AN APPROACH TO ACCELERATOR DRIVEN THERMAL REACTORS AND INCENTIVES TO NUCLEAR DATA IMPROVEMENTS

V.D. Kazaritsky, P.P. Blagovolin, V.R. Mladov
(ITEP, Moscow, Russia)

8th Journees SATURNE
Accelerator applied to the Nuclear Waste Problem ,Saclay,May 5-6, 1994

AN APPROACH TO ACCELERATOR DRIVEN THERMAL REACTORS AND INCENTIVES TO NUCLEAR DATA IMPROVEMENTS

V.D. Kazaritsky, P.P. Blagovolin, V.R. Mladov

Institute for Theoretical and Experimental Physics (ITEP)
25 B. Cheremushkinskaja, Moscow, Russia 117259
Telephone : (095)125-0292
Fax: (095)123-6584
Internet: KAZARITS@vxitep. itep.msk.su

ABSTRACT

A synergetic accelerator-reactor system capable of drawing all thorium resources rnto nuclear power is considered. Such resources are practically inexhaustible. The transuranium contamination by thorium-uranium fuel cycling is well below the uranium-plutonium contamination. If fluid fuel is used , reprocessing of the fuel m the closed cycle maybe greatly simplified. Nuclear safety of operation on fluid fuel is expected to be ensured with subcritical regime, the neutron balance being sustained by an external source based on an accelerator of intermediate energy protons. Besides being a prospective fast breeder alternative, the hybrid accelerator-reactor system can at present time fulfil a safe and efficient incineration of all built plutonium and minor actinide stock . Incentives to extension of estimated nuclear data pertaining to the field are discussed.

INTRODUCTION

Even though the existing nuclear power m Russia is based on enriched uranium, the outlook of the nuclear power is associated mainly with the concept of a closed nuclear fuel cycle involving spent fuel reprocessing, reuse of recovered uranium and plutonium combined with monitored storage of waste. The fuel cycle is expected to decrease the radiotoxic material losses m the reprocessing, to concentrate nuclear engineering sites, to decrease irradiated materials shipment. Besides, waste partitioning followed by transmutation of the most hazardous fractions is believed to cut the long-lived radioactivity of the storage. Transuraniums and several long-lived fission products are classed with the most hazardous wastes. Transmutation is practicable only if the amount of transmuted products is cut by several orders of magnitude. That can only be achieved through repeated transmutation within a closed cycle realized as an entire partitioning and transmutation chain.

Some countries have already initiated the uranium-plutonium closed fuel cycle on fast breeders. But the reactor core, blanket and other parts of the fuel cycle of a fast breeder contain a great quantity of highly toxic plutonium (several tons per 1 GWe).

The whole plutonium mass circulates around the reprocessing path,. which makes it difficult to avoid losses of the plutonium and other actinides. The level of the losses must be very low. While several facilities are currently operating in the world on the scale required to process plutonium and to fabricate MOX fuel, all of them were not designed with inherent capability to ensure that the concentration of *a – waste* be sufficiently low m the final disposed waste form.

We assume that conditions for minimal losses of radioactive materials and a low steady-state inventory of the most hazardous long-lived radionuclides can be ensured by fission reactors on fluid fuel with a high thermal neutron flux, where an external neutron source driven by an accelerator can furnish nuclear safety and further use of waste actinides as fuel.

I. SYNERGETIC SYSTEM ALTERNATIVE TO FAST BREEDER

If fast breeders dominate m future nuclear power, the problems connected with the fuel cycle losses are certain to have strong repercussions. Alternatives must be looked at carefully from the standpoint of fuel cycle radiotoxicity. The most radical means for getting rid of the most toxic nuclear wastes is not to generate them, which can be achieved by a change to thorium-uranium cycle. If a reactor operates on uranium-233 fuel and its design makes it possible to remove fast the protactinium produced from the thorium (for example, with circulating fluid fuel), the waste reduction can be several orders of magnitude as compared to uranium-plutonium cycle on solid fuel. If accelerator driven conversion of thorium to uranium-233 solves the problem of breeding fuel for thermal reactors on thorium-uranium cycle, it will be enough to develop only the reactors recovering no more than 80-90°/0 of the fuel.

In going to the thorium-uranium cycle, the plutonium and minor actinides produced previously should be burnt down. Proposals on accelerator based plants for burning excess weapons and power plutonium were discussed [1,2]. The proposals might be interpreted as objections to developing future nuclear power entirely on fast reactors, for the bum-down of thermal reactor spent fuel plutonium means an elimination (or reduction) of a natural basis for running fast breeders.

We advocate an approach alternative to the fast breeder one. The approach is concerned with a synergetic system operating in the closed fuel cycle with enhanced safety and reduced environmental burden. The system is expected to use the following types of plants:

1) a power plant for burning down plutonium, minor actinides and the most hazardous fission products ;
2) a plant for producing uranium-233 to feed thermal reactors;
3) a power plant on thermal reactors for burning up uranium-233 with a thorium-to-uranium-233 conversion close to 900A.

A. CONCEPTUAL DESIGN FOR BURNING DOWN Pu

We assume that transuranium waste should be burnt down m a subcritical blanket driven by an external neutron source that operates from an rntermediate-energy proton accelerator. A subcritical mode ensures nuclear safety at burning down the waste which is m fluid form: water solution, shiny or molten salt. A fluid fuel cycle of continuos feeding and discharging fission products is believed to make feasible the greatest possible bum-up not attainable for any fixed fuel. The heavy water moderated blanket is the most favorable system to form a high flux of thermal neutrons. Our proposal described in [3,4] is connected with burning down actinide waste in the blanket. The attendant radiolitic problems and catalytic recombination of radiolitic gases is discussed m [4].

The proposed configuration of a transmutation plant consists of 1 GeV-100 mA class accelerator driving several subcritical blankets. Each blanket has a channel of an accelerator driven neutron source surrounded by a regular lattice of power channels to burn up the fuel, remove the deposited heat and utilize the heat. All of these elements of the blanket are placed inside a cold heavy water tank. A distinguishing feature of the suggested fluid-fuel channels is that the fuel circulates inside the irradiation core and does not enter the external heat exchanger for cooling, while the fuel heat is removed with the help of pressurized water coolant.

To maintain an intensive and stable circulation of the fuel, there is a circulator with a turbo-drive transforming part of the coolant power. The closed path of the fuel circulating through the central pipe and the peripheral pipes of a smaller diameter to provide necessary heat exchange (the rate is about 0.5 x $10^6\,kcal / M^2 / hr$) is illustrated m Fig. While moving up from the pump-circulator to the top of the central pipe, the fuel (slurry or solution) gets warmed up. Moving down the peripheral bundle of pipes, the fuel is cooled by the coolant flow. A thick outside pipe holds the pressure inside the channel. All of the pipes are made of proven Zr-Nb alloys. A high neutron flux is maintained in the fuel core of the channels, from which the fuel is continuously drawn m small portions for chemical reprocessing and fuel make-up.

There are proposals on transuranium incineration in molten salt blankets [2,5]. A molten salt agent offers thermal-to-electricity conversion twice as high as the heavy water one considered above. The merits of molten salts are their radiation and thermal stability. The demerits are that their melting points are very high, which causes problems of the facility start-up, a safe and stable operation of the piping and the heat exchanger. The fuel cycle chemistry is not sufficiently developed m order to treat plutonium and minor actinides.

B. ON PRODUCTION OF URANIUM-233

We would like to design a plant for uranium-233 production as a simple and reliable facility with minimal neutron losses and m doing so advocate the idea of an uniform lattice of lead channels m heavy water, which are bombarded with the accelerator beam. Heavy water slurry (or nitrate solution) of thorium should be m the room among the channels. The produced protactinium should be isolated chemically. The rate of processing in 0.5-03 d^{-1} should offer reasonable purity of uranium-233. Fission does not take place m the heavy water, which simplifies the radiolitic gas problem The deposited beam power is not utilized here and the channels are cooled with NTP heavy water. By our tentative estimation more than 70% of spallation neutrons my be productively captured. Among other proposals, there are single fluid systems on molten salt bombarded by the accelerator beam [6]. In this case the proton-to-neutron conversion and thorium transmutation to uranium-233 go in the same molten salt. This design should keep the secondary waste as small as possible. An additional advantage is that the removal and isolation of uranium with the fluoride volatility process is a proven technology.

C. HOW TO BURN UP THE URANIUM-233

For burning up the uranium-233 there were many proposals of critical reactors economical of fissile materials [7]. Their technologies, as a rule, have been proven in the existing fuel cycles. Use of thorium is not considered to lead to any tangible modification of the reactors. Fluid fuel systems should be considered here interchangeably with the routine reactors. The systems proposed in section A *may* work for economical bum up of uranium-233. For good reason, preference should be given to systems, which along with the safest operation have the advantages of simple, proven and full processing fuel.

II. REQUIREMENTS FOR NUCLEAR DATA IMPROVEMENTS

Since the introduction of reactor calculations with computers it is the error of the related nuclear data that is the main error source. Early activity on nuclear data improvement was oriented to fast breeder projects. Several national and international programs were developed due to which the BROND-2, CENDL-2, ENDF/B-6, JEF-2, JENDL-3 universal libraries of estimated data of most isotopes were produced. All those files except special files for limited purposes, such as the ENDF/B-6 high energy data [8], contain information on the neutron interactions below 20 MeV. Similar work must be extended up to 2 GeV for servicing the applications of intermediate energy proton accelerators. We have got around to this field.

A. HIGH-ENERGY DATA PROBLEM

The target processes driven by rntermediate-energy proton beams are known to be analysed mainly with codes of the HETC type. The codes are based on intranuclear cascade and evaporation particle models. They inherently produce their own nuclear data to use m the code transport part for simulation of internuclear cascades. The intranuclear cascade models, being m essence half-phenomenological, provide a description of fast particles that are scattered with quasi-free particles of nucleus and give rise to a secondary particle cascade. The cascade is run down until all of the scattered nuclear nucleons and new-born particles have escaped from the nucleus. The final stage is nuclear evaporation and fission, which compete with each other. Over all the stages, the described interaction processes go statistically. To get statistically reliable information about the particles escaping from the nuclei one must simulate a great number of the interactions.

In contrast to the above mentioned, the phenomenological models, based on approximation of experimental and theoretical information, describe double-differential cross sections of non-elastic hadron-nuclear interactions. High-energy particle transport codes, giving rise to particles with the help of inclusive method, have long been m use of accelerator shield calculations [9,10]. These and other approximations for the reaction cross sections [11] can be used as a means for extension of the estimated data files mentioned above. Some kinds of the approximations could be developed for the special purpose of transport simulation with Monte Carlo methods.

Nucleus evaporated neutrons have got mainly the energy as lower as 20 MeV. These neutron tracks are further followed with the methods developed for nuclear reactor neutronics, the estimated nuclear data files can be used.

B. SENSITIVITY ANALYSIS ROLE

In [11] there is a proposal of subjecting the field of 20-100 MeV to the same procedures of estimation as that have been used m the 0-20 MeV field. It is not evident that such an extension is sufficiently large so that a tangible accuracy in the calculation might be gained. A sensitivity analysis is expected to help m the most important range and cross sections identification. Sensitivity studies have already proved useful m the evaluation of nuclear data needs for reactor and shield designs.

Hadron-cascade calculations of cross-section uncertainty effects on the estimates of the facility parameters are difficult to realise. To begin with the calculations can be carried out with the most simplified methods from those developed in reactor application studies ranging from "direct" calculations of cross-section uncertainty effects to more detailed and systematic studies of parameter sensitivities based on generalised perturbation theory [12].

In estimation of accelerator driven facility performance a "variable separation" is often used, in which the most critical characteristics maybe represented as a product of proton-to-neutron conversion coefficient into values connected with low-energy neutron multiplicity coefficient and associated cross-sections. With the help of this approach a sensitivity analysis may be performed on two (high-energy particle and low-energy neutron) components m tandem along with the advantages of using the existing methods for the energy range below 20 MeV.

C. LOW-ENERGY-NEUTRON DATA STATUS

Due to the tandem calculations mentioned above requirements for data of low-energy neutron cross sections m the blanket and requirements for the high-energy data may be considered separately. By a blanket we mean a facility's part which is more complex than a target and contains neutron converted materials. If the target is integral to the blanket, then by blanket processes we mean the processes induced by below-20 MeV neutrons. At present time universal estimated nuclear data files contain (or may contain before long) information on all nuclei drawn rnto transmutation processes or promising fuel cycles. A deficiency of experimental data on minor actinides is compensated with the calculation based estimates.

Specific requirements for the blanket performance estimate accuracy, which is determined by subcritical mode operation, have not been studied m detail. The requirements are considered to be the same as those for critical reactors of a suitable type. As for thermal reactors, the reactor calculations have long been based on few-group constant libraries, whose parameters were often adjusted with the results of critical experiments. In the whole world there takes place a progressive change to thermal reactor calculations based on universal libraries of estimated cross sections that are low sensitive to a specific reactor type. But as indicated m a comprehensive review of nuclear data for thermal reactor calculations [13], estimated data files can not be considered as the best and especially as the only information source of cross-section libraries for thermal reactors.

This is primarily true m regard to cross sections of unresolved resonances. Information m this region remains on frequent occasions unreliable and conflicting. For now, estimated nuclear data cannot compete in accuracy with many-group constant libraries [14], except that use of those libraries m thermal reactor calculation may result m errors of neutron capture estimation for resolved resonance region, since the libraries' data have been forced to fit fast breeder benchmarks exclusively. Calculations in the neutron thermalization field often present difficulties. There are not many thermal reactor benchmarks [15]. Moreover the data allows to check only U-235 and U-238 cross sections. Limited information is obtained with critical facilities on low Pu-239 content fuel and with subcritical facilities on U-233 and thorium fuel.

In conceptual studies of subcritical blankets on fluid fuel extension of nuclear data on construction materials has not yet taken place. Such studies are generally based on an actinide transmutation analysis, which invites further improvements in transuranium data for thermal-neutron induced fission spectra. The improvements can make it possible to calculate trustworthy both average prompt and delayed neutron yields, average cross sections of neutron capture with fission products, the radio-activity and the decay heat from irradiated fuel or transmuted compositions etc. Depending on the expected mode of irradiation, fuel circulation and processing, accuracy requirements imposed on the data may differ.

CONCLUSION

A synergetic accelerator-reactor system capable of drawing all thorium resources rnto nuclear power is considered. The advocated approach is alternative to the fast breeder one. The synergetic system can operate in closed fuel cycle with enhanced safety and reduced environmental burden. It consists of several types of plants that should bum down plutonium and minor actinides, should produce uranium-233 to feed thermal reactors and should burn up uranium-233. Transuranium contamination by a thorium-uranium fuel cycle is expected to be well below the uranium-plutonium contamination. Fluid fuel offers the advantages of simple and full processing. The nuclear safety of operation on fluid fuel is expected to be ensured with a subcritical regime, the neutron balance being sustained by an external source based on an accelerator of intermediate energy protons. Besides being a fast breeder prospective alternative the hybrid accelerator-reactor system can at present time fulfil a safe and efficient incineration of all built plutonium and minor actinide stock. A conceptual design of accelerator driven blankets needs extension of estimated nuclear data on the higher energy range, invites further improvements m transuranium data and m the data for studies of the thorium-uranium cycle with various modes of irradiation, fuel circulation and processing.

REFERENCES

1. M. Cappiello, J. Ireland, J. Sapir, B. Krohn , "Los Alamos Aqueous Target/Blanket System Design for the Accelerator Transmutation of Waste Concept", Proceedings of International Conference and Technology Exhibition on Future Nuclear Systems : Emerging Fuel Cycles and Waste Disposal Options, September 12-17,1993, Seattle,Washington,v. 1,pp. 397-401.
2. R.J.Jensen, T. J. Trapp, E.D.Arthur, J. W. Davidson, R.K.Linford, "Accelerator-Based Conversion (ABC) of Reactor and Weapons Plutonium",ibid.,v.2,pp. 833-841.
3. V. D. Kazaritsky, P. P. Blagovolin, E.A.Zolotarjeva, V. R.Mladov, E. S.Nicolaevsky, M. L. Okhlopkov, "Plutonium-Doped Incineration of Minor Actinides m Fluid Fuel Elements of Accelerator Driven Heavy Water Blanket", Preprint ITEP, No.72, Moscow, 1993. (m Russian)

4. V. D. Kazaritsky, P. P. Blagovolin, V. R.Mladov, M.L. Okhlopkov, E.B. Strakhov, "Problem of Fluid Agent for Blankets with Fuel Circulation", Preprint ITEP, No.20, Moscow, 1994. (m Russian)
5. V. D. Kazaritsky, KFurukawa, G. V. Kiselev, N. Hirakawa, "Practical Treatment of Minor Actinides by Single-Fluid Molten Salt Reactor Concepts", Proceedings of International Conference on Design and Safety of Advanced Nuclear Power Plants, October 25-29, 1992, Tokyo,vol. 1, pp.P3.8-(1-5).
6 .K.Furukawa, K.Tsukada, Y. Nakahara, "Single Fluid Type Accelerator Molten Salt Breeder Concept", Journal of Nuclear Science and Technology, 1981, v. 18,N1,p.79.
7. V. M. Murogov, M. F. Troyanov, A.N. Shmelev, "Use of Thorium in Nuclear Reactors", Energoatomizdat, Moscow, 1983.
8. Nuclear Data Newsletter, IAEA, ISSUE No. 18, November 1993.
9. I. S. Bayshev, S. L. Kuchinin, N. V. Mokhov, "Monte Carlo Calculation of Three-Dimensional Hadron Cascades at the 20 MeV- 3000 GeV range, Preprint IFVE-ORI 78-2, Serpukhov, 1978. (m Russian)
10. B.S. Sychev, A.Ya. Serov, B. V. Manjko, "Analytic approximation of double-differential cross sections of non-elastic hadron-nuclear interactions at energies as more as 20 MeV, Preprint RTI-799, Moscow, 1979. (m Russian)
11. A. J.Koning, "Review of High-Energy Data and Model Codes for Accelerator-Based Transmutation", Nuclear Energy Agency (OECD) report NEA/NSC/DOC9(92)12, 1992.
12. L. N. Usachev, "Perturbation Theory for the Breeding Ratio and for other Number Ratios pertaining to Various Reactor Process", J. Nuclear Energy, A/B, 18, 571 (1964).
13. L. V. Mayorov, M. S. Yudkevich, "Neutronics Constants for Calculations of Thermal-Neutron Reactors", M, Energoatomizdat, 1988, (Nuclear Reactor Physics and Engineering, issue 34) (in Russian)
14. Group Constants for Reactor and Shield Calculations: Hand-Book/ L. P. Abagyan, N. O. Basasyants, M. N.Nicolaev, AN. Tsybulya: Ed. by M.N. Nicolaev, Moscow, Energoizdat, 1981. (in Russian)
15. Thermal Reactor Data Testing and Applications Subcommittee, ENDF/B-V Data Testing Report, 1981.

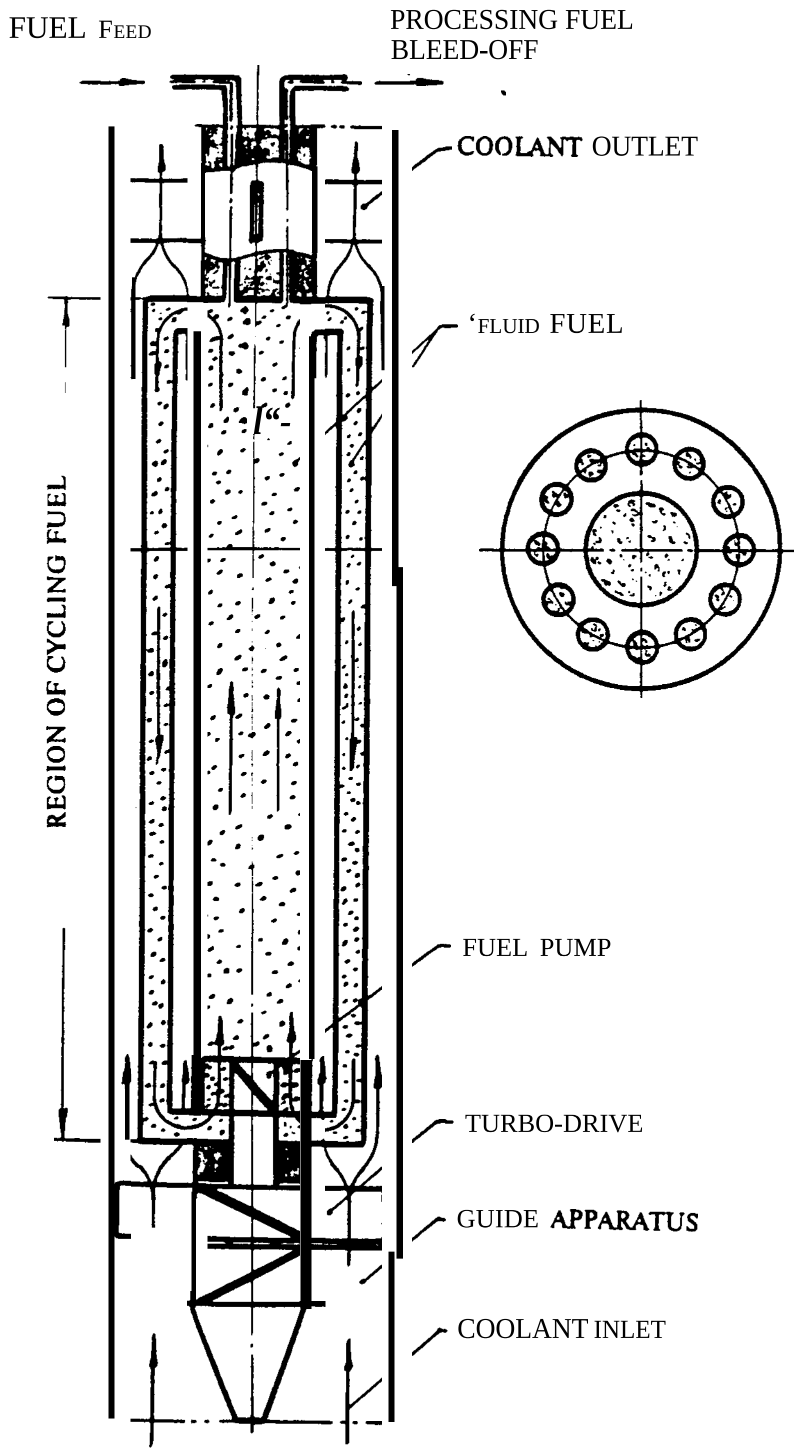

FIG. CONCEPTUAL DESIGN OF CYCLING FUEL