoc allocated human and financial resources.
4. The scale of the demonstration facility is that of a regional facility. European collaboration is therefore crucial. Governments should rise immediate action in order to seek interest of other European partners in the program; EU support within the 5th Framework program. During the R&D phase collaborations are recommended with USA, where a similar program is being pursued and in Russia where important know-how on the technology of Lead-Bismuth coolants exist."

The group indicated also the most important technological topics which should be primarily addressed:

- Accelerator technologies
- Window technologies
- Liquid metal coolant technoloe
- Material testing
- Fuel cycles
- Safety and site licensing

The construction of As-Soon-As-Possible (ASAP) Demo-facility is recommended by this expert group. Some technical details on ADS proposed as ASAP-Demo is given in the paragraphs describing French and Italian programs.

3.3. France

In France ADS are considered as mainly an alternative option for an advanced transmutation strategy. It is believed that ADS can play an important role both in a scenario of further development of nuclear power as well as in a scenario of phasing out nuclear. In a developing scenario ADS may become an option for subcritical nuclear energy production mainly for future Thorium based fuel cycle. Thorium fuel cycle can reduce the source term in waste radiotoxicity compare with Uranium fuel cycle. In symbiosis with conventional critical reactors ADS can contribute significantly to reduction of waste radiotoxicity as Minor Actinide burners and possibly incinerator of some long-lived fission products, like ^{129}I or ^{99}Tc. The role of ADS is seen as an assisting technology making geological disposal of final remnants of fuel cycle more acceptable and easier licensable. Even in the "pessimistic" scenario of phasing out nuclear power ADS can play an important role as waste burner (Pu and Minor Actinides) of once-through fuel cycle or not fully implemented multiple-strata fuel cycle [21].

In 1997 French Ministry for Research has launched an initiative to assess a potential impact of ADS on nuclear fuel cycle and to define R&D needs for a possible demonstration experiment, a demo-facility of about 100 MWth. In this activity is embedded now a three-countries initiative (French-Spanish-Italian collaboration described above) to define the principle characteristics of a demonstration experiment.

Since 1996 an R&D "research group" called GEDEON is actively coordinating research efforts of CEA and CNRS with the participation of industrial partners from EdF and FRAMATOME. GEDEON is a network for basic research on ADS and Thorium studies with about 150 scientists involved in concerted actions mainly. The scientific and technical topics which are of interest for GEDEON-network are:

- Spallation target physics (including some activities from SATURNE program)
- Neutron production from heavy metal targets
- Heat, radiotoxicity and corrosion of spallation products
- Validation of intra- and inter-nuclear cascade codes
- Nuclear data
- Differential and integral cross section measurements
- Extending neutron cross-section libraries from 20 to 200 MeV, mainly for constructional materials
- Inventory of nuclear data needs for ADS
- Studies of new materials and follow-up of ISTC 559 project
- Window materials for spallation target, focused on radiation damages in neutron and proton irradiation
- Material compatibility with liquid Pb and Pb/Bi: corrosion embrittlement and irradiation effects
- Neutronics study on a subcritical system: experiments with the MASURCA reactor at CEA/Cadarache
- Scenario studies and system studies, including impact of ADS on transmutation scenarios, assessment of demonstration experiment, integration of target and subcritical core etc.
- Development of high power accelerators
- Assessment of pyrochemistry for advanced waste management options

ADS being considered in France as a possible option for an advanced transmutation technology and also an advanced energy producer attracted in France a lot attention which resulted in an impressive research effort. A combination of theoretical and experimental work which has been done in last few years is becoming a solid ground on which a demonstration facility can be designed and built in a relatively short time. It is frequently expressed and visible that French research groups are seeking wider European collaboration to conduct actively this research. Hopefully, the 5th Framework Programme of European Union will create a solid platform for ADS.

3.4. Japan

Accelerator-Driven Transmutation research in Japan is by any standards best integrated into the broad programme of fundamental and applied nuclear physics. From October 1988 research on partitioning and transmutation in Japan has been conducted in the frame OMEGA programme (OMEGA stands for ”Options for Making Extra Gain of Actinides and fission products generated in the nuclear fuel cycle”) [22]. Since 1996 Accelerator-Driven Transmutation is a common research topic in OMEGA and Neutron Science Project and is well placed in a broad scientific programme focused on:

Basic Science

- Neutron Scattering for: Structural Biology, Material Science
- Materials Irradiation
- High Energy Neutron Physics
- Creation of Transactinides with spallation neutrons, radioactive beams, muon science, etc.

Accelerator Driven Transmutation

- High-level radioactive waste management

Accelerator Development for Industry Application

- High Reliability & Stable Operation

In more details Accelerator-Driven Transmutation research is and will be focused on:

- Development of high power accelerators: a superconducting high-intensity proton accelerator with energy 1 - 1.5 GeV, current several 10s mA is under development. The accelerator is expected to be taken into operation in around the year 2005, and to be supplemented by an experimental transmutation facility after the year 2008
- 5MW Spallation Target
    - Experimental Facility Complex: with:
    - ADS Target System
    - Spallation RI Beam Science
    - Nuclear Physics
    - Material Irradiation
    - Muon Science

ADS system which are considered should 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.

Both molten chloride and liquid Pb (Pb/Bi) have material compatibily problems which have to be solved.

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 with the double strata fuel cycle - see Figure 7.

Development scenario of Accelerator-driven Transmutation System in Japan is presented on Figure 8. In about 15 years from now the first demonstration facility - 30 MWth ADS driven by 2.3 MW beam power can be operationa. It would be a half way to a full commercial plant of about 1 GWth driven by 60 MW accelerator which can be ready by the year 2030.

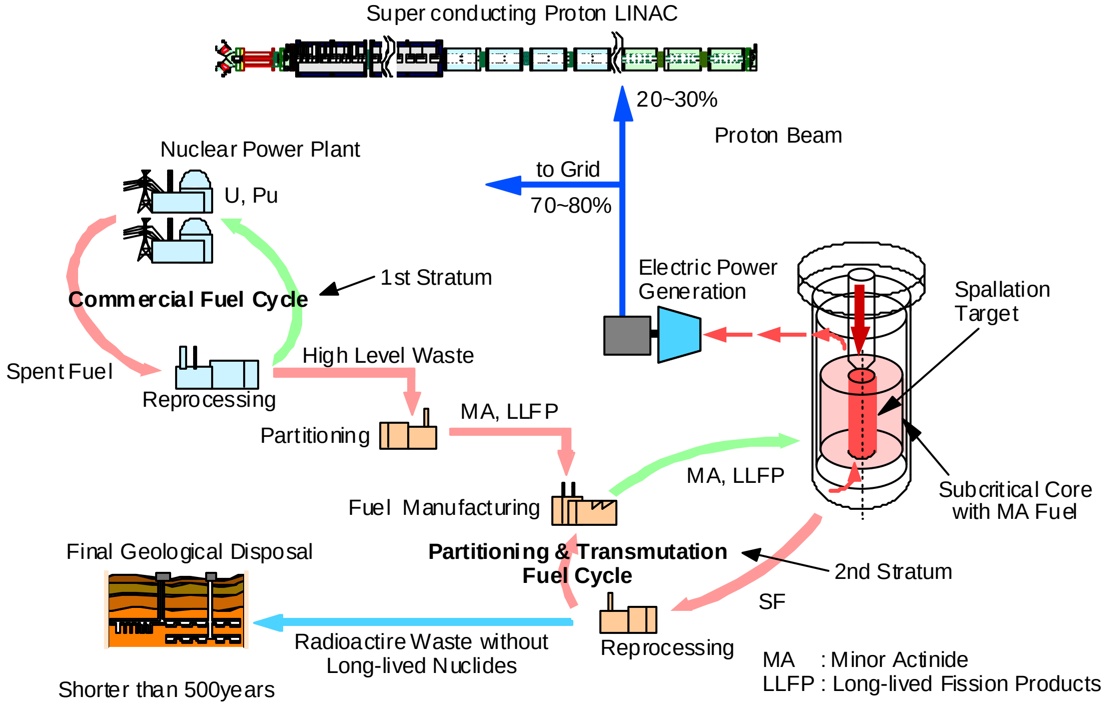

Figure 7. A potential place of Accelerator-Driven System in Japanese Double-Strata fuel cycle strategy (courtesy T. Mukaiyama)

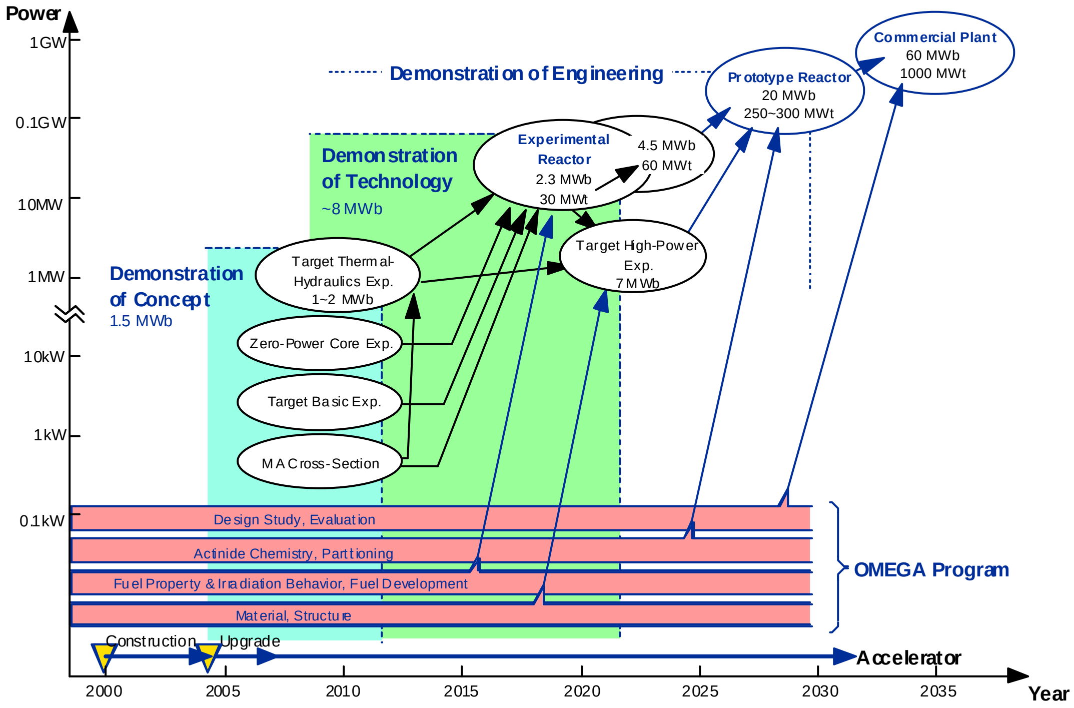

Figure 8. Development scenario of Accelerator-Driven Transmutation System in Japan.

3.5. Italy

The Italian programme TRASCO, started in 1998, is aimed to study physics and to develop technologies necessary to design an Accelerator Driven System (ADS) for nuclear waste transmutation. The programme was prepared in a close reference to Carlo Rubbia's Energy Amplifier proposal [20].

The programme, lead by two institutes: Italian Energy Research Institute (ENEA) and Institute of Nuclear Physics (INFN), consists of two main parts. One is ficused on accelerator development, the other on ADS system studies.

The main objectives of the TRASCO research programme can be summarised as follows:

- Conceptual design of a 1 GeV - 30 mA proton LINAC;
- Design and construction of the proton source and of the first section of the RFQ, and prototype cavities for the superconducting LINAC;
- System studies for EA-like subcritical system: neutronics, thermal-hydraulic calculations, preliminary safety assessment;
- Materials research to develop materials and technology for liquid Lead/Lead-Bismuth coolant;

- Validation experiments for Lead/Lead-Bismuth technology material compatibility studies.

Moreover there is an industrial programme started in parallel, focused on engineering design studies of DEMO-facility of Energy Amplifier like system. This programme is intimately related to French-Italian-Spanish initiative which is mentioned in other article.

3.6. Sweden

Swedish activities in ADS are concentrated mainly at three universities, Royal Institute of Technology in Stockholm, Chalmers University of Technology in Gothenburg and Upppsala University [12]. The complementary competence in these universities lead to few topics which are of main interest in Sweden

At the Royal Institute of Technolgy (RIT) research has been focused on ADS core/blanket-target system, particularly:

- Development of the simulation tools for accelerator-driven transmutation calculations including an integrated Monte-Carlo burnup module and improvements of neutron energy fission yield simulations ,
- Processing of the evaluated nuclear data files including preparation of the temperature dependent neutron cross-sections, development of nuclear data for a medium energy range for some isotopes,
- Development of the models and codes for radiation damage simulations,
- System studies for the spent fuel ”transmuter”, based on heavy metal coolant and advanced nuclear fuel,
- Spallation target design and validation in collaboration with IPPE, Obninsk, LANL, Los Alamos and CEA, Cadarache.
- Accelerator reliability studies.

Activities at Chalmers University of Technology comprise the development of new aqueous-based partitioning processes and, to reduce the volume of waste from future advanced partitioning processes the extractants only contain carbon, hydrogen, oxygen and nitrogen which means that the reagents are completely incinerable and do not contribute to the secondary waste. Five different types of reagent are being studied.

Research activities in University of Uppsala are concentrated on microscopic data measurments, mainly on neutron-induced nuclear reactions for energy around 100 MeV.

Measurements are to be conducted at the unique quasimonoenergetic neutron beam facility at The Svedberg Laboratory. A prototype of SCANDAL (SCAttered Neutron Detection Assembly) has been constructed and installed in connection to the neutron beam. The rig consists of two identical arms; with scattering angles of between 10 and 50 degrees as well as between 30 and 70 degrees. Each arm consists of a thin veto scintillator For rapid discrimination of charged particles, a plastic scintillator for triggering, two operating chambers for proton followup and a series of cesium-iodine detectors for determining energy. The veto scintillator mainly reacts to charged particles and the signal from this can therefore be used to block other signals which occur when a charged particle comes from outside. The equipment is therefore insensitive to incoming charged particles and mainly reacts to phenomena which are triggered by incoming neutrons. The rig is designed for an energy of about 2.5 MeV, which is sufficient to isolate the ground state from the initial excited state in most of the nuclei of interest. Moreover, experiments to establish the distribution of fission products during fast fission of ^{232}Th and ^{233}U as well as the expansion of transport codes and cross-section data libraries to the energy range of 20-150 MeV are being carried out at the OSIRIS facility at Studsvik.

Most of ADS-related research in Sweden is financed by the Swedish Nuclear Fuel and Waste Management Co. - SKB.

3.7. The Russian Federation

Three different concepts for actinide transmutation are being considered in Russia, namely, accelerator-driven subcritical systems, molten salt reactor or accelerator-driven system and fast reactors cooled with liquid metal (Pb, Bi).

The national programme in ADS in Russia is focused on [23]:

- Investigation of ADS technology and economy
- The assessment of the potential ADS role in future large scale nuclear power
- Comparative analyses of critical reactors and ADS safety
- Conceptual design of a demonstration ADS with a fast-thermal ”neutron valve” blanket based on 1 GeV, 23 mA beam

Basic experimental facilities of relevance for ADS in Russia:

- Neutron generator at the Institute of Theoretical and Experimental Physics (ITEP) (ISTRA36 proton linac coupled with heavy water blanket)
- 660 MeV proton cyclotron and pulsed fast reactor in Dubna
- Fast pulsed pile (ABV-F) coupled with high current electron linac LU-50 in Sarov (Arzamas)
- Pulsed neutron source IN-06 of the Moscow Meson Factory (INR RAS Troitsk)
- Subcritical/critical assembly BNS coupled with microtron (IPPE, Obninsk)

Moreover there are both competence and laboratories equipped with loops for development of molten salt systems (Kurchatov Institute and

Dmitrovgrad)

Since 1994, several Russian research institutes have been involved in research on accelerator-driven systems as a possible means of eliminating weapons-grade Plutonium and nuclear waste. The studies have comprised the realization of a linear proton accelerator to drive a specially designed subcritical transmutation core as well as reprocessing processes which can be applied in an integrated transmutation facility. The work has largely been financed by ISTC. The transmutation facility which was studied comprised a target of liquid Lead-Bismuth as well as a subcritical core with two zones. Important results which have emerged include the recommendation of using lighter material such as titanium and graphite as window material for the proton beam as well as the conclusion that problems with the accumulation of ^{210}Po in Lead-Bismuth-cooled systems are less important than previously believed.

In Russia, there is a unique experience (a total of about 70 operating years) of Lead-Bismuth as a coolant for reactors in submarines. Within the ISTC's project #559 which was financed and granted permission to start in 1996, a liquid Lead-Bismuth target will be designed in Obninsk to be irradiated in Los Alamos at LANSCE. This may be an experiment which will be decisive for the development of a demonstration facility. IPPE (Obninsk), LANL; CEA/Cadarache and RIT are participating in the experiment. IPPE plays now an important role in transferring liquid Pb/Bi technology from miltary to civilian use.

There are also several other projects related to ADS which are currently financed through ISTC. Part of these projects are focused on cross-section measurements and evaluations for different reactions on neutrons and protons in energy ranges from GeV down to meV. Also basic studies important for the solid spallation target construction are under way in Russia.

3.8. Other national projects

In Belgium, Germany, the Netherlands, Spain, South Korea, Czech Republic and Belorus are conducted ADS - related projects of interest.

In Belgium [25) the Myrrha Project, focusing on the production of isotopes for medical purposes, has been further developed into ADS-direction. Research groups at SCK-CEN and IBA (Ion Beam Applications) have shown that two small cyclotrons of a type that is already being produced on a commercial basis by IBA (150 MeV, 2mA) applied in an accelerator-driven system should be sufficient to cover the global need for ^{99m}Mo, for example giving some important experimental base for general ADS development. The cost of the system, based on a target of liquid Lead-Bismuth as well as a blanket of enriched Uranium plate, would probably be lower than the cost of special reactors for the same purpose.

In Germany, FZK in Karlsruhe and KFA in Jülich actively participate in international projects on ADS system studies, preparing the computational base for ADS research (FZK) through adopting fast reactor code systems to external source driven subcritical systems. Moreover FZK is designing interesting multiple-target core designs, KFA Jülich is developing its original liquid Lead, thermal neutron spectrum ADS. FZK is currently launching quite large project on liquid Pb/Bi thermal hydraulics.

In the Netherlands, since 1991, the NRG Institute (former ECN) in Petten has had a transmutation research programme which is referred to as RAS. The aim is to contribute to international research on transmutation and fuel recycling and o show whether it is possible to introduce such a process in an acceptable manner in the waste management system. After an initial review of the project, the Government has approved a continuation (1994-1997) of the project which will aim at evaluating the technical possibilities and risks of partitioning and transmutation and at proposing a possible strategy for waste management.

Spanish universities and Spanish industry have recently (1996-1998) launched a research programme concerning accelerator-driven systems in co-operation with CERN. First was the co-operation in the form of a company founded through the LAESA consortium, whose primary task was to convince the local population and the Spanish Government of the need to construct a prototype of CERN's energy amplifier on Spanish soil in Zaragosa. Now, collaboration within the French-Italian-Spanish agreement on Energy Amplifier coordinated research is the common platform for current research.

In South Korea, Since 1992, a long-term research project has been in progress at KAERI (Korean Atomic Energy Research Institute) with the aim of developing a method for reducing the radiotoxicity of high-level waste [25]. This programme comprises the evaluation of data, the study of the possibility of transmuting heavy actinides in PWRs, the development of codes for the calculation of transmutation rates and the design of transmutation systems. Conventional reactors, fast reactors and hybrid systems consisting of a subcritical reactor and an accelerator are being studied. In 1997, the programme was reviewed and a decision was made that research on accelerator-driven systems will be one of KAERI's main areas of work up to the year 2007.

The Czech Republic has considerable experience of molten salt and pyrometallurgical methods and therefore accelerator driven-systems can be considered to be a possible solution to the problem of nuclear waste management in a densely populated country. The research institutes and the industry (SKODA) have formed a consortium to co-operate on the development of techniques for molten salts and are planning a complex experiment called LA-0 to test a number of parameters in a fluoride-based subcritical reactor and related chemical processes. Furthermore, the Czech Republic will arrange a conference on accelerator-driven transmutation technology and applications in 1999.

In Belorussia, an interesting experiment is currently being conducted at the Institute of Radiation Physics and Chemistry in Sosny with ISTC funding. A powerful 14 MeV DT neutron generator has been built and is being used to measure transmutation rates for fission products and actinides in subcritical cores with different neutron spectra. This experiment will be significant in the validation of code systems and cross-section databases.

3.9. European Union (EU)

The European Union has launched in 1994 a specific programme on Nuclear Fission Safety in the Framework Programme for the European Community (1994-1998) [25] covering research activities on reactor safety, radioactive waste management and disposal and radiation protection. Research projects in partitioning and transmutation were divided in three research tasks: strategy studies, partitioning techniques and transmutation techniques. Nine projects have been covering these tasks with five in the field of strategy studies, two in partitioning techniques and two in transmutation techniques. They involve different European research organisations, which are partly funded by the European Commission.

3.9.1. Impact of Accelerator Based Technologies on nuclear fission safety.

The research project ”Impact of Accelerator Based Technologies on nuclear fission safety” (IABAT) is being funded by the European Union and was started in 1996 with 11 participating institutes/universities from six countries. The project has been divided into four parts:

- System studies of accelerator-driven hybrid systems.
- Evaluation of accelerator technology with cost estimation of circular accelerators.
- Basic cross-section and materials data.
- Studies of fuel cycles for accelerator-driven systems.

The main results of the project cover a wide spectrum of accelerator-driven system simulations and analysis, some basic theoretical work on core kinetics and also some experiments and nuclear data work. The results can be summarized:

- Development and validation of simulation tools: High Energy Transport + Monte Carlo/Deterministic Transport + Burn-up (and transient) modules;
- Development of the transport code systems including ”low energy transport” modules up to 150 MeV (or even 300 in the future);
- Fission yield measurements for ^{232}Th and ^{233}U fast fission, development of cross-section data libraries for medium neutron and proton energy (up to 150 MeV);

- Analysis of different conceptual designs leading to convergence to fast spectrum and liquid Lead or Pb/Bi-eutectic cooling; development of multiple spallation source ideas;
- Theoretical studies of ADS dynamics (interpretation of reactivity control, point approximation and space dependent dynamics), subcriticality control methodology;
- Accelerator performance analysis indicating serious problems for the reliability of accelerator-driven systems and thermal hydraulic caused by accelerator trips;
- Investiagations and better understanding of molten salt subcritcal systems

3.9.2. Neutron driven nuclear transmutation by adiabatic resonance crossing

The TARC project has been carried out by CERN as coordinator, Univ. Autonoma in Madrid, CNRS Grenoble and the Universities of Athens and Thessaloniki [26] as a part of much broader research on the Energy Amplifier carried out at CERN.

The main objective of the project has been a development of a new integral cross-section measurement method using so called adiabatic resonance crossing (ARC). The experiments have proved usefulness of Lead as diffusive medium in systems for incineration of isotopes having strong cross-section resonances, like ^{99}Tc and ^{129}I .

The project had 6 workpackages:

- Setting up of the Lead assembly and preparation and instrumentation of the beam line;
- Experiments on ARC including timing experiments (CeF_3 counters) and activation experiments (delayed γ counting);
- Study of advanced neutronics in Lead by electronic experiments, activation measurements and temperature measurements;
- Development of an appropriate formalism and computational tools for ARC;
- Conceptual design of an incinerating device based on ARC;
- Other applications of ARC

Moreover computational tools indispensable for the interpretation of the experimental data have been developed in parallel. The various detectors have been simulated and the results of simulation have been compared with experimental data in a systematic way. The final assessment of the experimental data confirms the possibility of incineration in an effective way the isotopes of ^{99}Tc and ^{129}I by using the ARC method, as well as extending this concept to other applications.

4. CONCLUSIONS

Development of Accelerator-Driven Transmutation Technologies has already become an exciting R&D topic of an interdisciplinary dimension, covering 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 recognized and common research and development programmes have been formulated and launched.

The most urgent topics to which fundamental nuclear physics can and should contribute are:

- 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)
- System design and studies leading to better design of ADS
- 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 hopefully may start quite soon. A future success of ADS research depends very much on a close collaboration between fundamental and applied sciences, particularly fundamental and applied nuclear physics and on the ability of addressing public needs, worries and hopes, as well as on ability to communicate between science&technology and general public. We do not necessarily need an enthusiastic spirit of the dawn of nuclear era. What we need is a serious research and open communication between the scientific community and the general public, without false promises, non-realistic hopes and neglected concerns. The goal of environmentally optimal energy supply for current and coming generations is too serious to be left only for emotions.

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