COUPLED FAST / THERMAL SPECTRUM SUBCRITICAL BLANKET FOR ADS

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ABSTRACT

The technical problem of long-life fission products and minor actinides incineration, production of energy in the prospective nuclear systems will arise at significant scales of nuclear power industry development. Subcritical nuclear reactors driven by external neutron sources are considered as incinerators of toxicity of nuclear industry with simultaneous energy production: fission-fusion hybrids, accelerator driven systems (ADS). In the frames of this concept, the subcritical reactor part for ADS consisting of two coupled blanket regions (inner fast neutron spectrum core and outer thermal core) driven by spallation neutron source is discussed. Such a "cascade" energy amplifier has a set of advantages in energy production, transmutation efficiency and therefore in economics in comparison with traditional concepts of "single" spectrum ADS blanket.

1. INTRODUCTION

Several concepts of nuclear installations have been developed for subcritical blankets controlled by external neutron source: fission-fusion hybrids, including laser-driven inertial confinement fusion power reactors [Ref. 1] and magnetic thermonuclear reactors [Ref. 2], accelerator driven systems [Ref. 3]. These systems could be used for safe production of thermal and/or electric power and transmutation of long-lived products existing in radioactive wastes, involvement of weapon grade plutonium into the energy production and fuel cycle, etc.

Deep subcriticality of blanket eliminates a possibility of global reactivity accidents (uncontrolled power bursts caused by spontaneous fission chain reaction). Subcritical reactor is controlled by external neutron source, which could be easily "switched off" by operator or automatic safety system. Consequences of transients in the blanket core after the shutdown of neutron source depend on the level of its subcriticality only. Decay heat removal capability depends only on the power density of the installation. Radioactivity confinement in ADS is provided by "barriers" like in commercial power reactors: subcritical reactor vessel, containment, etc. Subcriticality also makes it possible to be more flexible in isotope composition of the blanket, its type (molten salt, solid fuel, various coolant types) and neutron spectrum in the core. It is very suitable option for burning/transmutation tasks. So, the main advantage of ADS is the subcritical core. However, high level of subcriticality means more powerful external source of neutrons, and therefore the large value of required accelerator proton beam current. The initial accelerator uses output electric power, but blanket generates a thermal energy which could be converted into electricity by steam generator and turbines with efficiency up to maximum value 40%. Further, the electrical power could be transformed into the power of proton beam with limited efficiency (see Fig.1). Furthermore, fraction of output electrical energy must be destined to the grid at the competitive price level.

The main problem is to construct ADS as energy-self-sufficient systems using technically feasible high intensity accelerators. High current accelerators are also very expensive devices that could avoid all advantages of ADS from economical point of view. There is permanent trade-off between value of accelerator beam current and subcriticality level of blanket. Thus, one of the main problems of ADS blanket concepts is to optimally combine these alternative parameters: to essentially increase a production of fission energy in the blanket core without rise in the neutron output from the source and without increasing level of subcriticality. How to achieve it? It is possible to solve this problem and achieve more efficient energy production in the coupled fast/thermal spectrum subcritical reactor for ADS. The system consists of a coupled fast and thermal fissile deeply subcritical cores driven by a neutron source. The blanket concept is based on the principle of the "cascade amplification" of neutrons from a source.

2. CONCEPT DESCRIPTION

The accelerator driven system consists of an proton accelerator (LINAC or cyclotron), a target and two-section subcritical blanket system (Fig.1).

The idea of cascade amplification is to obtain the maximal fission energy per single source neutron in a one-directly coupled, from "fast" to "thermal", subcritical fissile zones of a blanket [Ref. 4]. A fast spallation source neutrons are multiplying in inner fast zone with production of energy (so-called first cascade of amplification), then the leakage fast neutrons transported into outer thermal region are moderating and multiplying with fission energy production (second cascade of energy amplification). The boron coating of inner fast core makes it possible to capture a thermal leakage neutrons from outer blanket zone. Fast neutrons could pass over the boron, so the feedback neutron coupling is about zero value (like in the diode, where electrons can flow only in one direction). In our case, inner subcritical fast blanket core behaves oneself as a reactor with the high leakage of neutrons, controlled by external source inside its core and surrounded by reflector (outer core). Outer thermal reactor behaves oneself as a reactor with external source inside its core (this source is formed by leakage neutrons from inner fast core). The level of subcriticality of such one-directly coupled dual-spectrum system (or K_{eff} value of whole system of these two cores) depends on subcriticality of its coupled parts and neutron exchange between them. Physics of these processes is discussed in detail in Refs.4,5.

The operation mode of system is as follows. Proton beam with energy W_p watts transported from an accelerator into the target initiates the spallation reaction with neutron emission. Neutrons produce the chain fission reaction in the first cascade of amplification of blanket with production of fission energy E_1. Fast neutrons leak from the fast blanket core through boron shield produce chain fission reaction in second amplification cascade with production of fission energy E_2. Coolant system of both cascades absorbs a released fission energy (E_1 and E_2), and then traditional steam-generator and turbine systems convert thermal energy W_1+W_2 watts into the output electric power $W_{el}=(W_1+W_2)\cdot h_e$ watts with efficiency $h_e \approx 0.4$. Low-potential thermal energy is utilized. A fraction 1-X of W_{el} is destined to the grid. A fraction X of W_{el} is used to feed the proton accelerator and converted into proton beam current of energy W_p with conversion factor$\cdot h_p \approx 0.5$. The fast/thermal blanket "amplifies" energy with a gain $G=(W_1+W_2)/W_p$. It is important to note that the proposed system could operate in two modes, pulse-periodical mode and steady-state mode. Expressions for interrelationship of "amplification" factors of whole system and both cascades, neutronics parameters of system (K_{eff} of whole coupled system, multiplication factors of both cascades, coefficients of neutron coupling between them) and neutron source output were obtained in Ref.4 for both modes.

A prototype of the coupled fast/thermal blanket system for ADS which produces 100 fissions per one neutron produced by spallation target is shown in Fig.2. The internal blanket zone is a subcritical fast core (uranium dioxide fuel enriched by 26 %). The core is cylindrical (height 130 cm, and diameter - 138 cm) with an internal axial cavity (diam. 48 cm), which is designed to contain the target, the beam guide and window, etc. In order to reduce the coupling coefficient of the thermal blanket to the fast blanket, the fast blanket is surrounded with a 1-cm thick coating filled with boron carbide of natural enrichment.

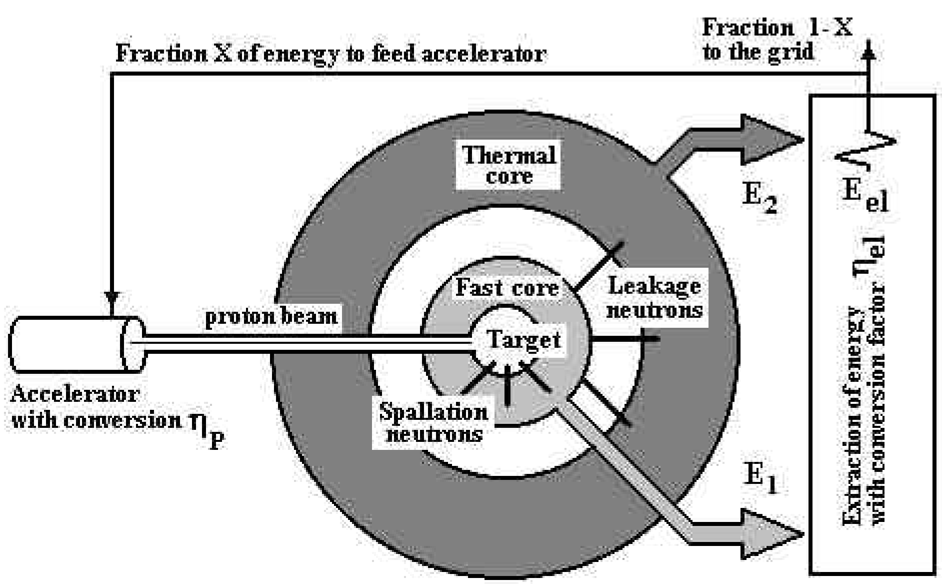

Figure 1. Schematic of the ADS.

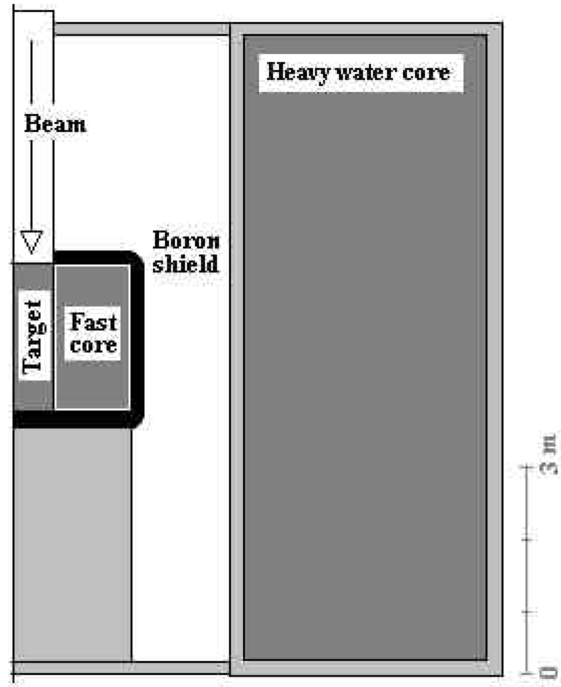

Figure 2. Coupled fast/thermal spectrum blanket system.

To remove the heat released as a result of nuclear reactions, the fast blanket's core is supplied with a metal Pb-Bi cooling system. The same liquid metal is considered as a target material. The external blanket zone is a subcritical heavy-water reactor with a thermal neutron spectrum containing fuel pins consisting of aluminum pipes (0.0838-cm thick; external diameter - 1.1506 cm) filled with uranium of natural enrichment (~0.7 %). The pins are placed in a triangular lattice (step - 3.806 cm) inside a cylindrical steel tank filled with heavy water. The external radius of a tank is 425 cm, internal radius - 250 cm, the thickness of the steel wall - 3 cm. The top and bottom of the system are closed with a 3-cm thick beryllium neutron reflector.

So, all reactor technologies used in this ADS blanket design are feasible, tested during years of operation and commercially available.

3. FISSION ENERGY PRODUCTION

The power parameters and neutronics of coupled fast/thermal blanket for ADS, which make it possible to provide the multiplication of source neutrons by factor 00, are studied in detail for both the steady-state and pulse-periodical operation modes using the codes for computation of neutronics (Monte Carlo method) and dynamic parameters. The elaborated mathematical models and software were tested on steady-state and unsteady-state experiments using special critical assembly and twin-core pulse reactor coupled with thermal module and shown to be adequate [Refs. 6,7].

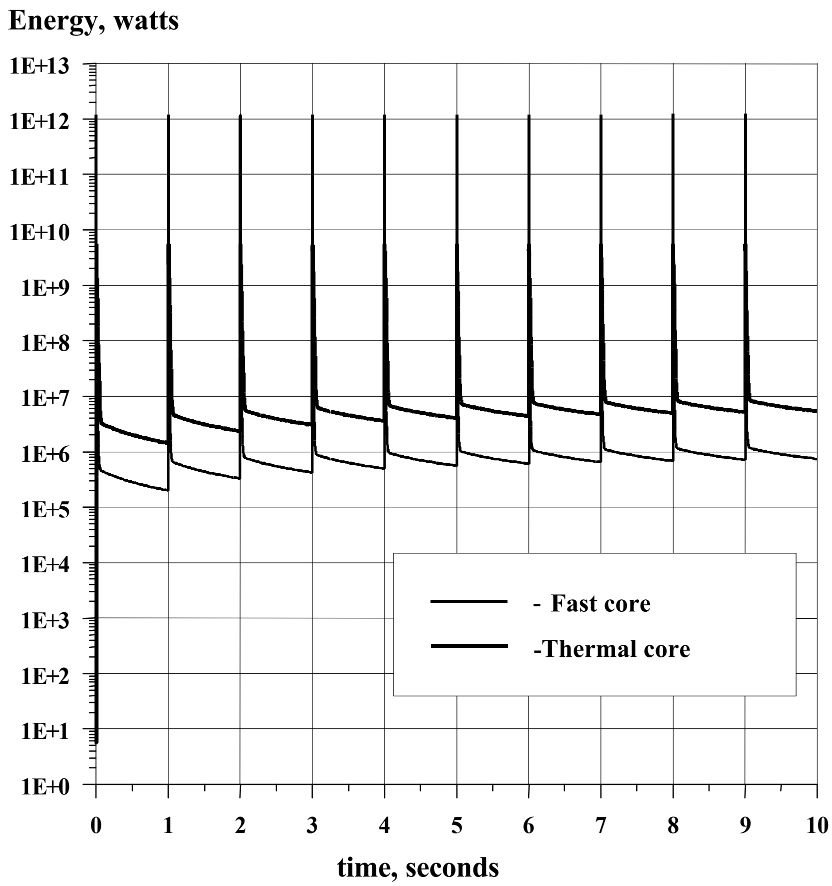

Figure 3. Transient processes in blanket zones for pulse-periodical mode.

Table 1. Parameters of ADS with thermal power output 1 GWth.

Parameter	"Single" spectrum blanket	Fast/thermal spectrum blanket
K_{eff} of the blanket	0.96	0.96
Number of fissions in the blanket per one source neutron	10	100
Power of proton current with energy 500 MeV, MW	30	3

The multiplication values for fissions in inner and outer blanket zones and the whole system produced by one initial thermonuclear neutron from the spallation target were evaluated. Note that it is possible to interpret these parameters as multiplications in the first and second cascades of amplification, respectively. The dependencies multiplication factor of the system of blankets on change of feedback neutron coupling coefficient were analysed under conditions where net system multiplication is 100. For the system mentioned above, multiplication factors are ~0.95 for both cascades of blanket, direct "fast-thermal" coefficient of neutron coupling between them is 0.25, feedback coefficient of neutron coupling is $1.6 \cdot 10^{-3}$. The K_{eff} of the whole two-cascade blanket is 0.96. It is clear (see Table 1) that it is possible, using "cascade" principle, to achieve in deeply subcritical (K_{eff}=0.95-0.96) coupled system more high power output, up to 10 times in comparison with traditional "single" core under the same multiplication factor, then the source requirements (or proton current value) could be essentially reduced. Example of transient processes in blanket zones for pulse-periodical mode with proton accelerator frequency 1 Hz is shown in Fig.3. Both these features might be very useful for charge particle accelerators from economical point of view, too.

4. BURNING AND TRANSMUTATION

The coupled blanket system utilizes the fast and the thermal cores in one reactor unit, which might be effectively used as for burning/transmutation of long-life fission products, as for minor actinides and weapon graded plutonium. Lets show it on the example of burning of spent fuel unloaded from LWR commercial reactors, i.e. mixture of heavy nuclei with high percentage of americium and curium, and some portion of lantanides.

Burning of technetium is complicated by its cross-section blocking in large volume without a moderator. Energy dependencies for cross-section of radiation capture of Tc^{99} and iron are shown in Fig. 4. Cross-section for iron is shown for illustration of feasibility level of such a method of burning of long-lived fission products. It is clear that probability of burning of technetium and probability of activation of reactor hardware materials have the same value. There is only one way to increase the part of burned out Tc^{99} and decrease the unproductive loss of neutrons: effective "softening" of spectrum up to energy level about some dickers of eV. So, "single" hard spectrum core is not effective for burning of technetium.

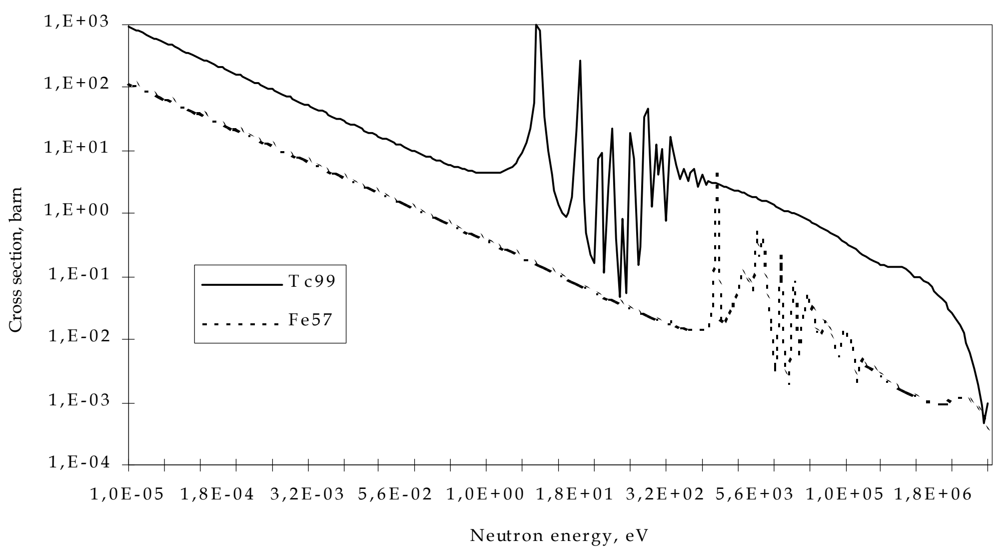

Figure 4. Energy dependencies of radiation capture cross-sections for Tc^{99} and Fe^{57}.

Waste stream of the dual fast/thermal spectrum blanket might be separated into fast and thermal cores and have an optimum effect for the transmutation rates. The scenario of burning of minor actinides in the fast spectrum inner core and burning of technetium in thermal spectrum core with heavy water moderator is studied. Inventory calculations were performed using precise code with sensitivity analysis for application of systematic approach of fuel cycle analysis [Ref. 8].

One of strong reasons for using the hard spectrum for incineration of minor actinides is high thermal energy release of spent fuel. Dependencies of relative growth of thermal power release of spent fuel because of reactions of radioactive decay are shown in Table 2. It is clear that some problems could appear for cooling of spent fuel during burning process. Such a problems could be solved by using of fast reactor technologies.

In Tables 3 and 4, relative change of amount of heavy nuclei and technetium are shown for the scenario of burning in two cores of dual neutron spectrum blanket. As mentioned above, it is needed to burn minor actinides in fast spectrum core. Here, burning process spreads over seven years with following exposure during four years. It is possible to burn technetium in both thermal spectrum and hard spectrum. But is it is clear that burning of technetium in thermal spectrum is more effective and its amount is substantially decreased in comparison with hard spectrum.

In our opinion, possibility of synchronous incineration of minor actinides and long-lived fission products is the main advantage of such a system with dual spectrum cores. Another important features of this system might be the possibility of reduction of protactinium effects in thorium fuel cycle [Ref. 9] and reduction of inventory of neptunium and its impact to the long-term radiological hazard in comparison with the "single" hard spectrum blanket.

Table 2. Relative growth of thermal power release of spent fuel.

Time, Years	Cm, %	Am, %	Pu, %	U, %	Np, %
0	90	1	8	0	0
1	173	10	18	0	30
2	157	8	18	0	22
4	107	6	16	0	11
7	62	4	12	0	4
11	32	3	7	0	1

Table 3. Relative change of amount of heavy nuclei during burning process.

Time, Years	Am, %	Cm, %	Pu, %	U, %	Np, %
0	100,00	100,00	100,00	100,00	100,00
1	88,96	94,56	86,40	99,54	71,02
2	79,90	81,63	75,03	98,48	50,38
4	66,07	56,69	56,64	94,36	25,52
7	51,25	31,01	36,99	83,29	9,52
11	36,52	13,41	20,87	64,10	2,96

Table 4. Relative change of amount of technetium during burning process.

Period of burning, years	Heavy water core, %	Fast spectrum core, %
0	100,00	100,00
1	17,41	90,25
2	3,03	81,45
4	0,09	66,34
7	0,00	48,76
11	0,00	32,35

CONCLUSIONS

Fast/thermal spectrum "cascade" energy amplifier has a set of advantages in energy production, transmutation efficiency and therefore in economics in comparison with traditional concepts of "single" spectrum ADS blanket. Such a blanket makes it possible to achieve in deeply subcritical coupled system more high power output in comparison with traditional "single" core under the same multiplication factor K_{eff}=0.95-0.96, then the spallation source requirements (or value of proton current) could be essentially reduced, up to 10 times. Small current value reduces the radiation damage of the beam window and target assembly. ADS blanket could operate in two modes, pulse-periodical and steady-state. These features might be very useful for charge particle accelerators from economical point of view, too. The coupled fast/thermal blanket utilizes the fast and the thermal cores in one reactor unit, which might be effectively used for both burning/transmutation of long-lived fission products and minor actinides. The coupled cores have a high level of inherent safety: the system is always deeply subcritical, neutron leakage from the system is very low, and it is not necessary to provide complex control and shielding systems. Further, the heavy-water core makes it possible to use uranium of natural enrichment.

It should be noted that so high energy gain makes it possible to consider coupled fast/thermal subcritical blanket for applications which were impractical because of low neutron output from a source available for current level of accelerator technology.

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