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# Lessons from the Chernobyl Accident for the Modern Nuclear Power Industry Environmental Safety

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**Abstract.** A review of well-known statements on the causes Chernobyl nuclear power plant severe accident and lessons drawn thereof is presented. Based on the analysis of this accident causes and consequences, formulated and substantiated are its main lessons which are highly relevant for modern nuclear energy industry.

The Chernobyl accident lessons serve to identify the insufficient effectiveness of safety systems ensuring the emergency processes management while minimizing the personnel actions impact.

The causes and consequences of the Chernobyl accident determine the priority importance of using deterministic indicators and criteria of nuclear fuel damage conditions and protective safety barriers destruction for the analysis of nuclear power plants safety

An urgent issue of the nuclear energy industry in global scale (including Ukraine) refers to the development of effective strategies for the prevention and management of low-probability accidents with catastrophic environmental consequences, based on the joint use of probabilistic and deterministic analysis of nuclear, radiation and environmental safety.

**Keywords:** probabilistic analysis, safety criteria, emergency release, accident management strategies

## 1 Introduction

It passed more than 35 years since the largest in nuclear power engineering history accident at Unit 4 of the Chernobyl nuclear power plant, but this accident lessons for the nuclear energy safety remain relevant today. The main lessons drawn from the Chernobyl accident for the modern nuclear power engineering safety relate to the need for reviewing the priority of probabilistic criteria and safety analysis methods, improvement and development of systems for accident prevention and management in automatic mode minimizing the human factor, and improvements to operational documentation for prevention, management and consequences elimination when relatively unlikely accidents with catastrophic radiation and environmental consequences: improving the personnel and population psychological training for extreme stressful events: improving the monitoring and analysis of radiation exposure and other relevant lessons.

This article presents an analysis of some current lessons the Chernobyl accident experience implies for modern nuclear energy.

## 2 Reference Sources Analysis

Numerous studies have been devoted to the analysis of causes and consequences to the largest accident in the nuclear energy history at the Chernobyl nuclear power plant that involved catastrophic environmental consequences [1–18], etc.

The most objective representation of the Chernobyl accident reasons and radiation consequences in given by those tragic events participants in works [1–3]:

1) The conducted research as well as analysis of various models and scenarios of that accident development allowed the following conclusion to be formulated:

- the accident at the RBMK type reactor was this one unavoidable due to the serious design flaws that existed at that time, the reactor plant's specific nuclear and physical characteristics due to its core design, the low efficiency of its control and protection system, the reactor emergency protection rods incorrect design, and a poor quality of technological regulations for power units 3, 4 operation at the Chernobyl NPP;
- the accident was caused by the introduction of positive reactivity in the reactor lower part when the emergency protection triggered under conditions of a positive power reactivity coefficient.

2. As a result of the reactor's explosion, all physical barriers that served to localize radioactive materials were destroyed or damaged. The reactor core complete destruction on the one hand, led to the fission chain reaction termination, and on the other it involved the loss of technical ability to remove the residual fuel heat and the loss of control over the power unit as a source of radioactive release.

The initial emissions estimate assumed that 100% of the inert radioactive gases were released into the atmosphere, including 10-20 % of more volatile elements like iodine, tellurium and caesium. The total release of caesium-137 was estimated at 70 PBq. Further analysis of results of the reactor core remains and the deposited radioactive substances inside the reactor facility building

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studies, in fact, represented an independent objective assessment of atmospheric release occurred in that accident. According to these studies, the share of caesium-137 released into the atmosphere was 20–40% (85 ±26 PBq) based on the average share of nuclear fuel emissions of 47%, followed by the remaining emissions retention in the reactor facility building. As for iodine-131, the most accurate estimate was from 50 to 60% of the reactor core at the the level of 3200 PBq.

3. To date, much information has been accumulated about the patterns of living systems and in particular the living cell exposure to radioactive emission. However, this alone criterion is not sufficient to quantify the relationship between dose and radiation quality, exposure time, cell response, etc., and generally, between dose and effect. For such a quantitative assessment, a comprehensive knowledge of specific intracellular structures (their arrangment, shape, size) and the consistent development of radiobiology theoretical concepts are still necessary [11].

The scheme of primary physical and chemical processes on the way from ionization to the final biological effect is shown in Figure 1. Radiolysis products, primarily free radicals containing unpaired electrons, are characterized by extremely high reactivity, so that their lifetime is from $10^{-10}$ to fractions of a second. During this period, they either recombine with each other or react with nearby organic compounds.

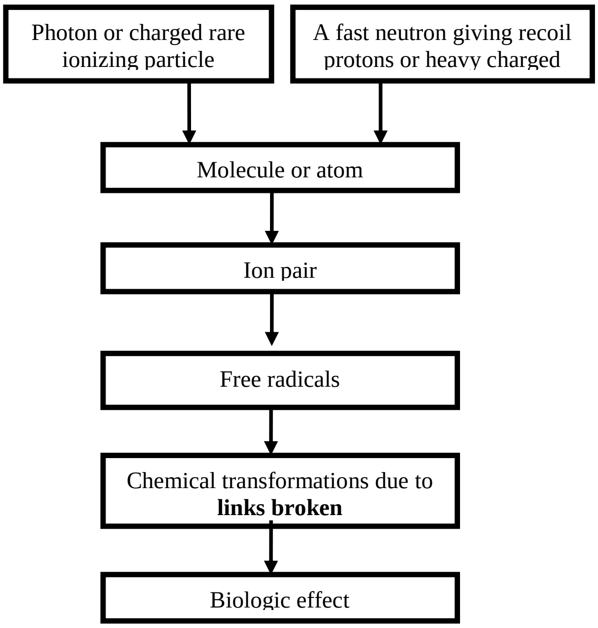


Figure 1. Scheme of primary physical and chemical processes on the path from ionization to the final biological effect.

The biological effect of ionizing radiation is reduced to a change in the structure or destruction of various organic substances (molecules) the human body is built of, that leads to disorders in the body cells' biochemical processes, or even to cells death, which can render disastrous effects to the body as a whole.

The ionizing radiation influence engages in the body such breaches as disorders in the hematopoietic organs function, an increase in the permeability and fragility of blood vessels, disorders of gastrointestinal tract, a decrease in the body's immunity, its depletion, the degeneration of normal cells into malignant cells, etc. These effects develop over different periods of time: from fractions of seconds to many years.

Various forms of manifestation of the radiation's damaging effect on the body are called radiation sickness. These manifestations variety depends on the following factors: type of exposure – general or local, external or from incorporated radioactive substances; time factor – single, repeated, prolonged, chronic exposure; spatial factor – uniform or uneven exposure; volume and localization of the irradiated segment of the body and skin surface.

## 3 The Chernobyl Accident Experience Main Lessons for the Modern Nuclear Power Industry

One of the main lessons from the Chernobyl accident is related to the need in review of the attitude to the probabilistic criteria and conditions of nuclear and radiation safety established in the world practice of nuclear power industry.

Generally accepted probabilistic safety criteria are such indicators as:

— core damage frequency – **CDF**;

— maximum emergency release frequency – **MERF**.

The criteria values are shown in Table 1.

The criteria upper limits are defined for operating nuclear power units, and the lower limits are defined for those under construction.

Within the generally accepted probabilistic security analysis (PSA) framework, the probabilistic criteria are determined by the following dependencies [12, 13]:

$$\mathrm{CDF} = \sum_{i}^{N} \left( I_i \left( 1 - \prod_{ij}^{M1_i} (1 - P_{ij}) \right) \right) \tag{1}$$

$$\mathrm{MERF} = \sum_{i}^{N} \left( I_i \left( 1 - \prod_{ij}^{M2_i} (1 - P_{ij}) \right) \right), \tag{2}$$

where $I_i$ is the frequency of the $i$-th initial event occurrence that can lead to an accident; $P_{ij}$ – probability of the $i$-th

Table 1. Criteria values for the core damage frequency and the maximum emergency release frequency

| Criterion name | For operating power units | | For designed power units | |
|---|---|---|---|---|
| (per reactor annually year) never above: | Estimated value | It is necessary to strive for ensuring the estimated value as | Estimated value | It is necessary to strive for ensuring the estimated value as |
| **CDF**, 1/year | $10^{-4}$ | $10^{-5}$ | $10^{-5}$ | $5 \times 10^{-6}$ |
| **MERF,** 1/year | $10^{-5}$ | $10^{-6}$ | $10^{-6}$ | $10^{-7}$ |

safety function failure in the emergency sequences of the $i$-th initial event; $N$ – is the total number of initial events that can cause an emergency; $M1_i$ – is the set of safety functions required to prevent severe core damage when implementing the $i$-th initial event; $M2_i$ – is the set of safety functions necessary to prevent the maximum emergency release when the $i$-th initial event takes place.

Lessons from the Chernobyl accident causes and consequences allow us to draw the following conclusions about the validity of probabilistic criteria and conditions for nuclear and radiation safety.

1. The probabilistic safety criteria for nuclear power plants (1) and (2) actually allow for the possibility of a core damage severe accident once every 10,000 or more years of operation, and when exceeding the emergency release limit tha probability is once every 100,000 years or more. Formally, the Chernobyl accident meets these requirements, as the station will never be operated again.

2. The probabilistic approach to the nuclear power plants (NPPs) safety analysis does actually determine the non-priority of emergency measures for relatively unlikely accidents which involve catastrophic consequences. In particular, such an attitude to NPPs equipped with WWER took place when initial emergency events with complete long-term de-energization of power units.

After the Fukushima-1 nuclear power plant accidents with complete long-term blacking out, the urgent relevance of emergency measures to improve the power supply systems reliability and the effectiveness of accident management strategies with complete de-energization has become a priority for the entire global nuclear power industry.

The second relevant lesson for the world nuclear power industry (including for Ukraine) drawn from the Chernobyl accident is associated with the need to improve strategies for preventing unlikely accidents with catastrophic environmental consequences, and in the event of their occurrence it implies the need for effective accident management to bring the NPP to a stable controlled state minimizing environmental consequences. The lack of such effective operational instructions/regulations was one of the main reasons for several unintentional erroneous actions of the Chernobyl nuclear power plant personnel, as well as later it was at the Fukushima-1 nuclear power plant.

After the Fukushima-1 accident, the safety regulatory authority of the largest nuclear power state (NRCUS) initially ruled out the possibility of a similar accident in the United States due to the absence of such earthquakes and tsunamis. However, subsequently the NRCUS conducted double inspections at each power unit, that check revealed that the adopted strategies for managing accidents with complete long-term de-energization (similar to the accident at the Fukushima-1 nuclear power plant) were not sufficiently effective.

The analysis of developed operational instructions/guidelines for accident management at WWER NPPs carried out in [14–18] also determined the insufficient effectiveness of strategies for preventing and managing relatively unlikely accidents with catastrophic environmental consequences. In particular, for accidents with a complete continued blacking out, mainly defined are the personnel's actions to restore power supply or connect all alternative power supply and cooling means and tools available at the NPPs. The Fukushima accident lessons revealed the inadequacy of such measures to prevent catastrophic consequences.

The next relevant Chernobyl accident lesson for modern nuclear power engineering is related to the need for improved safety systems that ensure accident management while minimizing the personnel actions impact. Particularly, a promising approach to the management of accidents with de-energized WWER NPPs refers to the use of safety systems based on steam generators replenishment with steam pumps for relatively high steam pressures in the steam generator and the natural circulation passive heat removal systems with relatively low residual heat in the reactor operated automatically, such mode implying minimum intrusion from the personnel part.

Another important lesson of the Chernobyl accident indicates to the need of improved radiation and environmental monitoring and methods of accidents' consequences for personnel, the population and the environment post-accident forecasting. The main limitations of the known stochastic and deterministic methods on predicting the accidental radiation exposure impact for the personnel, the population and the environment are related to the lack of statistical databases validity and the deterministic impact of ionizing radiation sources on bio- and ecosystems.

Taking into account the Chernobyl accident lessons, it is necessary to improve the methods and ways of psychological training concerning both personnel and the population in extremely stressful situations. Unintentionally erroneous actions of personnel during the accident and when emergency consequences elimination, as well as panic and mental negative phenomena in the population were largely associated with insufficient psychological training of personnel and the population in an extremely stressful situation.

## 4 Conclusions

Analysis of the Chernobyl accident causes and consequences allows us to formulate the main lessons of this accident for modern nuclear energy domain:

— deterministic indicators and criteria of conditions under which the nuclear fuel damage and safety protective barriers destruction take place should be priority in the analysis of nuclear power plants safety;

— essential is to carry out the deterministic safety analysis and development of emergency measures, including these for relatively unlikely events that could involve catastrophic consequences;

— improvement and development of safety systems that ensure the emergency processes management minimizing the impact of personnel actions (including for relatively unlikely initial emergency events with catastrophic consequences);

— improving operational documentation for the management of relatively unlikely accidents capable to involve catastrophic consequences;

— improvement of the nuclear energy facilities radiation and ecological monitoring system, as well as methodological support for forecasting the accidents' and normal operating conditions breaches' radiation consequences for personnel, the population and the environment;

— improving the system of staff and population psychological training for extremely stressful situations and others.

The analysis of the Fukushima nuclear power plant 2011 accident causes and consequences shows that the Chernobyl accident lessons were insufficiently taken into account in terms of the unlikely accidents with catastrophic consequences occurrence conditions and management.

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