ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

UDC 621.039

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SAFETY OF UKRAINE'S NUCLEAR POWER INDUSTRY IN EXTREME OPERATING CONDITIONS

В. Скалозубов, І. Козлов, О. Козлов, Д. Бундєв, С. Косенко. **Безпека ядерної енергетики україни в екстремальних умовах експлуатації.** Актуальним питанням стану (рівню) безпеки ядерної енергетики України в екстремальних умовах є ситуація нанайбільшій у Європі Запорізькій АЕС з причин розташування станції в зоні бойових дій та труднощів в управлінні та експлуатації, а також регулювання безпеки станції на окупованій території. На основі розробленої гідродинамічної моделі та розрахункових обґрунтувань визначено умови можливого затоплення проммайданчика ЗАЕС залежно від потужності бойового заряду з відповідною силою дії. Імовірнісні підходи оцінки об'єктивного стану (рівня) безпеки Запорізької АЕС у екстремальних умовах недостатньо обґрунтовані з урахуванням уроків найбільших ядерних та радіаційних аварій. На основі детерміністського підходу визначено умови критичного для безпеки затоплення проммайданчика Запорізької АЕС внаслідок екстремальних бойових дій. Затоплення проммайданчика станції може бути причиною виникнення двох початкових аварійних подій: повне тривале знеструмлення енергоблоків та порушення умов теплообміну у сухих сховищах відпрацьованого ядерного палива. Запобігання затопленню проммайданчика Запорізької АЕС може бути засноване на будівництві захисних бар'єрів затоплення на узбережжі ставка-охолоджувача. Визначено перспективні напрями підвищення ефективності управління аваріями пов'язаних з модернізацією пасивних систем безпеки ядерних енергоблоків та вдосконаленням експлуатаційних симптомно-орієнтованих аварійних інструкцій/посібників з керування важкими (ядерними) аваріями. Ефективна стратегія управління аваріями з повним тривалим знеструмленням енергоблоків із ВВЕР може бути заснована на комплексній модернізації систем аварійного підживлення парогенераторів насосами з paроприводами та контурами природної циркуляції систем пасивного відведення тепла від гермооб'єму реакторної установки.
Ключові слова: екстремальні умови, імовірнісні показники, детерміністський аналіз, управління аваріями

V. Skalozubov, I. Kozlov, O. Kozlov, D. Bundev, S. Kosenko. **Safety of ukraine's nuclear power industry in extreme operating conditions.** An urgent issue of the state (level) of safety of Ukraine's nuclear power industry in extreme conditions is the situation of the Zaporizhzhia NPP, the largest in Europe, due to the station's location in the war zone and difficulties in its management and operation, as well as the safety regulation of the station in the occupied territory. In the proposed article, the possibility of Zaporizhia NPP industrial site flooding is analyzed from the elaborated hydrodynamic model and justifying calculation; the conditions of ZNPP industrial site possible flooding are determined depending on the warhead power producing a corresponding destructive effect. Probabilistic approaches to assessing the Zaporizhia NPP safety objective state (level) in extreme conditions are insufficiently justified taking into account the lessons of the largest nuclear and radiation accidents. On the basis of a deterministic approach, the conditions of Zaporizhia NPP industrial site critical flooding due to extreme military action are identified. Flooding of the plant's industrial site may cause two initial emergency events: a complete long-term de-energization of power units and violation of heat exchange conditions in spent nuclear fuel dry storage facilities. Prevention of flooding of the Zaporizhia NPP industrial site can be based on the construction of protective flood barriers on the cooling pond coast. Prospective directions to increase the accident management efficiency related to the nuclear power units' passive safety systems modernization and improvement of operational symptom-oriented emergency instructions/manuals for managing severe (nuclear) accidents have been identified. An effective accident management strategy with complete long-term de-energization of WWER power units can be based on a comprehensive modernization of emergency recharge systems of steam generators with steam driven pumps and natural circulation circuits of passive heat removal systems from the pressurized reactor unit.
Keywords: extreme conditions, probabilistic indicators, deterministic analysis, accident management

1. Introduction

Currently, due to the military action in Ukraine extreme operating conditions of Ukrainian nuclear power plants have been developed. Particularly difficult operating conditions take place at the largest in Europe ZNPP for the following main reasons:

– The nuclear power plant is located immediately in the combat zone. Only in the last three months there occurred 4 emergency shutdowns with the complete de-energization of power units (similar to the initial emergency event at the Fukushima-1 NPP).

– The ZNPP location in the temporarily occupied territory determines the objective difficulties with its operation, management and safety regulation.

Therefore, a reasonable assessment of ZNPP safety condition regarding the possibility of nuclear and radiation accidents is an urgent problem. The proposed study is dedicated to solving these issues.

DOI: 10.15276/opu.2.66.2022.09

2. Reference sources data analysis and problem statement

The Europe's largest Zaporizhia NPP (ZNPP) is located at an altitude of 22 m near the Kakhovka Reservoir, making part of the Dnipro Cascade of Hydroelectric Power Plants (HPP) (Kyiv, Kaniv, Kremenchuk, Dniprodzerzhynsk, Dnipro HPP) reservoirs, which system total height is 103 m. [1].

In works [2, 3, 4], an analysis of possibility of the ZNPP industrial site flooding as a result of natural extreme phenomena such as earthquakes, tornadoes and hurricanes has been done. However, in the stress tests' [6] analysis cited in [5], it was declared the factual impossibility of ZNPP industrial site flooding under any extreme conditions, that provision contradicting the results given in [1 – 4]. The source [7] presents the methodological principles of NPP safety probabilistic analysis. However, the Fukushima accident lessons served to determine the limitations of probabilistic approaches to NPP safety assessment using probabilistic methods [8]. Priority should be given to deterministic methods of safety analysis, taking into account the Fukushima accident lessons [9].

Thus, an urgent issue here is the assessment of ZNPP safety under extreme operation conditions using deterministic methods.

3. Research methods and tasks

In the conditions of military operations in Ukraine, extreme conditions of Ukrainian nuclear power plants' operation have developed therefore an assessment of the Ukrainian nuclear power industry safety under such extreme conditions of operation represents an urgent issue.

The presented work purpose is to assess the safety of ZNPP in extreme operating conditions using deterministic and probabilistic methods.

4. Assessment of NPPs nuclear and radiation safety status

Traditionally, the assessment of the state (level) of NPP nuclear and radiation safety is based on probabilistic and deterministic safety indicators [2, 7, 8, 9].

The main probabilistic indicators of safety in global nuclear energy:

– the probability of a nuclear (severe) accident with damage to nuclear fuel (FDRC – the frequency of damage to the reactor core): the probability of occurrence of a maximum permissible radioactive release.

The main probabilistic safety indicators in the global nuclear power industry:

– probability of occurrence of a nuclear (severe) accident with damage to nuclear fuel (FDRC – frequency of damage to the reactor:

$$\mathrm{FDRC} \sim IP_s; \tag{1}$$

– probability of occurrence of the maximum permissible radioactive release:

$$\mathrm{FPRR} \sim \mathrm{FDRC} \times P_b, \tag{2}$$

where I is the probability of the initial emergency event (IEE) occurrence;

P_s – probability of the nuclear power plant safety systems critical configurations failure;

P_b – probability of failure of protective safety barriers preventing from radioactive emissions occurrence.

Events/incidents/violations of normal operating conditions that lead to the reactor's emergency shutdown regulated as IEE:

– leaks/ruptures of pipelines and steam pipelines of systems important for the nuclear power plants safety (NPP SIS);

– de-energizing the power units;

– SIS failures under normal operation;

– extreme natural phenomena (earthquakes, floods, tornadoes, hurricanes, etc.);

– fall of large objects on the power unit, etc.

In particular, emergency shutdowns of Fukushima-Daiichi NPP power units in 2011 occurred automatically on the registered signal of a powerful earthquake (with an epicenter in the Pacific Ocean at a distance of more than 100 km from the powerplants location coast).

Probabilistic criteria for nuclear safety [10]:

$$\begin{aligned} &\mathrm{FDRC} = \begin{cases} 10^{-4}\,1/(\mathrm{reaktor} \cdot \mathrm{year}) - \text{for existing NPP;} \\ 10^{-5}\,1/(\mathrm{reaktor} \cdot \mathrm{year}) - \text{for new NPP,} \end{cases} \\ &\mathrm{N} = \mathrm{NPAZ} = \begin{cases} 10^{-4}\,1/(\mathrm{reaktor} \cdot \mathrm{year}) - \text{forexistingNPP;} \\ 10^{-5}\,1/(\mathrm{reaktor} \cdot \mathrm{year}) - \text{fornewNPP.} \end{cases} \end{aligned} \tag{3}$$

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

Probabilistic criteria of radiation safety:

$$\text{FDRC} = \begin{cases} 10^{-6} 1/(\text{reaktor} \cdot \text{year}) - \text{for existing NPP;} \\ 10^{-7} 1/(\text{reaktor} \cdot \text{year}) - \text{for new NPP.} \end{cases} \quad (4)$$

The long-term global experience of nuclear power plant operation and safety regulation, as well as the lessons of major nuclear and radiation accidents have determined the insufficient validity of traditional probabilistic indicators and safety criteria (1) – (4). In particular, all the Fukushima-Daiichi NPP power units at the time of that big accident in 2011 met the established criteria for nuclear and radiation safety. Other examples may be related to the results of a probabilistic safety analysis (PSA) of Ukrainian nuclear power plants with WWER-type reactors, where it was assumed that the occurrence of an IEE with a complete long-term power units blackout (analogue of the Fukushima-Daiichi NPP IEE) or a tornado of any intensity class unambiguously lead to failure of safety-critical systems (P_s=1). However, the probabilities of these IEE *I* were assumed to be a sufficiently small value satisfying the established criteria and safety conditions. One of the main lessons of the Fukushima accident refers to the need to provide for the possibility of relatively unlikely IEE that involves catastrophic consequences [2].

Deterministic criteria of nuclear and radiation safety are usually defined by:

– maximum permissible temperatures of nuclear fuel and fuel element shells;

– maximum permissible pressures in the reactor and hermetic volume (containment);

– maximum permissible concentration of hydrogen;

– maximum permissible doses of radiation exposure to personnel, the public and the environment.

The Chernobyl and Fukushima accidents' lessons determine the relevance of following additional deterministic safety criteria:

– maximum permissible conditions for the occurrence of steam energy explosions;

– maximum permissible conditions of extreme external influences (earthquakes, tornadoes, hurricanes, flooding of industrial sites, loss of the final heat sink, fall of huge objects on the NPP industrial site), etc.

Nuclear power plants with WWER have the necessary systems to prevent nuclear and radiation accidents at IEE taken into account at project level (pipeline leaks, de-energization of the power unit, failures of normally operated SIS, unintentional erroneous actions of personnel, earthquakes, etc.). However, in extreme operating conditions of difficult wartime, it is necessary to assess the safety level of Ukraine's nuclear power plants, that is the purpose of the proposed study.

5. Assessments of the nuclear power industry of Ukraine safety state in extreme wartime conditions

Assessment of the state of safety of Ukraine's nuclear power industry in extreme wartime conditions.

The situation with the largest in Europe Zaporizhia NPP is the key issue as to the state of the Ukraine's nuclear power industry safety under extreme wartime conditions for the following reasons.

The NPP is located in the military operations region. Therefore, under such conditions, the probability of both intentional and unintentional IEE increases, and, accordingly, an increase in the core damage frequency [1].

Objective difficulties in the management, operation and regulation of safety due to the presence of the NPP in the temporarily occupied territory.

Currently, in the global nuclear power industry (including in Ukraine), the principle of "security downgrade acceptability (SDA)" has become widespread during nuclear power plant upgrades [2]. In accordance with this principle, the nuclear power plants safety level downgrade is permissible under the condition:

$$\frac{\Delta \text{FDR}C}{\text{FDR}C_0} << 1, \quad (5)$$

where $\text{FDR}C_0$ is the basic probabilistic estimate of FDR*C*;

ΔFDR*C* is a deliberate or unintentional increase in FDRC.

In NPP, extreme operating conditions the Δ FDRC may be associated with an increase in the probability of IEE *I*, and if the events/incidents/violations of normal operation satisfy condition [11], then the necessary level of safety is maintained and further operation of power units is permissible at the current time. However, this does not exclude the possibility of new IEE with violation of condition [12]. In addition, as mentioned above, the lessons of well-known nuclear accidents call into question the validity of the entire VAB methodology for an objective assessment of the safety status of nuclear power plants (including the SDA principle).

A deterministic approach based on modeling the impact of specific extreme events on security conditions is more justified for an objective assessment of security state (level) One of such topical issues may be the assessment of the flooding conditions of NPP industrial site due to the ingress of live charges into the dam or the Kakhovka reservoir or into the cooling pond. The flooding of the Fukushima-Daiichi NPP industrial site in 2011 with the tsunami was the determining cause of the complete long-term blackout (CLB) of power units, nuclear accidents and catastrophic environmental consequences.

In the stress tests on the reassessment of the safety of Ukraine's nuclear power plants, taking into account the lessons of the Fukushima accident, a deterministic analysis of the possibility of flooding of the NPP industrial site due to the destruction of the dams of the Dnipro cascade of reservoirs under the influence of a beyond-design earthquake was carried out. As a result, it was found that there was no possibility of flooding the Zaporizhia NPP industrial site. However, when modeling flooding processes in stress tests, simplified quasi-stationary hydraulic models were used, and the influence of extreme events (earthquakes, tornadoes, hurricanes) directly on the volume of the Kakhovka reservoir and cooling pond was not taken into account.

In [2, 3], an improved hydrodynamic model of possible flooding of the industrial site of the NPP due to the impact of extreme events on the dam and the volume of the Kakhovka reservoir and cooling pond was developed. Extrapolation of these simulation results to extreme military conditions of the Zaporizhia NPP allows us to believe that flooding of the NPP industrial site is possible when warheads hit the dam and the volume of the Kakhovka reservoir and cooling pond is capable of destroying more than 30 % of the dam or would be equivalent to an earthquake with an acceleration response on the ground surface of more than 1.2*g* or a tornado of more than class 2 intensity or a hurricane with a wind speed of more than 80 km/h.

Taking into account the above results, the conditions of flooding of the NPP industrial site at the power of the combat charge with the impact force *F*:

$$F > 1.2\rho H S_1 g\,, \tag{6}$$

and/or

$$F > \Delta P_2 S_1\,, \tag{7}$$

and/or

$$F > 0.3\sigma S_2\,, \tag{8}$$

and/or

$$F > v_c^2 \rho H S_1 / L\,, \tag{9}$$

where ρ is the water density;

H – height of the NPP industrial site above the cooling pond level;

S_1, S_2 are the cooling pond surface area and the surface area of the Kakhovka reservoir dam respectively;

g – acceleration of gravity;

ΔP_2 – pressure dilution in a tornado of the 2nd intensity class;

σ – maximum permissible stress of the Kakhovka reservoir dam concrete destruction;

v_c – maximum permissible speed of hurricane wind;

L – the equivalent (reduced) length of the cooling pond.

In the post-Fukushima period, emergency measures were developed for Ukrainian nuclear power plants, mainly related to the qualification of diesel generator systems, the installation of powerful DC batteries, the expansion of the capabilities of passive safety systems, the introduction of operational instructions/manuals for the management of accidents with limit acceptable conditions, etc. However, the effectiveness of all these measures to overcome the consequences of flooding is not obvious

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

enough, since at the time of the accident at the Fukushima-Daiichi nuclear power plant, all of the above measures were implemented, but it ultimately failed to prevent nuclear accidents, destructive combined-cycle explosions and catastrophic environmental consequences.

In addition, it is necessary to take into account that dry storage facilities of spent nuclear fuel are located at the NPP industrial site, when the cooling of nuclear fuel is carried out by natural air circulation. In case of flooding together with garbage, the conditions for the necessary cooling of the storage system may be violated, which corresponds to additional IEE.

Thus, the critical consequences of flooding of the NPP industrial site can be represented with IEE:

– complete long-term de-energization of the power unit;

– violation of the conditions of heat exchange in the dry storage for spent nuclear fuel.

The operating organization of the State Enterprise NAEK Energoatom performed a deterministic analysis of the limit permissible conditions IEE in the nuclear power plant with WWER-1000, as a result of which the nuclear accident conditions occurrence was stated (according to the criterion of the fuel element shells maximum permissible temperature) with a residual heat output of less than 2 % of the nominal reactor power and complete dehumidification of steam generators (SG). It was also found that in order to prevent a nuclear accident with the LAC and the IEE sufficient is to ensure the SG feeding along the 2nd circuit with a feed water flow rate corresponding to the flow rate of one emergency feeding electric pump (EPEP).

Promising areas for improving the efficiency of accident management at the WWER nuclear power plant are associated with the modernization of passive safety systems for emergency SG feeding and the improvement of operational symptom-oriented emergency instructions/manuals for the management of severe (nuclear) accidents (SOEI/MMSA).

One of the modern approaches to the modernization of passive safety systems for emergency SG feeding is based on connecting the volume of SG along the 2nd circuit to the system of passive heat removal from the hermetic volume (SPHR HV) of the nuclear power plant [13, 14, 15]. The SPHR HV consists of a closed natural circulation circuit with a heat exchanger located outside the HV, and is designed to remove heat and reduce pressure in the HV.

Equation of motion in a closed loop of natural circulation in a stationary approximation:

$$(\rho_1-\rho_2)gH=\xi\frac{G^2}{\rho F^2}, \tag{10}$$

where ρ_1, ρ_2 are the density of the flow medium in the lowering and lifting sections of the natural circulation circuit, respectively;

g – acceleration of gravity;

H – circuit height;

ξ – total coefficient of hydraulic resistance;

G – mass flow rate;

F – area of the flow section of pipelines.

Equation (10) implies the required height of the natural circulation contour of the:

$$H\geq\frac{\xi G^2}{\rho(\rho_1-\rho_2)gF^2}. \tag{11}$$

Thus, in order to ensure the flow rate in the natural circulation circuit of the SPHR SG pipelines equivalent to the flow rate of the EFEP, the required height of the SPHR SG above the hermetic tank can be hundreds of meters. The installed SPHR SG do not meet these requirements.

Another approach to the modernization of passive safety systems for emergency SG feeding is based on the proposal of Professor A.V. Korolev [16] to duplicate the EFEP with emergency steam-driven pumps from SG (EPSD) with a similar pressure-flow characteristic. However, the effective performance of the EPSD is possible at relatively high pressures in the volume of SG along the 2nd circuit.

Thus, a comprehensive approach to the modernization of the accident management system with limit acceptable conditions is advisable: at the initial stage of the accident, the SG recharge can be carried out by the EPSD, and at the final stages – the SPHR SG.

In the WWER-1000 SOEI/MMSA developed in the post-Fukushima period, the actions of operational personnel to manage accidents with limit acceptable conditions are actually reduced to measures to restore power supply and connect all available means of cooling the reactor core (including DC batteries to ensure the operability of electric pumps of active safety systems). It should be noted that attempts to implement all these measures were also made while the Fukushima accident occurred. However, it was not possible to avoid nuclear accidents, destructive explosions and catastrophic environmental consequences. Therefore, there are no grounds for the effectiveness of these measures in extreme conditions of flooding of the NPP industrial site.

To prevent possible flooding of the NPP industrial site the construction of dams on the coast of the cooling pond can be effective.

Conclusions

1. The situation at the Zaporizhia NPP, the largest in Europe one, illuminates an urgent issue of the nuclear power industry safety state (level) in Ukraine in extreme conditions for reasons of the station's location in the combat zone and difficulties in its management and operation, as well as regulating the safety of the station in the occupied territory.

2. Probabilistic approaches to assessing the objective state (level) of safety of the Zaporizhia NPP in extreme conditions are insufficiently justified taking into account the lessons of the largest nuclear and radiation accidents.

3. On the basis of a deterministic approach, the conditions of industrial site critical flooding at the Zaporizhia NPP due to extreme military action are determined.

4. Flooding of the plant's industrial site may be the cause of two initial emergency events: complete long-term de-energization of power units and violation of heat exchange conditions in dry storage facilities of spent nuclear fuel. Prevention of flooding of the Zaporizhia NPP industrial site can be based on the construction of protective flood barriers on the cooling pond coast.

5. An effective strategy for managing accidents with complete long-term de-energization of WWER power units can be based on a comprehensive modernization of steam generators emergency recharge systems with steam-driven pumps and natural circulation circuits of passive heat removal systems from the pressurized reactor unit.

Література

1. Метод оцінки критеріїв затоплення проммайданчика Запорізької АЕС у разі позапроектних землетрусів / В.І. Скалозубов, В.В. Богодист, І.Л. Козлов та ін. *Ядерна та радіаційна безпека.* 2013. 4 (60), С. 16–19. URL: https://doi.org/10.32918/nrs.2013.4(60).03.
2. Скалозубов В.И., Оборский Г.А. Козлов И.Л., и др. Комплекс методов переоценки безопасности атомной энергетики Украины с учетом уроков экологических катастроф в Чернобыле и Фукусиме: монография / Под ред. В. И. Скалозубова. Одесса : Астропринт, 2013. 242 с. ISBN 978-966-190-824-5.
3. Гідродинамічна модель можливого затоплення проммайданчика Запорізької АЕС при спільному впливі позапроектного землетрусу та смерчу в ставку-охолоджувачі / В.І. Скалозубов, І.Л. Козлов, Т.В. Габлая, та ін. *Проблеми безпеки атомних електростанцій і Чорнобиля*. 2014. (23). С. 22–25. URL: http://dspace.opu.ua/jspui/bitstream/123456789/6595/1/c22.pdf.
4. Козлов І. Л. Критерії затоплення промплощадок АЕС спільною дією смерчів і землетрусів в ставку-охолоджувачі. *Eastern-European Journal of Enterprise Technologies.* 2015. 3(6(75). С. 53–58. DOI: 10.15587/1729-4061.2015.42146.
5. Результаты экспертной оценки стресс-тестов действующих энергоблоков АЭС Украины с учетом уроков аварии на АЭС «Фукусима-1» в Японии / Г. В. Громов, А. М. Дыбач, О. В. Зеленый, и др. *Ядерна та радіаційна безпека*. 2012. 1(53). С. 3–9. DOI: 10.32918/nrs.2012.1(53).01.
6. Національний звіт України щодо результатів проведення «стрес-тестів» для АЕС України. ДІЯРУ, 2011. 124 с. URL: https://snriu.gov.ua/news/natsionalniy-zvit-shchodo-rezultativ-provedennya-stres-testiv-dlya-aes-ukraini-vidteper-dostupniy-rosiyskoyu-movoyu.
7. сОстрейковский В. А., Швыряев Ю. В. Безопасность атомных станций. Вероятностный анализ безопасности. М. : ФИЗМАТЛИТ, 2008. 352 с. URL: https://books.google.com.ua/books?id=Wwd4CwAAQBAJ&pg=PA2&lpg=PA2&dq.
8. Dybach O.M. Methodological bases of analysis and consideration of uncertainties of probabilistic analysis of NPP safety. *Nuclear and radiation safety*. 2014. 4(64). P. 8–16. URL: http://dspace.nbuv.gov.ua/bitstream/handle/123456789/97631/02.
9. Бойчук В.С., Гашев М.Х., Миколайчук О.А. План дій щодо впровадження на АЕС України заходів з підвищення безпеки за результатами стрес-тестів. *Ядерна та радіаційна безпека*. 2013. 2(58). С. 3–7. DOI: 10.32918/nrs.2013.2(58).01.

10. Загальні положення безпеки атомних станцій. Норми і правила з ядерної і радіаційної безпеки. НП 306.2.141-2008. 2008. 62 с. URL: http://www.aep.org.ua/fileadmin/user_upload/NP-141.pdf.
11. Грищенко Б. Ю., Полянській М. О., Сєвбо А. Є., Семенюк І. О. Застосування імовірнісних методів аналізу безпеки АЕС у дослідженні порушення крихкої міцності корпусу реактора. *Ядерна та радіаційна безпека*. 2013. 1(57). С. 22–25. DOI: 10.32918/nrs.2013.1(57).04.
12. Борисенко В. І. Про деякі закономірності наслідків аварій на АЕС. *Проблеми безпеки АЕС і Чорнобиля*. 2012. (18). С. 6–15. URL: http://www.ispnpp.kiev.ua/wp-content/uploads/2017/2012_18/c6.pdf.
13. Наффаа Х. М., Герлига В. А., Шевельов Д. В., Балашевський О. С. Оцінка ефективності системи пасивного відводу тепла від захисної оболонки РУ з ВВЕР в умовах тривалого знеструмлення. *Ядерна та радіаційна безпека*. 2013. 2 (58). С. 27–31. URL: http://dspace.nbuv.gov.ua/handle/123456789/97457.
14. Наффаа Х.М., Шевелев Д.В., Балашевский А.С. Расчетное моделирование работы и оценка эффективности системы пассивного отвода тепла от гермообъема (СПОТ ГО) при разрыве паропровода острого пара с неизоляцией аварийного ПГ по питводе на АЭС с ВВЭР-1000. *Глобальная ядерная безопасность.* 2014. 1 (10). С. 5–9. URL: https://cyberleninka.ru/article/n/raschetnoe-modelirovanie-raboty-i-otsenka-effektivnosti-sistemy-passivnogo-otvoda-tepla-ot-germoobema-spot-go-pri-razryve-paroprovoda.
15. Наффаа Х.М., Дубковський В.А. Класифікація систем пасивного відводу залишкових тепловиділень від захисних оболонок ядерних реакторів. *Праці Одеського політехнічного університету.* 2014. 1 (43). С. 104–112. URL: http://dspace.opu.ua/jspui/bitstream/123456789/2579/1/7.pdf.
16. Корольов О.В., Дерев'янко О.В. Резервне підживлення парогенераторів АЕС в умовах елекрознеструмлення енегроблока. *Ядерна та радіаційна безпека*. 2014. 2 (62). С. 10–12. URL: http://dspace.opu.ua/xmlui/handle/123456789/1471.

References

1. Skalozubov, V.I. Bogodist, V.V. & Kozlov, I.L., et al. (2013). Method for assessing the criteria for flooding the Zaporizhskaya AES industrial dam in different design earthquakes. *Nuclear and radiation safety*, 4 (60), 16–19. Retrieved from https://doi.org/10.32918/nrs.2013.4(60).03me conditions.
2. Skalozubov, V.I., Oborsky, G.A., & Kozlov, I.L. et al. (2013). *A set of methods for reassessing the safety of nuclear energy in Ukraine, taking into account the lessons of environmental disasters in Chernobyl and Fukushima:* monograph. Odessa: Astroprint, 242 p. ISBN 978-966-190-824-5.
3. Skalozubov, V.I., Kozlov, I.L., & Gablaya, T.V., et al. (2014). Hydrodynamic model of possible flooding of an industrial platform of the Zaporozhye Nuclear Power Plant at joint impact of a beyond design basis earthquake and a tornado in a pond cooler. *Problems of nuclear power plants' safety and of Chornobyl,* (23), 22–25. Retrieved from http://dspace.opu.ua/jspui/bitstream/123456789/6595/1/c22.pdf.
4. Kozlov, I.L. (2015). Criteria for NPP industrial site flooding by combined impact of tornadoes and earthquakes in the cooling pond. *Eastern-European Journal of Enterprise Technologies,* 3(6(75)), 53–58. DOI: 10.15587/1729-4061.2015.42146.
5. Gromov, G.V., Dybach, O.M., & Zeleny, O.V., et al. (2012). Results of expert assessment of the Ukrainian operating nuclear power units stress tests, taking into account the Fukushima-1 nuclear power plant accident in Japan lessons. *Nuclear and radiation safety,* 1(53), 3–9. DOI: 10.32918/nrs.2012.1(53).01.
6. National report on the results of "stress tests" for NPPs of Ukraine. (2011). *State Nuclear Regulatory Inspectorate of Ukraine,* 124 p. Retrieved from https://snriu.gov.ua/news/natsionalniy-zvit-shchodo-rezultativ-provedennya-stres-testiv-dlya-aes-ukraini-vidteper-dostupniy-rosiyskoyu-movoyu.
7. Ostreikovsky, V.A., & Shvyryaev, Yu.V. (2008). *Safety of nuclear power plants. Probabilistic security analysis.* M.: FIZMATLIT, 352 p. Retrieved from https://books.google.com.ua/books?id=Wwd4CwAAQBAJ&pg=PA2&lpg=PA2&dq.
8. Dybach, O.M. (2014). Methodological bases of analysis and consideration of uncertainties of probabilistic analysis of NPP safety. *Nuclear and radiation safety*, 4(64), 8–16. Retrieved from http://dspace.nbuv.gov.ua/bitstream/handle/123456789/97631/02.
9. Boichuk, V., Gashev, M., & Mykolaichuk, O. (2013). Action plan for the implementation of measures to increase safety at NPPs of Ukraine based on the results of stress tests. *Nuclear and radiation safety,* 2(58), 3–7. DOI: 10.32918/nrs.2013.2(58).01.

10. General safety provisions of nuclear power plants. (2008). *Norms and rules on nuclear and radiation safety*. NP 306.2.141-2008. 62 p. Retrieved from http://www.aep.org.ua/fileadmin/user_upload/NP-141.pdf.
11. Gryschenko, B., Polyanskyi, M., & Sevbo, O., et al. (2013). The application of probabilistic methods of nuclear power plant safety analysis in the investigation of damage to the fragile strength of the reactor body. *Nuclear and radiation safety*, 1(57), 22–25. DOI: 10.32918/nrs.2013.1(57).04.
12. Borysenko, V. I. (2012). About some regularities of consequences of accidents at NPP. *Security problems of the NPP and Chernobyl*, (18), 6–15. Retrieved from http://www.ispnpp.kiev.ua/wp-content/uploads/2017/2012_18/c6.pdf.
13. Naffaa, Kh., Gerliga, V., & Shevelev, D., et al. (2013). Assessing the Effectiveness of Passive System of Heat Removal from the WWER Containment under Long-Term Blackout. *Nuclear and radiation safety*, 2 (58), 27–31. Retrieved from http://dspace.nbuv.gov.ua/handle/123456789/97457.
14. Khaled, N., Shevelev, D.V, & Balashevsky, A.S. (2014). Computational modeling of the operation and evaluation of the effectiveness of the passive heat removal system from the hermetic volume (spot) in the event of a rupture of the steam pipeline of hot steam with non-isolation of emergency gas on the feed line at the NPP with VVER-1000. *Global nuclear security*, 1 (10), 5–9. Retrieved from https:// cyberleninka.ru/ article/n/raschetnoe-modelirovanie-raboty-i-otsenka-effektivnosti-sistemy-passivnogo-otvoda-tepla-ot-germoobema-spot-go-pri-razryve-paroprovoda.
15. Naffaa, Kh. M., & Dubkovsky, V.A. (2014). Classification of passive heat residual removal systems from reactors containments. *Proceedings of Odessa Polytechnic University*, 1 (43), 104–112. Retrieved from http://dspace.opu.ua/jspui/bitstream/123456789/2579/1/7.pdf.
16. Korolyov, A, & Derevianko, O. (2014). Emergency Makeup of Nuclear Steam Generators in Blackout Conditions. *Nuclear and radiation safety*, 2(62), 10–12. Retrieved from http://dspace.opu.ua/ xmlui/handle/123456789/1471.

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Received October 16, 2022
Accepted December 05, 2022