APPLICATION OF THEORY OF CATASTROPHES FOR MODELING OF ACCIDENTAL PROCESSES IN VVER SPENT FUEL PONDS

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Abstract

Here we present our work devoted to modeling of complex coupled processes in severe accident in spent fuel cooling pond. The work is development of an idea, which was initially put in /1/. We believe that any explicit model of accidental process can be recognized as appropriate because it definitely very rigid and consequently structurally unreliable. We offer for using set of so-called “soft” mathematical model in terms of academician Arnold /2/.

The second idea is a fact that nobody can prove that nuclear system in any way will avoid criticality accident in any cases (during reprocessing, saving and transportation). Thus, safety assurance is reduced to substantiation of safety barriers in any accident (and in script of initial events we can not exclude any of ones having very small possibilities).

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. And this set of criteria we’ll not concern below. 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.

The second group of criteria - is risk of the severe failures, which can be recognized as catastrophe. Acceptable of any event in this case is only proof of exception of heavy consequences of it, i.e. with reference to nuclear power the principle of acceptable risk in severe accidents should be transformed to a principle of the determined exception of their heavy consequences.

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. It concerns first of all to problem of proving of safety. If we deal with severe accident we must recognize that any small probability of any event is not proof of acceptability of using of nuclear system. Because in this case we should prove that catastrophe never can occur. Moreover considering of scenarios of accident process one behind another we would prove that there are not any other events and scenarios. But it is impossible because of their number is unlimited.

But analysis of scripts of events in severe accidents can be replaced on optimization procedure to searching of 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 protection facilities. Analysis should be based on mathematical modeling and this model in its case should be built on model of coupled processes. We can formulate several principles of development of such models. They are followed.

- Modeling should be carried out as set of coupled processes.
- All simple process should be modeled by very trying out codes and algorithms.
- Codes and models should be able to simulate accident process completely.

Let consider accident process in water cooled nuclear system. 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, liquid fluid, mass and heat transfer, steam generation of fluid water etc. Model should be built on lamp parameters and during derivation of average values we can define managing function.

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

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

Concentration of the predecessors:

$$\frac{\partial C_i}{\partial \tau} = -\lambda_i C_i + \frac{\beta_i}{\Lambda} n \text{, } i = 1..6 \qquad (2\div 7)$$

Energy balance of fuel pellet:

$$\frac{\partial E_U}{\partial \tau} = \frac{1}{\gamma_U} \left(\frac{\varepsilon_F n}{\nu_F \Lambda} - \frac{2}{R_U} q_{SF} \right) - \frac{2 P_U u}{R_U \gamma_U} , \tag{8}$$

The equation of heat transfer in terms of average values:

$$\frac{\partial h}{\partial \tau} = \frac{q_S \Pi}{\gamma F} - \frac{2 w \zeta_1}{H \zeta_2} \left(h - h_0(\zeta_5) \right), \tag{9}$$

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:

$$\frac{\partial u}{\partial \tau} = \frac{\zeta_3}{\gamma} + \left(\frac{\gamma_0(\zeta_5)}{\gamma} - 1 \right) gH - \xi_{TP} \frac{H}{2d_\Gamma} w^2 - 2\zeta_1 x \left(\frac{\gamma'}{\gamma''} - 1 \right) \frac{\gamma w^2}{\gamma'}, \tag{10}$$

where $\varepsilon = \varepsilon(t)$ - is amendment on difference of the form of the channel from the vertical cylinder.

$$\frac{\partial \eta}{\partial \tau} = Q_\eta - \frac{\eta w}{H}, \tag{11}$$

$$\frac{\partial E_n}{\partial \tau} = n, \tag{12}$$

$$\frac{\partial T_M}{\partial \tau} = \frac{1}{\gamma_M C_M} \left(\frac{\omega_M \varepsilon_F n}{\nu_F \Lambda} - \frac{2}{R_M} q_{SM} \right), \tag{13}$$

$$\frac{\partial R_U}{\partial \tau} = u, \tag{14}$$

$$\frac{\partial u}{\partial \tau} = \frac{2 R_U \Delta P_U}{\gamma_{U0} R_{U0}^2}, \tag{15}$$

$$\frac{\partial s}{\partial \tau} = \zeta_4 \cdot \left(1 - e^{-\kappa |x-1|} \right). \tag{16}$$

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):

$$F(\tau) = \sum_{i=0}^{N} \alpha_i \tau^i, \tag{17}$$

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.

Temperature distribution in fuel block could be obtained by semi-static model.

$$q_S = k_\Sigma (T_U - T). \tag{18}$$

$$T_U(r) = \frac{q_V R_U^2}{4\lambda_U}\left(1-\left(\frac{r}{R_U}\right)^2\right) + T_W\,, \tag{19}$$

$$q_S = k_U \cdot \frac{q_V R_U^2}{4\lambda_U} \cdot \frac{1}{\pi R_U^2} \int_0^{R_U} 2\pi r\left(1-\left(\frac{r}{R_U}\right)^2\right) dr = k_U \cdot \frac{q_V R_U^2}{8\lambda_U} = k_U \cdot \frac{q_S R_U}{4\lambda_U}\,, \tag{20}$$

$$k_U = \frac{4\lambda_U}{R_U}\,. \tag{21}$$

Where k_U is coefficient of thermal conductivity of fuel pellet, T_W is temperature of cladding.

$$k_\Sigma = \left(\frac{R_U}{4\lambda} + \frac{1}{k_W} + \frac{1}{\alpha}\right)^{-1}, \tag{22}$$

where k_W is complete effective coefficient of heat transfer, α is heat carries coefficient.

Closing system we include empirical data of α и ξ_{TP}, and equations of states fuel end coolant. There are some peculiarities of application of empirical formulae in our equation. They are connecting to the margins of various regimes of fluid flow, boiling etc. For avoid (or at least mitigate) problems with unreliability of solution we use special “soft margin” conditions.

$$\begin{aligned}\alpha = \alpha_{O\Phi} \cdot \left(1 - erf\,\frac{h-h_{\Pi K}}{\sigma_h} + erf\,\frac{h-h''}{\sigma_h}\right) \\ + \alpha_{\Pi K} \cdot \left(erf\,\frac{h-h_{\Pi K}}{\sigma_h} - erf\,\frac{h-h'}{\sigma_h}\right) + \alpha_{\text{Д}\Phi} \cdot \left(erf\,\frac{h-h'}{\sigma_h} - erf\,\frac{h-h''}{\sigma_h}\right)\end{aligned} \tag{23}$$

Fuel element deformation is described by simplified model of covered fuel state.

$$\frac{\partial u}{\partial \tau} = -\frac{R_U}{\gamma_{U0} r} \cdot \frac{\partial P_U}{\partial r}\,, \tag{24}$$

$$\frac{\partial E_U}{\partial \tau} = Q_F - Q_S - P_U \frac{\partial V_U}{\partial \tau}\,. \tag{25}$$

Average density of fuel block we can describe by following expression:

$$\gamma_U = \gamma_{U0} \left(\frac{R_{U0}}{R_U} \right)^2 . \tag{26}$$

System of ordinary differential equation we should added by equation (simplified) of media state:

$$p_U = \begin{cases} 0 \text{ при } E_U \le Q_p \\ k_p \gamma_U \left(E_U - Q_p \right) \text{при } E_U \ge Q_p \end{cases}$$
$$T_U = \begin{cases} k_{T1} E_U + T_{U,ref} \text{ при } E_U \le Q_T \\ k_{T2} \left(E_U - Q_T \right) + T_{U,ref} \text{ при } E_U \ge \dfrac{\left(k_{T1} + k_{T2} \right) Q_T}{k_{T2}} \\ k_{T1} Q_T + T_{U,ref} \text{ при } Q_T \le E_U \le \dfrac{\left(k_{T1} + k_{T2} \right) Q_T}{k_{T2}} \end{cases} \tag{27}$$

Model of accidental process

Talking about management of spent fuel we should allocate several types of typical accident, which can be typical for stage of fuel management on nuclear power station.

Not taking into account their possibility it should be choose only two of them.

The first of them is accident with stop of circulation pump and decreasing of water level in cooling pond. It is classical thermal accident without criticality and barriers of safety in this case should be reserving of equipment (pumps and water circuits) and ventilation system for removing of radioactive gases if they will be let out from fuel rods.

The second one is accident with falling of penal with fuel assemblies in cooling pond during storage or loading. In this case we deal with possibility of criticality if fuel assemblies being immersed into water more then three or five.

Later we try to describe accidental process of second type in common-type values. Position and trajectory of moving of fuel assemblies into water tank determine behavior of all process. Their relative position and inclination influence on temperature distribution, part of steam in channels between fuel rods, fluid flow rate etc. Even knowing all mechanical data (position = coordinate of each fuel element, velocity and rotation) we in any way cannot describe process accurately because small deviation in stem generation, small oscillation and uncertainties in physical parameters of multi-component water-steam fluid and their interaction lead to significant (catastrophic) deviation in calculated values.

Thus we apply described above theoretical model and code Dyn2k. Data of simplified model are presented in table 1.

Table 1 Initial data and result for calculations of accidental process.

Variable or data	unit	value
Process		Falling of assembly in cooling pond
Time period	T, sec	10
model		Coupled kinetics in lumped parameters
maximization		Total power
Initial data		
Water		
Temperature	t, ^{o}C	30
pressure	P, ata	1
Initial velocity of falling	V, m/sec	5
Results without optimization		
Max power	Q, kW	$2.407\ 10^{3}$
Max temperature		
Fuel	t, ^{o}C	397.2
Cladding	t, ^{o}C	330.4
coolant	t, ^{o}C	100
Results with maximization		
Max power	Q, kW	$8.587\ 10^{3}$
Max temperature		
Fuel	t, ^{o}C	754.24
Cladding	t, ^{o}C	719.96
Coolant	t, ^{o}C	69.55
Results with minimization		
Max power	Q, kW	$1.616\ 10^{-11}$
Max temperature		
Fuel	t, ^{o}C	62
Cladding	t, ^{o}C	32.906
coolant	t, ^{o}C	32.67

Fig 1

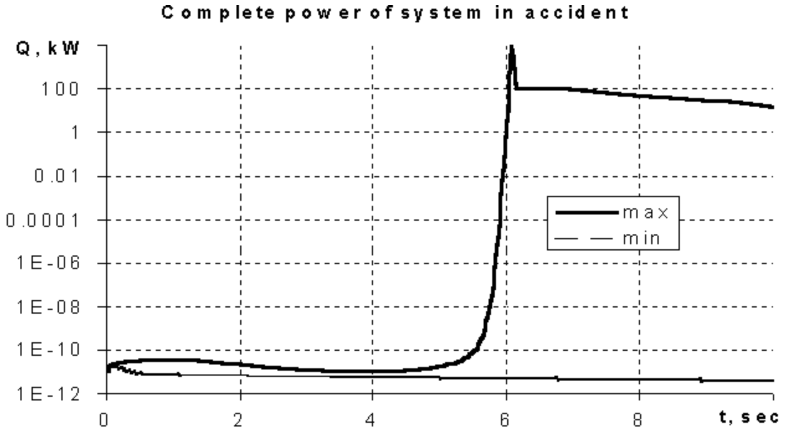


Fig 2

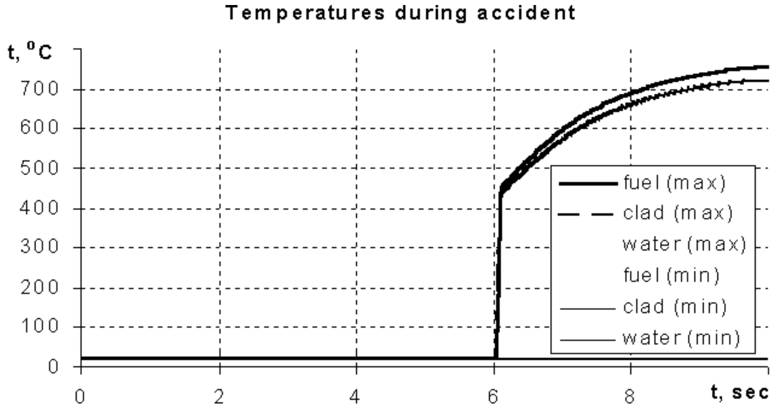
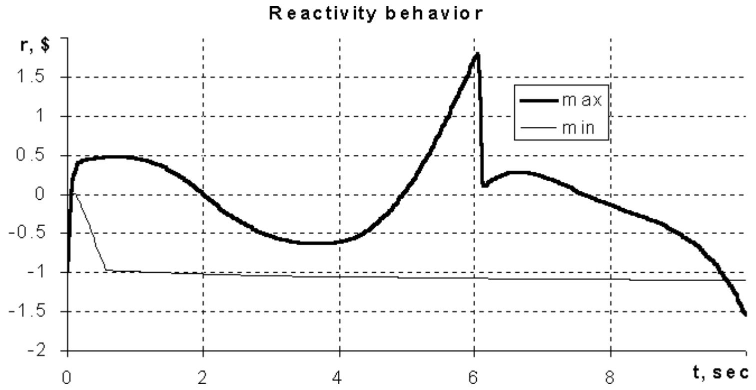


Fig 3



We can see that including of coupled processes with optimization of heaviest danger result to significant difference in resulting power yield and temperature of fuel between optimizing (ultimate) process and standard without accounting of unpredicted changes of positions and uncertainties in physical data.

Conclusions

We separate failures, which are inherent only for nuclear engineering i.e. managed by criticality.

Actual problem in safety assurance is the problem of substantiation of safety barriers in any accident. It is very complex problem, which cannot be solved completely only by accumulation of an operational experience. There are aspects of prediction of accidental states, which cannot be study in any way except for modeling.

When the substantiation of nuclear safety demands physically proved estimations of possible consequences of nuclear failures and the description of an emergency condition of nuclear system, **it is impossible to carry out the detailed analysis of all possible scripts of development of emergency process**.

The primary goal of the analysis of safety is a choice of means of protection. Then detailed modeling of processes can be replaced by optimization procedure where the simplified model of process is used, and **the function containing the information on detailed behavior of system, enters into managing parameter of optimization.**

As a result of optimization estimations of the ultimate consequences of failure without the detailed description of the script resulting in these can be received.

As the special case of application of such approach is offered a technique of settlement research of an emergency condition of unguided nuclear systems. **The offered technique is based on general view decisions and excludes necessity of detailed modeling of real scripts of emergency process.**

The basic requirements to models:

- Structural stability;
- Informatics completeness and stability;
- Opportunity of check of separate elements of model.

The chosen models:

- The integrated dynamic model of process is accepted;
- Research of real scripts of failure is replaced with search of the maximal consequences of failure;
- Results of calculation are the initial data for designing barriers of safety.

Results are received:

- “Soft” (on V.I. Arnold classification) model;
- It is shown, that search of the heaviest failure and a substantiation of conservatism of estimations is a not trivial problem.

Areas of applicability:

- The formulation of criteria of similarity for a substantiation of safety (search of the decision on “ a surface of the ultimate damage “);
- Practical calculations of sufficiency of design means of protection.

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