TECHNIQUE OF RESEARCH OF SEVERE ACCIDENTS AND SUBSTANTIATION OF SAFETY OF NUCLEAR SYSTEMS

E.A. Ivanov, S.V. Tchernov

State Scientific Center of Russian Federation
"The Institute for Physics and Power Engineering", named after academician A.I.Leypunsky
Bondarenko Sq. 1, Obninsk, Kaluga reg., Russia, 249020
tel: 7 (08439) 98504, e-mail: ivanoff@ippe.obninsk.ru

Abstract
It is offered the technique of theoretical research of severe accidents. It is based on principles distinct from ideology of probabilistic analysis of safety. Significant feature of the technique is that using of it we can estimate the parameters of heaviest consequences of accident (maximal damage) without of analysis of a sequence of initial events in details.

Introduction
In the modern concepts of nuclear and radiation safety there are two sets of criteria of safety. The first set of criteria is the concept of socially acceptable risk. The safety in frame of this criteria is defined in terms of probabilities (risks) of one or another events. The task of estimation of risks is an engineering problem, which concerns for each concrete system and its condition. This set of criteria we will not concern here.
The second group of criteria is the risk of the severe failures, which can be recognized as catastrophes. Acceptance of any event in this case can be proved only by guaranteed exception of heavy consequences. It means that if we deal with nuclear power the principle of acceptable risk in severe accidents should be transformed to a principle of the determined exception of their heavy consequences. Thus safety is sustainability of system from changing of stocks of external resource, which are pretended for repair harm from failure.
Therefore we have got two levels of safety. And it's obvious that analysis of potential of safety (level of defense) of nuclear systems must be differed on first and second levels. If we deal with severe accident any small probability of failure can not be reason to ensure in safety of nuclear system. Because in this case we should prove that catastrophe never can occur. Moreover it is impossible to prove exception of heavy hazards if we will consider different scenarios of accident process one behind another because their number is unlimited.
But analysis of scripts of events in severe accidents can be replaced by optimization procedure where we can search the heaviest condition of accident's consequences. But how can we do it in practice? One way of solution of this problem is shown below.
Formulation of new techniques of analysis of safety is especially important in substantiation of safety of a disposition and transmutation of radioactive wastes of nuclear industry.
The concept of risk can be kept here, but the problem arises at an estimation of size of risk as probabilities of damage. But complex evolutionary process of chemical and nuclear nature in long storage (from tens up to hundreds years) or depository of dangerous objects make theoretically impossible to simulate probabilities of each events. Strictly speaking, uncertainty in basic physical processes and their interrelation (chemical transformations, determined by nuclear processes, of structure of a matrix containing radioactive wastes) made impossibility of using of formalism of Markov's and semi-Markov's processes at the analysis of probabilities of events. However, it does not mean impossibility of other estimations of risks and consequences of probable events.

But analysis of accidents are carried out for development of means of protection and therefore there is no necessity to describe exactly of all scripts of chains of events, it is enough only to estimate maximal impact of set of any events, which are physically allowed.

Put of problem

Our task is to develop the technique of analysis of severe accidents and of analysis of protection facilities. Analysis should be based on mathematical modeling and this model should be built on model of coupled processes. We can formulate a number of principles of development of such models. They are following:

– modeling should be carried out as set of coupled processes;
– all simple process should be modeled by very trying out codes and algorithms;
– all codes and models should be able to simulate accident process completely.

Let consider accident process in cooled by light water nuclear systems. Asymptotically behavior of this system can be described as static regime with balanced reactivity from initial perturbation and temperature and coolant density.

Model must include models of neutron kinetics, hydrodynamics of coolant, mass and heat transfer, steam generation in water etc. Model should be built in lamp parameters.

Model of emergency process

Accident in this work is modeled by dynamic model in lamp parameter. Here we use followed approximations:

- it's used the point kinetics of neutrons;
- it's applied semi-stationary model of power distribution;
- the coolant is acoustically incompressible liquid;
- the fuel is motionless.

The description of a field of neutrons

$$\frac{\partial n}{\partial \tau}=\frac{\rho-\beta}{\Lambda}n+\sum_i \lambda_i C_i+Q_n, \qquad (1)$$

Concentration of the predecessors:

$$\frac{\partial C_i}{\partial \tau}=-\lambda_i C_i+\frac{\beta_i}{\Lambda}n, \qquad (2)$$

The equation of heat transfer in terms of average values:

$$\frac{\partial h}{\partial \tau}=\frac{q_s \Pi}{\gamma F}-\frac{2\cdot u\cdot \theta(\tau)}{H}(h-h_0), \qquad (3)$$

where $\theta=\theta(t)$ - is amendment on difference of the form of the channel from the vertical cylinder and on acceleration of a flow.

Description of average velocity of coolant fluid:

$$\frac{\partial u}{\partial \tau}+\frac{\varepsilon}{2}\left(u^2_{âûõ}-u^2_{âõ}\right)=\frac{\varepsilon}{\gamma}\left(p_{âõ}-p_{âûõ}\right)-\xi_{ÒÐ}\frac{Hu^2}{2d_{Ã}}, \qquad (4)$$

where $\varepsilon=\varepsilon(t)$ - is amendment on difference of the form of the channel from the vertical cylinder. Keeping losses on acceleration of a flow we receive

$$\frac{\partial u}{\partial \tau}=\left(\frac{\gamma_0}{\gamma}-1\right)g\cdot H\cdot\varepsilon(t)-\xi_{ÒÐ}\frac{H}{2d_{Ã}}u^2-2\cdot\varepsilon(t)\cdot x\left(\frac{\gamma'}{\gamma''}-1\right)\frac{\gamma u^2}{\gamma'}. \qquad (5)$$

The functions $\varepsilon=\varepsilon(t)$ and $\theta=\theta(t)$ contain the information on real deformation of the channel. They can change into margins from 0 up to 1 and are managing parameters in the searching of the greatest value of consequences of emergency process. *Such formulation* allows us to define heaviest of physically accessible levels of damages. These functions can be submitted as the trial forms - functions F (t):

$$F(\tau) = \sum_{i=0}^{N} \alpha_i \tau^i , \qquad (6)$$

The technique allows us to estimate maximal dangerous impact of severe (hypothetical) accident because it is based on the decisions of a general view and excludes necessity of detailed modeling of the real scripts of emergency process.

Examples of calculations

Let consider emergency processes in unmanaged nuclear systems with light water as coolant. We show below variants of accident on spent fuel cooling pond, falling of space nuclear reactor in hydrogen contented media and accident in experimental facility pretended for trying-out fuel rods for prospective light water reactor. It must be noted that we consider only hypothetical events – both of them did not realized in reality.
We expect that after all transient processes in such systems will stand asymptotic mode with constant level of power and part of steam, temperature and velocity of coolant.

Falling of damaged space power nuclear reactor

We consider the model where heated up to 670ÎÑ subcritial nuclear reactor with zero capacity are falling into a reservoir. The falling is chaotic and deformed reactor has lost beryllium reflector. Evidently that it is impossible to describe the process of immersing of reactor precisely because in this case we have got a continuum of initial conditions. Therefore it is natural, that this task should be considered in the described above model, where the script of process is not detailed, and the maximal consequences of failure are defined during solution.

Table 1 Data of kinetics of nuclear reactor in lamp parameters

Average lifetime of prompt neutrons	Λ, sec	$12.2\ 10^{-6}$
Effective part of decay neutrons	β_{ef}	0.00745
Approximations of feed back reactivity coefficients		
on water's density		$0.00986 + 11.54\ 10^{-5}\ \rho + 0.001725\ 10^{-6}\ \rho^2$
on fuel's temperature		$0.011448 - 1.5\ 10^{-5}\ t + 4.55\ 10^{-9}\ t^2$
on moderator's temperature		$-1.1\ 10^{-8}\ t_{ZrH}$

Maximal value of external reactivity, which can be brought by water, is not greater than 12%. Behavior of neutron field in reactor is described by point kinetics (table 1), interrelation between different processes are determined by coefficients of reactivity feedback. Water during transient process boils and power of reactor stabilized on some small value when reactivity becomes zero.

Carrying out calculation we find such scenarios, which gives maximal and minimal power yield and with maximal and minimal temperatures of fuel in emergency. It is shown that (namely in this task) scenario with maximal flux differs from one with maximal temperature.

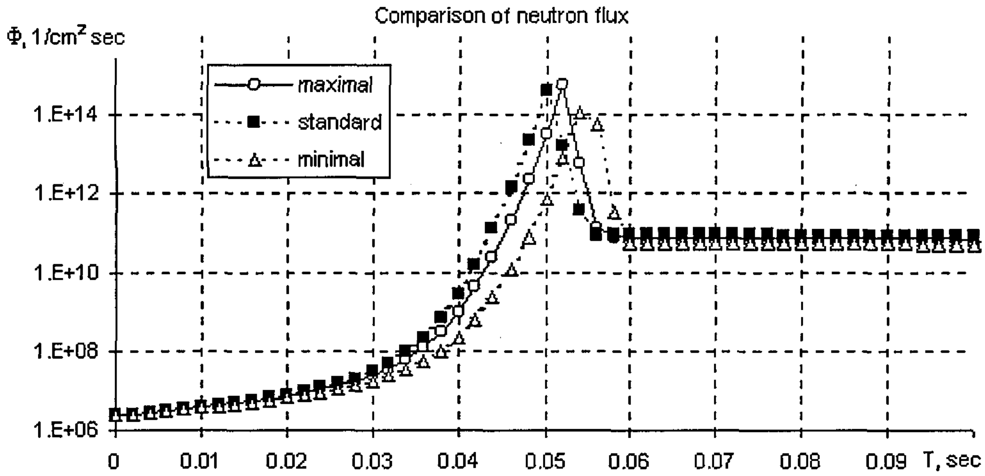

Fig.1 Dependence of neutron flux during transient process

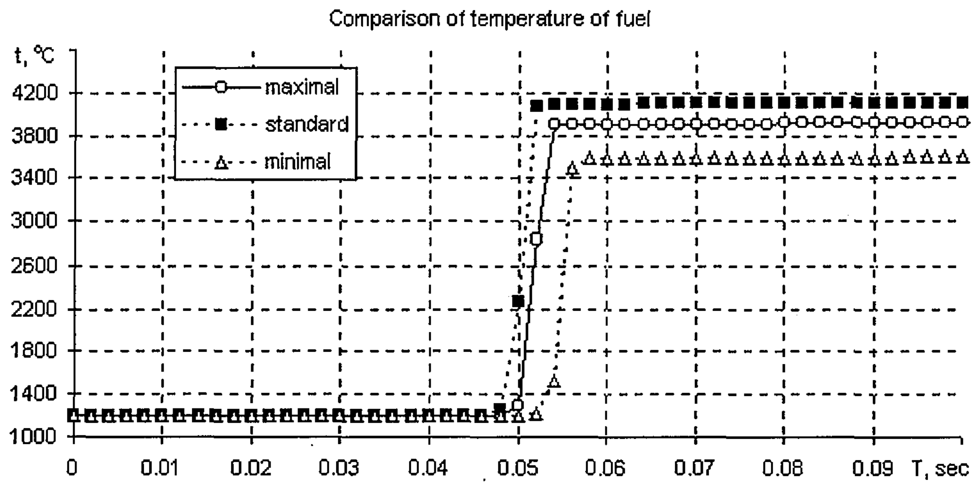

Fig. 2 Changing of fuel temperature during transient process

Accident on water-uranium criticality stand (experimental facility)

As in previous variant here we consider accidental event on experimental facility, which simulates VVER-type reactor fuel lattice. Accident begins with increasing of reactivity (for example by failure of control system). Initially temperature of water (pressure as in VVER) is about 320°C, temperature of fuel equal temperature of water, coolant is not moved. Value of external reactivity 1.6% and it is included for two seconds. Core is cooled by natural convection of water.

We find such regimes, which supply maximal value fission density by artificial decreasing of hydraulic diameter of channel. Results are shown on Fig. 3 and 4. It is shown that only variation of managing parameter during accident gives maximal flux and temperature. It means that only special searching (as in this case) allows us to estimate maximal physically possible value of accident impact.

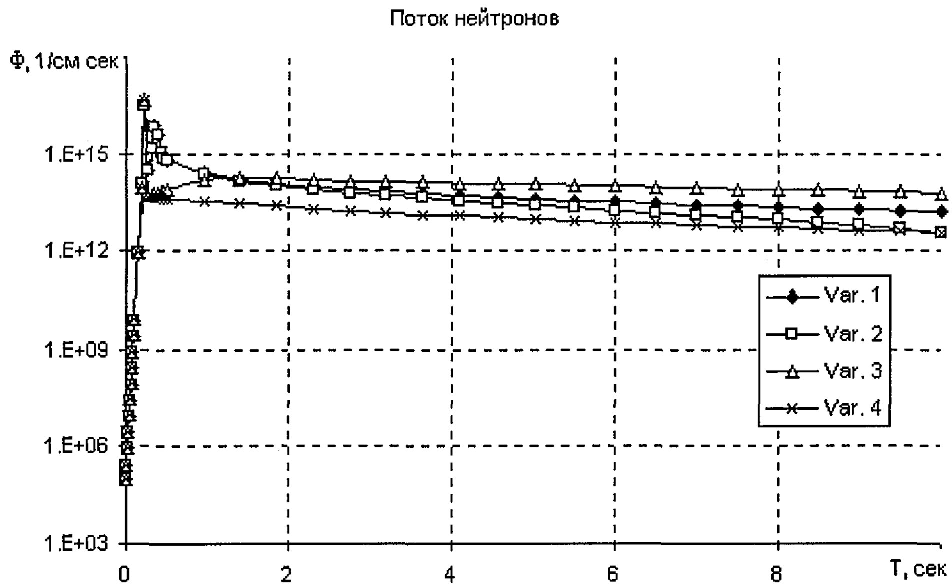

Fig. 3 Dependence of neutron flux during transient process

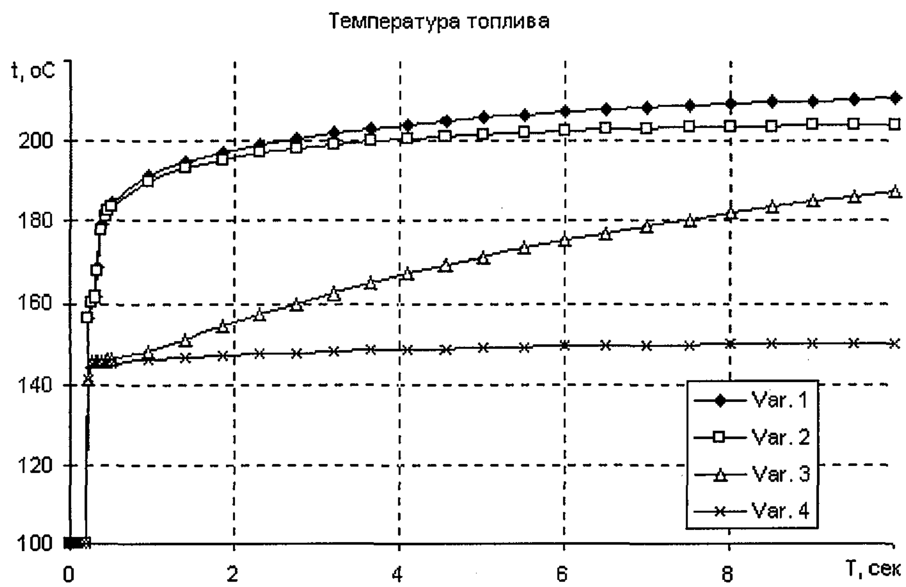

Fig. 4 Changing of fuel temperature during transient process

Conclusions

Work is devoted to development of possible ways of solution of the problems of nuclear safety substantiation. We believe that safety in severe accidents is one of significant factors, which restrict value of nuclear industry in future power production.

In connection with it we can conclude followed items.

- Substantiation of safety in severe accidents in nuclear system should be built on deterministically guaranteed exception of heavy consequences.
- It is easy that this aim can be achieved by modeling in functions of common type.
- Main purpose of this work is to show that it is possible to estimate physical allowed state of system in emergency and find of trajectory of heaviest scenarios by optimization procedure.

– In this work we developed new method and computer code purposed for study of accident conditions of water cooled unmanaged nuclear systems such as cooling ponds of spent fuel, experimental facilities etc.

Table 2
Structure of a methodological and mathematical substantiation of safety

Description of stage	First level of safety	Second level of safety
General definition	Estimation of final risks	Proof of impossibility of heavy consequence
Level of acceptance of decisions	Commercial risk and insurance maintenance	Risk of brunches of economy, which are not connected with nuclear industry.
Used approach	Probabilistic analysis of safety	Research of physical allowed principles of protection
Requirements for mathematical modeling	Development of statistical models	Development of models of severe accidents

The place of our technique may be shown as in table 2
Described above method and code can be used also in probabilistic safety analysis in the part where probable chain of events are cut off.
They also can be used in estimation of cost of protection facilities in terms of external prizes.

References

1. V. Arnold Theory of Catastrophes/ Fizmatlit Publishing Company, Nauka Publishers, Moscow, 1990
2. E.A. Ivanov, S.V.Tchernov Issues of methodology of substantiation of limits of safety of complex nuclear and radiation dangerous systems/ Proceedings of workshop on physics of reactors "Volga 2000", Moscow, MEPhI, 2000
3. Hermann Haken Information and Self-Organization. A Macroscopic Approach to Complex Systems/ Spriger - Verlag Berlin Heidelberg New York London Paris Tokyo, 1988