A Methodology for Ranking of Diverse Nuclear Facilities As a Tool to Improve Nuclear Safety Supervision

Alexander Khamaza[a], Mikhail Lankin[a*],

[a] Scientific and Engineering Centre for Nuclear and Radiation Safety, Moscow, Russia

Abstract: Nuclear regulatory body can exercise supervision of a considerable number of different nuclear facilities: NPPs of different capacities, generations and types, research reactors, various fuel cycle facilities, radioactive sources etc. This article presents a methodology of ranking different nuclear facilities according to the potential hazard level they represent, for the scope of optimizing controlling and supervising practices of Regulatory Body.

Four criteria are proposed to be used for ranking. The first criterion is the scale of a hypothetical accident in a situation of total inefficiency of safety barriers. Depending on whether maximum hypothetical accident leads to off-site consequences and what these consequences are, as well as depending on the A/D ratio, four categories have been identified, the third of which has been further divided into four subcategories.

The second and the third criteria, used for ranking, are estimated values of probabilities that operational occurrences could take place at the facility and corresponding conditional probabilities that the said occurrences would not develop into an accident of a specific level of severity.

And, finally, the fourth criterion is efficiency of defence in depth of the facility. This article sets forth an algorithm of assessment of the said efficiency. It also contains a nomenclature of threats to Defence in depth and algorithm of evaluation of Defence in Depth vulnerability of the facility in respect of each of the threats and to the mechanisms of their implementation. Based on the assessment results for defence in Depth efficiency, the facility under consideration is ranked as belonging to one of the four categories.

According to the rules, described in the article, after the facility under consideration has been rated according to all of the four criteria (or only according to some of them if evaluation according to the others is not possible), it is being assigned a final resulting rating of potential hazard.

Keywords: Risk-Informed Decision Making, Probabilistic Safety Analysis, Nuclear Facilities, Defence in Depth

1 INTRODUCTION

Nuclear Safety Authority may need to exercise safety regulation of different types of nuclear facilities, such as nuclear installations (nuclear power plants, research reactors, critical and subcritical installations), fuel cycle facilities, radionuclide sources, radioactive waste storages and other facilities. Homotypic facilities (for example, nuclear power plants) may also belong to different generations and have safety issues of different significance. Since regulatory body is usually limited in its resources, there is a question of ranking supervised facilities according to the hazard level they represent in order to correlate it with the necessary control volume and to optimize regulatory activity.

From paragraphs 3.1, 3.2 of Safety Fundamentals [1] it can be concluded that there are three aspects in nuclear facilities safety:

Aspect 1 providing normal conditions of nuclear facility operation, guaranteeing absence of either nuclear facility personnel overexposure or considerable emission of nuclear materials (radiation) into the environment;

Aspect 2 prevention of departures from normal operation at nuclear facilities, including prevention of accidents;

* lankin@secnrs.ru

Aspect 3 mitigation of possible incident and accident consequences for the personnel, public and the environment should they, despite all the safety measures, occur.

The first aspect characterizes *active* component of nuclear facility safety (i.e. normal operational safety), the second and the third ones - *potential* component of safety (in the conditions of normal operation of nuclear facility absence of unacceptable risk for the personnel, the population and the environment in a result of facility accident).

Assessment of the first of these aspects is quite developed in regulatory practice and is based on control of the three fundamental principles of providing radiation safety: normalization, substantiation and optimization. As for the second and the third aspects of nuclear facility safety, namely, radiation accident risk reduction and mitigation of man (personnel and population) and environment exposure in case of an eventual accident, their assessment is influenced by the following nuclear facility characteristics:

Factor 1 Scale of the most severe accident possible at a given nuclear facility, which is directly defined by the quantity and radionuclide composition of radioactive materials, potentially hazardous for the personnel, the population and the environment.

Factor 2 Probability of breach of facility normal operation, which, in the absence of response from facility systems/equipment and/or personnel would result in a radiation accident;

Factor 3 Conditional probability that a breach of facility operation would develop into an accident (taking into consideration operation of facility equipment and/or personnel);

Factor 4 Presence and state (actual effectiveness) of physical barriers on the way of radioactive substances spread (as of the ionizing radiation) from facility into the environment, and state of technical and organizational measures taken to protect the above mentioned barriers, as well as personnel, public and the environment.

This idea is presented in a graphic way in Figure 1 below.

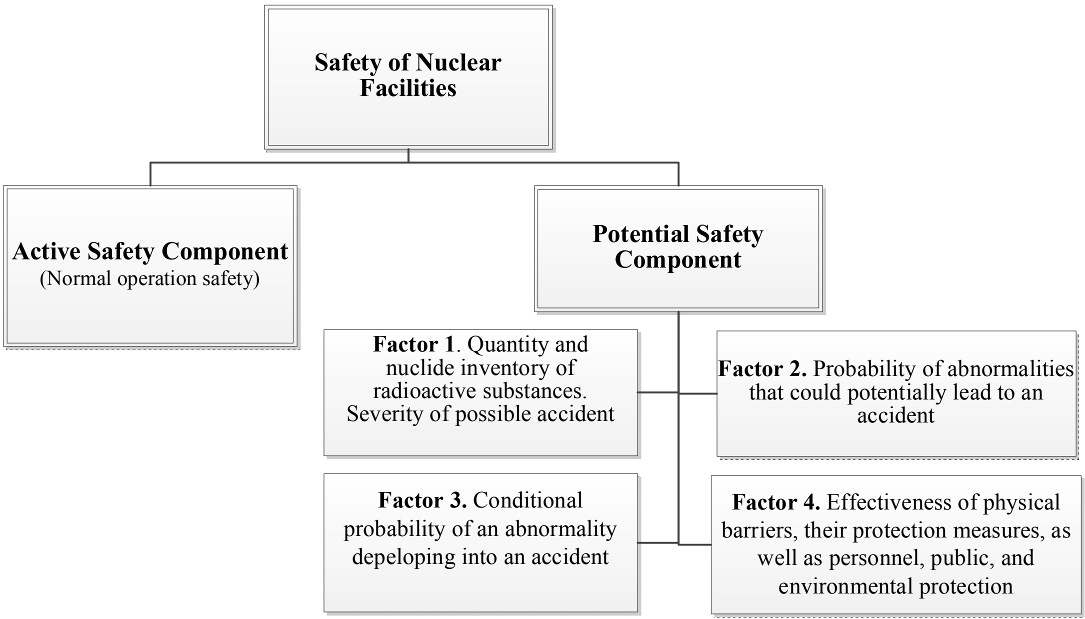

Figure 1. Nuclear facility safety and its components

In order to obtain facility potential risk assessment and on the basis of this complex assessment to perform facilities ranking according to the potential hazard level, it is necessary to take into account all of the four abovementioned Factors. Meanwhile, for ranking different-type nuclear facilities according to the potential hazard, in the majority of cases it is enough to assess the ranked facilities only according to Factor 1. If we have a different task, namely, differentiation of the same-type nuclear facilities (for instance, in case of ranking by potential hazard of different NPP units) then

Factors 2, 3 and 4 are to be used to solve the task.

If some of the factors cannot be accounted for (for example, when regulatory authority does not dispose of analytical model for a certain facility, allowing to assess probability of abnormal operation and of it developing into a radiation accident), facility potential risk assessment can be performed on the basis of those factors which are available. Nevertheless, analysts must be aware of the limitations and one-sidedness of such assessment, based, operating with only part of the information, defining facility safety.

Figure 2 presents in the form of algorithm recommendations on choosing factors to be used for facilities ranking, depending on the scope of nuclear facility potential risk ranking.

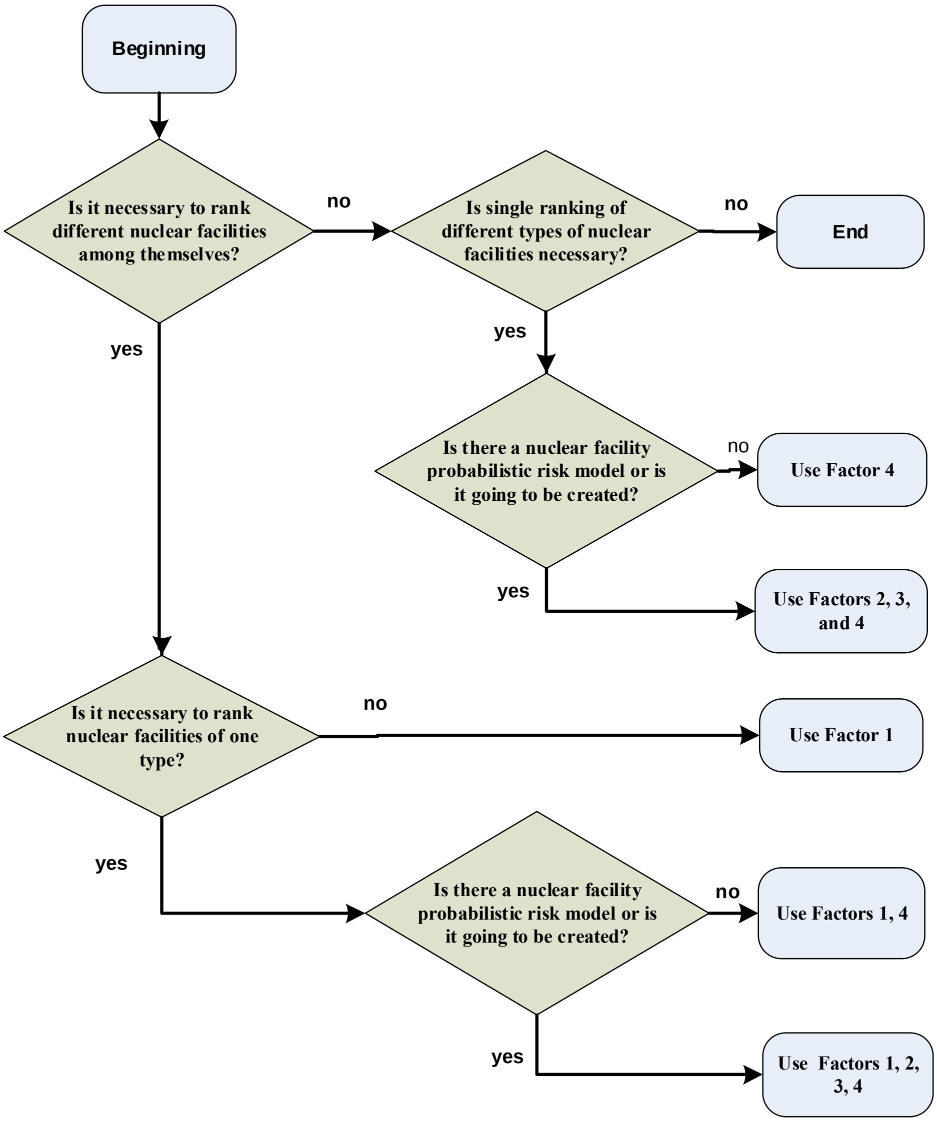

Figure 2. Selection algorithm for factors, representing potential hazard, in nuclear facility ranking

2. ASSESSMENT OF FACTOR “MAXIMAL SCALE OF A HYPOTHETICAL ACCIDENT”

The first factor, characterizing level of facility potential hazard, is quantity and radionuclide composition of radioactive materials, potentially hazardous for people and the environment in case of an accident. This factor defines maximum radioactive exposure that a facility can produce in absence of all protective barriers and technical and organizational measures of preventing radioactive substances from dispersal into the environment and locations with people. The basic factor of the nuclear facility potential hazard assessment (ranking) is the level of radiation impact in case of an accident (including unlikely but physically probable accidents).

The proposed classification of nuclear facilities presented below in Table 1 below is based on IAEA Safety Standard GS-R-2 classification [2], reworked in consideration of Russian Federal Law on Use of Atomic Energy [3], and for radionuclide sources, apart from the above - taking into consideration provisions of Russian Safety Guidelines [4] and IAEA-TECDOC-1344 [5]. The classification takes into account accident severity scale (in particular, whether population has been afflicted by the accident or not). In such cases when under no conditions would the accident lead to severe consequences beyond the NF territory, quantity and radionuclide composition of NF radioactive materials (the so-called A/D correlation - see [6]) are additionally accounted for.

Table 1. Assessment of potential nuclear facility hazards according to Factor "The Maximal Scale of a Hypothetical Accident."

Hazard Category		Description of nuclear facilities, falling into the analysed category	
		Maximum accident consequences	**Amount and inventory of radioactive substances at a nuclear facility**
I		Nuclear facilities, accidents at which (including those unlikely ones) can lead to serious deterministic effects on health beyond protection zone (beyond site) in case of non-application of protective actions or where similar accidents have been registered at the same-type facilities.	Not considered
II		Nuclear facilities, not assessed as Category I and accidents at which can lead to radiation exposure of humans beyond facility protection zone (beyond site), requiring urgent protective actions or where similar accidents have been registered at the same-type facilities.	Not considered
III	**III A**	Nuclear facilities, not assessed as Category I or II but accidents at which might lead to radiation exposure and contamination, requiring urgent protective actions on facility site, or where similar accidents have been registered at the same-type facilities.	Extremely hazardous ($A/D \geq 1000$)
	III B		Very hazardous ($10 \leq A/D < 1000$)
	III C		Hazardous ($1 \leq A/D < 10$)
	III D		Nor very hazardous ($0{,}01 \leq A/D < 1$)
IV		Nuclear facilities, not assessed as Category I, II or III, but falling under regulatory control.	Not considered

In order to specify the classification, given in Table 1, when ranking is done exclusively on the basis of Factor 1 or Factors 1 and 4 (whereas assessment of Factors 2 and 3 is not being done[1] and thus, numeric safety characteristics of the existing safety barriers and their protective actions are not available), he following additional rule can be recommended to be introduced:

[1] Factor enumeration – in accordance with Figure 1.

Additional Rule

A nuclear facility which, according to Table 1, should be assessed as Hazard Category III and which has one of the following properties: *a) facility disposes of nuclear materials in quantity, sufficient for a self-sustaining chain reaction and beginning of such reaction is not excluded in case of breach of normal operation;* *b) physical barriers on the dispersal path of radioactive materials into the environment are operating under overpressure of over 20 bar;* *c) physical barriers on the dispersal path of radioactive materials into the environment in case of departure from normal operation may suffer blast effect (as a result of chemical reaction or thermophysical process) or be hit by flying objects with considerable kinetic energy;* *d) physical barriers on the dispersal path of radioactive materials/ionizing radiation into the environment in abnormal operation may suffer considerable thermal or chemical effect, exceeding limit values of their operating capability.* *is to be classified one subcategory above the one, originally assigned to it in accordance with Table 1.*

3. ASSESSMENT OF FACTORS "PROBABILITY OF ABNORMAL OPERATION, POTENTIALLY LEADING TO AN ACCIDENT" AND "CONDITIONAL PROBABILITIES OF ABNORMAL OPERATION DEVELOPING INTO AN ACCIDENT"

Accident probability at a nuclear facility is one of the basic characteristics for evaluating its potential hazard.

Accident probability can be represented as a product of two values:

- Probabilities of breach of facility normal operation, capable of leading to an accident[2] (in absence of response from systems/equipment and/or facility personnel);
- Conditional probabilities that a case of departure from normal NF operation will lead to radiation or nuclear accident[3].

Probability P_a (year^{-1}) of radiation accident occurring at a NF can be presented as:

$$P_a = \sum_{j=1}^{N} Q_j \cdot S_j \qquad \textbf{(1)}$$

where: **N** – number of different potential modes of breaches from normal facility operation that can lead to radiation accident;

$\mathbf{Q_j}$ – probability of departure from normal operation of j-type;

$\mathbf{S_j}$ – conditional probability that departure from normal operation of j-type will lead to radiation or nuclear accident.

Breaches of normal operation, potentially leading to an accident, include equipment failures, personnel errors, such events as onsite fires and floodings and external environmental exposures of natural and man-made origin.

Since different radiation accidents can be characterized by different amount of damage to life and health of people and to the environment, in assessment of facility potential hazard according to Factors 2 and 3, it is possible to implement a concept of probability of a certain severity accident. For

---

[2] Values of these probabilities characterize facility capability to prevent breaches of normal operation.

[3] Values of the analyzed conditional probabilities characterize facility's capability to prevent breach of normal operation from developing into accidents.

example, for nuclear installations such terms as probability P_{SA} of a severe accident[4] and probability P_{LR} of a large release accident are traditionally used:

$$P_{SA} = \sum_j Q_j \cdot S_{SAj} \tag{2}$$

$$P_{LR} = \sum_j Q_j \cdot S_{LRj} \tag{3}$$

Here: $\mathbf{Q_j}$ – probability of breach of normal operation of j-type; $\mathbf{S_{SAj}}$, $\mathbf{S_{LRj}}$ – conditional probabilities that breach from normal operation j will lead to severe beyond design basis accident and to accident with large release accordingly.

Difficulty in assessment of risk values $\mathbf{P_A}$ ($\mathbf{P_{SA}}$, $\mathbf{P_{LR}}$ or others), calculated in this way, depends on the complexity of the analysed nuclear facility. In particular, for NPP, the most complex nuclear facilities, in order to assess $\mathbf{P_A}$ probabilistic safety analyses are carried out as a complex research, divided into several independent tasks – such analyses as initiating event frequency, accident scenario development, systems and equipment reliability analysis, personnel reliability analysis etc. At the same time, for less complex facilities, it is possible to implement simpler methods of calculating P_A.

The ideal conditions for carrying out assessment of facility potential hazard for the scope of safety management according to Factors 2 and 3 is availability of a PSA model for the facilities under analyses.

Based on the results of the performed analysis, potential hazard of nuclear facilities according to Factors 2 and 3 is assessed in accordance with Table 2 below. According to the Table, one of the four potential hazard categories (A, B, C, D in descending order of potential hazard level) is assigned to a facility on the basis of probability $\mathbf{P_A}$, obtained within probabilistic assessment, and on severity of the radiation accident accepted for the analysis.

Information, acquired as a result of the analysis, apart from assessment of facility potential hazard as a whole, allows to assess contributions of different aspects to the integral radiation accident risk value, namely, contributions of different accident scenarios, single initiating events, safety of single equipment units and facility personnel reliability.

Table 2. Ranking of nuclear facility potential hazards according to Factors 2 and 3

Qualitative description of radiation accident frequency	**Probability P_a of radiation accident, 1/year**	**RADIATION ACCIDENT CONSEQUENCES**				
		Severe determined health effects beyond facility site in case of lack of protective actions	Radiation dose exposure for people beyond facility site requires urgent protective actions	Urgent protective actions onsite are required.		
				Quantity of radioactive material is extremely hazardous ($A/D \geq 1000$)[5]	Quantity of radioactive material at facility is very hazardous ($10 \leq A/D < 1000$)	Quantity of radioactive material at facility is hazardous ($1 \leq A/D < 10$)
Frequent	**> 1**	**A**	**A**	**A**	**B**	**C**
Probable	**$1 - 10^{-2}$**	**A**	**A**	**B**	**B**	**C**
Possible	**$10^{-2} - 10^{-4}$**	**A**	**B**	**C**	**C**	**D**
Rare	**$10^{-4} - 10^{-6}$**	**C**	**C**	**D**	**D**	**D**
Practically improbable	**$< 10^{-6}$**	**D**	**D**	**D**	**D**	**D**

[4] Core damage probability.

[5] Comments on parameter A/D value – see [5].

4. EVALUATION OF "STATE OF DEFENCE-IN-DEPTH" FACTOR

At the heart of nuclear safety, according to present-day consensus on nuclear and radioactive safety, there is implementation at a nuclear facility of defence-in-depth concept, based on a system of successive physical barriers on the dispersal path of radioactive materials and ionizing radiation into the environment, as well as systems of technical and organizational measures of protection for barriers and their functionality and measures of protection of personnel, population and the environment.[6]

As a rule, radiation sources, making part of a nuclear facility, are separated from the environment by several successive physical barriers. Composition and number of these barriers depend on the facility potential hazard which is, in its turn, defined both by the quantity and composition of radioactive materials that in case of breach of facility normal operation may be released into the environment and by the energy potential of those processes that can disrupt barriers' integrity. For example, such factors as high pressure and high temperature or presence of nuclear materials that can form critical mass, require stronger measures of physical barriers protection and more developed defence–in-depth than in case of absence of the abovementioned factors.

For the most complex types of nuclear facilities – nuclear installations (in particular, for NPP units), characterised both by high level of cumulate radioactivity and processes with high energy potential (chain fission reaction, containers and pipelines operating with high parameters), five levels of defence-in-depth are required. Their scope is maintaining effectiveness of physical barriers between nuclear and radioactive materials, situated in fuel elements (as well as in other locations) and the environment in cases of normal operation and departures from normal operation, including accidents – design basis and beyond design basis ones (as well as severe accidents). According to the requirements of regulatory documents, there should be four barriers for a NPP: fuel matrix, fuel element cladding, primary circuit boundary and containment. Designs of less complex facilities may provide for smaller numbers of physical barriers.

In assessment of defence-in-depth state at nuclear facility, we propose to utilize the following algorithm:

Step 1 Making a nomenclature of potential threats for the analysed nuclear facility in conditions of normal operation and departures from normal operation, including accidents, by selecting from Nomenclature, presented in [7] those threats, which are relative to the facility under analysis.

Step 2 Assessment (on the basis of rounds, analyses of design and operational documentation) of the state of affairs at facility, considering confrontation of defense in depth with each threat included into Step 1 nomenclature in compliance with a three-stage scale: 1) ***safe****;* 2) ***adequate****;* 3) ***inadequate***.

Facility condition in respect of a threat is considered to be ***safe*** if all the regulatory requirements this facility are being met.

Facility condition in respect of a threat is considered to be ***adequate***, if there are deviations from regulatory and other applicable requirements, if there are deviations from corresponding regulatory requirements and other applicable requirements negatively affecting facility capability to withstand a threat. But with that, safety function, corresponding to the given threat, may, according to the analyst's opinion, be performed adequately, if not to a lower extent.

Facility condition in respect of a threat is considered to be ***inadequate***, if there are such deviations from appropriate regulatory requirements and other applicable requirements, negatively affecting facility capability to withstand a threat, which, according to the analyst's opinion, render facility safety level contextually inadequate and safety function, corresponding to the analysed threat, is not performed adequately.

---

[6] Fundamental presentation of defence in depth concept is found in [6].

Step 3 For threat spectrum, in respect of which facility condition has been in the previous step defined as adequate or inadequate, it is necessary to assess influence of the given deviations on the probability of breaches of normal operation and on a chance of it developing into a radiation accident. It is necessary to assess all the possible modes of normal operation breaches, which may be used to make a judgment about adequate or unsatisfactory condition of the facility.

If there is no possibility to evaluate numerically influence of the given failings in defence-in-depth on changes in frequency of departures from normal operation or on facility capability to prevent them from developing into an accident, such influence should be evaluated qualitatively according to the following scale: 1) ***considerable;*** 2) ***medium***; 3) ***minor.***

Influence is thought to be ***considerable*****,** if, due to deficiencies of defense-in-depth, there is a dramatic increase in risk of breach of normal operation which may evolve into an accident upon non-response of systems and personnel, or if risk of breach of normal operation developing into a radiation accident increases dramatically (should it suddenly happen).

Influence is thought to be ***medium***, if, due to deficiencies in defense-in-depth there is a risk of breach of normal operation which may develop into an accident upon non-response of the systems and personnel of the facility, or if there is a risk of breach of normal operation evolution into a radiation accident.

Influence is thought to be ***minor***, if available deficiency in defense in depth does not give any reason to expect either any significant increase of risk of breach of normal operation of potentially hazardous type, or any significant increase of risk of departure from normal operation evolution into a nuclear or radiation accident.

Step 4 Perform ranking in compliance with the matrix in Table 3 below, applying as a basis, assessments of conditions at a nuclear facility, its capability to withstand threats to defense-in-depth and influence of initiating events frequencies, as well as conditional probabilities of an initiating event developing into a nuclear and radiation accident.

Table 3 Ranking of potential facility hazards according to Factor 4

Facility condition in respect to threats to defence in depth	Influence on breach of normal facility operation frequency and/or on the probability that breach of normal operation will develop into radiation accident		
	Considerable	Medium	Minor
Safe	-	-	Acceptable
Adequate	Unsafe	Unsafe	Acceptable
Inadequate	Dangerous	Unsafe	Unsafe

5 CONCLUSIONS

This article presents a methodology of ranking nuclear facilities according to their potential hazard. The said ranking can serve for the scope of further optimization of the Regulatory authority activity in the field of safety supervision and control at nuclear facilities.

Four factors, defining potential threat of nuclear facility have been examined:

- Accident scale of the most severe accident possible;
- Probability of breach from normal operation, which, in the absence of response from facility systems/equipment and/or personnel will result in a radiation accident;
- Conditional probabilities that the breach of normal operation will develop into an accident;

– State of defence-in-depth at nuclear facility.

Depending on the base data and those resources that an analytic disposes of for assessment, as well as on the purpose of facility ranking (necessity to just rank different groups of same-type facilities or to proceed with differentiation inside the said groups according to potential hazard as well), integral assessment may be based both on research of all of the four factors, defining facility potential hazard and only on some of them.

Presented in the article methodology contain algorithms for potential hazard assessment of a nuclear facility according to each of the four abovementioned factors and introduces a system of categories of facility potential hazard for all of the analysed factors.

REFERENCES

1. Fundamental Safety Principles. IAEA Safety Standards Series SF-1. Vienna, 2006
2. Preparedness and Response for a Nuclear or Radiological Emergency. Safety Requirements. IAEA Safety Standards Series GS-R-2. IAEA, Vienna, 2002.
3. Federal Law on Use of Atomic Energy No 170-FZ. Moscow,1995.
4. Safety Guidelines. Methods of Categorization of Sealed Radioactive Sources According to Potential Radiation Hazard. RB-042-07. Moscow, 2007.
5. Categorization of Radioactive Sources. Revision of IAEA-TECDOC-1191, Categorization of radiation sources, IAEA-TECDOC-1344, IAEA, Vienna, 2003.
6. INSAG-10. Defence-In-Depth in Nuclear Safety. A Report by the International Nuclear Safety Advisory Group. IAEA, Vienna, 1996.
7. Assessment of Defence in Depth for Nuclear Power Plants. Safety Reports Series 46. IAEA, 2005.