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APPROACH TO THE ANALYSIS OF SUCCESS CRITERIA AS A COMPONENT OF PROBABILISTIC PHYSICAL PROTECTION ANALYSIS OF NUCLEAR FACILITIES

S.O. Horbachyk, V.A. Kondratyuk, S.V. Klevtsov
NTUU "Igor Sikorsky Kyiv Polytechnic Institute",
Kyiv, Ukraine
E-mail: s.horbachyk@gmail.com

An approach to adapting the methodology for analyzing success criteria from traditional probabilistic safety analysis (PSA) of nuclear power plants (NPPs) to probabilistic physical protection analysis (PPA) of nuclear facilities is demonstrated using the hypothetical nuclear facility SNRI as an example. Generally speaking, using the traditional PSA methodology for assessing the physical protection of nuclear facilities allows for the identification of new vulnerabilities in the physical protection systems of nuclear facilities, the development of recommendations to enhance physical protection efficiency, the performance of more substantiated cost-benefit analyses, and more.

INTRODUCTION

Ukraine possesses a substantial complex of nuclear facilities. Considering the introduction of martial law in Ukraine, it is necessary to make appropriate efforts to achieve the required level of physical protection for these nuclear facilities, as new threats could compromise nuclear security and have unforeseen consequences.

The primary mechanism to prevent the unlawful acquisition of nuclear and radioactive materials at nuclear facilities is the physical protection system (PPS). Currently, the PPS of nuclear facilities in our country is at a fairly high level. However, humanity does not "stand still", and with the advancement of technologies, new opportunities to bypass PPS for the unauthorized removal of nuclear materials arise.

Therefore, to enhance the effectiveness of PPS, it is proposed to apply a tool proven in the safety analysis of NPPs – probabilistic safety analysis (PSA).

To demonstrate the applicability of adapted probabilistic analysis methods to PPS, a hypothetical nuclear facility of the Institute for Nuclear Research "Shapash" (SNRI) is taken as a basis.

1. GENERAL CHARACTERISTICS OF THE HYPOTHETICAL NUCLEAR FACILITY SNRI

The hypothetical nuclear facility SNRI is a research reactor. The SNRI site is divided into two zones [1]:

1) administrative zone – the activities in this zone are not directly related to production processes;

2) Protected Zone – a high-security zone (strict control) that includes the research reactor itself, the fuel fabrication building, auxiliary structures, a bunker storage for uranium dioxide (UO_2), and the cargo receiving and dispatch terminal.

The administrative zone is enclosed on three sides by a fence and includes administrative buildings and auxiliary technical facilities.

The protected zone includes the research reactor, the fuel fabrication shop, the access control building (comprising a checkpoint (CP), central security post (CSP), and rapid response team room), the cargo receiving and dispatch terminal connected by road and rail, the UO_2 storage bunker, an X-ray facility, administrative technical complexes, an analytical laboratory, and a waste measurement installation [1].

The perimeter of the Protected Zone is secured with two wire mesh fences. Observation towers are located at each corner inside the perimeter of the Protected Zone.

The access control building houses the checkpoint. For illustrative purposes, the floor plan of the access control building is shown in Fig. 1.

The research reactor is directly located in the reactor building.

The uranium dioxide storage bunker is sealed, has no windows and has only one entrance. The door can be opened by sequentially entering two different access codes. According to the IAEA classification, nuclear materials of category I (more than 5 kg of unirradiated uranium with enrichment of more than 20% in ^{235}U) are stored in the bunker [2].

The analytical laboratory stores a small amount of nuclear materials in the form of technological samples.

In order to carry out the calculation process of the probability that the event will occur (for example, the extraction of nuclear materials from the storage bunker of uranium dioxide), it is necessary to specify the PPS characteristic of the hypothetical nuclear facility SNRI.

2. CHARACTERISTICS OF THE PHYSICAL PROTECTION SYSTEM (PPS) OF THE HYPOTHETICAL SNRI NUCLEAR FACILITY

Employees must pass through a checkpoint at the access control building to enter the protected area and undergo an identification process followed by screening through an X-ray machine, a walk-through metal detector, and a radiation portal monitor. If an alarm is triggered while passing through the metal detector or radiation monitor, the employee must repeat the screening and undergo additional inspection using handheld portable metal detectors or ionizing radiation detection devices as appropriate [1].

The fuel fabrication area on the site includes control zones within the fuel fabrication shop building where Category I nuclear material is present. The checkpoints for the fuel fabrication area and the research reactor building are similar to the entry/exit checkpoints of the protected area, with equivalent PPS equipment.

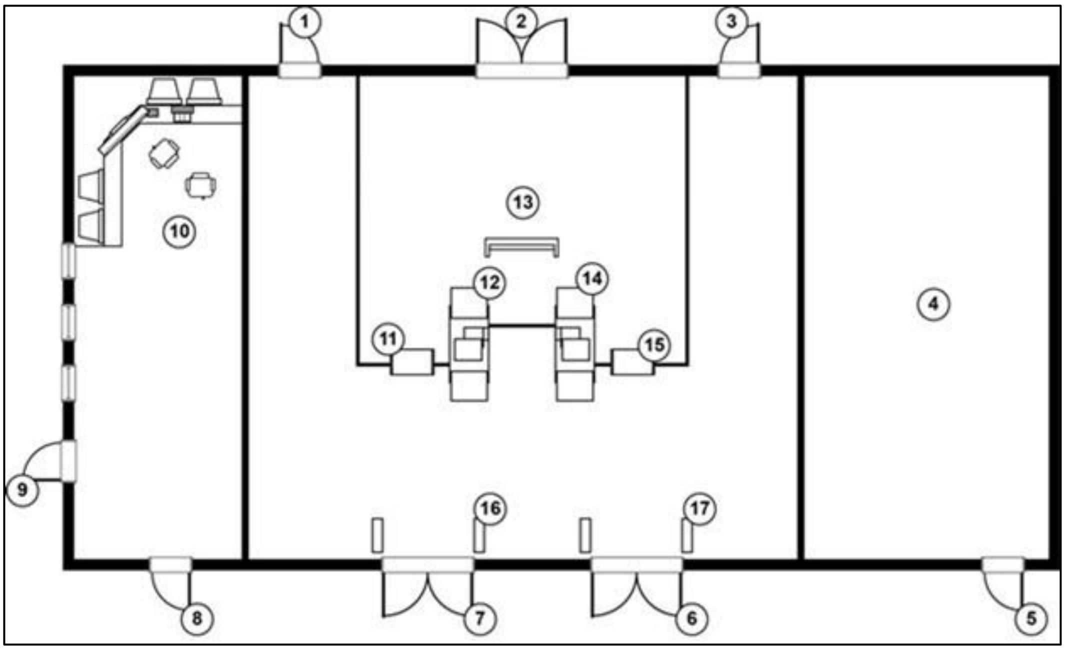

Fig. 1. Layout of the Access Control Building of the Protected Zone:
1, 3 – special entrance; 2 – entrance to the lobby; 4 – special response team; 5 – entrance to the alert station; 6, 7 – entrance to the technical zone; 8 – entrance to the central alarm control panel; 9 – access to the commercial transport zone; 10 – central alarm control panel; 11, 15 – metal detector; 12, 14 – X-ray Installations; 13 – Security Zone; 16, 17 – Radiation Detectors

3. APPROACH TO THE ANALYSIS OF SUCCESS CRITERIA

One of the most important components of probabilistic analysis, which requires adaptation for use in prospective probabilistic analysis of the physical protection of nuclear installations [3], is the analysis of success criteria (SC). It is proposed to develop adapted methods for analyzing the SC of security functions performed by PPS.

To formulate the SC, it is first necessary to determine the security functions.

One of the initial steps required for conducting a probabilistic analysis of the physical protection of nuclear installations is to define the list of design basis threats.

The term "design basis threat" refers to the attributes and characteristics of potential adversaries whose actions could be aimed at committing sabotage, theft, or any other unauthorized removal of radioactive materials, against which the PPS is designed to protect [4].

Since the information regarding the design basis threat of existing nuclear installations and their PPS is classified, hypothetical nuclear installations are typically used in such cases. For the hypothetical SNRI nuclear facility, the following design basis threats are considered [1]:

1) one active insider secretly carrying out the sudden unauthorized removal of nuclear materials;

2) one active insider secretly carrying out the unauthorized removal of nuclear materials over an extended period;

3) one active insider committing an act of sabotage resulting in unacceptable radiological consequences.

The PPS must ensure timely prevention, detection, delay, and appropriate response [5]. These are referred to as the functions of the physical protection system. Thus, a security function (SF) is any PPS function that prevents the realization of an adversary scenario. For the adapted definition of a SF for nuclear security, the PPS functions are as follows:

SF 1 – Prevention: Aimed at creating conditions that limit the possibility of adversary actions. This function should be considered when evaluating initiating events in the context of a design basis threat.

SF 2 – Detection: Ensures the timely detection of boundary breaches in restricted areas. Detection includes monitoring the PPS barriers and assessing signals from engineering and technical measures.

SF 3 – Delay: The time required for an adversary to overcome PPS barriers to execute or cause an undesirable event, essentially a measure of the resilience of physical barriers at the nuclear facility.

SF 4 – Response: Provides the capability to appropriately respond to an alarm to interrupt adversary actions.

Each SF is associated with its own SC, with corresponding acceptance criteria (AC) defined for each.

If we adapt the definition of SC from traditional probabilistic risk assessment (PRA), SC can be formulated as the minimum set of requirements for the performance of the PPS that defines the condition for the successful execution of a SF, considering the specific conditions imposed in each particular case of a design basis threat.

For the adaptation of the term "acceptance criteria", the following definition is proposed: it is a threshold expressed numerically that determines whether a success criterion is met or not.

Primary SC define the minimum set of requirements for the PPS, both in general and with respect to its performance of the required SF.

Secondary SC define the set of requirements for the relevant support system in terms of maintaining the minimum necessary conditions to ensure the functionality of the PPS.

In a PPS, a number of SC can be identified, determined by the objectives of the probabilistic analysis for physical protection. For example:

1) interruption of sabotage aimed at causing severe damage to the reactor's core;

2) interruption of sabotage aimed at creating an excessive accidental release into the environment;

3) interruption of the PPS for the removal of nuclear materials;

4) interruption of the PPS for the removal of radioactive materials.

The corresponding AC for these SCs are as follows:

1) not exceeding the design limit of 1200 °C for the cladding temperature of the most heavily loaded fuel element (FE) (TVEL);

2) the values of equivalent individual doses, calculated under the worst weather conditions at the NPP site, at the boundary of the sanitary protection zone, and beyond, should not exceed:

A – 0.3 Sv/year (30 rem/year) to children's thyroid due to inhalation,

B – 0.1 Sv/year (10 rem/year) to the whole body due to external radiation exposure;

3) the response time of the security forces to interrupt the actions of an offender attempting to remove nuclear materials should be less than the time required for the offender to achieve their objective;

4) the response time of the security forces to interrupt the actions of an offender attempting to remove radioactive materials should be less than the time required for the offender to achieve their objective.

It should be noted that the definitions of AC 3 and 4 are qualitative in nature and, unlike the ACs of traditional NPP PSA, such criteria in quantitative form need to be determined separately for each offender scenario. This means that each event tree and its associated accident sequence will have its own quantitative values for these ACs.

When discussing secondary SCs, the acceptability criterion refers to the permissible limits of operating parameters, such as voltage applied to the equipment, ambient temperature and humidity, lighting, quality, and speed of information transmission.

We will apply PSA for the probabilistic analysis of physical protection using the hypothetical SNRI facility as an example. To demonstrate the approach, we will select one nuclear material balance area. Given the amount of material and its radiation level, the storage bunker for highly enriched unirradiated uranium is chosen, as it contains 250 kg of uranium with an enrichment of up to 36%, including 90 kg of ^{235}U, and its radiation level is low, meaning the self-protection properties of this nuclear material are insignificant.

Let's consider which components of the PPS of the hypothetical nuclear facility SNRI correspond to the respective SFs they are meant to perform.

For SF 2 – Detection: the relevant means and measures include those necessary for detecting breaches of restricted access zones and the associated physical barriers (X-ray machine, radiometers, metal detectors, radiation installation, relay sensors on doors, motion detectors, code devices, alarms).

For SF 3 – Delay: the relevant physical barriers include external fences, walls, doors, etc.

For SF 4 – Response: timely deployment of the rapid response team and effective communication are essential.

To conduct a qualitative analysis of SCs, it is necessary to develop an event tree for the PPS components, where the relevant SCs for each AC are identified.

It is considered that the offender is an insider, allowing them to enter the restricted access zone through the checkpoint. With the necessary access, the insider reaches the uranium dioxide storage bunker to obtain nuclear materials, on the basis of which the PPS is modeled to prevent removal. The offender's escape route mirrors the path taken to the nuclear materials but in reverse order. This time, however, they need to cross the checkpoint with the nuclear materials in tow. Based on this scenario, the relevant PPS barriers that counteract the unauthorized removal of nuclear materials and the corresponding SFs are considered. Since the offender is an insider, the probability of their detection within the protected zone before the removal is extremely low.

According to the algorithm, in order to gain access to the uranium dioxide storage bunker and exit with the stolen nuclear material, the perpetrator must bypass several layers of PPS. Specifically, the perpetrator must enter the uranium dioxide storage bunker without triggering the magnetic relay door sensor or the infrared motion detector. Additionally, the perpetrator must undergo identification through a code entry device. To exit the controlled access area, the perpetrator must pass through a checkpoint equipped with an X-ray system and a radiation portal monitor (it is assumed that the perpetrator is also checked with a handheld radiometer detector).

The aforementioned SFs correspond to the following defined SCs and their respective ACs:

1) detection: in this case, the SC is the activation of at least one detection device, which allows the confirmation of a security threat (detection of the perpetrator). The AC is the time required to report the presence of the perpetrator;

2) delay: the SC involves creating obstacles to slow down the perpetrator's actions and further progress. The AC is the time required to initiate actions to interrupt the perpetrator's criminal activities;

3) response: the SC in this context is the timely deployment of a response team with maximum possible situational awareness. The AC is the time, which must

be less than the time needed for the perpetrator to achieve their goal.

Two scenarios are considered where, if either occurs, the perpetrator reaches their objective:

1) hardware failure, which leads to the malfunction of equipment responsible for detection, notification, and preventing the perpetrator's further progress;

2) prolonged power outage, caused by the failure of two power supply channels, generator failure or failure to start, and battery failure.

The event tree for hardware failure is illustrated in Fig. 2. The event tree for a total power outage is illustrated in Fig. 3.

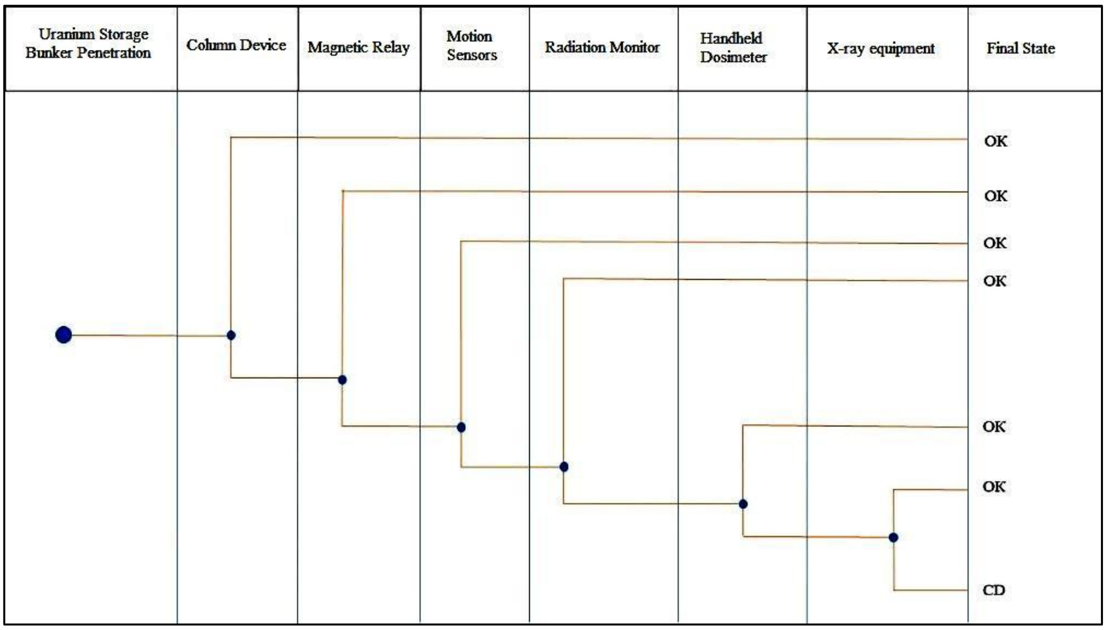

Fig. 2. The event tree for the scenario of an offender entering the UO_2 storage bunker due to hardware failure

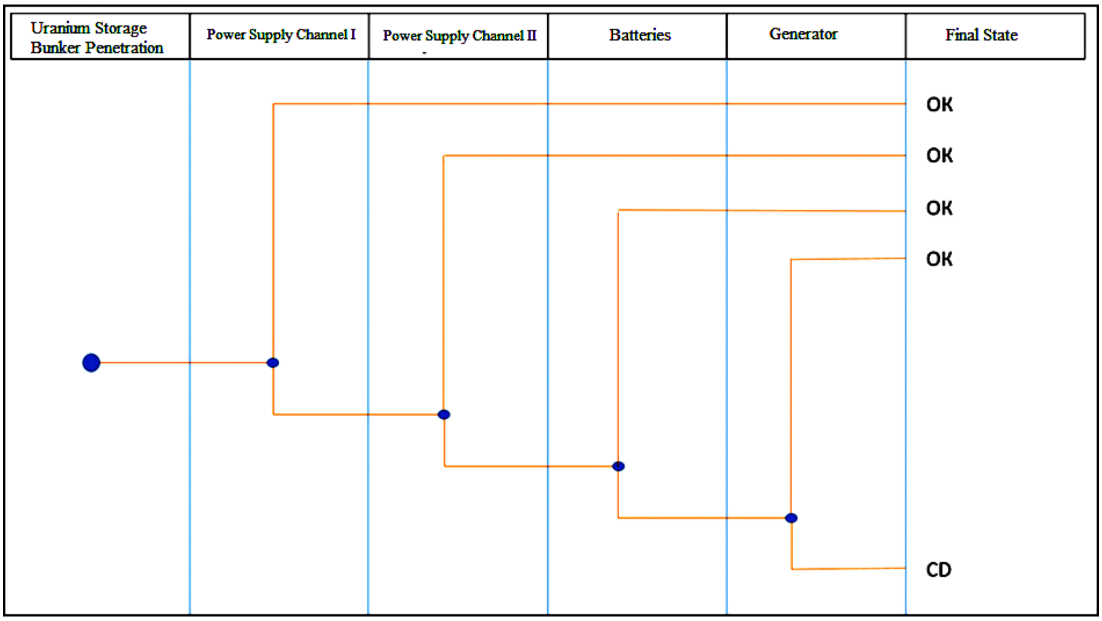

Fig. 3. Event tree for the scenario of an offender entering the UO_2 storage bunker due to complete power outage

The calculation process was carried out using the specialized computational software “SAPHIRE”. It is assumed that the hypothetical nuclear installation SNRI has two independent power supply channels.

The SC will be the interruption of the PSS for the removal of nuclear materials. This represents the minimum set of requirements necessary to ensure the prevention, detection, and response to the actions of a perpetrator.

4. CALCULATION RESULTS

The elements, subsystems, and equipment of the PSS for the hypothetical nuclear installation SNRI, along with their failure types, failure probabilities, error factors, operational modes, and testing periods, are presented in Table.

Certain elements and equipment of the PSS of the SNRI nuclear installation are not considered and are not included in the calculations as they do not impact the functioning of the PSS in performing the studied SF.

Fig. 4 illustrates the fault tree where the primary event is the intrusion of a perpetrator into the UO_2 storage bunker.

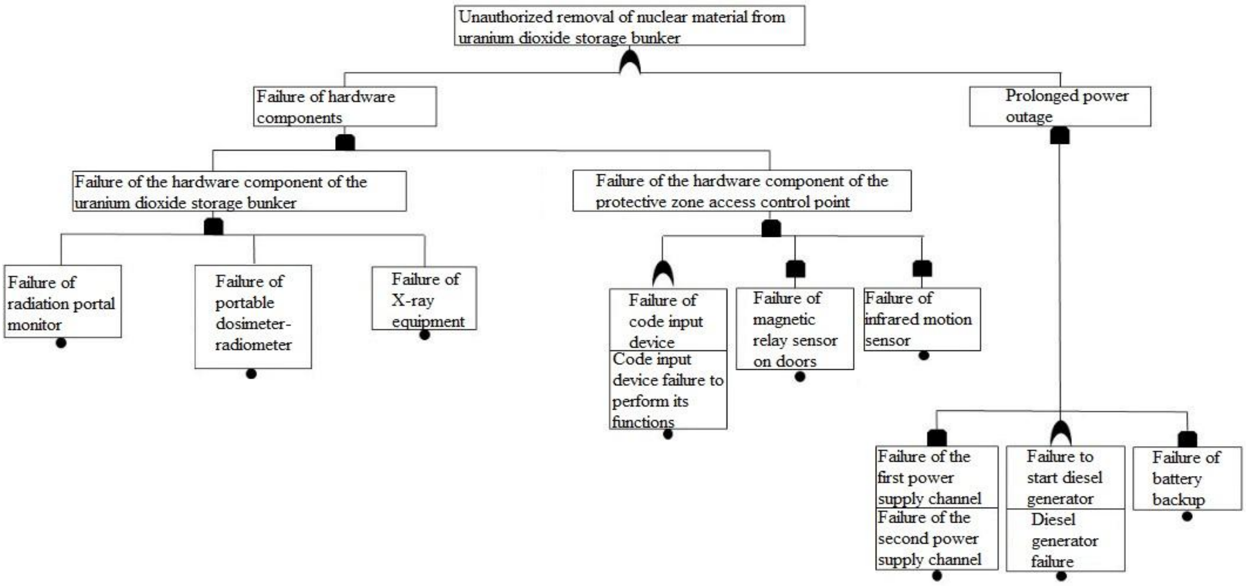

Fig. 4. Failure tree for the case when an intruder gains access to the uranium dioxide storage bunker UO_2

A fault tree is a graphical representation of a logical model that depicts the combinations of failures leading to a predetermined undesirable event [6].

According to the calculation, the probability of such an event occurring is extremely low, at $1.85 \cdot 10^{-13}$. The primary contribution to the occurrence of this event is due to prolonged power outages, particularly the scenario involving the failure of two independent power supply channels followed by the generator's failure to start and the battery's failure – accounting for 81.1% of the total probability, with an event probability of $1.5 \cdot 10^{-13}$. The scenario where two independent power supply channels fail followed by the failure of both the generator and the batteries is less likely, contributing 18.92% with an event probability of $3.5 \cdot 10^{-14}$. The scenario involving hardware failure is the least likely, with a probability close to zero and a contribution of less than 0.08%.

Description of the elements/subsystems/equipment of the SNRI physical protection system

Equipment	Failure Type	Failure Probability and error factor (EF)	Operating Mode	Testing Period
1. X-ray machine	Operational failure (no response)	0.000001 EF = 5	Normal operation mode (standby), triggering mode	Once a month
2. Radiation portal monitor	–“–	0.000001 EF = 5	–“–	–“–
3. Dosimeter-radiometer	–“–	0.00001 EF = 10	–“–	–“–
4. Generator	Failure to start	0.015 EF = 7	–“–	Once every 3 months
	Operational failure	$\lambda = 3.5 \cdot 10^{-3}$		
5. Accumulator batteries	–“–	0.00001 EF = 10	–“–	–“–
6. Magnetic relay sensors on doors	Operational failure (no response)	0.00001 EF = 10	–“–	Once a month
7. Infrared motion sensors	–“–	0.00001 EF = 10	–“–	–“–
8. Code input device	Operational failure	0.00001 EF = 10	–“–	–“–
	Refusal to perform its functions	0.000001 EF = 5		

CONCLUSIONS

The simplified and reduced task demonstrates that, using an adapted methodology from traditional PSA (Probabilistic Safety Assessment) for nuclear power plants, it is possible to conduct a probabilistic analysis of the physical protection of nuclear installations.

Further development of the proposed approach is necessary to create an appropriate methodology and procedure for performing the SC probabilistic analysis of physical protection for nuclear installations.

Adapted methodology: it has been shown that it is possible to calculate and analyze the entire PSS using adapted methods from traditional PSA, which will allow the identification of its most vulnerable elements, subsystems, and equipment concerning the full spectrum of design-basis threat scenarios.

Reliability and improvements: based on such probabilistic analysis, it can be determined what requires immediate improvement, considering the reliability of engineering and technical means and the operational features of the PSS. With qualitative characteristics of the objects subject to criminal actions, SCs are developed, corresponding to defined ACs.

Balanced PSS design: the adapted SC analysis within the probabilistic analysis of PSS will enable the construction of a comprehensively balanced PSS with an effective level of physical security.

Reliability data: preliminary quantitative results significantly depend on the reliability indicators of the equipment. For obtaining accurate and justified results, work must be carried out to collect reliable data.

This study shows that by leveraging the established methodologies of PSA from the nuclear industry, it is feasible to extend these practices to the domain of physical security. This approach provides a structured and quantifiable means to assess and enhance the security measures of nuclear installations, ensuring robust protection against potential threats.

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ПІДХІД ДО АНАЛІЗУ КРИТЕРІЇВ УСПІХУ ЯК СКЛАДОВОЇ ІМОВІРНІСНОГО АНАЛІЗУ ФІЗИЧНОГО ЗАХИСТУ ЯДЕРНИХ УСТАНОВОК

С.О. Горбачик, В.А. Кондратюк, С.В. Клевцов

Продемонстровано підхід до адаптації методології аналізу критеріїв успіху традиційного імовірнісного аналізу безпеки АЕС для імовірнісного аналізу фізичного захисту ядерних установок на прикладі гіпотетичної ядерної установки SNRI. Якщо говорити в цілому, використання методології традиційного імовірнісного аналізу безпеки АЕС для оцінки фізичного захисту ядерних установок надає можливість визначити нові вразливості у системах фізичного захисту ядерних установок, розробляти рекомендації для підвищення ефективності фізичного захисту, виконувати більш обґрунтований аналіз типу «витрата-вигода» та інше.