DOI: 10.20535/1810-0546.2018.4.142218
UDC 621.039

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METHOD OF THE SAFETY MARGINS MANAGEMENT OF NUCLEAR POWER PLANTS

Background. Nowadays, there is widely used only one methodology that allows numerically measure NPP safety level and ensures safety optimization. This is Probabilistic Safety Assessment. Therefore, NPP safety is still justified using deterministic approach. As a main tool for deterministic approach Design Basis Accident Analysis is used for NPP designing and safety justification. It has widely recognized and sustainable methodology, procedure and experience of application. Thus, there is contradiction between safety measurement and safety justification.
Objective. Article provides concept of the method that on a basis of deterministic approach allows evaluate and manage safety margins for Nuclear Power Plant for safety and expenses optimization purposes.
Methods. As a main tool for deterministic approach and safety margins calculation the Design Basis Accident (DBA) Analysis was applied. The main objective of DBA analysis is to demonstrate based on conservative approach exceeding or non-exceeding of so called acceptance criteria that are established and justified in the NPP design. Since, acceptance criteria have different physical background, dimensions and numerical values it is proposed to transform them into dimensionless form by dividing value of corresponded calculated parameter on value of acceptance criterion. The result of ratio is the dimensionless safety deficit while difference between the dimensionless acceptance criterion (that is always equal to 1) and safety deficit is the dimensionless safety margin. Also, it is proposed to establish for each acceptance criterion a 10% zone (its lower boundary corresponds to 0.9 – value of limiting safety deficit) as a deterministic safety criterion and apply it in the nuclear regulations. If calculated value of safety deficit is within this zone than it is proposed to use time limitation and recognize necessity to develop and apply safety measures on decreasing of a safety deficit. Such method allows reveal as safety deficiencies so excessive safety margins.
Results. The proposed method was applied for DBA Analysis of Zaporizhzhya NPP unit 5. Safety deficits were evaluated for each initiating event and corresponding safety profiles were drawn for each acceptance criterion.
Conclusions. Methodol is recommended for usage in regulatory activity, during the NPP designing and operation, and, for justification of the safety systems maintenance and repair activity at reactor power operation.
Keywords: safety deficit; average safety deficit; dimensionless safety margin; deterministic safety criteria.

Introduction

At present time, the nuclear industry is under big constant pressure, especially, after the Fukusima accident. This leads to highly cost requirements that are demanded to be applied as by traditional international organizations like IAEA, so by public organizations like Greenpeace. Meanwhile, Ukrainian nuclear law [1] and IAEA [2] policy still state that there should be no any unduly limiting of nuclear power utilization.

Such situation requires establishing of the balance between high safety level of Nuclear Power Plants (NPPs) and expenses needed for its support. Currently, the most applicable approach for establishing of the balance is the Integrated Risk-Informed Decision Making (IRIDM) [3]. IRIDM is widely applied at US NPPs and IAEA encourage its application by other countries, for example, in publication INSAG-25 [4]. This approach is based on evaluation of multiple safety factors like defense-in-depth, safety culture, risk, deterministic safety margin, nuclear security, etc. Meanwhile, all these factors are qualitative except of probabilistic one. This creates cases when safety decisions are made based mainly on risk considerations. Therefore, it is generally accepted to justify safety using deterministic approaches that is complemented by probabilistic safety assessment. Other words, there is a lack of quantitative deterministic factor in IRIDM that is capable to provide numerical measurement of safety level and allows manage the safety and thus, establishing more justified and balanced decision making on NPPs safe and reliable operation.

Problem Statement

As it is demonstrated above there is a need in development of deterministic method and criteria that capable as complement existing NPP safety management approach, so for standalone application.

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Thus, the purpose of the article is to demonstrate deterministic method that on a basis of existing methodology of deterministic safety analysis allows numerically evaluate safety and safety level as for Nuclear Power Plant (NPP), so for each physical safety barrier. It should satisfy provisions of the fundamental safety principle – "Optimization of Protection" [2]. Above capabilities could be realized as by independent implementation of the method or in the framework of Integrated Risk-Informed Decision Making.

Such method would allow eliminate contradiction between the deterministic safety justification of NPPs and safety improvement that currently is based entirely on Probabilistic Safety Assessment (PSA).

Theoretical Basis of the Method

The main objective of DBA analysis is to demonstrate based on conservative approach exceeding or non-exceeding of so called acceptance criteria (or safety limits) that are established in the NPP design or in the norms, rules and standards on nuclear and radiation safety. In general, acceptance criteria are characterized by a certain reactor parameters and established to protect physical safety barriers (fuel, fuel rod cladding, boundaries of reactor coolant system, containment). These parameters are calculated in DBA and characterize effectiveness of the safety systems. Relations between safety barrier, acceptance criteria and calculated conservative parameter are demonstrated on Fig. 1.

It is evident that, then larger is safety margin then safer is the reactor facility. Given that, it is proposed do not limit the efforts by calculation of exceeding or non-exceeding of acceptance criteria. It is proposed to go further: to calculate differences between the acceptance criteria and calculated value in DBA that is to evaluate the margin or other words – safety margin.

Therefore, acceptance criteria have different physical background, dimensions and numerical values and cannot be manipulated in such form. It is proposed to transform them into dimensionless form by dividing value of corresponded calculated parameter on value of acceptance criterion in order to establish the basis for the possibility of comparative analysis. The result of ratio is the dimensionless safety deficit while difference between the dimensionless acceptance criterion (that is always equal to 1) and safety deficit is the dimensionless safety margin.

Mathematically, safety deficit can be expressed like:

$$D_i = R_i / K_i \text{ or } D_i = \left(\frac{R_i}{K_i}\right) \times 100\ \% \qquad (1)$$

where D_i – safety deficit for acceptance criterion number i; R_i – calculated conservative value of a parameter for acceptance criterion number i; K_i – value of acceptance criterion number i.

As it follows from the above definition dimensionless acceptance criterion is always equal to 1. Dimensionless safety margin is calculated as:

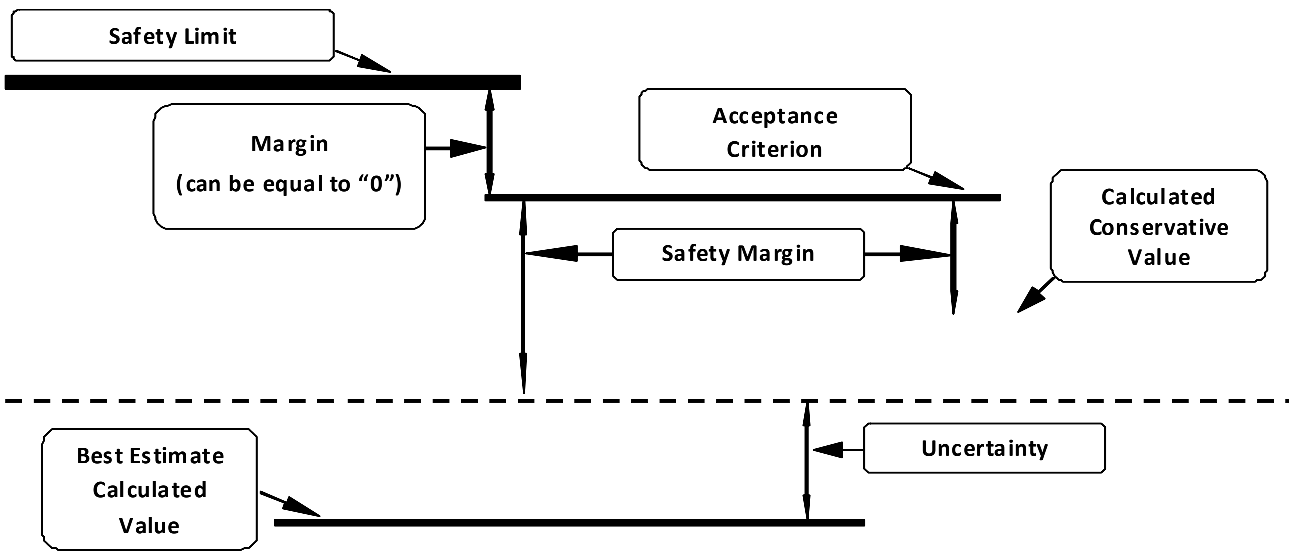

Fig. 1. Relations between safety barrier, acceptance criteria and calculated conservative parameter

$$Z_i = 1 - D_i .$$

Definitions of safety deficit (SD) and dimensionless safety margin are demonstrated on Fig. 2.

Fig. 2. Relations between safety deficit, dimensionless safety margin and dimensionless acceptance criterion

Introducing of dimensionless approach allows develop a method for safety margin management since it is possible now to compare impact of different initiating events, safety barriers, reactor facilities on safety margins as well as to establish new regulatory requirement in a form of dimensionless deterministic 10% safety criterion. Some additional definition might be also useful and are provided below.

Average Value of Safety Deficit could be defined for an initiating event, safety barrier or acceptance criterion:

$$D_i^{\text{aver}} = D_i^t / N_{ij} \tag{2}$$

where N_{ij} – number of initiation event for which acceptance criterion i was calculated; D_i^t is calculated as:

$$D_i^t = \Sigma\Sigma D_{ij} , \tag{3}$$

i – acceptance criterion index; j – initiating event index.

Safety profile – safety deficit values reflected on a single scale. It allows perform visual evaluation of safety deficits and dimensionless safety margins that are subject of the lack of the safety or demonstrate excessive safety.

Deterministic Safety Criterion – minimal margin to acceptance criterion that is established in the norms, rules and standards on nuclear and radia-

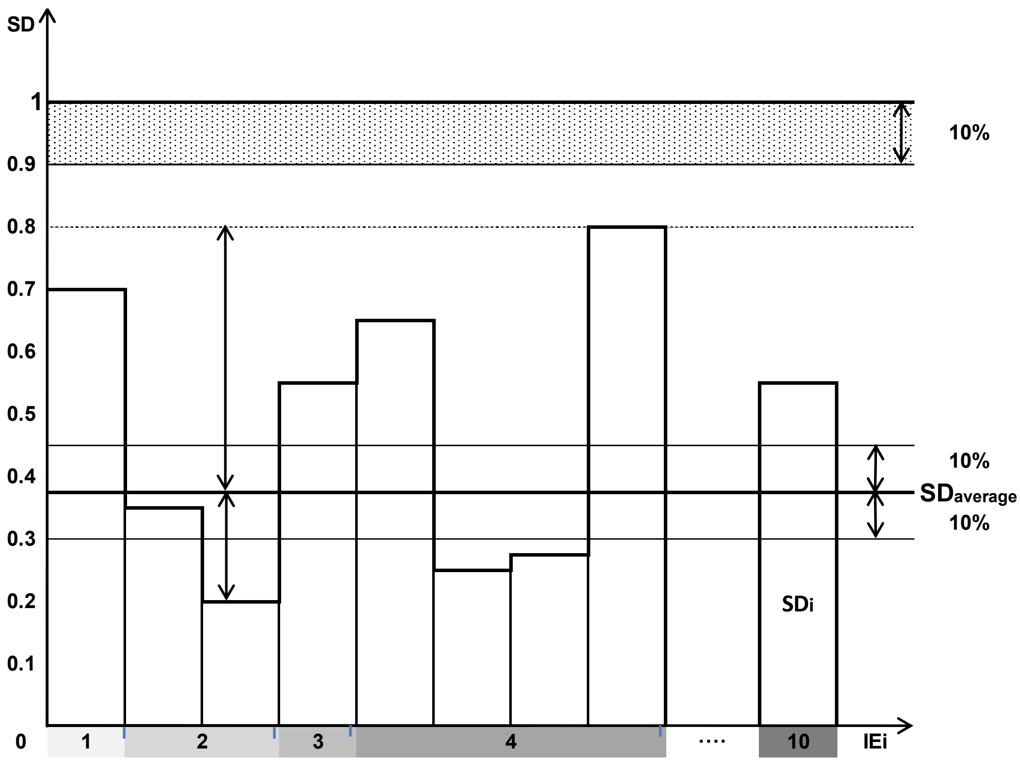

Fig. 3. Illustration of the definitions

tion safety. It is proposed to use 10 % margin (see Fig. 3). If conservative calculated value is within the 10 % margin then special safety measures should be undertaken.

Practical Demonstration of the Method

According to the DBA methodology [5] acceptance criteria are established separately for transients (frequency of these Initiating Events (IE) is more than once per 100 years) with and postulated accident (frequency of these IEs is less than once per 100 years). Totally, there are 7 acceptance criteria that are established in the Design of NPP and in the norms, rules and standards on nuclear and radiation safety for WWER-1000:

1. Departure from Nuclear Boiling Ratio should be more than 1.

2. Maximum fresh fuel temperature should be less than 2840 °C and – 2570 °C for spent fuel.

3. Maximal fresh fuel enthalpy should be less than 963 kDj/kg and – 840 kDj/kg for spent fuel.

4. Pressure in equipment and piping should not exceed operational one on 15 %:

- for reactor coolant system it is 207 kg/cm^2;
- for steam generators – 92 kg/cm^2.
- Maximal containment pressure and temperature should be less than:
- 150 °C;
- 5 kg/cm^2.

6. Maximal design limit should be less than:

- fuel cladding temperature 1200 °C.
- depth of cladding oxidation 18 %;
- portion of 1 % of the reacted zirconium of its mass in the fuel claddings.

7. Maximal value of radioactive releases should be limited by:

- 0.3 Zv on на thyroid gland due to inhalation;
- 0.1 Zv for all body due to external irradiation.

The first acceptance criterion is valid only for transients. The forth acceptance criterion is applied for both transients and postulated accident. The rest ones are used for postulated accidents only. It should be noted that acceptance criteria for transients are stricter than for postulated accident (PA) since prevention of accidents is of more concern than mitigation.

Based on documentation of Design Basis Accident Analysis for Zaporizhzhya NPP Unit 5 [6] with the WWER-1000/320 reactor (totally, there are 11 such reactors in Ukraine) calculated values of parameters that correspond to relevant acceptance criteria were transferred to dimensionless form using equation (1). Equations (2) and (3) were used to quantify average values for Safety Deficits (SD). These data were used to draw diagrams for each acceptance criterion and each initiating events. Results of this effort are provided on Figs. 4–13.

Also, it should be noted that in DBA analysis different sets of acceptance criteria are applied for different initiating events.

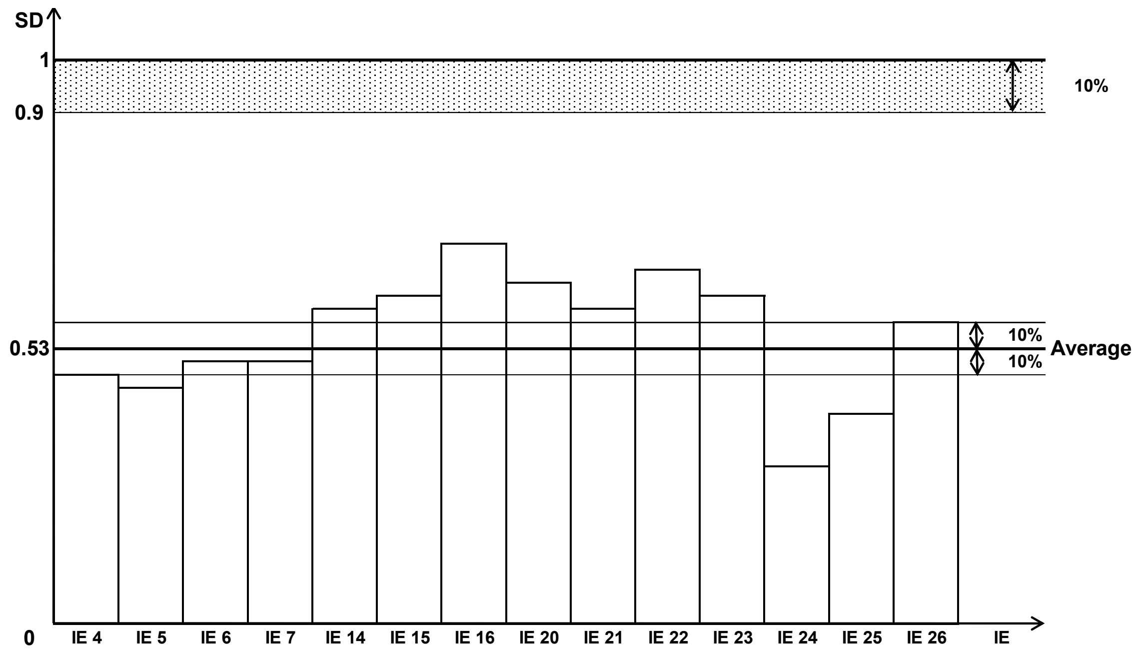

Fig. 4. Safety deficits for acceptance criterion #1 for transients

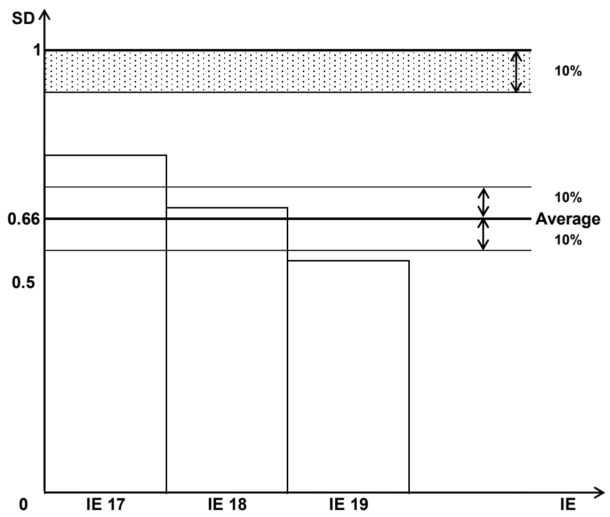

Fig. 5. Safety deficits for acceptance criterion #2 for postulated accidents

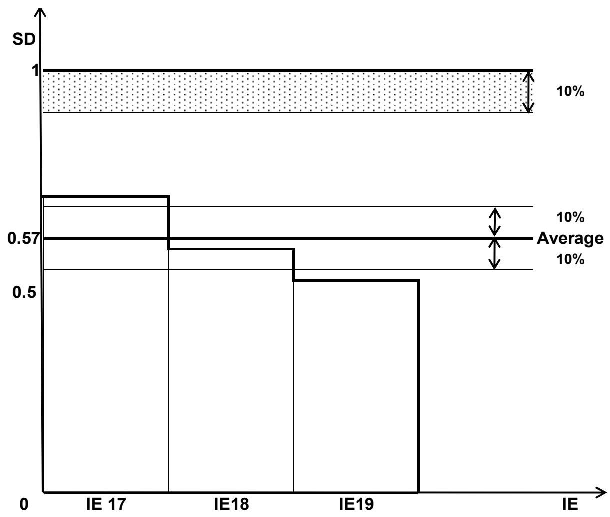

Fig. 6. Safety deficits for acceptance criterion #3 for postulated accidents

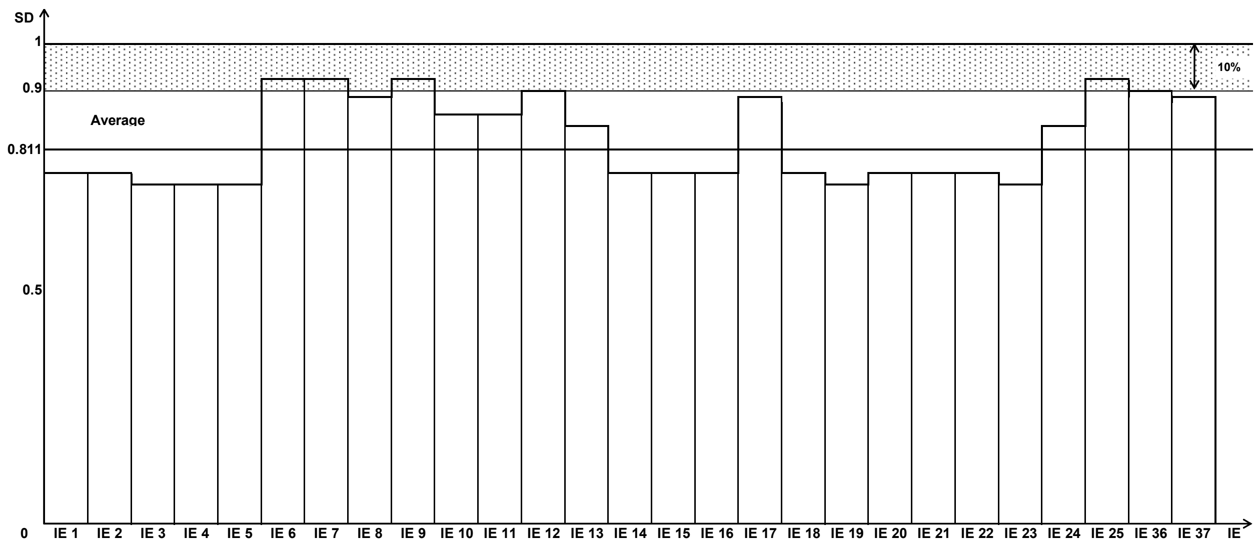

Fig. 7. Safety deficits for acceptance criterion #4-1 for all IEs

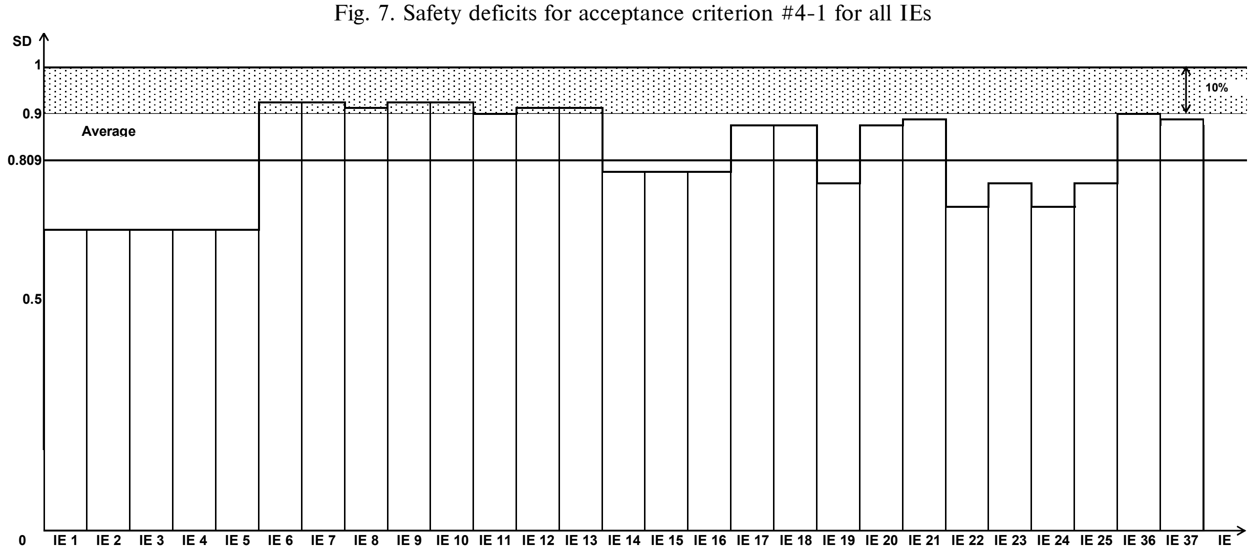

Fig. 8. Safety deficits for acceptance criterion #4-2 for all IEs

Figs. 4, 5 and 6 demonstrate significant safety margins for acceptance criteria #1, 2 and 3 calculated for transients (acceptance criterion #1) and postulated accidents (acceptance criteria #2 and 3). That is there are excessive safety margins. This fact shows significant potential for expenses optimization dealt with the systems involved into these initiating events while preserving high level of the safety.

As it can be seen from Figs. 7 and 8 for the acceptance criterion #4 on primary and secondary pressures the deterministic safety criterion (10 % zone) is violated for a number of initiating events both transients and postulated accidents. This means that initially hidden safety deficits are revealed and corresponded safety measures shall be developed and implemented in this respect. This involves an analysis of the reasons resulted in such results and search of effective measures that are able to decrease level of safety deficits.

For acceptance criteria on containment boundaries violation of deterministic criterion is also observed (see Figs. 9 and 10). Comparing with the violation of acceptance criterion #4 it can be seen that safety margins for containment boundaries are larger. Meanwhile, relevant safety measures shall be developed and implemented too.

Significant safety margins are observed for acceptance criterion on radioactive exposure. This does not explicitly means that excessive safety margins allow implement measures on decrease of associated expenses, since the relevant initiating events are dealt with the containment bypass via failed steam generator. This is a good example of the fact that any methodology should be applied very carefully and any decision based on a methodology should be well justified.

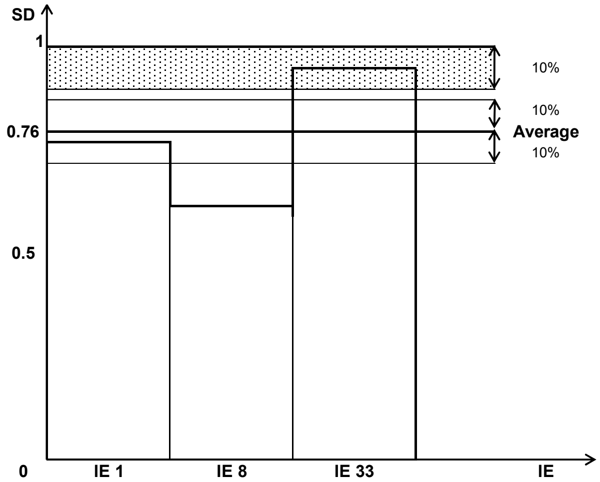

Fig. 9. Safety deficits for acceptance criterion #5-1 for postulated accidents

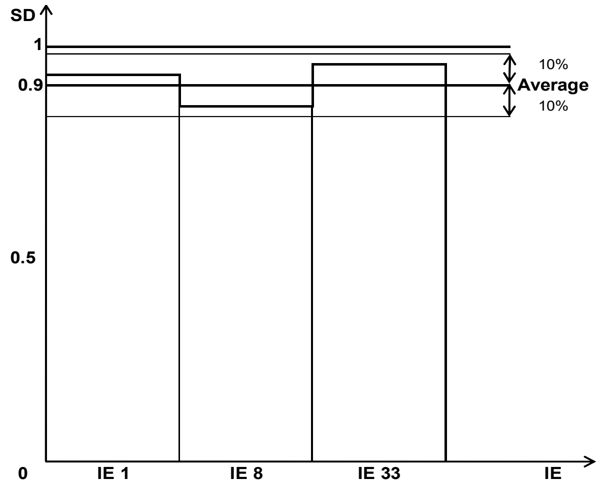

Fig. 10. Safety deficits for acceptance criterion #5-2 for PAs

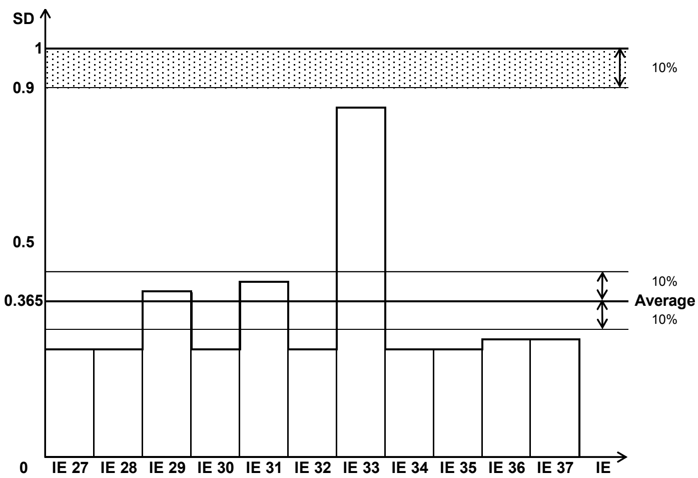

Fig. 11. Safety deficits for acceptance criterion #6 for PAs

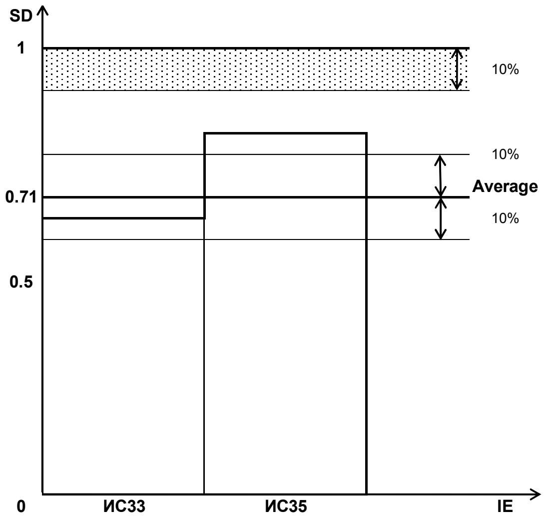

Fig. 12. Safety deficits for acceptance criterion #7-1 for PAs

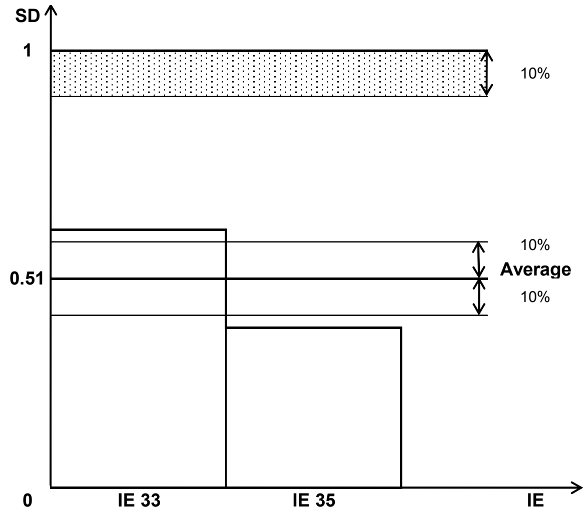

Fig. 13. Safety deficits for acceptance criterion #7-2 for PAs

Conclusions

Developed method allows evaluate for each initiating event (transient or anticipated accident) the safety deficits and excessive safety margins for each acceptance criterion. Introduction of the average and integrated safety deficit makes possible to perform comparative analysis between different initiating events, acceptance criteria, physical protection barriers and types of nuclear reactors.

Also, it is proposed to establish for each acceptance criterion a 10 % zone (corresponds to 0.9 value limiting safety deficit) as a deterministic safety criterion and apply it in the norms, rules and standards on nuclear and radiation safety.

Graphical representation of safety deficits evaluated for the initiating events, acceptance criteria, and physical protection barriers reflects the safety profile and demonstrate violation of the deterministic safety criterion and deviation from the average value of safety deficit. This allows reveal as safety deficiencies so excessive safety margins. If the first one requires development of the corresponded safety measures then the second one – establishes the basis on implementation of "Optimization of protection" fundamental safety principle and develop measures aimed on decrease of expenses on reliable and safe NPP operation along with keeping established high level of safety. Process of the achievement of the both purposes establishes basis of the safety margin management.

The method proposed was applied using Design Basis Accident Analysis of Zaporizhzhya NPP unit 5. Safety deficits were evaluated for each initiating event and corresponded safety profiles were draw for each acceptance criterion. As a result, the violation of acceptance criteria on primary, secondary and containment pressure were revealed. Also, excessive safety margins were revealed that ensures possibilities for justified decrease of expenses spent on safety.

Method is recommended for usage in regulatory activity, during the NPP designing and operation, and, for optimization of the safety systems maintenance and repair activity and its fulfillment on operating at power reactor.

Also, method has a good potential for further development into the complete methodology and procedure which can be used as for independent application, so as part of the IRIDM approach.

References

[1] Supreme Council of Ukraine, "About Activity in Area of Nuclear Power Utilization", 2000.

[2] *Fundamental Safety Principles*, IAEA Safety Standards, Ser. No. SF-1, IAEA, 2006.

[3] *Integrated Risk Informed Decision Making Process Guidance*, IAEA Safety Standard, IAEA-TECDOC DS 365 Draft 1, IAEA, April 2008.

[4] *A Framework for an Integrated Risk Informed Decision Making Process*, International Atomic Energy Agency, INSAG-25, STI/PUB/1499, Vienna, 2014.

[5] *Safety Assessment for Facilities and Activities*, IAEA Safety Standards, Ser. No. GSR, Part 4, 2009.

[6] *Safety Analysis Report. Design Basis Accident Analysis. Unit 5 of Zaporizhzhya NPP.* 21.5.70.OB.02., 2003.

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СПОСІБ УПРАВЛІННЯ ЗАПАСАМИ БЕЗПЕКИ ЕНЕРГОБЛОКІВ АТОМНИХ СТАНЦІЙ

Проблематика. На сьогодні існує та широко застосовується тільки одна методологія, яка дає змогу кількісно виміряти рівень безпеки атомних електростанцій (АЕС) і забезпечити оптимізацію захисту. Це імовірнісний аналіз безпеки. Проте безпека АЕС, як і раніше, ґрунтується на підставі детерміністичного підходу. Як основний інструмент детерміністичного підходу використовується аналіз проектних аварій як для проектування АЕС, так і для обґрунтування її безпеки. Він має загальновизнану і усталену методологію, процедуру та досвід застосування. Таким чином, виникає протиріччя між вимірюванням рівня і обґрунтуванням безпеки.

Мета дослідження. У статті наводиться спосіб, який на підставі детерміністичного підходу дає змогу оцінити та управляти запасами безпеки АЕС з метою оптимізації безпеки та витрат на підвищення безпеки.

Методика реалізації. Як інструмент детерміністичного підходу і розрахунку запасів безпеки використовувався аналіз проектних аварій (АПА). Мета АПА полягає в тому, щоб на підставі консервативного підходу оцінити перевищення або неперевищення так званих критеріїв прийнятності, які встановлюються і обґрунтовуються в Проекті АЕС. Оскільки критерії прийнятності мають різну фізичну природу, одиниці виміру та числові значення, то пропонується перевести їх у безрозмірну форму діленням розрахункового значення параметра на значення критерію прийнятності. Результатом буде безрозмірне значення дефіциту безпеки, а різниця між безрозмірним значенням критерію прийнятності (завжди дорівнює 1) і дефіцитом безпеки буде безрозмірним значенням запасу безпеки. Також пропонується для кожного критерію прийнятності встановити 10 %-ну зону (нижня межа якої дорівнює 0,9 – граничне значення дефіциту безпеки) як детерміністичний критерій безпеки і використовувати його при ядерному регулюванні. Якщо розрахункове значення дефіциту безпеки потрапляє в 10 %-ну зону, то пропонується вводити тимчасові обмеження на експлуатацію енергоблока і реалізовувати заходи щодо безпеки для зниження дефіциту безпеки. Така концепція дає змогу виявити як дефіцити, так і надлишкові запаси безпеки.

Результати дослідження. Запропонований спосіб застосовано до АПА енергоблока № 5 Запорізької АЕС. Для кожної вихідної події були розраховані дефіцити безпеки і графічно побудовані профілі безпеки для кожного критерію прийнятності.

Висновки. Спосіб рекомендується для застосування в регулювальній діяльності, при проектуванні та експлуатації АЕС, у т.ч. для обґрунтування ремонту обладнання на працюючому енергоблоці.

Ключові слова: дефіцит безпеки; середнє значення дефіциту безпеки; безрозмірне значення запасу безпеки; детерміністичний критерій безпеки.

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СПОСОБ УПРАВЛЕНИЯ ЗАПАСАМИ БЕЗОПАСНОСТИ ЭНЕРГОБЛОКОВ АТОМНЫХ СТАНЦИЙ

Проблематика. В настоящее время существует и широко применяется только одна методология, которая позволяет количественно измерить уровень безопасности атомных электростанций (АЭС) и обеспечить оптимизацию защиты. Это вероятностный анализ безопасности. Тем не менее безопасность АЭС по-прежнему обосновывается на основании детерминистического подхода. В качестве основного инструмента детерминистического подхода используется анализ проектных аварий как для проектирования АЭС, так и для обоснования ее безопасности. Он обладает общепризнанной и устоявшейся методологией, процедурой и опытом применения. Таким образом, возникает противоречие между измерением уровня и обоснованием безопасности.

Цель исследования. В статье описан способ, который на основании детерминистического подхода позволяет оценить запасы безопасности АЭС для целей оптимизации безопасности и затрат на повышение безопасности.

Методика реализации. В качестве инструмента детерминистического подхода и расчета запасов безопасности использовался анализ проектных аварий (АПА). Цель АПА заключается в том, чтобы на основании консервативного подхода оценить превышение или непревышение так называемых критериев приемлемости, которые устанавливаются и обосновываются в Проекте АЭС. Поскольку критерии приемлемости имеют различную физическую природу, единицы измерения и численные значения, то предлагается перевести их в безразмерную форму путем деления расчетного значения параметра на значение критерия приемлемости. Результатом будет безразмерное значение дефицита безопасности, а разница между безразмерным значением критерия приемлемости (всегда равно 1) и дефицитом безопасности будет безразмерным значением запаса безопасности. Также предлагается для каждого критерия приемлемости установить 10 %-ную зону (нижняя граница которой равна 0,9 –предельное значение дефицита безопасности) в качестве детерминистического критерия безопасности и использовать его при ядерном регулировании. Если расчетное значение дефицита безопасности попадает в 10 %-ную зону, то предлагается вводить временные ограничения на эксплуатацию энергоблока и реализовывать мероприятия по безопасности для снижения дефицита безопасности. Такой способ позволяет выявить как дефициты, так и избыточные запасы безопасности.

Результаты исследования. Предлагаемый способ применен к АПА энергоблока № 5 Запорожской АЭС. Для каждого исходного события были рассчитаны дефициты безопасности и графически построены профили безопасности для каждого критерия приемлемости.

Выводы. Способ рекомендуется для применения в регулирующей деятельности, при проектировании и эксплуатации АЭС, в т.ч. для обоснования ремонта оборудования на работающем энергоблоке.

Ключевые слова: дефицит безопасности; безразмерное значение запаса безопасности; детерминистический критерий безопасности.

Рекомендована Радою
теплоенергетичного факультету
КПІ ім. Ігоря Сікорського

Надійшла до редакції
30 травня 2018 року

Прийнята до публікації
6 вересня 2018 року