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SAFETY IN NUCLEAR POWER ENGINEERING

Proposals for Reducing the Accident Rate on Nuclear Power Plants and Minimizing of Accident Consequences

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Abstract. The operation of nuclear power plants (NPP) is associated with the risk of major accidents. To avoid them, technical improvements and strict safety rules are used. The growth of demand for electricity occurs against the backdrop of aging electrical equipment, and therefore increases the accident rate. There is a need to increase the number of parameters for monitoring worn-out equipment in the online mode. Thermal and vibration sensors are additionally installed on the turbogenerators of the NPP units, the indicators from which are output to the control panels. The load on the operators grows, risks of critical errors also grow. To avoid this, it was proposed to abandon the installation of additional thermal sensors. Enough to install additional vibration sensors as more informative. Work to reduce the accident rate should be carried out in several directions. Analysis of emergency measures shows the ability to reduce the negative impact of the "human factor" by transferring a number of human functions to automation, robots and computer systems. Legal immunity for liability for professional errors and insurance of risks in the work of NPP operators and managers will allow to more reliably investigate the causes of accidents and more reliably evaluate subsequent actions. The use of fire robots NPP will increase the effectiveness of extinguishing fires, save lives and property. But infrastructure changes, special routes for robots will be required. In ensuring the safety of NPP, Ukraine faces both typical problems for the world nuclear power industry and additional threats of nuclear terrorism, including the risks of physical and cyber-attacks. To reduce the risk of cyber-attacks, additional measures are needed to protect computer systems and limit unauthorized access to them. Improvements are needed in software that can be conducted by Ukrainian IT specialists at the expense of the wartime state budget (for defense and security).

Keywords: nuclear energy, NPP safety, accident rate, electrical equipment wear, service life extension, human factor, cyber-security, nuclear terrorism.

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INTRODUCTION

The total amount of energy that mankind consumes annually is currently 5303 million toe (Mtoe). For the last hundred years, its consumption has doubled every 25 years, i.e. growth is 3-5% per year [1]. Electricity consumption on the planet is also constantly increasing. And to meet these needs without nuclear energy in the coming decades will not work, in accordance with variety of boundary scenarios for the development of world energy and the world economy [2]. Currently, nuclear power plants produce about 11% of the world's electricity. According to the average forecast [3], Despite the improvement of energy-saving technologies and the increase in energy efficiency of production, by 2050 the annual electricity consumption per person will increase from the current 3000 [4] to approximately 5000 kW·hour, the share of electricity in the final energy consumption will increase by 1.5 times, and the share of nuclear power plants in the generation of electricity will increase by 1.2 times. Since the middle of the last century, the total power of used nuclear reactors has steadily increased. Probably this trend will continue until 2050. This prediction may be revised in cases of a breakthrough in the testing of fusion reactors [5] or the discovery of fundamentally new energy sources. But in any case, safety requirements for existing NPPs will be increased.

Technical systems of great complexity and power, which include nuclear power facilities, are characterized by a high risk of accidents that are dangerous to people and the environment. Even a single accident can have disastrous consequences, as evidenced by some of the largest accidents at nuclear power plants - at Three Mile Island (USA, 1979), the Chernobyl NPP (USSR, 1986) and Fukushima-1 (Japan, 2011 year). Both agrarian, and industrially developed countries refuse nuclear power. The operation of all NPPs in Italy and Kazakhstan has already been terminated. Germany, Switzerland, Sweden, Austria are following the path of abandoning nuclear power. But with regard to the use of nuclear energy, countries have different views, and this policy may change depending on the circumstances. Belarus, Bangladesh, Turkey, United Arab Emirates are build their first NPPs.

A total of 452 nuclear reactors with a total electrical capacity of 398.67 GW are operating in 30 countries of the world [7]. Even if the number of countries operating nuclear reactors decreases or remains at the same level, the increase in installed capacity will continue [8]. Energy and economists agree that nuclear energy can provide the planet with cheaper and cleaner energy, reduce the greenhouse effect, and preserve fossil fuels for future generations. But the cheapness of nuclear energy is achieved due to the fact that we shift the solution of the problem of used nuclear fuel and the consequences of major radiation accidents on the shoulders of the next generations.

To eliminate the long-term consequences of radiation accidents and to safely store used nuclear fuel is no less important than to prevent new accidents. It is possible to reduce the accident rate by improving nuclear power plants, first of all nuclear reactors and the rules for their safe operation. For this, it is important to constantly critically evaluate the existing safety rules and discuss both systematically and in individual areas if they are not sufficiently developed. We consider the accident rate of nuclear power plants on the second principle, due to the aging and deterioration of electrical equipment in the world and in Ukraine, the growing importance for the safety of computer systems, the consistently high value of "human factor", the risk and damage from fires, the danger of wars and terrorist acts for nuclear facilities.

PURPOSE AND TASKS OF RESEARCH

1. Of all the organizational, technical and personnel issues of reducing the accident rate of NPPs, it is necessary to choose those methods that are least worked out and critically evaluated by the IAEA and Ukrainian organizations for monitoring and managing nuclear facilities.
2. Official statistics should be analyzed to assess the impact of the “human factor” on the development of emergency situations, evaluate the actions of personnel to eliminate the consequences of accidents, suggest ways of reducing the role of the “human factor” in identifying accidents, its impact on the outcome and eliminating their consequences.
3. To identify the most destructive drivers of accidents and the risks to the safety of Ukrainian NPP. Suggest methods to reduce the destructive effects of these factors.
4. Compare the global problems of safety in the nuclear power industry with similar problems in Ukraine.

Methods and techniques used to solve problems

Considered scientific publications, legislative acts, media reports, recommendations of the IAEA, SE "NNEGC "Energoatom" (national licensed operator of all Ukrainian NPPs units). The results of probabilistic analysis and forecasting based are discussed. The article contains several separate proposals for different vectors of the development of NPP safety systems and elimination consequences of accidents.

1. General issues of safety and accidents of NPP, extending the life of equipment

NPP safety assessment includes the aging of equipment and its modifications, including for new types of fuel assemblies. Uncompromising are decisions regarding radiation safety. Violation of such safety rules cannot be explained by a shortage of funds from a licensee who has the right to operate nuclear facilities. For individuals, air in stations, air and water emissions maximum permissible radiation standards are set. The consequences of major accidents at nuclear power plants affect large areas, affect the ecosystem, animal and plant life, air, water, soil, food grown in contaminated areas. They are felt by several generations living after accidents. Therefore, work to ensure safety is carried out to prevent failures, emergency situations, loss of control over the rectors and other sources of radioactive radiation. To prevent accidents and mitigate their effects, "defense in depth" is used, due to which a single technical, human or organizational failure cannot lead to serious consequences, and combinations of several types of failures make severe consequences unlikely. The in-depth defense relies on an established safety culture, the moxie of operational personnel and management to ensure safety, redundant (with a margin of safety) design, engineering solutions (constructions, technologies, materials), control systems, restrictions, observations, protocols and means of emergency readiness. During accidents, it is necessary to protect and inform personnel, the public, activate emergency plans and correct them as events unfold [9].

15 units of 4 Ukrainian NPPs under the control of SE "Energoatom" provide for about 55% of electricity [10]. Another 36% provide Thermal Power Plants (TPP) and Thermoelectric Central, 7% - Hydroelectric Power Stations and Pumped-Storage Power Plants, 2% - other sources, including renewable [11]. Ukraine's developed nuclear power industry and the legacy of the Chernobyl accident make it necessary to constantly discuss nuclear safety issues, both in society and in the professional environment. On the issues of nuclear safety of nuclear power plants, Ukraine closely cooperates with the IAEA [12] and Euratom [13]. Ukraine's cooperation with the CIS Commission on the use of atomic energy for peaceful purposes was discontinued due to the military aggression of the Russian Federation towards Ukraine [14]. National industry standards of Ukraine include the norms of engineering, operational and radiation safety, rules for waste management, methods for evaluating the effecttiveness of safety programs. These standards are binding on Ukrainian nuclear facilities, have the force of law. They are often a copy of the relevant IAEA documents. It should be noted that the IAEA is not the official international regulatory body: the documents developed by the IAEA are advisory.

After the collapse of the USSR, the Russian Federation constantly used energy resources as an instrument of political pressure on Ukraine. For energy independence, Ukraine did not use all available opportunities. Perhaps the incentive to do this will be a hybrid war that began in 2014. In nuclear power, the desire to become energy independent is manifested in the transfer of Ukrainian NPPs to American-made fuel assemblies (Westinghouse Electric Corporation) from Russian ones (JSC "TVEL"). However, upgrades for new fuel assemblies are an additional factor in possible accidents [15].

When an accident is detected, urgent actions are taken to eliminate it and to protect personnel [16]. The emergency plan of the NPP is put into operation. To eliminate accidents on the reactor, turbine and generator equipment, separate specialized teams are formed. Crisis centers are activeted, warning, emergency restoration and repair work is carried out, operators continue to work at the console, if the scale of the accident allows and dosimetric control indicators. The main "radiation risks" are associated with the loss of control over the core of a nuclear reactor and the nuclear chain reaction.

The probability of a major accident at modern NPPs is estimated to be about 10^{-5}-10^{-6}, depending on the reactors used. That is, due to an unfavorable set of circumstances, taking into account the real reliability of mechanisms, instruments, materials and humans, one object destruction per 10^{5}-10^{6} object-years is possible [17]. But reactors and safety rules in the nuclear power industry are constantly being improved, being replenished with the data of scientific research and "work on the mistakes" made during liquidation of accidents. This allows us to hope for the fulfillment of the plan for reducing the risk of severe accidents by 2060 at nuclear power plants by 3 orders of magnitude (from 10^{-6} to

10^{-9}), to the level of "negligible" [18]. To fulfill such a plan, it will be necessary to take into account the aging of the electrical equipment of the NPP. By 2017, 47% of the world's reactors were in operation for 30-40 years, 17% - more than 40 years [19], with a design life of 25-30 years. Due to the global economic crisis, there are no funds for the complete replacement of equipment that has spent its designed service life. Many countries, including Ukraine, extend the life of NPP units. Wear and tear of equipment not only increases the risk of accidents, but also increases the burden on NPP operating personnel, as the frequency of repairs and the required number of monitoring parameters increase. To increase the probability of equipment failure-free operation, additional sensors are installed, and more information is output to the control panel of the NPP unit, which increases the workload for operating personnel. There are limits to the flow of information that can be brought to the console of one operator in order to preserve his ability to critically assess the situation and make the right decisions to carry out the response. Our research [20] shows that the load on operators is often increased without taking into account the capabilities of the human-operator, which leads to an increase in the risk of critical errors in decision making.

Among the electrical equipment of NPP, turbogenerators (TG) deserve special attention. Traditionally, in operating TG, on-line temperature and vibration levels are monitored by sensor readings that are installed on slide bearings, on the housing, in the area of the frontal parts of the stator windings. It is necessary to install dozens of sensors on the worn out TG. When searching for a balance between the need for additional control and the capabilities of a human-operator, we consider it possible to abandon the simultaneous full installation of thermal and vibration sensors in favor of installing only vibration sensors, since a change in the thermal state of individual elements and nodes of the TG manifests itself in a change in their vibration level [21]. The change in vibration can be used to assess the occurrence of overheating zones, which will make it possible to timely diagnose, for example, short circuits in the windings and problems in the plain bearings [22]. The data on changes in the vibration spectrum is sufficient for timely determination of the solidity loss by the stator core, for determining the destruction of its fastening elements to the body, deterioration of crimping, leaks in laminated packages, insufficient tightening of the pressure flange nuts, both from the contact rings side and from turbines side. Increased vibration causes electric discharge phenomena in the TG. In this case, the danger is determined by the appearance of fretting corrosion products and destruction of laminated stator core sheets. Small steel particles fall on the insulation of the stator winding and, when vibrated, cause local damage to the cabinet insulation of the winding rods. To protect against this phenomenon, sensors for continuous monitoring of the vibration state are additionally installed, fig. 1. Studies have shown that the installed vibration control system will allow timely identification of the emergence of slot and partial discharges in the groove of the TG stator and increase the reliability of its operation [6].

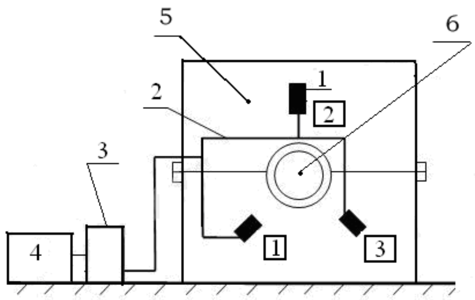

Fig. 1. Block diagram of sensors location on the TG butt side shield for continuous monitoring of its vibration state.

1 - sensor monitoring the activity of the electric discharge process; 2 - cable connection; 3 - pulse analyzer electric discharge process; 4 - control sensor control system; 5 - TG butt side shield; 6 - the end of the rotor shaft.

In order to detect defects in bearing supports, vibration (vibration velocity) measurement is carried out relative to the shaft line in three mutually perpendicular directions: in the axial, in the radial vertical and in the radial transverse directions. The appearance of defects in the fastening elements of the stator core to the housing is also signaled by vibration sensors mounted on the housing (Fig. 2).

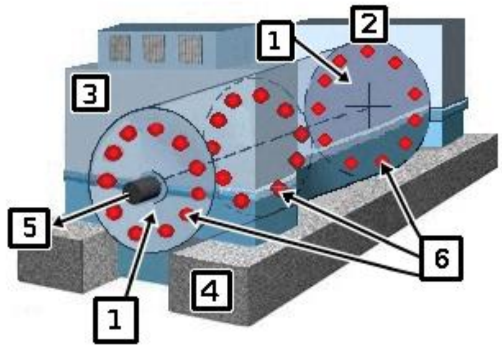

Fig. 2. Layout of placement of additional vibration sensors on the case and on the butt side shields of turbogenerator.
1 - TG butt side shield; 2 - installation of vibration sensors from the side of contact rings; 3 - installation of vibration sensors from the side of the turbine; 4 - foundation; 5 - the direction of measurement of axial vibration; 6 - additional vibration sensors.

The vibration velocity established using these sensors in the 10-1000 Hz frequency band determines the level of response to the defect that has appeared: an increase in vibration velocity of up to 4.5 mm/s indicates the need to take action within 30 days, up to 7.1 mm/s - up to 7 days, when a vibration level of 11.2 mm/s is reached, an immediate stop is required. The violation of these rules by the operator leads to a TG accident, fig. 3 [40].

Similarly, it is possible to diagnose the state of the brush-contact unit, the coaxis of the TG shaft and the turbine, the absolute vibration of the shaft, etc. In general, the "vibration" methods allow timely detection of signs of deterioration of the TG state at an early stage of occurrence of defects, which will increase its reliability. The given examples of improving the reliability of TG according to vibration control data indicate that for each type of equipment, when choosing the most informative state control channels, it is necessary to look for an individual solution. For example, to monitor the state of large asynchronous motors (AM), it is sufficient to control the harmonic spectrum of stator winding currents, which can warn of stator and rotor damage (breakage of rods, weakening of the attachment of rods to slip rings, latent casting defects), displacement of motor shafts and drive from one axis, etc. AM installed in many drives of equipment of NPP units, for example, in the main circulation pumps of the reactor zone.

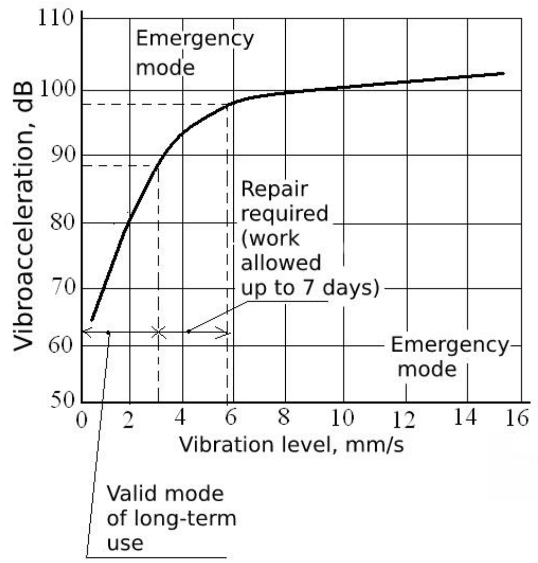

Fig. 3. Dependence of vibration acceleration on vibration velocity according to vibration sensors mounted on the TG case.

The next step in reducing accidents related to equipment wear will be to create a reliable model of artificial intelligence response with minimal operator participation or no at all [23]. However, at the current stage it is impossible to do without human participation.

2. "Human factor" in NPP’s work

It is impossible to achieve the required level of safety of nuclear power plants without a safety culture, which involves individual and collective determination to ensure safety, minimizing the "human factor". A lot of work has been devoted to the assessment of NPP personnel errors. Errors are classified, known, but constantly repeated. The probability of new errors also exists in connection with upgrades, equipment aging. The estimation of the probability of errors is also worked out in detail, but is rather complicated [24]. To get the result, it is necessary to evaluate the available time, stress and stressors, experience and training, complexity, ergonomics, including man-machine interface (HMI), procedures, work processes, willingness to work, personal qualities of the operator (motivation, level of training, ergonomic support of activities , including the comfort of working conditions, the adequacy and simplicity of algorithms for identifying and correcting an emergency), relationships with colleagues, etc. Emergency response procedures are also complex. Their logic is often different from the logic of operators, so operators are forced to perform a regulated sequence of actions according to a learned plan. Such work requires operators of high discipline and meticulous thoroughness. The adequacy in the performance of most emergency procedures in the work of operators has not been assessed by scientists, even by itself, not to mention the performance of procedures by operators with different types of nervous activity and various factors of stress accidents. Research scientists should lead to the creation of computer programs that in the future will be able to replace the human-operator. When drafting action algorithms, it will be necessary to take into account all possible actions of operators, including erroneous ones. Such a description should be carried out without distorting the facts. Systematization is complicated by the shortage of specialists who know the psychology and technical aspects of NPP operation equally well. The lack of detailed instructions for work, drawn up with regard to psychology, is also associated with the variability of abnormal situations depending on the degree of wear and tear of equipment. At this stage, the complexity of the operators' action algorithms is compensated for by the so-called symptom-oriented approach, in which operators are taught to identify symptoms of block accidents common to various emergencies. This simplifies the understanding of the problem, but often causes contravention the emergency protocols [25].

The very notion of "human factor" has a negative sound: it is a synonym for mistakes, inattention, inadequate retaliatory action. To mitigate the "human factor" can be due to the constant training of personnel and "work on the bugs". However, error analysis is hampered by the concealment of the "human factor" behind equipment failures, imperfect technical safety systems and emergency response protocols. Attempts to hide NPP personnel errors can be explained:

- unwillingness to "wash dirty linen in public",
- the fear of bringing the operational personnel and station management to criminal liability,
- unwillingness to pay on claims of people, property and health of which suffered as a result of accidents at NPP.

It is considered [26] that 30% of accidents at nuclear power plants are related to the "human factor". However, some studies [24] show that this figure is underestimated by 1.5-2.5 times, including for the reasons stated above. We also believe that there is a link between minimizing the importance of the "human factor" and the global unhealthy tendency of recent decades, to look for the guilty and punish professional mistakes. The concealment of truthful information about the real actions of NPP operating personnel during accidents makes it difficult to improve the algorithms into digital models of NPPs for emergency response [27]. Immunity for professional errors should be returned to public opinion and court practice, by analogy with medical errors. Professionals can be punished only for negligence, a gross violation of the basic rules, but not for unintentional fallacy in which, according to previously common legal practice, there was no crime [28]. The list of such basic rules should be public and exhaustive. In the presence of immunity, error analysis will give a more objective picture and reduce the frequency of error repeating by staff.

The credibility of investigations into the actions of station personnel can increase by professional liability insurance. The experience of directors and managers liability insurance can be analyzed using the example of countries with developing [29] or developed professional liability insurance systems (for example, in the USA and Japan). Such insurance (D&O, Directors and Officers Liability Insurance) has a positive effect on the development of nuclear energy in general, although it does not cover all losses. So, after the accident at Fukushima-1, part of the claims of the "Tokyo Electric Power" company's shareholders to the leadership of the NPP (for a total amount of damages of $ 68 billion) were covered by insurance funds (for example, at the expense of Nippon Life Insurance Company).

Ukraine insures the operation of its nuclear power plants for small amounts of several million hryvnia. At the same time, western insurance companies that decide to conclude such insurance contracts, as a rule, reinsure risks abroad [30]. This means minimum insurance payments in case of major accidents. The state does not express readiness to cover damage to the health and property of citizens in the event of an accident at a nuclear power plant jointly and severally with insurance companies. One major accident in this case could lead to the bankruptcy of the state, which already lives in debt through IMF loans. In addition, large insurance payments in case of accidents at nuclear power plants could also destroy the already small insurance market in Ukraine. There is only one way out: do not allow major accidents.

To assess the state of possibility of further operation of electrical equipment that has worked its life, it is advisable to use the theory of reliability and statistical methods for analyzing its vital activity, "aging" and degradation. The protective measures tested by these methods should significantly exceed the radiation risks. Then their high cost is justified [31]. In case of beyond design basis accidents, it is necessary to make a decision when the risks of obtaining high doses of radiation to personnel are still justified by the possibility of regaining control over the reactor, and when personnel already need to be moved to a safe distance from the main sources of radiation. The consequences of such decisions may be less dramatic in the case of greater robotization of nuclear power plants, including both used fire robots, and promising robots for rehabilitation work. In addition, when extinguishing a fire, the "human factor" usually forces one to retreat to a distant line earlier than a person can withstand.

3. Driving forces of accidents at NPP

Despite detailed IAEA instructions for ensuring the safety of NPP, accidents and incidents often occur, which have long-term economic and environmental negative consequences [32]. During major accidents at NPP, fires, loss of control over the reactor and chain reaction, release of radiation substances, contamination of their territories, often death of operating personnel and emergency response workers, evacuation of the population living near the NPP occur. The main factor in the death of personnel, destruction of equipment and buildings are fires. An NPP accident review of the United States Atomic Energy Commission showed that the contribution of fires to the reactor core damage frequency is at the level of the contribution from all other destructive factors combined, and the damage from fires exceeds 60% of the total damage from all accidents and malfunctions at nuclear power plants [33].

For example, the accident with the melting of the reactor core at the Three Mile Island NPP in the USA did not lead to the death of personnel, but the damage from it was about 7 billion US dollars. The damage from the Chernobyl accident amounted to 8 billion US dollars [34]. In addition, stopping the operation of blocks after accidents also causes significant economic damage. Thus, every day of the downtime of the failed two reactors at the Browns Ferry NPP (USA) caused damage of 240 thousand dollars [35].

Due to the aging of NPP electrical equipment in recent years, the number of large fires and accidents at power facilities has increased. The number of operating personnel affected during the extinguishing of fires from high temperatures, falls, collapse of structures, radioactive substances entering the body, and inhalation of toxic substances has naturally increased. Because of the risk of injury, burns, radiation and toxic damage, fire extinguishing work has to be interrupted and personnel should be taken to a safe distance. The output can be the use of remote-controlled robots. It is economically feasible and can save the lives of personnel who take part in extinguishing fires. The areas in which robots are primarily needed - cable rooms, places of bulky concentration of electrical equipment, the reactor zone. Fire robots showed themselves well in extinguishing a fire on the roof of the reactor of the 3rd unit of the Chernobyl nuclear power plant [36]. Robots are able to withstand significantly higher temperatures near the burning centers, however, the patterns of their movement insid the station and individual points of their design deserve discussion.

To extinguish fires in the machine rooms of NPP, robots are equipped with means for supplying fire extinguishing substances with a flow rate of at least 0.20 l/(m^2·s), which will provide the necessary intensity of fire extinguishing, protect building structures and precipitate suspended particles, including radioactive, to create water curtains in chemical and radiation accidents [37]. The dimensions of the robot must ensure its free movement on the object, but it is in contradiction to have its own stock of extinguishing agents. Their delivery to the robot goes on the firehose, for the deployment of which must be provided for a place in any part of NPP. To monitor the fire situation and conduct reconnaissance, the fire robot must have a video surveillance system, a thermal imager and lighting equipment. Robots must have enough traction to move their own weight and firehoses filled with fire extinguishing agents. The firehoses and the body of the robot are made of fire-resistant materials. Despite this, it is the damaged firehoses that most often cause robots to fail early. The disadvantages of the "robot-firehose-hydrant" ligament are: limited hose length, a small number of hydrants in the most fire hazardous areas of stations, and the absence of a relatively simple mechanism for most robots to detach one firehose and attach another. Fire extinguishing agents are jetted under alternating pressure from a remote-controlled fire monitors. Even a small fire robot (weighing 100 kg or more) can create a jet of fire-fighting mixture with a height of about 70 meters. Two options for the appearance and configuration of fire robots are presented at Fig. 4.

Field testing of robots for fire extinguishing also show high efficiency at NPP [38]. The mobility of fire robots on self-propelled chassis allows the use of retreat tactics to the next line in cases where the fire temperature is critical for the "survival" of the robot, or if the firehose is damaged.

With design II (Fig. 4), the robot can retreat to a safe line or to a new source of supply of a mixture for fire fighting, automatically connect a new fire hose and continue extinguishing the fire. We propose also to envisage routes for the movement of fire robots in compliance with two principles:

1. at several possible fire extinguishing lines, robots should be able to connect new fire hoses;

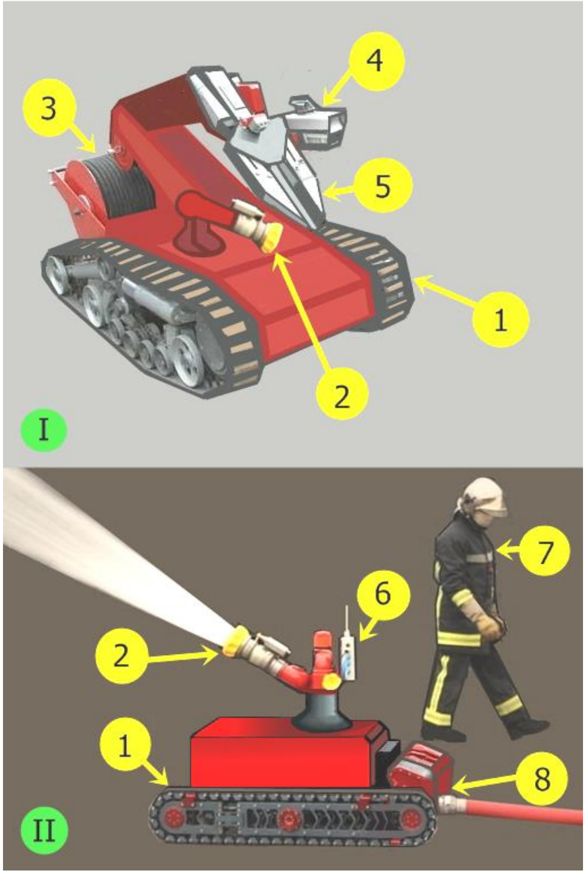

Fig. 4. Sketches of fire robots.
I - the robot with a claw manipulator;
II - a robot with a minimum configuration:
1 - self-propelled chassis; 2 - remotely controlled fire monitors (in design II, with a valve for manually stopping the supply of the fire extinguishing mixture); 3 – fire hose on the coil; 4 - video camera, thermal imager; 5 - manipulator claw; 6 - means of communication of the robot with the operator; 7 - fireman (depicted to understand the scale); 8 - device for connecting a fire hose

2. critical NPP infrastructure objects that are at high risk of fire should be protected by redundant fire extinguishing equipment with access simultaneously from several sides (Fig. 5).

Fire prevention is one of the main goals of improving NPP protection protocols. To achieve this goal, work is being done to reduce the risk of short circuits and overloads of electrical machines.

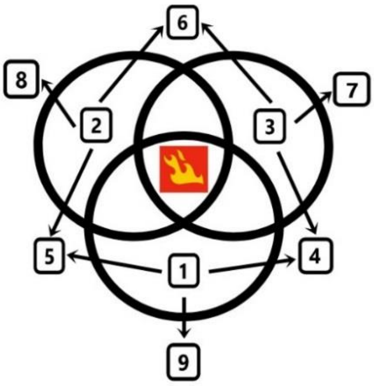

Fig. 5. Layout of robots during fire extinguishing at nuclear power plants and points of connection of fire hoses to fire hydrants.
1-3 - possible points for the placement of fire robots with the designation of the placement of the hydrants providing them; 4-9 - fire hydrants.

The most difficult to extinguish are fires that occur in the cable structures of NPP. The presence of energized equipment creates the danger of firefighters being shocked by electrical current. In cable networks, the main combustible material is insulation, and the amount of combustible material in one room is measured in tons, and the possible burning area is tens and even hundreds of square meters. The most dangerous for people are toxic products of combustion. Therefore, insulation of cables for nuclear power plants is made of flame-retardant materials (for example, from expensive silicon-organic rubber or from self-extinguishing polyethylene) and sealed the joints of adapters with vacuum-tight metal-ceramic insulators. Places for cable passage through walls are treated with flame retardants based on phenol-formaldehyde resins [39]. Also, the objects of complex fires are often generators and pumping installations.

After the start of the war with the Russian Federation in 2014, the risk of terrorist attacks on Ukrainian nuclear power plants using drones increased. The flights of drones over nuclear power plants of Ukraine are prohibited by a joint order of the State Aviation Service of Ukraine and the Ministry of Defense of Ukraine No. 430/210 dated May 11, 2018 [40], and, if necessary, destroyed by dronefights and other air defense weapons. Anti-terrorism trainings are conducted at Ukrainian NPPs more often.

4. Cybersecurity of NPP

The problem of nuclear cyber security is also relevant for Ukraine [41]. At the end of 2015, the national electric grid Ukraine underwent a cyber-attack, as a result of which more than 600 thousand inhabitants were left without electricity [42]. In June 2017, a cyber-attack to Ukraine using the ciphering virus Petya affected the work of the Chernobyl NPP [43]. Both cyber-attacks by law enforcement agencies of Ukraine are associated with the sabotage activities of the Russian special services. Therefore, since 2015, anti-virus software of Kaspersky Lab is prohibited in Ukraine.

The security and defense budget of wartime amounts to about 5% of Ukraine's GDP (212 billion hryvnias), including 30.2 billion hryvnias intended for the development of weapons and military equipment [44]. Some of these funds can be directed to the cybersecurity of energy facilities.

In ensuring cybersecurity, Ukraine should rely on your own staff and on the development national IT-companies. Ukraine has a developed IT-industry, which accounts for more than 3% of GDP and ranks third in terms of export earnings [45]. These companies may be given a state order to develop their own anti-virus software and special software for NPP. The development of technologies for digital copies of NPPs on which any emergencies can be simulated should also be entrusted to Ukrainian IT-specialists. Computer networks of NPPs should be as isolated as possible, access to various programs should be strictly authorized, and all system calls and operator actions should be registrated.

CONCLUSIONS

1. Ukraine is a country with a developed nuclear energetic. The economic development programs of the country until 2050 rely, among other things, on further increasing the capacity of Ukrainian NPPs by completing the construction of new units and increasing the unit capacity of operating units. Considering the consequences of the Chernobyl NPP accident and the risks of nuclear terrorism, as well as the increasing requirements of nuclear safety, as defined by the IAEA, it is necessary to improve the technological

processes and equipment of Ukrainian NPPs and the rules for their safe operation.

2. The global tendency to extend the NPP operating life that have completed their project deadlines also applies to Ukraine: there are not enough funds to replace worn-out equipment of NPP, equipment is being upgraded to extend its life. The use of worn-out equipment requires more frequent repairs and control more parameters during the operation of electrical equipment. So, on the most complex and expensive equipment, on turbogenerators, sensors are installed that control temperature and vibration. This solution significantly increases the information load on the operators of the consoles. The analysis of TG operation, the collected statistical data allow us to offer only additional installation of vibration sensors, which will provide information not only about changes in the mechanical state, destruction of individual components and elements of TG, but also about the origin of defects, which appear in the appearance of zones with exceeded temperature caused by violations electromagnetic character. Reducing the information load on a human-operator reduces the risk of critical errors in making emergency decisions.

3. "The human factor" adversely affects the safety of NPP. To reduce the accident rate of NPP, this factor should be reduced as much as possible. Analysis of operators errors is complicated by hiding the real picture of their actions during accidents. The situation can be rectified by the officially introduced legal immunity for professional errors and liability insurance for their commission. The functions of a person, in the performance of which the most critical errors occur, should be transferred to automation, robots, and artificial intelligence systems.

4. The main destructive force in case of accidents at nuclear power plants are fires. For their effective extinguishing, improved fire robots are required. To move around the station for fire robots, you need routes that allow you to maneuver around the outbreaks, retreat to new frontiers, carry out extinguishing simultaneously from several sides, automatically disconnect and connect new firehoses.

5. Cyber-attacks on NPP and other energy facilities of Ukraine lead to the need to improve computer security systems. New software for NPP should be created by Ukrainian IT-specialists, at the expense of the state budget of wartime.

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