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Yu.V. Veryuzhsky, Dr. Sci. (Eng.)

PROBABILISTIC AND DETERMINISTIC RISK ASSESSMENT FOR EXTREME OBJECTS AND ECOLOGICALLY HAZARDOUS SYSTEMS

Institute of Transport Technologies, NAU, e-mail: veruzhsky@inbox.com.ua

The paper include mostly the results of works of the Research Institute for Mechanics of Quick-proceeding Processes united in a general research direction – creation of the methodology for risk assessment and risk management for ecologically hazardous systems, consisting of the set of different technological analyzed objects. The elements of system can be characterized by high level of radiation, toxic, explosion, fire and other hazards. The probalistic and deterministic approach for risk assessment, based on mathematical methods of system analysis, non-liner dynamics and computer simulation, has been developed. Branching in problem definition, as well as diversity of factor and criteria for determination of system status, is also taken into account. The risks caused by both objective and subjective factors (including human factor) are examined. In many performed studies, the leading structural element, dominating in determination of the system safety, is the structural part of an object. The methodology is implemented for the safety analysis (risk assessment) for Chernobyl NPP Shelton Object and other industrial buildings.

Introduction

According to the concept of sustainable development of the civilization [1], the leading role in the solution of actual problems of management strategy for human activities belongs to new scientific interdisciplinary approach – applied risks theory.

The typical examples of EO are: the Shelton Object (SO) – a special structure for localization of Chernobyl NPP Unit 4, suffered as a result of nuclear accident in 1986 (fig. 1) [2]; Odessa's terminal of Chemicals (fig. 2) and number of other industrial buildings of such type [3].

Fig. 1

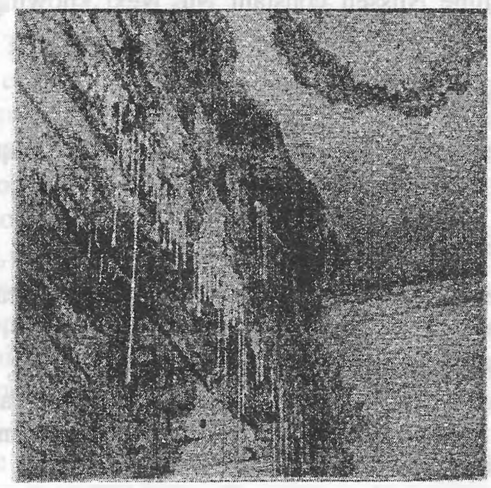

Fig. 2

The methodology for risk assessment and management for ecologically hazardous systems (EHS) is examined. The elements of EHS are characterized by high level of potential hazard (radiation, toxic, explosive, fire, etc.) for the humans and the environment.

The extreme objects (EO) are one of the latest studied EHS classes. They consist of buildings, structures, machines, instruments, equipment and protection means, not intended for work under the conditions of extremely high risks and occasionally found themselves in the area of increased risk as a result of the accident.

The general EO theory is based on studying the peculiarities, specific for the whole class of such objects, i.e. regardless of their functionality. So, damaged atomic submarine or space vehicle can be easily repaired to the normal state under the deployment conditions. But the damages, occurring far from the base, could transform the repair into a hardly solvable problem that has elements of statement, common for the both objects. The common is that the initially closed system, as a result of an accident, becomes the subsystem of more complicate many-dimensional system. As a result of an accident, something like dissolution of the initial system in the macrosystem, including not only technical, but also most complicate normative, legal, human, economical problems, etc.

These characteristic aspects are relevant also to SO. This object, if the nuclear and radiation hazard factors are excluded, could turn into an ordinary reconstruction object [2]. But its status of an object of nuclear power engineering complicates risks analysis and management so much that during last 17 years no significant achievements, adequate to spent resources and efforts, have been reached.

There are five main peculiarities of EO:

– condition of object does not comply with the existing standards by any parameter;

– uniqueness of its functionality;

– dominating significance of solution of the main problem (EO dominant), which all other goals are subjected to;

– exceptional complexity and individuality of the problem that has complex interdisciplinary features;

– determinative role of research to exclude errors with significant negative consequences.

Almost all investigation methods have deep prove to be inconsistent in analysis of such systems [2; 3].

The deterministic methods, as basic theoretical apparatus to ensure "absolutely" reliable forecast of changes in object properties and to develop efficient countermeasures, became substantially insufficient to overcome increasing difficulties and uncertainties, characteristic for EO.

From the certain threshold of difficulties, the probabilistic analysis has become the basic regulated mean to assess risks (aviation, cosmonautics, nuclear power engineering, etc. [4; 5]). But decrease of actual probabilities as the main way in risk management becomes unacceptable for the objects, containing unique elements of system [6]. To analyze such systems, it is impossible to apply classical reliability methods because of absence of required statistically representative data.

Branch methods, developed even for quite complicate systems, taking into account mutual influence of different elements and links, cannot be extended to EO whose main features principally differ from those of typical objects. So, using traditional approaches of the reliability theory, consisting in formation of the event and failure tree in NPP operation analysis, it is possible to obtain for SO comparatively short and tamely ramified trees, determining the influence of initial events on system behavior. But correct probability assessment is quite difficult by two main reasons:

– complexity of the mathematical apparatus (non-linearity of the dynamic processes, presence of distributions with "heavy tails" [3], that are characterized by significant, but quite rare events – they are "cut" in traditional statistical analysis);

– high uncertainty of the initial information.

This complexity of the mathematical problem is a reflection of discrepancy of the method, necessary for EO analysis, with the regulating requirements for the analysis of single-type objects of the branch, worked out basing on data collection and statistical generalization on the representative set of standard elements. Two other important factors are also manifested:

– principal difference between technological processes for EO and typical industrial objects;

– practical unreasonableness of implementation of engineering solutions, being made without appropriate clarity of the results, that ensures only insubstantial level of safety.

At SO and other EO, the disadvantages of set-theoretic expert approaches have been manifested in significant extent. These approaches require involving of many high-skilled and well-informed specialists whose opinions are analyzed and synthesized using different methods for processing of expert appraisal. Under the conditions of incompleteness of valid initial information, for actual level of individual and common knowledge about SO, the "variety" of result summarizing methods can just veil but not improve the current situation when "averaged" conclusion becomes invalid.

That is why the determination of methodology without the above disadvantages is extremely important.

Basic principles of the investigation method proposed

Selection and substantiation of the efficient risk management system for EO functioning is possible with usage of system approach only. The probabilistic and deterministic apparatus for risk investigation in based on mathematical methods of system analysis, non-linear dynamics and computer simulation.

The necessity in system approach is caused by the formulation of many ramified statements of common problem, diverse factors and criteria of system status, selections of efficient management strategies. The risks are examined on both objective and subjective basis (in particular, taking into account the human factor).

Application of system analysis methods for EO risk management has shown that, to achieve valid results, not only strict observance of actual maintenance (operation) norms and object status assessment rules is required, but also scientific substantiation of reasonable deviations from rules and norms in force.

Basing on study of the set of EO, it is possible to mark out the following basic statements of the method of combined numerical, simulation and experimental investigations, related to organization of risk management activities:

– the problem of system multiple-factor safety analysis is examined; the safety is determined by the risks of damage of protection barriers as a result of degradation or catastrophic changes in EO structure;

– the behavior is described by solution of bound non-linear dynamic tasks that represent the process of change of the system and its effect on the environment up to complete exhaustion of operating abilities; in this case EO is represented as space-time structure from the elements of different nature;

– the main instrument of the analysis is the apparatus of probabilistic and deterministic simulation, where only valid information (documentary materials on reference areas) is used for verification of the results, and the expert appraisals are used as minimal, as necessary;

– the research apparatus is created, taking into account certain EO peculiarities.

Full lists of initial events are envisaged by branch norms, but performing EO analysis, in view of short-term calculated extreme period, the substantiated attempts to reduce this list by excluding the events, the probability of occurrence of those is negligible (e.g., strong earthquake), are being carried out.

However, because of stochastic character of such events, mechanical exclusion of the rarest events with possible catastrophic consequences, that is sometimes proposed to do volitionally, could become unjustified.

It should be noted that composition of this list for EO (as well as working out the most important safety criteria, that is an important part of risk theory methodology) undergoes the significant influence of the forcible "human factor", though it is performed on the scientific basis.

On the certain stages of research organization on SO, the method of expert appraisals prevailed even when making quite important decisions; and this fact leaded to non-justified increase of "human factor". The reason of these failures was in impossibility to form the commission of statistically representative set of specialists, having necessary knowledge about SO. Because of complexity and inconvenience of this information, the agreement procedure often leaded to division of specialists into two groups – majority, where the opinion of leaders was of main importance, and minority, defending their individual opinions.

The probabilistic part of the methodology includes description and analysis of the random functions, definition of stochastic models of the dynamic processes (loads, physical, mechanical and other initial parameters, technological situations and their effect on the system-forming parameters and other components with significantly uncertain conditions). The results of intermediate stages of probabilistic analysis consist of assessment and formation of the most changeable initial data for the deterministic calculations. Successive examination of the whole event tree during simulation of the negative scenario allows obtaining of basic probabilistic quantitative risk evaluation for possible releases, contamination, increase of exposure rates, damages and other process characteristics.

The deterministic part of the analysis consists in successive computer simulation of system evolution, degradation and destructurization stages. Possibilities for buckling failure are determined on each characteristic section of system development trajectory. This effect occurs under manifestations of sensitivity to slight actions near the bifurcation points, when in antecedent state the vicinity of manifestation of soft branching or rigid catastrophic jump of extreme or degradation changes.

Problem statement and SO safety investigation methods

As a basic example for EO risks assessment, SO is considered.

SO risk is a multiple-factor value and signifies the threat of additional radiation damage for the staff, environment and population, in the case when the share of radioactive materials, localized now inside SO and at adjacent industrial site, will lose existing engineering and natural safety barriers. The concept of risk includes the character of the events, their probability, nature and weight of hazardous consequences.

The statement of investigations considered such specific SO features [7], which are characteristic for mitigation of the consequences of earthquakes and similar damages:

– the design documentation for the whole object, as well as detailed documentation for the majority of SO premises where the activities are supposed to be performed, is absent.

– chaos as the most specific feature of the premises where the major part of the Fuel Containing Materials (FCM) and Radioactive Waste (RW) is located. It makes working out new design documentation more difficult.

– the dangerous status of many SO premises make more difficult (or even impossible) performance of active process operations without carrying out preliminary analysis and prevention of possible consequences of applied mechanical actions.

There are characteristics for SO and mining activities (underground and open-cast), including uranium mining:

– spatial (dimensional) restrictions inside SO are to be taken into account when examining access to FCM accumulations, as well as performing process operations;

– climatic conditions inside SO (temperature, humidity, velocity and direction of air streams) practically cannot be regulated and are determined by weather conditions outside SO;

– non-fixed radioactive dust is the determinative factor for radiation safety of the staff. Generation of radioactive dust during performance of process operation can lead to spreading of radioactive contamination through other SO and ChNPP premises, as well as to contamination of technical means, equipment and environment.

– content of fissile nuclear materials (^{235}U, $^{239,\,241}$Pu, $^{241,\,243}$Am) in FCM is small in comparison with the mass of FCM and other RW and is characterized by significant non-uniformity by SO premises.

– FCM are located not only in internal SO premises, but also at the industrial site, where they can interact with atmospheric precipitates and groundwater.

There are characteristics for SO and for atomic industry and mitigation of the consequences of accidents on nuclear objects:

– potential hazard for initiation of chain reaction when dealing with FCM requires observance of acting rules and norms of nuclear safety, worked out for management with fissile nuclear materials.

– high radiation fields limit (or exclude) participation of staff in carrying out the activities, repair and maintenance of the equipment.

Essential part of SO consists of the elements of destroyed Unit 4, so system safety is determined by the reliability of its structures. Failure of these structures can lead to changes in configuration of nuclear hazardous materials, as well as to release of radionuclides to the environment and other negative consequences. SO does not comply with the requirements of normative documents of the nuclear power engineering. The methods of direct investigations and measurements in essential part of SO are ineffective because of high level of radiation and blocking of the access routes.

The dominant of SO, according to its status, is the primary task to transform the damaged unit into the controllable state. To reach this goal, such items are investigated:

– potentially unreliable and vulnerable complicate system, consisting of qualitatively different elements;

– dynamic transient bifurcation processes with fuzzy buckling failure criteria on the path sections;

– various initial events and failures;

– essentially incomplete and incorrect components of databases;

– technical and technological monitoring means;

– system to work out controlling decisions and to react under emergency situations.

The main obstacle in solution of dominating SO task is uncertainty in data on risk factors. The key risk factors are the parameters of sources of nuclear, radiation and other hazards, as well as characteristics of structure damages. To obtain necessary information, during recent years, a great scope of work has been performed at SO. Overcoming exceptional difficulties, various data on SO system components were accumulated. A part of these characteristics can be used to build fragments of adequate SO models and to verify the results of indirect studies. However, in whole, initial SO information is insufficient. This is proved by the attempts to analyze SO status made by the leading organizations, that, in fact, had no success [2].

As an example, the results of evaluation of process idea of grouting in concrete the main part of SO internal space to conserve it for many years. The investigations were performed by three groups of high-skilled experts that applied similar certified methods and powerful software. The difference in approaches was determined only by boundary conditions in task statements, where the location of nuclear hazardous materials was fixed.

There were obtained three mathematical results, substantiating fundamentally different proposals. In the first option, there was proved that long-term safety of monolithic structure would be guaranteed even if ordinary concrete were used. In the second, there was determined that to eliminate negative local heat and nuclear effects when grouting areas with hazardous sources, special processes and materials should be used. The third conclusion had shown full inconsistency of this idea, because its implementation must lead to inadmissible consequences.

The similar situation arises when evaluating SO structure reliability. In this case, different high-skilled experts are making mutually exclusive conclusions regarding the same units of SO structures, although there is the functional basis of structure mechanics and theory. These analysis means allow not only valid calculation of stages of elastic and non-linear deformation of elements using normative criteria of marginal states, but also simulation of their behavior up to full-destruction. For quite accurate representation of damage parameters and pre-history of design-basis operation of elements, it is possible to determine the residual bearing capacity and other characteristics of the “critical areas”, as well as the whole SO structure.

But the validity of the initial information is ensured only for a part of damaged SO structures (for slightly damaged fragments, normative methods are used, fully destroyed areas are excluded). Intermediate damage characteristics for other structures of Unit 4, belonging to SO, are into this wide range. So, dependent on the choice of presuppositions for formation of initial information, significantly different results can be obtained.

Two main streams for SO status assessment have been formed.

In the first stream, the statements of nuclear power engineering norms are strictly used. If the problem specification is insufficient, it is supplemented with the worst possible conditions basing on the conservatism principle. In this approach, the defect SO structure is calculated for action of excessive loads, because the necessity to take into account the extreme situations is strictly regulated, although these situations have quite low probability to appear. Such events include intensive earthquakes, hurricanes and tornadoes with significant velocities of air streams and pressure pulses, aircraft crashes, explosions inside and outside SO, fires, and exclusively unfavorable combination of different factors. The situation is complicated by conservatism in assessments of development in weakening of structures as a result of corrosion, erosion, creep and embitterment of structures, decrease in crack resistance, settlements and watering of foundation, other physical and chemical degradations. As a result, the conclusion is made that SO structure does not comply with the actual criteria. This is a foundation for conclusions on possibility of emergency destruction of nuclear and radiation safety barriers, as well as on high level of negative consequences of the most dangerous (but improbable) initial events.

The current SO operation and transformation strategy is based on the second approach, using “softening” of the normative requirements of nuclear power engineering. This choice is substantiated not only by the fact that SO does not correspond to any standard class and the existing status of mitigation of the consequences at ChNPP accident, but also by more important arguments. So, the development of the designs for SO structure stabilization has shown that the conservatism principle leads to very expensive decisions. But the illogicality of such investments is explained by two main considerations.

Firstly, SO as temporary structure should not be more reliable than other ChNPP objects and permanent structures, erected without taking into account such strong impacts.

Secondly, branch methods, where simplified analytical models and quite high coefficients for reliability margin are used, do not allow taking into account SO peculiarities and, therefore, do not ensure its safety after reconstruction and during carrying out the activities.

SO: natural, maximal and main component of risk

It is evident that radioactive materials inside SO and at the industrial site are the open sources of ionizing radiation. So, SO radiological risk in any moment of time is proportional to the total activity, localized in SO and at the industrial site. Hence, if keeping the localization, risk will decrease with the rate of radioactive decay of fission fragments and transuranium elements. Because this process is not controllable, let us call the risk, proportional to total activity, the natural risk. SO natural risk can be decreased only in one way – if the quantity of radioactive materials inside SO will be decreased by their transportation to another place, e.g. to RW storage.

Thanks to SO maintenance, natural risk is managed to be localized inside SO, i.e. natural risk is rather a characteristic of an object itself than an indicator of damage for population and environment.

Let us examine the hypothetical case when the maintenance of SO is stopped by some reasons. Neither the staff, nor population does not intervene in the natural processes in SO. Non-intervention is also a kind of activity in post-accidental period.

The possible scenario for SO evolution is the following:

– the building structures are slowly destroying, the presence of moisture (condensed or precipitating), along with seasonal fluctuations in temperature, hasten this process;

– slow destruction of FCM and leaching of heavy metals occur, fission fragments and transuranium elements come into the solution, flow down and are accumulating at SO lower levels;

– at the certain moment of time, the roof will fall down, the walls will become partially destroyed, the looseness in the foundation will appear and the activity, still existing at that moment, will have practically unlimited contact with the environment;

– any external extreme impacts can significantly fasten any processes in the non-interference scenario.

So, the consequence of non-intervention is destruction of existing SO safety barriers and direct contact of radioactive materials with the environment. Expected risk (damage) for non-intervention by this reason is the maximal. Any SO activity can be justified if it leads to decrease of expected risk (damage) for further non-intervention.

Current SO status is characterized by four main risk components.

Risk of collapse – existing SO structure has limited service life – 30 years from November 1986; Self-destruction or collapse can transform SO into practically open source of ionizing radiation with total activity up to 10 MCi, so such event should be classified as radiation accident;

Risk of failure – some SO structure elements are in dangerous state and need to be repaired urgently; failure of such structures can initiate SO collapse; in any case, this event also is a radiation accident;

Risk of criticality – location of a share of spent nuclear fuel (SNF) inside SO is unknown, hence, it is impossible to make the forecast for its criticality. Independently from the consequences, reaching the criticality level is a radiation accident;

Radiological risk – a share of FCM is located at SO industrial site and is a direct source of local radioactive contamination of groundwater; the area of radioactive contamination increases as a result of migration of radio nuclides; when it will reach the water-bearing strata or Pripyaf river basin, the increase in collective dose for population of Ukraine will become inevitable.

Now, working out and implementation of countermeasures can be performed in parallel to minimize each risk component. In case of transformation of risk as probabilistic event into sure event, i.e. in case of appearance of criticality, failure, collapse or various combinations of these factors, the risks will become interrelated, and the catastrophic increase in fourth component – radiological risk – will occur. The last assertion is based on the assumption that in case of any radiation accident in SO, major share of activity will leave inside SO industrial site (as results from FCM composition and properties).

Therefore, the radiological risk is the determinative factor both for current SO status (R_0) and for any its evolution including evolution of first three risk components. Hence, the determinative risk is the total risk R: $R = R_0 + \Delta R$, where ΔR is the increase of radiation risk as a result of additional contamination, that occurs during the release of radio nuclides outside SO, caused by any radiation accident. Additional risk ΔR can arise also as a result of release of dust and/or aerosols during performance of activities inside SO without taking adequate measures to ensure safety, or as a result of discharge of SO radioactive water, caused by foundation seal failure or failure in waterproofing of SO lower levels.

Risk assessment methodology

An efficiency of applying a methodology of extreme objects problems solution built upon an interdisciplinary base to research of the SO encasement is demonstrated [2]. The encasement with connected components is considered to be a subject to multi-factor analysis of nuclear, radiation, environmental and common safety in the course of current exploitation and transformations. The key point of the research is a prognosis of behavior of the SO structure being degradate under extremely combined influences. A vast-purposed technique is developed for deterministic and probabilistic numerical modeling, risk assessment, experimental and design works. Individual tool for considering peculiarities of the SO is a complex technique of determining the system's state (in scarcely available areas) based upon the sequential analysis of the reactor core accident, the 4th Unit's destruction and the SO erection.

A structural scheme of operational state of the CNPP 4 block is built with usage of archival documents. Various versions of spatial finite element models are developed; they allow the realization of the 4 block structural scheme with various extents of detailing, using application software packages. Analyses of peculiar stress-deformed states of the 4th block under various combinations of loads and influences are performed in order to estimate efficiency of the FEM models versions developed. Based on the result consideration a computational model of the 4th block is chosen for further numerical analysis of its constructions' mechanical behavior, including that in the course of the core accident and in the course of localization and mitigation of the accident consequences.

Processes, which took place at the beginning stage of the 1986-year accident, are analyzed. The main attention is given to changing of pressure in reactor volume with consideration of entering of heat transmitter in active zone through destroyed technological channels and simultaneously exiting steam through permanent steam-exiting system and through creating clearances in protector shell. On this base the movement of the reactor's cover is studied, and the interaction between going up reactor's cover and unload-load machine is considered.

The pressure of gas in reactor volume is determined and on this base the pressure on walls and covers of central hall and housings of separators is calculated, which took place after steam going up from reactor volume into neighboring housings.

The general procedure for the determination of topography of the reactor active core wreckage ejected by explosion as a result of the Chernobyl NPP accident has been developed. The regions of the failure and the reactor active core ejection have been constructed by the numerical experiment series. The active core wreckage motion in the field of gravity has been explored. The ejected fragments topography for the case of the active core explosion in the standard position and over the reactor section plating has been constructed.

The paper [2] exhibits the usage of developed mans for numerical modeling of destruction process of the constructions of the Chernobyl NPP Unit 4 Reactor during the core accident; reliable facts related to intermediate and final states of the constructions are used as a base to verify the results obtained.

The paper deals with modeling of the Unit 4 building constructions behavior under explosion influence during the initial phase of the core accident. One of possible versions of the accident was under consideration. Values of accident influences were obtained from aerodynamic analysis. Numerical research of the Unit 4 constructions behavior under explosion was performed by finite elements. To analyze the system's dynamic response to the given loading, new mark numerical integration of the motion equations was applied. A technique to determine ferroconcrete constructions destruction criteria was developed; consideration of the analysis' results was performed.

Analysis of methods of the safety assessment of the SO encasement demonstrates that the existing standard codes and technical support are insufficient to obtain true quantitative characteristics of the encasement for the case of initial event's realization. Failure of assumptions have resulted in decreasing the level of risk assessment conservatism adopted in official requirements. It is proposed that system analysis approach be used to research and assess negative consequences of the SO protection barriers' destruction. A solution is obtained from synthesis of probabilistic and deterministic methods as well as from usage of tool inspections and expert estimates to verify source data and results. The direction being proposed is implemented for all phases of risk assessment. Characteristic examples are presented for the analysis of consequences of the initial events of an aircraft falling upon the SO and external explosions.

Characteristic peculiarities of a procedure applied during safety analysis (risk assessment) of the SO encasement are discussed, as well as those of the encasement itself which take effect on developing such procedure. Indicators (functions) of risk to be used are formulated; the efficiency of their choice is discussed. A mathematical aspect of considering the parameters uncertainty within the SO when modeling accident processes is characterized, as well as this uncertainty's influence upon values of risk functions. Some quantitative estimation of risk indicators is presented along with conclusions about their quality.

At SO, when performing probabilistic part of risk assessment, it was proposed not to operate with the terms of continuous time, but to attach Markov properties to an object in the discrete moments of time, divisible by a year. In this case, SO evolution model comes to Markov chain with finite number of states. Estimation of transient probabilities and formation of transient operators of Markov chain allow reduction of the analysis to matrix transformations of chain with finite number of states. As a result, there were formally detected:

– reliability factors with estimation of probabilities for safe operation, as well as of arising of the catastrophic states during given number of years in terms of strict probabilistic definitions [5];

– average time before the catastrophic state will come (was estimated as system longevity), as well as dispersion of this time.

As the dispersion is quite high, the forecast becomes very sensitive to accuracy of initial data.

To assess efficiency of measures, taken to increase SO safety level, transient operators of the Markov chain reflected change of probabilities of events, related to determinate interference of humans. Adaptive observation algorithms were used. These algorithms ensure the interval assessment of transient probabilities in comparison with the global characteristics of SO evolution, fixed previously.

Analysis of hypothetical accident scenarios was performed in the following way:

– estimation of probabilities of initial events;

– progression of accident situation (deterministic simulation);

– assessment of the possibility for origination of the nuclear hazard;

– estimation of volumes, quality and topography of releases outside SO;

– estimation of values of risk functions.

Value

$$F_k = p\{E_k\}S_k, \quad k = \overline{1,N}, \tag{1}$$

is taken as a criterium E_k, $p\{E_k\}$ is a separate source event and its probability, S_k – a total activity of material, abandoning SO as a result of realization of given negative scenario. The Stochastic multiplier $p\{E_k\}$ was valued as a result of calculation of Markov's chain.

In general different determining problems of this section (dynamic and static of building design, convection and diffusion in water-colloidal ambience inwardly SO and others) is described by quasilinear system with local interaction:

$$\lambda_k \Delta^* u_k + F_k(t,x,u,a) = \frac{du_k}{dt};$$

$$x \in V;\ t \geq 0; \quad (2)$$

$$I_k^0(u,x,\rho) = 0;\ x \in V;\ t = 0; \quad (3)$$

$$B_k(t,x,u,(Ln)u,\beta) = 0;$$

$$k = \overline{1,N};\ x \in \partial V;\ t \geq 0, \quad (4)$$

where Δ^* – a linear differential operator 2nd order (Laplas, Navie etc.); L – is a linear differential operator 1st order ("operator of the flow")'; d/dt – usual, private or substational derivative on time; $u = (u_1,...,u_N) = u(t,x)$ – a collection of dynamic variables, which describes the condition of the system, and is a function of the spatial coordinates $x = (x,y,z) \in V \subset R^3$ and time t; ∂V – a border of the spatial area V.

The parameters α, β, ρ wholly define the parameters of the self-excitation and external influence, so analytical type to functions F_k, I_k^0, B_k depends from physical essence of the process only.

Acceptance of initial (3) and border (4) of the conditions in nontraditional type is connected with that the parameters are measured and exist not directly; and inaccuracy of the indirect observation is one of the factor to uncertainties. So, in [3] is noted that places of FCM are fixed with such indirect way of the observations as: ultrasonic, heat exchange, radar and neutron flows, which are checked by systems "Tent" and "Finish", displacement of responsible designs are measured with strain gauge, etc.

We take that parameters $\lambda_k, \alpha, \beta, \rho$ have small inaccuracy and in tasks (2) – (4) they are averaged by some methods. Then on space-time of definitional domain dynamic variables **u** there exists "microinaccuracy" i.e. small detours δλ, δα, δβ from averaged value. Hereupon decision of averaged tasks (2)–(4) **u** is deviate from real **u**, on value $\nu = u_r - u$. The question is correct delivered to a problem, in which decision continuously depends on conditions of the problem. So ν is taken small; it is herewith noted that linear correlations for ν are built for the reason of determinations of the trends on the behavior of ν.

The problem consists of: presents of decision **u** of averaged problems (2)–(4) under investigation phenomena with acceptable accuracy, or "microuncertaities", for "leads away" of averaged problem from reality, but to reach the required small size to inaccuracy, it was necessary to fix the condition of the problem with unrealistic accuracy. The above problem -is an engineering analogue of the question about stability of the moving mechanical system and question of correctness of mathematical model.

Trend of the divergence of the decisions is defined by behavior of the outraged decision **u+ν**, which satisfies to problems (2)–(4) with outraged parameters, $\lambda_k + \delta\lambda_k$, $\alpha + \delta\alpha$, $\rho + \delta\rho$. The necessary linearization is possible in view of a priori small size of the indignations problem:

$$\lambda_k \Delta^* \nu_k + \sum_m f_{km}\nu_m + \delta g_k = \frac{d\nu_k}{dt}; \quad (5)$$

$$\nu_k(0,x) = \delta\nu_k^0(x),\ k = \overline{1,N}; \quad (6)$$

$$(Ln)\nu + K\nu = \delta\psi + \delta\varphi, \quad x \in \partial V, \quad (7)$$

where incorporated indications are:

$$f_{km} = \frac{\partial F_k}{\partial u_m};\quad \delta g_k = \left[\delta\lambda_k \Delta^* u_k + \sum_m \frac{\partial F_k}{\partial \alpha_m}\delta\alpha_m\right];$$

$$K = \left(\frac{DB}{Dp}\right)^{-1}\frac{DB}{Du};$$

$$\delta\psi = -(L\delta n)u;$$

$$\delta\varphi = -\left(\frac{DB}{Dp}\right)^{-1}\frac{DB}{D\beta}\delta\beta;$$

$$p = (Ln)u;$$

$$\delta\nu_k^0 : \sum_m \left[\frac{\partial I_k^0}{\partial u_m}\partial\nu_m^0 + \frac{\partial L_k^0}{\partial \rho_m}\delta\rho_m\right] = 0.$$

We solve the system (5)–(7) in the manner of decompositions on own functions:

$$\nu(t,x) = \nu_b(t,x) + \sum_{k=0}^{\infty} W^{(k)} e^{\mu_k t} \int_V W(k) \times$$

$$\times\left[\delta\nu^0(x) - \nu_b(0,x) + \int_0^t e^{-\mu_k t}\left(\delta g - \frac{\partial\nu}{\partial t}\right)d\tau\right]dV, \quad (8)$$

where μ_k – own importances linearize systems; $\overline{W}^{(k)}$ – an ortonormal to own functions; $\nu_b(t,x)$ – a decision of quasistationar problem:

$$\lambda_k \Delta^* \nu_k + \sum_m f_{km}\nu_m = 0, \quad x \in V; \quad (9)$$

$$(Ln)\nu + K\nu = \delta\psi + \delta\varphi, \quad x \in \partial V, \quad (10)$$

which shows that trend of the development to inaccuracy ν at time is defined by signs of the real parts of Lyapunov's values μ_k, then gradients of the own forms define the trend of the influence of the border conditions and features of the ambience.

Because of their numerical implementation, statistical and dynamical calculations for building structures (for dead weight, snow, earthquake, aircraft crash, etc. [4]) are carrying out for point (not continual) models, where dynamical variables, describing the status of system, have high number of dimension (up to several thousand points).

However, use of conservative assessments does not exclude essential errors in the analysis of real SO state. For example, it takes place during the assessment of long-term bearing capacity of SO building structures. Owing to climatic, radiation and other processes, these structures are aging and are characterized by uncertainty in elastic characteristics and grip conditions, decreased rigidity propertied compared with the normative (reference) properties. The latter are accepted for dynamical calculations with the empirical weakening coefficients. Under these conditions it can be supposed that calculated stress and displacement fields would be the conservative estimate – upper estimate. But more complicate cases also can occur. Because of many microcracks, the rigidity parameters can change macroscopically as a result of elastic wave passing. However, in materials, weakened with high concentration of micro cracks, the mechanism of accumulation of fatigue after wave passing seems more probable; in this case, the rigidity parameters become worse monotonically. As a second example, the bifurcation analysis for temperature fields can be given. Estimation of the temperature fields of residual heat in subcritical FCM is based on multiple assumptions, because there is no valid information on heat exchange, geometry and composition of FCM. The reason to exclude them from consideration during safety analysis is not only their non-determinacy, but also difficulty of constructive probabilistic assessment. In other words, at least for "soft" safety analysis [4], such effects are not taken into account. However, this fact can lead to great discrepancy in simulation and nature investigations. The general regularity is observed: the possibility of such discrepancy appears there, where in the model small non-linearity is neglected.

The Analysis to stability greatly nonlinear models have gained in recently multiple exhibits. In particular, to studies of the kinetics are broadly used methods of the nonlinear functional analysis and theory of bifurcation in dynamic systems. The Main theoretical positions in consequence of their generalities are carried as well as on dynamic of the processes in SO. For the numerical analysis it is effectively to use the variational wordings, on base on which are built variational-set (certainly-element) of the scheme. The Vector-function, and $u(/,x)$, describing physical process, which is possible to model by differential initial-marginal Problem with limited variation of coefficients, minimizes certain terminal-integral nonlinear and not square-law functional;

$$\Phi(u,\alpha)=\int_{t_1}^{t_2}\left[\int_V \psi_V(t,x,u,\alpha)dV+\int_{\partial V}\psi_\partial(t,x,u,\alpha)\right]dt+\int_V \Omega_V(t_1,t_2,x,u,\alpha)+\int_{\partial V}\Omega_\partial(t_1,t_2,x,u,\alpha)d(\partial V)\,. \quad (11)$$

Here α marks the collection of parameters, which defines the ambience, parameters of the self-excitation and external influence; the underintegralto functions, as a rule, comprise itself of differential operators of 1-st or more high order. The Necessities condition of extremum $\delta\Phi(u;\ \alpha) = 0$ must be executed for all small variations of the decision δu, including that, which is caused by small variations of parameters $\delta\alpha$.

$$\Phi'_\alpha\delta\alpha+\Phi'_u\delta \acute{u}=0\,. \quad (12)$$

Variation δu is hung. On the grounds of correlations (12) loss to stability to models is possible to interpreted with the general position as loss of insufficiency by operator Φa. The last is guaranteed, for instance, in problem of building mechanical engineering only for problems from class Sen-Venan; herewith in FCM current condition of many designs removes them from given class. Under limited operator Φú and unlimited $\Phi\alpha$, vagary is guaranteed. The loss of stability in consequence of an excess by external influence of certain level and indignations of parameters of ambiences is entered here. There are known such quotient events, as loss forms of the balance by designs or origin of selfsupporting chain reaction.

So, it is seen that when potential accidental process with extreme parameters is calculated, any simplify-cation should be well substantiated, though such substantiation could be as complicate as calculation by "accurate" model. That is why the response in model problem is the numerical characteristic that describes in full extent the negative aspects of the process and that is not sensitive, at least, to the above-mentioned inaccuracies.

So, the model calculation [2] has shown that SO roof collapse, that is the main type of functional failure, will lead to the release of about 2 tons of radioactive dust with total activity of about 2600 Ci into the environment. Validity of the initial data, different scenarios and reasons of collapse, accompanying natural and man-caused events can increase or decrease this estimation.

Assessment of influence of initial events on the stability of SO safety analysis has shown that there is great dispersion in the final estimates of risk functions. So, these estimates seem to be the expert estimates, though they are reflecting high level of hazard of this group of initial events. The first such event is SO failure, caused by degradation. It has the probability, which varies, by different estimates [4], from 0.08 to 0.1, and its risk function varies from 200 to 260 Ci/a. The second event is fire inside SO. For this event, mechanism and quantity of released materials is not clarified completely, as well as its influence on probability of SO failure.

Countermeasures

Basing on brief risk analysis and possible scenarios for arising and progression of radiation accidents inside SO, three types of countermeasures could be formulated.

Tactical countermeasures: measures, performed at SO to prevent collapse, failure, criticality and radiological hazard. These measures, as a rule, are short-term. They require involving human and material resources during, in fact, undefined period of SO operation. At the same time, there is no absolute assurance that these tactical countermeasures would prevent radiation accident at SO. Stabilization is a basic element of tactical countermeasures. Along with strengthening of building structures, it is necessary also to stabilize current conditions of FCM accumulations, elements of the reactor system and hydrogeological situation at the industrial site.

Passive countermeasures: measures, performed at SO to decrease consequences of radiation accidents at SO by timely creation of accident localization systems. These countermeasures are long-term measures. They require involving significant human and material resources in short period of time (construction phase) and constant operation during, in fact, undefined period of time. Creation of SO-2, either as containment (heavy Sheter-2) or as confinement (light SO-2) is the key element of passive countermeasures. To prevent release of radionuclides outside the industrial site, as a passive countermeasure, hydro geological protection, localizing FCM and other RW outside SO, should be created.

Active countermeasures: measures, performed at SO to exclude radiation hazard, if an accident occurs. These are the measures eliminating the causes of radiation accidents, i.e. excluding the accidents at all. Active countermeasures require involving significant human and material resources during limited period of time (active phase), transform SO and the industrial site into radiation safe object after completion of the active phase. The problem of SO dismantling and conversion of SO industrial site into "green lawn" can be postponed by uncertain term and performed, if necessary, according to the rules of ordinary civil engineering. FCM and other FCM retrieval from SO solves all questions necessary for significant decrease of radiation risk from SO existence and for decommissioning of destroyed ChNPP Unit 4.

Characteristic peculiarities of a procedure applied during safety analysis (risk assessment) of the SO encasement are discussed, as well as those of the encasement itself which take effect on developing such procedure. Indicators (functions) of risk to be used are formulated; the efficiency of their choice is discussed. A mathematical aspect of considering the parameters uncertainty within the SO when modeling accident processes is characterized, as well as this uncertainty's influence upon values of risk functions. Some quantitative estimation of risk indicators is presented along with conclusions about their quality.

Results of numerical analysis of stress-deformed State of supporting constructions of the beams Bl, B2 of the SO encasement roof are presented, the beams being located on the axes 50 intersection. The structural scheme of the encasement with consideration of present destructions has been restored based upon data of archival research and visual inspection of available constructions. It is shown that the structural scheme must include not only direct supporting of the beams B1 and B2 but also a pile of fallen constructions and friable materials, steam separators, walls and bars of the block B lying lower. A finite element model of the beams support junction is implemented with consideration of the structural scheme. Computations are performed for various principal and peculiar combinations of loads. Basing on consideration of results obtained, most dangerous loads and influences combinations are discovered as well as structure's zones loaded most strongly.

The mathematical model of formation and movement of dust cloud in the SO encasement when its roof falls has been developed. The proposed method and computer program allow to research process of formation of cloud at different scenarios of the SO destruction. The numeral research results can be used for developing of dust suppression system and other measures for elimination of consequences of Chernobyl accident.

A complex operative model of PS numerical prognosis on the speed fields of wind, temperature, pressure, nebulosity, precipitation and on the formation and transfer of the pollution fields from instantaneous and permanent sources of admixture ejections into the atmosphere under real weather conditions in the region of arbitrary linear dimensions. The model allows solving the problem of atmospheric status prognosis due to a technogenic impact of industrial enterprise work in regular or accident regimes. The problem solution will find its application in transborder transfers prognoses of pollutions in the atmosphere.

There is evaluated effectiveness of one alternative emergency fight-dust system of object "SO". Investigation of interaction between particles of dust and drops of fight-dust fluid is based on probability methods. Movement of air and particles of dust ad drops or liquid is investigated by numerical finite-difference method, which is based on method Mc'Cormac. The results of calculations of effectiveness fight-dust system are presented for two values of speed of air – 5 and 35 m/s.

It deals with purposes and features of an application program package developed for researching thermal and mechanical phenomena within SO encasement, Chernobyl 1986 accident and potentially possible ones modeling, reliability and safety analysis of the encasement. The structure and purpose of databases for keeping and classifying information related to the "SO" encasement are described. Perspectives of the package and the databases control systems development are reviewed.

The elaboration of automatic control systems, based on radar technology for interest safety SO encasement and Chernobyl zone are described in this article. Three systems are described. First, this is automatic radio geodesy system for measuring of shift of roof beams of SO encasement. Second, this is radio technical system for distance discovery of fires in Chernobyl zone, based on principle of multichannel heat direction finder. Third, this is combine system of distance sounding of underground environment for discovery of radioactive materials.

The general procedure for the determination of topography of the reactor active core wreckage ejected by explosion as a result of the Chernobyl NPP accident has been developed. The regions of the failure and the reactor active core ejection have been constructed by the numerical experiment series. The active core wreckage motion in the field of gravity has been explored. The ejected fragments topography for the case of the active core explosion in the standard position and over the reactor section plating has been constructed.

A structural scheme of operational state of the CNPP 4 block is built with usage of archival documents. Various versions of spatial finite element models are developed; they allow the realization of the 4 block structural scheme with various extents of detailing, using application software packages COSMOS, SCAD and ROBOT.

Analyses of peculiar stress-deformed states of the 4 block under various combinations of loads and influences are performed in order to estimate efficiency of the FEM models versions developed. Based on the result consideration a computational model of the 4 block is chosen for further numerical analysis of its constructions' mechanical behavior, including that in the course of the core accident and in the course of localization and mitigation of the accident consequences.

Analysis of methods of the safety assessment of the "Ukritiye" encasement demonstrates that the existing standard codes and technical support are insufficient to obtain true quantitative characteristics of the encasement for the case of initial event's causation. Mistaken assumptions have resulted in decreasing the level of risk assessment conservatism adopted in official requirements. It is proposed that system analysis approach be used to research and assess negative consequences of the "Ukritiye" protection barriers' destruction. A solution is obtained from synthesis of probabilistic and deterministic methods as well as from usage of tool inspections and expert estimates to verify source data and results. The direction being proposed is implemented for all phases of risk assessment.

Characteristic examples are presented for the analysis of consequences of the initial events of an aircraft falling upon the "Ukritiye" and external explosions.

Characteristic peculiarities of a procedure applied during safety analysis (risk assessment) of the "Ukrytiye" encasement are discussed, as well as those of the encasement itself which take effect on developing such procedure. Indicators (functions) of risk to be used are formulated; the efficiency of their choice is discussed. A mathematical aspect of considering the parameters' uncertainty within the "Shelter" when modeling accident processes is characterized, as well as this uncertainty's influence upon values of risk functions. Some quantitative estimation of risk indicators is presented along with conclusions about their quality.

Conclusions

As a result of investigation of SO, as the most characteristic representative of EO class, it was determined that the problem of theoretical safety analysis includes the questions of modification of normative methods for NPP aimed at working out SO risk assessment method. For this purpose, object evolution models are used. These models are based on applied aspects of the theory of random processes. Uncertainty of parameters, characteristic for SO, makes analysis of qualitative behavior of mathematical models of physical processes and actual part of calculations. In this connection, rational choice of risk functions is based both on considerations of completeness of description of consequences of hypothetical accidents and on considerations of possibility for constructive assessment of values of these functions. The latter is done to ensure that use of these functions during making design decisions will be really productive and will demonstrate the efficiency of performed theoretical analysis.

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Ю.В. Верюжський

Імовірність та детерміністична оцінка ризиків екстремальних об'єктів і екологічно загрозливих систем

Наведено основні результати робіт Науково-дослідного інституту механіки швидкоплинних процесів, спрямованих на створення методології оцінки ризиків і керування ризиками екологічно загрозливих систем, що складаються з різноманітних технологічних об'єктів і елементи яких можуть характеризуватися високим рівнем радіаційної, токсичної, експлуатаційної, пожежної та іншими загрозами. Описано ймовірнісну і детерміністичну частини оцінки ризиків, які базуються на математичних методах системного аналізу, нелінійної динаміки та комп'ютерного моделювання. Враховано множину розгалужень загальної задачі, різні фактори та критерії, що впливають на стан системи і вибір стратегії керування ризиками. Розглянуто ризики як на суб'єктивній, так і на об'єктивній підставі з урахуванням людського фактора. Показано, що основним елементом досліджень, домінуючим у визначенні безпеки системи, є аналіз конструктивної частини об'єкта. Запропоновано методологію оцінки ризиків використовувати для аналізу безпеки об'єкта "Укриття" Чорнобильської АЕС та інших промислових об'єктів.

Ю.В. Верюжский

Вероятностная и детерминистическая оценка рисков экстремальных объектов и экологически опасных систем

Приведены основные результаты работ Научно-исследовательского института механики быстротечных процессов, направленных на создание методологии оценки рисков и управление рисками экологически опасных систем, которые состоят из разнообразных технологических объектов и элементы которых могут характеризоваться высоким уровнем радиационной, токсичной, эксплуатационной и пожарной опасности. Описаны вероятность и детерминистические части оценки рисков, которые базируются на математических методах системного анализа, нелинейной динамики и компьютерного моделирования. Учтено множество разветвлений общей задачи, разные факторы и критерии, влияющие на состояние системы и выбор стратегии управления рисками. Рассмотрены риски как на субъективной, так и на объективной основе с учетом человеческого фактора. Показано, что главным элементом исследований, доминирующим в определении безопасности системы, является анализ конструктивной части объекта. Предложено методологию оценки рисков использовать для анализа безопасности объекта «Укрытие» Чернобыльской АЭС и других промышленных объектов.