NEW ORIGINAL IDEAS ON ACCELERATOR DRIVEN SYSTEMS IN RUSSIA AS BASE FOR EFFECTIVE INCINERATION OF FISSION PRODUCTS AND MINOR ACTINIDES

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Abstract

The analysis of original ideas on ADS proposed by Russian specialists in the last time is given for a joint consideration by specialists dealing with ADS. Ideas are concerned by the following problems of ADS design: accelerator, target, sub-critical blanket, sectioned blanket, necessity of high neutron flux for transmutation of long-lived fission products and minor actinides, two-blanket installation with fluid fuel, denaturation of weapon-grade plutonium by joint irradiation with neptunium, use of secondary nuclear fuel in ADS with reduced requirements to level of purification of spent fuel.

1. Introduction

During the last years leading Russian nuclear centres conducted conceptual researches of various variants of electronuclear installations (ADS). This study stimulated occurrence of a number of original technological ideas, directed on improvement of the characteristics ADS with the purpose, first of all, of the effective destruction of long-lived radioactive waste (LLRW). The review of these offers is not only a question of priority but is also of interest for the development of ADS future projects. In the beginning of the review the author presents a brief description of ADS technological schema with an indication of the current problems related to the realisation of ADS.

2. General aim of ADS

From the author's point of view, the main purpose of ADS consists of the effective destruction (transmutation) of long-lived products of fission (FP) and minor actinides (MA) up to level at which probably radiation – equivalent burial of LLRW – as it is offered by the experts of the RDIPE [1]. If to proceed from indicated purpose, it is necessary to develop the concept and, accordingly, design blanket with high flux of thermal neutrons, as it is shown in many papers of experts of the SSC RF ITEP and MEPI, see, for example, [2]. The creation of such high flux blanket by thermal capacity not less than 1 000 MWt with density of thermal neutron flux 10^{15} $cm^{-2}c^{-1}$ and higher with small campaign for fuel is already enough complex technological problem, even at modern level of nuclear engineering. However it does not reach the list of technological problems, claiming their decision and experimental study.

After these brief remarks, we shall pass to a compendious description of new, original ideas, concerning to ADS and formulated by the Russian experts in different time. We shall originally stay on exposition of the offers, relating to ADS blanket, as its design in many respects determines the basic schema and parameters of ADS.

3. Sub-critical blanket of ADS

3.1 Sectional blanket

It is possible to note without exaggeration, that really technically the revolutionary idea concerns to blanket of ADS, i.e. division of blanket on multiplied sections with one-sided neutron connection.

The idea of the neutron multiplier, stated for the first time more than 40 years ago by L.B. Borst [3], was originally supposed to be used in systems with "initiating" reactor for reception of higher burn-up for fuel in sub-critical sections and for reception of extremely high flux of thermal neutrons. In USSR Dr. B.G. Dubovsky from the SSC RF Institute of Physics Power Engineering (IPPE) in Obninsk has briefly considered this topic for the first time of activity on atomic power [4]. The significant theoretical contribution to development of idea of sectioning or connected reactors or reactors with one-sided neutron connection for pulsed systems and ADS was proposed by the experts of the Federal Centre Institute of Experimental Physics (FNC VNIEP, Arzamas-16) under management of V.P. Kolesov. In papers of experts of the FNC VNIEP a basic opportunity of essential increase of a level of multiplication of neutrons for an external source and decrease of requirements to proton's current in 5-10 times for sectional blanket with by loading of neptunium in first fast section was shown [5].

During conceptual investigations of ADS the experts of SSC RF ITEP N.M. Danilov, Yu.D. Kàtargnov, G.V. Kiselev, V.V. Kushin, V.G. Nedopekin, S.V. Plotnikov, S.V. Rogov and I.V. Chuvilo and the expert of the FNC Institute of Technical Physics (VNIITP), K.F. Grebenkin have offered a schema of ADS sectional blanket with compound neutron valve (NV) beginning 1993. The authors of this schema received the patent of Russian Federation with priority from 27.04.1993 [6]. According to the offered schema for the first multiplying section (2) of blanket of cylindrical form with fast spectrum of neutrons contains in centre of neutron-producing target, and on periphery – NV, separating from second of multiplying section with thermal spectrum of neutrons. Compound neutron valve NV consists of 2 parts: an absorber of thermal neutrons, for example, boron by thickness 2-5 mm, bounded with first multiplying section, and moderator of thermal neutrons, for example, graphite by thickness 30-50 cm, contiguous to second section, and is executed as continuous ring cylinder. The role of compound NV consists of maintenance unilateral neutron connection between sections of blanket. In result of investigations conducted by the various Russian experts it is possible to indicate following physical properties of sectional fast- thermal blanket:

- Multiplying property of thermal section poorly influence number of neutrons, born from fissions in fast section.
- The change of physical properties of thermal section poorly influences factor of multiplication for complete system.
- There is the limiting ratio between capacities of fast and thermal sections.
- There is the basic opportunity of decrease of a current of protons in case of realisation sectional blanket, by various estimations, from 2 up to 5 times.

However allocation of compound NV with layer of an absorber of neutrons, for example, from carbide of boron, results, first, in deterioration of the neutron balance in system, that, certainly, it is undesirable. Secondly, there is the problem of nuclear safety in case of probable emergency destruction of compound NV. Therefore expediently to consider a problem about optimum method of suppression of a feedback between sections, without essential deterioration of the neutron balance and maintenance of significance k_{eff} always it is less than unit in case of occurrence of an emergency and destruction compound NV.

In this connection the specialists of the SSC RF ITEP, G.V. Kiselev and MIPE V.A. Apse, G.G. Kulikov and A.N. Shmelev have conducted calculations of a compound NV, which does not worsen the neutron balance and at the same time provides sub-criticality of blanket in emergency. With this purpose was considered compound NV with use of depleted uranium oxide (first variant) and oxide of neptunium (second variant) in an absorber part NV [7]. It was shown (not staying on interesting and, at the same time, transparent physics), that the application of depleted uranium oxide does not provide necessary nuclear safety. Use compound NV, in structure of which was present oxide of neptunium-237, does sectional blankets of ADS completely safe at emergencies, as according to calculations destruction of a absorber layer of compound NV from oxide of neptunium results in reduction k_{eff}.

In paper of the specialists of SSC of the RF “Kurchatov Institute” P.N. Alekseev, V.V. Ignatjev, O.E. Kolayskin and other [8] is indicated opportunity of use of lanthanide’s GdF_4, SmF_4 as means for suppression of a feedback between sections of ADS blanket, which follows to include into structure first (fast) section, that completely, in their opinion, provides conditions of nuclear safety at emergency.

Other original proposal of the indicated above experts of the SSC RF ITEP and FNC VNIITP on sectional blanket of ADS concerns the mutual location of neutron-producing targets in sections of ADS blanket and use dipole triplet for management of a flux of protons [9]. In traditional configuration of ADS the neutron-producing target is placed in centre of vertical or horizontal blanket. In offered by the indicated authors [9] to the constructive schema of ADS some neutron-producing target in regular intervals place on volume external ring of multiplying section of the cylindrical form blanket. In each section are available CNV, passed through neutrons on direction from peripheral section to centre blanket, that permits to reach high density of a neutron flux in irradiated volume, were in centre of blanket, down to 10^{16} $cm^{-2}s^{-1}$. For realisation of this idea between horizontally located accelerator of protons, working in pulsing mode, and vertical blanket is entered so-called dipole triplet- system for distribution of a protons beam on targets. The dipole triplet consists from first dipole, executed in kind rotary on 90° magnets for change of a direction of a proton's beam from horizontal to vertically located target. The second and third dipoles of triplet serve for circular distribution of a proton's beam on targets and are executed in kind of a pair of high-cycling rejecting magnets, the phases of currents of which are moved on 90°, and the frequency F of sending of current pulses for start-up of the accelerator and frequency f of a current in windings of magnets are connected by a ratio F = nf, where number of targets n = 3-16. Availability of shift on phase 90° between currents in windings of magnets with frequency f, synchronised with frequency of repetition of accelerator pulses F, results in that a pulsing current protons turned on circle and the pulses of a proton's current consistently interact with neutron-producing target.

The authors of the patent [9] specify following advantages of the offered schema sectional blanket with dipole triplet:

- Basic opportunity of achievement of high density of a neutron's flux in irradiated volume, were in centre of blanket, that will allow to execute effective transmutation of LLRW.
- Opportunity of reduction of a accelerator current about in 10 times for three- sectional blanket with k_{eff} = 0,97 in comparison with traditional configuration blanket without sections, that will allow to reduce a proton's current and heat deposition of neutron-producing targets.
- To reduce consumption of power for supply of the accelerator at least in 5 times and more.

The main drawback of the indicated offer is the necessity of the introduction in ADS schema of appropriate blocking and additional trap of a proton's beam in case of loss of power supply or failures in dipole triplet operation. One trap of a proton's beam should be stipulated in any case at horizontal configuration of the accelerator protons and vertical blanket.

The important aspect of ADS nuclear safety provision during normal operation and transitive modes is the control of a level of blanket sub-criticality. This control acquires a special significance for ADS sectional blankets. For this purpose it is possible to use the offer developed by the experts of the SSC of RF ITEP N.M. Danilov, Yu.D. Katargnov, G.V. Kiselev, V.V. Kushin, V.G. Nedopekin, S.V. Plotnikov, S.V. Rogov and I.V. Chuvilo, on the use of special reactivity meter for sectional blanket and gauge of measurement of a current protons of the accelerator, the description of which is indicated in patent [10]. For illustration of the offered idea we shall consider three-sectional blanket of ADS with two CNV, passed through neutrons on direction from neutron-producing target to periphery of blanket. The reactivity meter for control of a sub-criticality level of each section operates together with gauge of a current protons and synchroniser mode of operations of the accelerator and consists from integrator-meter, connected through blocks of the co-ordination with neutron detectors, available a minimum on one in each multiplying section, block of formation of signals, block of

delay, interface and computer. The feature of the offered schema of measurement of a sub-criticality level consists that the pulse of a current in detector of neutrons in first multiplying section arises practically simultaneously with pulse from gauge of a proton's current. The pulses of a current in detector of neutrons in second and third multiplying sections are late on time of slowing down of neutrons in CNV. By estimation this time of delay makes about 100 ms for second section and can reach 200 ms for third section. According to it temporary characteristics of appropriate pulses of synchronisation in block of delay are established. At each pulse of a accelerator current the computer processes the indications of all integrator-meters and calculates current significances of effective multiplication factor $k_{ef.i}$ (t) for each multiplying section, which are compared with given benchmark size $k_{ef.i}$. By results of comparison a managing command on rods of system for monitoring and control is issued.

Expediently to develop the specific schema offered reactivity meter and to conduct its experimental examination in conditions of critical assembly. The proposed schema can be base for development of system of monitoring and control for ADS in future.

The idea on sectional blankets of ADS was investigated in various Russian nuclear centres during last years.

The experts of the SSC of the RF "Kurchatov Institute", P.N. Alekseev, V.V. Ignatjev, O.E. Kolayskin and others have offered fast-thermal cascade molten-salt blanket with two multiplying sections and internal properties of safety: in first section salt is used NaF53-$ZrF_4$41- MF_4 (4-6), in second section – LiF69-$BeF_2$28- MF_3 (3-5) (are indicated vol. shares) [8]. Using indicated sectional blanket permits to receive high multiplication of neutrons (before 1500), that enables to consider opportunity for application of electronic accelerators as external source of neutrons, though use proton's cyclotron, as means of reduction of the investments and operational costs is possible, on that specify the authors [8].

The experts of the FNC VNIITP under management of K.F. Grebenkin have offered the schema of ADS with unilateral connection in kind a multiplying target with k_{eff} = 0.95 and blanket with k_{eff} = by 0.92 and thermal capacities 500 MWt [11]. In one of variants loading in a multiplying target of nuclear fuel from oxide or nitride of uranium for type fuel assemblies of fast reactor with 20% by enrichment on ^{235}U is stipulated, liquid lead as coolant is considered. By evaluations, by use of the offered schema probably to reduce requests to current protons in 3-5 times, that increases realisation of ADS.

The experts of the SSC RF ITEP B.P. Kochurov, O.V. Shvedov and V.N. Konev have offered two-sectional blanket of ADS, consisting from internal section as pool type, contiguous to target and having fast spectrum of neutrons, with Pb-Bi eutectic as material of a target and coolant for the first section, and outside section with thermal spectrum of neutrons and heavy water as coolant in channels under pressure [12]. As fuel in both sections is used weapon-grade plutonium or mix weapon-grade and power plutonium. Technetium-99 is entered into coolant of thermal section for purposes transmutation and simultaneously the compensation of reactivity. On calculations the thermal and electrical capacity of fast section is equal 300 and 120 MWt, thermal section – 3 000 and 580 MWt accordingly. The steel wall of fast section and internal wall of thermal section serve NV, providing of function unilateral neutron connection. The significance k_{eff} of this system makes 0.99 at k_{eff} in thermal section 0.95, that permits to use a proton's current 10 mA at energy 1 GeV. Deep burn-up is about 70 GWtd/t in fast section and 35 GWtd/t in thermal section is reached by operation on nominal capacity during about 6 years. For this period more than 90% initial plutonium in thermal blanket transforms to fission products or minor actinides. During 30-years of period are transmuted about 25 t weapon-grade plutonium and 3 000 kg ^{99}Tc.

Other original offer about sectional molt-salt blanket of ADS by thermal capacity 2 000 ÌWt and k_{eff} 0.98 was investigated by the experts of the SSC of the RF VNIINM named after A. Bochvar V.I. Volk, A.Yu. Vahrushin and experts of the SSC RF ITEP, B.P. Kochurov, O.V. Shvedov, A.Yu. Kwarazheli and V.N. Konev [13]. Liquid salt $66PbF_2$-NaF with dissolution up to 10% of heavy particles (Pu, MA) as material of a target and carrier blanket, with temperature melting 498°C was considered.

Taking into account perspective of sectional sub-critical blanket of ADS expediently to provide continuation of their study and organisations of experimental researches of physics of this systems, including topic of safety.

3.2 Various variants sub-critical blankets of ADS

Except sectional blankets the Russian experts have considered a number of constructive schema's non-sectional blankets of ADS, which have novelty and differ from schema's, investigated by the foreign experts. Solid-fuel and liquid-fuel (or in kind of water solutions of salts or molten-salt) blankets with various coolant (helium, sodium, lead, Pb-Bi eutectic) and moderators (heavy and light water) were investigated.

3.2.1 Variants blankets, investigated in the SSC RF ITEP

The experts the SSC RF ITEP have conducted conceptual investigations of ADS for the following variants of blankets with solid and liquid fuel, for which common is first, the vertical configuration, secondly, location of a neutron-producing target in central part of blanket.

1. One of original offers, developed by the experts of the SSC RF ITEP in 1985, concerns the combination (or integrated) schema target-blanket of ADS as one vessel [14]. The combined design of target-blanket represents vertical vessel without pressure, inside which circulates from below – upwards Pb-Bi eutectic. As nuclear fuel and simultaneously a target material (alongside with Pb-Bi) is used depleted uranium in kind fuel of the spherical form as reactor HTGR fuel, weighted in flux of the coolant and interacting with proton's beam. The offered schema permits to exclude a steel wall between volumes of a target and blanket and, thus, to exclude a problem of its radiating damage and replacement.

   Late, during activity on project ICST #17 following integrated schema's as target-blanket of ADS as vessel were considered:

   – Combined target-blanket with Pb-Bi-eutectic as material of a target and molten-salt NaF-ZrF_4-PuF_3 as carrier in blanket [15].

   – Homogeneous blanket with solution of fuel in heavy water for ADS UTA with high density of thermal neutrons about $5 \cdot 10^{15}$ $cm^{-2}s^{-1}$, which the experts of Reactor Department of the SSC RF ITEP, B.R. Bergelson and others have justified [16]. On accounts of the authors one installation UTA can destroy MA from 40-45 reactors of a type VVER-1000 (PWR).

2. Channel-vessel design of ADS blanket with heavy water as coolant and (or) moderator is developed in following updating:

   – As designs of domestic industrial heavy-water reactors by thermal capacity near 1 000 ÌWt and density of a flux of thermal neutrons $5 \cdot 10^{14}$ $cm^{-2}s^{-1}$ and as core of heavy-water reactor CANDU by thermal capacity 2 064 MWt with various kinds of fuel (enriched uranium, weapon-grade and power Pu, Th) and targets in solid phase [17].

   – Heavy-water blanket with channels-modules, inside which compulsory circulate of liquid fuel in kind of a solution or slurry in heavy water with help of special independent pumps, located in the bottom part of each module is carried out. Each module has individual lines of extraction of a fuel mix for purification from fission products [18].

   – As core of heavy-water reactor CANDU with molten salt ^{7}LiF-BeF_2-PuF_4 (77%-22%-1%) and heavy-water moderator, in which is dissolved ^{99}Tc-for maintenance of a given sub-criticality level [19].

The number of the constructive schema's of blankets, except indicated above sectional blankets, was offered by the experts of other leading Russian nuclear centres.

Indicated here short description of the various conceptual original offers of the Russian experts under constructive schema sub-critical blanket of ADS testifies to availability enough justified base for realisation of comparison of these variants and subsequent choice of variant for development of the project for demonstration ADS.

4. Neutron-producing targets of ADS

Except constructive schema of neutron-producing targets, indicated in the previous section (integrated configuration of target-blanket and the active target with fuel assemblies of fast reactors, offered by FNC VNIITP), in the Russian nuclear centres were studied the following variants of targets.

4.1 Variants of targets, investigated in the SSC RF ITEP

The experts of the SSC RF ITEP independently and with the participation of other organisations have offered a number of various variants of ADS neutron-producing targets:

Tungsten solid target of the cone form, available in centre of heavy-water blanket, with cooling by heavy water and proton's current up to 30 mA [20]. The development of the constructive schema of this target is executed by the experts Design Bureau of Building Machinery (DBBM, N. Novgorod).

Leaden solid target in kind of a small diameter balls, hydraulic weighted in a interaction zone with beam of protons by pressure of heavy-water coolant [21]. Around target a buffer zone in kind of a layer of heavy water by thickness 50-70 mm with the purpose of break of connection on fast neutrons between target and blanket is provided. An absorber of neutrons (boron or gadolinium) for interruption of chain reaction in emergency case of blanket can be entered into buffer zone. This variant of a target permits to remove 62.7 MWt of thermal capacity at energy of protons 1 GeV and current 100 mA. The target has a diameter of 500 mm and height of a layer of 2 000 mm,

concentration of lead in heavy water about 0.3 at diameter of leaden spheres of 5 mm.

Lead-bismuth eutectic (Pb 44.5% + Bi 55.5%) target by capacity from 77 up to 116 MWt were offered by the experts of the ITEP and MEPI [22], a feature of which is availability of a window of the cone form from beryllium, sharing volumes of accelerator and target. As the authors [24] specify, the cones form of a window permits, on the one hand, to receive distributed on axis of blanket a source of converting neutrons, with other, to reduce about in 5 times fluence of fast neutrons by constructive elements of a target and blanket.

The vertical tantalum target by capacity 25 MWt executed a kind of set constituted by 15 flat horizontal cylindrical disks of a thickness of 30 mm each, with internal channels for pass of the coolant [23]. The target was developed for sub-critical light water blanket as core reactor PWR.

4.2 Design of the IPPE and the Design Bureau Hydropress (DBHP) target

The experts of the IPPE named after A.I. Leipunsky with participation of the experts of the DBHP were developed 2 conceptual projects of liquid targets: with lead on capacity 10 MWt and with Pb-Bi eutectic on capacity 25 MWt at energy of protons 1 GeV and current 25 mA. Advantage of a liquid target with Pb-Bi eutectic is availability of technology, developed for reactors of nuclear submarines. Defect of Pb-Bi coolant for a target is formation of polonium-210, defect of lead is high temperature melting (about 327°C) and high thermal expansion. A serious problem of liquid targets at high significance of heat deposition is regeneration (purification) of a target material from formed products of nuclear reactions. Now the experts of the IPPE with the participation of the DBHP execute experimental check of a Pb-Bi target on basis of ICST grant.

5. Accelerator of protons

5.1 Linear accelerator of protons

The modern variant of the block diagram for the linear accelerator of protons (LPA) for ADS with current and energy of protons 30 mA and 1 GeV accordingly, developed by the SSC RF ITEP and Moscow Radiotechnical Institute (MRTI), is constructed under single-channel circuit [24]. The accelerator consists from injector, initial, intermediate and main parts. A basic feature of the offered circuit is use of superconductivity (SP) resonators with low gap in intermediate part for acceleration of particles up to 100 MeV instead of traditional long multigap resonators, which were provided in initial variants LPA. It permits to choose distances between centers of accelerating gaps outside of dependence on speed of particles, that permits to reduced length of section to 30-40%, but also to continue process of acceleration even at failure of small amount of accelerating resonators or path's of their independent power supply, having postponed their repair up to scheduled stop. Basically, cylindrical resonators with drift tubes in intermediate part can be used. In main part, for acceleration of particles up to 1 GeV is provided to use multigap SP resonators. The project on accommodation in each cryoinstallation not less than 2 resonators is developed in the MRTI, each of which, in turn, consists of 9 accelerating cells of the ellipsoid form. Structurally SP resonators it is supposed to execute from niobium. Length and diameter of one resonator 0.41-1.12 m and 29-26 ñm accordingly. A rate of acceleration on length of the resonator from 5 up to 15 MeV/m can be achieved. The excitation of SP resonators is supposed to execute from clistron amplifiers by capacity 1.2 MWt each. The main calculation characteristics full-scale LPA (1 GeV, 30 mA) with SP accelerating resonators in main part [24] are indicated in Table 1.

Table 1. **Characteristics of the full-scale accelerator with SP resonators**

Parameter	**Warm**	**SP, 5 MeV/m**	**SP, 15 MeV/m**
Approximate length of LPA, m	1000	400	135
Efficiency of resonators	0.4	1	1
Efficiency of HF-generators with power supply	0.65	0.65	0.65
HF power, MWt	75	33	33
Efficiency of LPA	0.2	0.6	0.55
Cost of accelerating system, mln. dol.	50	69	23
Cost of HF-generators with power supply, mln. dol.	125	49.5	49.5
Cost of the non-standard equipment, mln. dol.	275	120	72
Total cost of the equipment, mln. dol.	313	179	109
Total cost of LPA, mln. dol.	437	233	142

From Table 1 it is obvious, that using a SP accelerating system and high rate of acceleration results in significant reduction of LPA cost up to 233-142 mln. dol. in comparison with cost of the "warm" accelerator 437 mln. dol. The offered technical decision on constructive circuit of LPA can render essential influence to technological characteristics of ADS.

6. Conclusion

The information on new original offers of Russian experts on ADS different units shows, at first, on high potential of Russian atomic science and engineering, at second, on existence of scientific base for development of project for Demonstration Transmutation ADS. But it is necessary to continue conceptual comparison study of ADS different versions and carry out large volume of R&D activity.

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