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THE STATUS OF WORK IN THE USSR ON USING INHERENT SELF-PROTECTION FEATURES OF FAST REACTORS, OF PASSIVE AND ACTIVE MEANS OF SHUTDOWN AND DECAY HEAT REMOVAL SYSTEM.

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INTRODUCTION

In the development of fast reactors in the USSR , three stages can be outlined. The first of these, which includes in itself the solution of scientific, engineering and technological problems, the development and testing of the reactor and its main equipment, the demonstration of this equipment reliability and safety under commercial operation conditions has been successfully completed.

The second stage includes the solution of scientific, engineering and technological problems of the external cycle, the development of the whole complex "reactor units - fuel cycle plants" , the demonstration of reliability and safety of the complex in the process of its operation. Within the frames of this stage, the BN-800 reactor design was developed. Putting this reactor into operation will be an important step in solving nuclear power problems.

Approaches to ensure NPPs safety, the criteria and limits determining the boundaries of technically feasible means for personnel and population protection from irradiation in case of emergency situations, are being steadily advanced in compliance with both the level of scientific and technical development and social conditions in a particular country or region.

After the Chernobyl NPP accident, of especially high priority became the improbable, beyond design basis accidents which include: unprotected transient overpower (UTOP); unprotected loss of flow (ULOF); loss of heat sink; propagation of an accident in an individual fuel subassembly to the whole core. Combinations of these are also possible. Regulatory documents adopted after the accident at the ChNPP demand that the assessed probability of a severe core disruption (meltdown) accident must not be above 10^{-5}1/reactor-year, and the probability of a radioactivity release beyond limits specified by these regulations to be not higher than 10^{-7} 1/reactor-year.

To resolve these problems one can employ the extensive as well as intensive methods. Until now, safeguarding the safety was performed extensive, mainly, methods, at the expense of highly conservative design approaches, by building up protection systems in number and making them redundant. Such an approach to safety problems has a negative effect upon economic characteristics of reactors.

Recently, intensive studies on the concept of reactor self-protection, based on inherent reactor safety features features and passive safety means, has begun. In connection with this, it seems necessary to determine what would be a reasonable combination of conventional methods of solving safety problems mainly on the basis of active means, with those defined generally by the term of "passive means".

Therefore, the third stage of fast reactor development in the USSR is connected with research and development of means for further increasing of safety and economic efficiency of reactors and fuel-cycle plants, for reducing to a minimum of their effect upon population and environment. Until now, there is still no clear and well-defined overall concept of safety for the next generation of fast reactors, which should include means to achieve high safety characteristics. It is likely that this cannot be done as far as the safety problems can be solved by different methods depending on reactor power and purposes for which it is designed.

Below is given a short review of the current status of works in the USSR on the subject of the meeting.

BN-800

In 1990-1991 this reactor design was undergoing expertise in various scientific and state commission and committees. By the end of 1991 work on modification and revision of the project in compliance with experts remarks is expected to be completed. Main activities performed in the safety area, in accordance with experts' decisions, is summarized as follows.

An extended list of postulated beyond design basis accidents, which includes ten types of accidents,has been analyzed . The main of them are:

- loss of off-site and on-site power supply;
- unprotected loss of flow (ULOF);
- leak of main and safety reactor vessels;
- impact of aircraft upon the reactor building;
- overall plant fire with safety systems damage;

In accordance with codes and specifications in the USSR, by the beyond design basis accident is implied an accident with more than one failure in safety systems. Then, it is required that the probabilities of core meltdown and radioactivity release outside

the reactor in such quantities, that would result in irradiation of population, for the first year's exposure at a distance of 25 km from a NPP, by doses above 10 rem (external irradiation) and 30 rem (child's thyroid), shall not be exceeded.

For the expertise, the reactor design with core of conventional arrangement and positive sodium void effect of ~ 2 % dk/k was submitted. An analyses of the loss of flow accident for this design, combined with the safety system failure, has shown that the regulations requirements are met. Nevertheless, the Commission of the USSR Academy of Sciences required to develop the reactor core with a negative or close to zero sodium void effect of reactivity. Now such a core has been developed. Its characteristic feature is that the upper axial blanket in it has been replaced by a sodium layer and thin boron carbide shield.. The void effect of reactivity for such core is about zero.

Despite the nil sodium void effect of reactivity, in addition to the existing systems there are introduced three absorbing rods based on passive principles. To prevent sodium boiling in the BN-800, it is sufficient to introduce a negative reactivity of 0.8 % dk/k. These rods cannot be considered as an alternative safety system of the reactor, because at present it is impossible to meet all those numerous requirements of codes and specifications which are imposed upon the safety system. Therefore, these rods are considered as additional means of reactivity control, for the beyond design basis accident management.

In accordance with the regulations, the management of the beyond design basis accident is interpreted as "the actions aimed at preventing the development of the design basis accidents into the beyond design basis ones and at mitigation of their consequences. For these purposes, any available operating technical means shall be used, designated for ensuring the design basis accident safety , or those designated specifically for mitigation of the consequences of beyond design basis accidents".

The development of the "passive" rods concept has been concentrated, mainly, upon the hydraulically supported rods and upon temperature sensitive devices based on Curie point magnet and shape memory alloy (for more details see below). Most advanced now are works on hydraulically suspended rods whose introduction would not call for any considerable revision of the design. For this purpose it is intended to use regular safety rods which are to be raised up in upper position by use of standard drives and which are to be disengaged from the grip at a coolant flow rate through the core not lower than 60% of the nominal one. These rods will fall into the core by gravitational force and shut the reactor down when the coolant flow of the reactor is interrupted by loss-of-flow event.

In order to exclude any introduction of positive reactivity as a result of uncontrolled withdrawal of compensation rods, their control circuits were also modified. Their automatic operation mode has been changed for the manual remote mode. The operator can control only one rod at a time. The possibility of all rods simultaneous upward movement is precluded.

Despite the measures taken for increasing the BN-800 safety, one cannot exclude a probability (even a minor one) of core meltdown. The reactor vessel has been designed for mechanical effects arising at molten fuel-sodium interaction. To prevent the melting through of the vessel bottom by core debris, an internal retention device for molten core masses was incorporated into the design. This catcher is cooled by sodium circulating from the intermediate heat exchangers through special tubes.

The BN-800 decay heat removal system including air heat exchangers comprises a lot of active elements: electromagnetic pumps, gates, valves. However,as was shown by calculations, in case of their failure no dangerous sodium temperature increase occurs during 24 hours owing to natural sodium circulation, heat losses from piping and steam generators and heat accumulation in the circuits as well. This time period is enough for carrying out appropriate active actions.

As a whole, the modification of the BN-800 design is directed towards using the passive methods for increasing its safety.

CURRENTLY DESIGNED REACTORS.

In the USSR, a search for the most acceptable (from the economics and safety viewpoint) reactor versions with a wide range of power, from 150 MW(e) (modular-type reactors) to 1600 MW(e) is in progress.

BN-1600

The concept of this reactor is based upon the requirements of ensuring close-to-zero sodium void effect of reactivity and of minimizing the burn-up reactivity swing. The latter is connected with a desire to reduce a risk of a positive reactivity insertion

due to uncontrolled withdrawal of compensation rods.

The possibility of achieving a zero burnup reactivity swing between reloading campaigns (intervals of the order of one year) has been studied sufficiently well and no fundamental difficulties arise in case of fuels of higher densities (carbide,nitride,metallic). The studies performed have shown that this can be also achieved while using oxide fuel within sufficiently simple heterogeneous arrangement with an axial breeding layer of metallic uranium. An additional condition for this arrangement is the use of fuel subassemblies with perforated ducts that allow to reduce the amount of steel.

As to the sodium void effect of reactivity, its positive value is connected with the principal properties of the large cores regardless of type of fuel employed.

The way out of such a situation can be the location, immediately above the core, of a sodium layer with small steel content, which would increase the negative component of the void effect due to neutron escape from the core.

The studies conducted have shown a feasibility of creating the core with both sodium void effect of reactivity and burn-up reactivity swing close to zero. The main features of such core are as follows:

- the use of higher density fuels: nitrogen-15 or carbide ones;
- the provision, immediately above the core, of a sodium layer,in which only fuel subassembly ducts and sodium are presented;
- the use of fuel subassemblies with perforated thin-walled ducts.

In the studies, both homogeneous and heterogeneous (with an axial interlayer) arrangements of cores with various fuels were being considered.

Main results of these studies are presented in Fig.1 in a generalized form. One can see from this figure that the best way to solve this problem would be to use nitride (nitrogen-15 based) or carbide fuel. Next to this solution would be to employ the nitride fuel based on natural nitrogen. This analysis was carried out for gas-filled fuel elements. In case of sodium-filled fuel elements with metallic fuel and so with upper position of gas plenum it was found impossible to achieve zero void effect together with zero burnup reactivity swing.

For the well-grounded choice of a fuel type for advancedfast reactors it is necessary to perform analysis ofreactivity effects in the cores, and characteristic features of their manifestation under transient and emergency conditions. The comparison of various fuel types by their temperature effects on reactivity has shown that only metallic fuel has an appreciable distinction from oxide fuel. It consists in a greater value of the sodium void coefficient of reactivity and in a lower Doppler effect. Evaluations of quasi-stationary states of reactor by the reactivity balance have revealed that for the ULOF accident, when oxide, carbide and nitride are used, the reactor parameters vary in a similar manner.

Without enhancement of the reactivity feedbacks, relevant, for example, to the expansion of grip rods and control rods, or caused by some other design features, one cannot avoid sodium boiling at such an accident, if these fuel types are used in the BN-1600 reactor. So, once the metal fuel is considered to be worse in the UTOP accident, then one can say that for a large reactor no type of fuel has any distinctive advantage from this point of view.

To increase self-protection of the reactor, it is necessary to increase those negative components of the temperature effects of reactivity which are caused by an increase of temperatures of coolant, fuel element, claddings, fuel subassembly ducts. However, an analysis of asymptotic correlations between feedback characteristics can give us erroneous results, because excessive strengthening of the reactivity feedback can result in reactor instability.

A danger of instability especially increases in the reactor regime with low flow rates. An analysis has shown that enhancement of the temperature effects constituents, especially those in a critical reactor under natural circulation conditions, can result in auto-oscillations. The character of the oscillations depends on the phase shift between the initial perturbation and temperature response. Calculations have shown that amplification of reactivity feedback, caused by those components which responds to the initial perturbation with a considerable phase shift, cannot ensure reactor self-protection. This circumstance calls for a careful analysis of the feedback components connected, for example, with thermal expansion of control rods and their movement relative the core.

BN-1600 reactor concept provides the use of two independent groups of safety rods, one of which is based fully upon the passive principles of operation. This group of passive rods should meet all the requirements of codes and specifications on the safety system efficiency with account for one rod failure in operation, its monitoring, etc.

The decay heat removal system takes an important place in the BN-1600 reactor concept. This system should ensure decay heat removal at a loss of water feed to steam generators. This system includes autonomous heat exchangers installed in the upper reactor

plenum, and air heat exchangers. A basic point of the concept is the provision of natural circulation of sodium in the primary and secondary circuits, and of air through the heat exchanger. At present, the problem of control of air flow rate through the air heat exchanger is under discussion.

Two solutions are considered. In the first solution, when reactor operates on power, the air gates are fully open, i.e.,the decay heat removal system is continuously in the operating state, so no active actions for its putting into operation would be needed. The gates are used only after reactor shutdown, in the period of its cooling down, to prevent the sodium temperature drop below allowable one. A disadvantage of this solution are constant heat losses, which could amount to ~ 100 MW during reactor operation.

In the second solution, at on-power reactor operation the gates are partially open. Its full opening is done by a passive drive of direct action, such as increase of pressure or change of sodium level in the expansion tank of the intermediate loop of the decay heat removal system, in case of sodium temperature rise in this loop. In this case no other active or passive (with moving parts) elements are used, and no action of operator or of any automatic systems is required.

After an incident with sodium leakage in the spent fuel storage drum at the SPX-1 reactor, more attention of regulatory bodies and public was drawn to accidents of such type. In the USSR, at present, the leakage of the main and safety vessels is considered as a beyond design basis accident. In the BN-1600 design concept it has been assumed that at such an accident, with the duration of a few hours, sodium drains from the reactor vessel into its vault. Inter-space volumes between the main vessel / safety vessel / vault are such that the sodium level does not come below subassembly heads. Sodium circulation in the primary circuit is discontinued. Decay heat removal from the core is done by intermediate heat exchangers owing to sodium natural circulation in the core and combined effect of heat conduction and convection in the sodium layer between the core and heat exchangers. In this case no heating of the reactor vessel beyond allowable temperatures should occur.

Despite all measures to prevent core meltdown, such an accident cannot be completely precluded; therefore, as the last boundary, preventing fuel escape from the reactor, is the internal catcher on which debris of the molten core would settle and cool down.

As may be seen from the above, the BN-1600 concept is aimed at increasing the role of intrinsic properties of self-protection and passive means for ensuring its safety.

The realization of these technical measures will facilitate a reduction of the probability of radioactivity release beyond allowable limits outside the reactor boundaries, during beyond design basis accidents, to the level of 10^{-8} - 10^{-9} 1/reactor-year.

Modular Reactors

Preliminary design studies for a reactor of small-power (~ 400 MW(th)) have been carried out. Four types of reactor's modular arrangements have been considered:

- arrangements within a vertical vessel with intra-vessel radiation shielding;
- arrangements within a vertical vessel, with improved natural circulation of sodium in the primary circuit and without intra-vessel shielding, the role of which is played by a sodium between the core and heat exchange equipment;
- arrangements with placing the core and primary circuit heat exchange equipment within separate vessels connected by short pipes (semi-integral type);
- arrangements with placing primary equipment within a cylindrical horizontal vessel.

The reactor design and arrangements were analyzed from the viewpoints of both safety and economics. One of economic requirements is the provision of a possibility to transport the prefabricated reactor vessel by water and/or by trailers.

From the safety point of view, on this reactor are imposed all requirements shown above for the BN-1600 reactor. Additionally, the developers' attention is brought to the task of ensuring inherent safety features of the oxide-fueled core, namely, the appropriate reactor power decrease and limitation of its components' temperature rise to permissible level,in case of a loss-of-flow accident and unprotected transient overpower without any active actions. Enhancement of negative reactivity feedback required in this case can be ensured by:

- smaller dimensions of the core, which should result in an increase of absolute values of the geometry-dependent constituents of the temperature coefficient of reactivity (while rector power decreases from 800 MW(e) to 100 MW(e) with the same specific power density , the axial component of reactivity increases ~ 3 times and the radial one by ~30%);

- optimization of subassembly design; introduction of a "flexible" core restrain round the periphery, securing the appropriate radial expansion of the core when sodium outlet temperature increases;
- lower specific power densities of the core and, as the result of it, of the fuel temperature and the fuel negative Doppler effect ;
- ensuring of low-inertia heating of control and safety system actuators` bars by sodium leaving the core.

The most important requirement for such type of reactors is to ensure their emergency cooling down by heat removal from the reactor and steam generator vessels with natural circulation of air.

The reactor decay heat removal system should meet the following criterion: for those accidents, the number of which for the reactor life time is more than 1, the reactor cooling down should proceed with sodium and reactor vessel temperatures not exceeding the nominal values; for accidents with recurrence of 1 or less for the reactor life time, a prolonged temperature rise on the reactor vessel, up to 700°C, is permissible, but no sodium boiling within fuel subassemblies and no loss of tightness of the main and safety vessels may take place. However, securing the reactor inherent safety comes in conflict with its economic characteristics, since the incentive to reduce the weight of reactor steel components leads to reduction in the external heat exchanging surfaces and in heat capacity of circuits. To assure a protracted cooling, it is necessary to have specific area of heat removal from the vessel of ~ 0,9 - 1,0 m^2/MW(th) and specific heat capacity of the primary circuit of 1,5-2,0 Mj/MW(th)°C. Therefore, a careful analysis on the optimization of these problems is still to be done.

Other types of reactors.

At present, design studies for a number of reactors differing in their capacity and purposes are underway in the USSR.

So, in addition to reactors considered above, reactors of 600 MW(e), 1000 MW(e) power are being analyzed. Besides, an idea of creating the reactor-"burner" for actinides is being considered. In such a reactor it is rather difficult to achieve a close to zero sodium void effect of reactivity, therefore some requirements on inherent safety, considered above, may be put aside.

SELF-ACTUATED SHUTDOWN SYSTEMS.

The development of self-actuated shutdown systems is aimed to creation of three types of devices based on passive principles: a device actuated by reactor coolant flow rate reduction; a temperature sensitive device based on Curie point magnet; a temperature sensitive device based on shape memory alloy.

In capacity of reactivity control means, the absorption rods are used. As was already mentioned above, for the BN-800 reactor it is intended to use hydraulically suspended rods. At present, a prototype device is being tested in a hydraulic rig. This device includes a standard sleeve and an assembly of absorption rods, of 16 kg by weight. The device design has such hydraulic characteristics that ensure of rods to stay in the lowered position at nominal sodium flow rate, and holding them in the upper position after their engagement, withdrawal and disengagement, when sodium flow rates are of 60% of the nominal one. This device has been patented. Testing of this device at the BN-600 reactor is planned for the year 1992..

Two devices with hydraulically supported rods confined completely within a fuel subassembly (absolutely passive ones) are tested in the BR-10 reactor. The time of their insertion into the core is 1,2 sec. and 0,7 sec., respectively. On completion of dynamic tests in 1992, they will be incorporated into the standard safety system.

The main requirements to temperature sensitive devices are the temperature of actuation of 650-670^{o}C, time response not more than 5 sec. A device with such characteristics is able to prevent sodium boiling, when its temperature rise at subassembly outlet is ~ 30^{o}C/sec. To meet these requirements, and to exclude any mechanical connection between core with below-the-core structures, the absorption rods will be positioned inside a standard fuel subassembly with a short fuel bundle.

Based on specified geometry, a device actuated by attaining the magnet Curie point has been developed. The magnet and screen 145 x 40 mm in size, when tested in the gaseous atmosphere, demonstrated the load capacity of ~ 8,2 kg at room temperature and ~ 2,8 at a temperature of 680^{o}C. Now this device is being prepared for durable testing in a sodium rig with simulation of operation and emergency conditions. Specimens of magnet material are put in in the BR-10 reactor for irradiation.

As to the device based on shape memory alloy, the Ti-Ta and Ti-Ta-Hf alloys and specimens of them with a temperature of shape recovery of ~650^{o}C have been obtained now. At present their

corrosion and mechanical testing is being carried out. A method for shaping the material as applied to different rod designs is being developed. At the same time, works on producing a titanium-based alloy with addition of rhodium, which would have a required shape memory temperature are being conducted. By the beginning of 1992 it is planned to make a final choice of alloy type and actuator design.

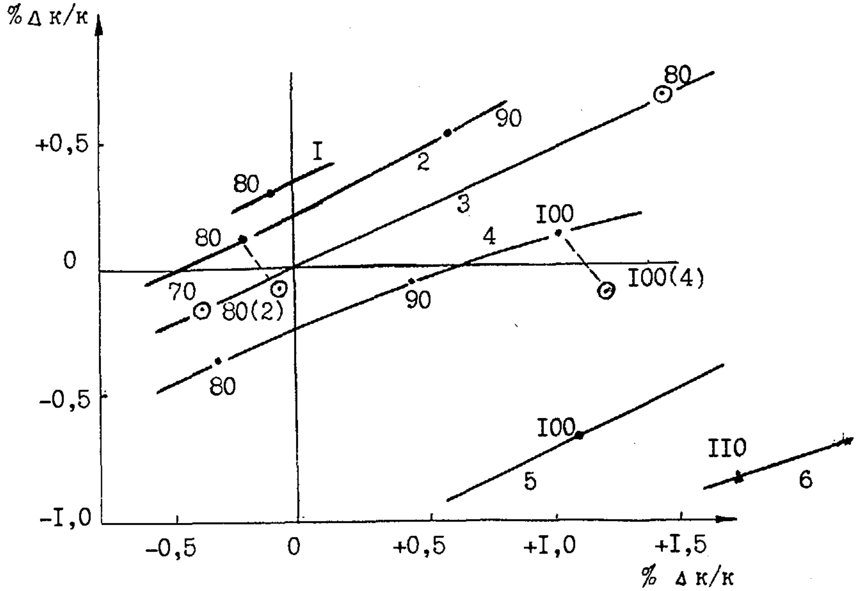
CONCLUSION

Extensive studies on fast reactors safety, aimed at increased intrinsic safety features and introduction of passive safety means, are under way in the USSR.

A design of the BN-800 reactor core with a close-to-zero sodium void effect of reactivity has been developed, complementary reactivity control means, based upon passive principles, are being implemented.

As a whole, after the Chernobyl accident, the preference is given in the USSR to the "passive" foolproof methods of safety. Our resolutions in this direction may possibly seem to be somewhat excessive, but after "having been once bitten we have to be twice shy", and this may result in some losses in reactor economical characteristics.

Sodium void effect of reactivity and burnup reactivity swing (Δk/k) for the cores with various fuels.



70,80,100,110 - the core height in cm
1 - nitride (with N-15)
2 - carbide
3 - metal (Pu-U- 10 Zr)
4 - nitride (natural nitrogen)
5 - oxide-metal
6 - nitride

o - homogeneous arrangement;
· - heterogeneous arrangement (interlayer 10 cm thick);
Δ - homogeneous arrangement with common (wrapped) fuel subassemblies;

Fig. 1