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METHODOLOGY FOR DETERMINING THE CONDITIONS FOR THE OCCURRENCE OF STEAM EXPLOSIONS DURING ACCIDENTS WITH COMPLETE POWER OUTAGES AND INTER-CIRCUIT LEAKS AT NUCLEAR POWER PLANTS WITH VVER

В. Скалозубов, Г. Дербеньов, Ю. Кацарський, Є. Мазур, В. Кочнєва. **Методика визначення умов виникнення парових вибухів під час аварій з повним знеструмленням та міжконтурними течами на ядерних енергоустановках з ВВЕР.** Розроблено детерміністський метод визначення умов і наслідків парових вибухів у процесі аварій з повним знеструмленням та міжконтурними течами ядерних енергоустановок з реакторами типу WWER/PWR. Необхідні умови парових вибухів визначаються на базі принципу термодинамічної нестійкості систем – одночасне збільшення тиску і маси в парових об'ємах реактора та/або парогенератора відповідає умовам парових вибухів. Визначальні параметри умов парових вибухів – швидкості збільшення тиску і парового об'єму. Наслідки парових вибухів визначаються енергетичною потужністю парових вибухів, яка залежить від швидкості збільшення тиску і парового об'єму. На основі розробленого методу встановлено найбільш критичні ситуації щодо умов і наслідків парових вибухів під час аварії з повним знеструмленням та між контурними течами ядерних енергоустановок з реакторами типу WWER/PWR. Установлено необхідні умови успішної кваліфікації на відкриття в умовах парових вибухів запобіжних клапанів реактора та парогенератора, а також паро-скидальних пристроїв парогенератора. Установлено необхідність модернізації системи аварійного підживлення об'ємів парогенератора для ефективного управління аваріями з повним знеструмленням та між-контурними течами ядерних енергоустановок з реакторами типу WWER/PWR та запобігання умовам і наслідкам парових вибухів. Розроблені методи визначення умов парових вибухів на ядерних енергоустановках можуть бути включені до складу детерміністських кодів моделювання аварій зі «щільним» реакторним контуром/між-контурними течами в об'ємі парогенераторів, а також до експлуатаційної документації (керівництва/інструкції з управління аваріями) для удосконалення/модернізації стратегій управління аваріями на ядерних енергоустановках з реакторами типу WWER/ PWR
Ключові слова: аварія, знеструмлення, міжконтурна теча, паровий вибух, ядерна енергоустановка

V. Skalozubov, H. Derbenov, Iu. Katsarskyi, Ye. Mazur, V. Kochnieva. **Methodology for determining the conditions for the occurrence of steam explosions during accidents with complete power outages and inter-circuit leaks at nuclear power plants with VVER.** A deterministic method has been developed to determine the conditions and consequences of steam explosions during **complete power outages** accidents with inter circuit leaks at nuclear power plants with WWER/PWR reactors. The required conditions for steam explosions are determined based on the principle of thermodynamic instability of systems – a simultaneous increase in pressure and mass in the steam volumes of the reactor and/or steam generator corresponds to the conditions for steam explosions. The determining parameters of the conditions for steam explosions are the rates of increase in pressure and steam volume. The consequences of steam explosions are determined by the energy capacity of steam explosions, which depends on the rate of increase in pressure and steam volume. Based on the developed method, the most critical situations regarding the conditions and consequences of steam explosions of complete power outages accidents with intercircuit leaks have been found for nuclear power plants with WWER/PWR reactors. The required conditions for successful qualification for opening the safety valves of the reactor and steam generator, as well as the steam dump devices of the steam generator under steam explosion conditions, have been found. The need to modernize the emergency feed system of the steam generator volumes has been recognized for the effective management of out with intercircuit leaks of nuclear power plants with WWER/PWR reactors and the prevention of the conditions and consequences of steam explosions. The developed methods to determine the conditions for steam explosions at nuclear power plants can be included in the deterministic codes for modelling accidents with a "tight" reactor circuit/intercircuit leaks in the volume of steam generators, as well as in the operational documentation (manuals/instructions for accident management) for the improvement/ modernization of accident management strategies at nuclear power plants with WWER/PWR reactors.
Keywords: accident, compete power outages, intercircuit leak, steam explosion, nuclear power plant

Introduction

In the traditional safety analysis of nuclear power plants with VVER/PWR reactors, the possibility of a steam explosion was excluded based on the results of design and operational tests of the reactor safety valves and steam generator, which were carried out at a quasi-static ("slow") increase in

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pressure to the level of maximum permissible values.

However, the conditions of design and operational tests of safety valves by a “slow” increase in pressure can differ significantly from the conditions of a steam explosion, which are characterized by a pulsed (“rapid”) increase in pressure. Therefore, in the conditions of a steam explosion, the safety valves may not have time to react to a “rapid” increase in pressure.

In addition, it should be noted that the failures of the reactor safety valves became the main cause of a serious accident at the TMI-2 NPP (USA, 1979) and an emergency incident at the Rivne NPP (2009).

During accidents with a sufficiently large intercircuit leak, steam explosion conditions may occur in the volume of the steam generator isolated from the 2nd circuit (requirements of accident management instructions). Under such emergency conditions, the “hot” coolant of the 1st circuit, which enters the volume of the steam generator, boils, which leads to an increase in steam pressure in the volume of the steam generator. At certain sizes of the intercircuit leak, the increase in steam pressure in the volume of the steam generator can be of a pulsed (“high-speed”) nature, when the steam boiler safety systems of the steam generator do not “have time” to work, which determines the conditions of a steam explosion in the volume of the steam generator in the process of accidents with intercircuit leaks.

With sufficiently small flow sizes, steam explosion conditions can occur in the 1st circuit in the case of a fairly rapid (impulse) increase in pressure in the reactor.

Thus, in the general case, when modeling and analyzing accidents in nuclear power plants, it is necessary to take into account the possibility of occurrence and consequences of a steam explosion.

For nuclear power plants with VVER/PWR, the conditions of a steam explosion can be realized in accidents with compete power outages of power units (an analogue of one of the causes of the Fukushima accident) and intercircuit leaks in steam generators (the dominant group of accidents in nuclear power plants with VVER/PWR), which determines the relevance of the presented work.

Analysis of known developments on the topic and problem statement

In the paper [1], based on the analysis of the experience of overcoming and learning from the Chornobyl accident, it was found that it was a powerful destructive steam explosion that became the main cause of catastrophic environmental consequences – the total emission of highly radioactive nuclides cesium and iodine into the environment amounted to more than $5.0 \cdot 10^{18}$ Bq.

Based on the analysis of the causes and consequences of the accidents at the Fukushima nuclear power plant (Japan, 2011), the IAEA mission of experts [2] established the causes of the steam explosion at the 2nd power unit. A devastating steam explosion at Unit 3 triggered the next hydrogen explosion and catastrophic environmental consequences in the environment. According to various experts, the total emission of highly radioactive nuclides cesium and iodine amounted to (0.3–1.4)·1018 Bq [3, 4]. At the same time, “Fukushima” highly radioactive nuclides were also recorded in the Kyiv region [5].

The paper [6] analyzes the results of operational tests of safety valves of reactors and steam generators in the process of scheduled repairs of power units with VVER. It was established that all tests were carried out in the mode of “slow” pressure increase to the maximum permissible value, corresponding to the opening of the reactor/steam generator safety valves.

In the paper [7], an analysis of the known results of simulation of accidents at nuclear power plants with VVER/PWR/SMR was carried out. It was established that the issue of determining the conditions and consequences of a steam explosion in the course of accidents was not considered. The main reasons for this situation are related to the fact that a priori the “absolute” reliability of the safety valves of reactors/steam generators was assumed, as well as the lack of sufficiently substantiated methods for determining the conditions and consequences of a steam explosion in nuclear power plants with VVER/PWR reactors.

The analysis of the known results allows you to formulate the purpose and objectives of the presented work.

The purpose of the study is to develop a method for determining the conditions and consequences of steam explosions during accidents with compete power outages of power units and intercircuit leaks in nuclear power plants with VVER/PWR reactors.

Main objectives of the study

1. To develop a method for determining the conditions and consequences of steam explosions during accidents with compete power outages of power units and intercircuit leaks (CPO-ICL).

2. To analyze the impact of the emergency state of the nuclear power plant on the conditions and consequences of a steam explosion during accidents with MB-IL.

Model of a steam explosion during accidents with compete power outages of power units and intercircuit leaks

Basic provisions and assumptions

1. A generalized scheme of the model of the nuclear installation with VVER/PWR in the process of an accident with CPO-ICL is shown in Fig. 1.

2. The following chronology of the initial stages of the accident is accepted:

– registration of signals/symptoms of an accident with the CPO-ICL;

– emergency shutdown of the reactor;

– emergency stop of the circulation pump;

– insulation of the 2nd circuit with shut-off valves of the steam pipeline and the supply water pipeline of the steam generator, as well as shutdown of the turbine plant.

3. As a result of a complete de-energization of the power unit, the failure of all active safety systems (with electric pumps) for the accident control of the reactor core cooling and emergency power supply of the steam generator is expected.

4. A refusal to open the safety valves of the pressure compensator, safety valves and steam discharge devices of the steam generator in the conditions of a steam explosion with a pulsed ("fast") pressure change in the reactor/steam generator is conservatively provided. The basis for such an assumption is the lack of design and operational tests of experimental qualification of pressure compensator safety valves, safety valves and steam generator spray devices under steam explosion conditions [6, 7].

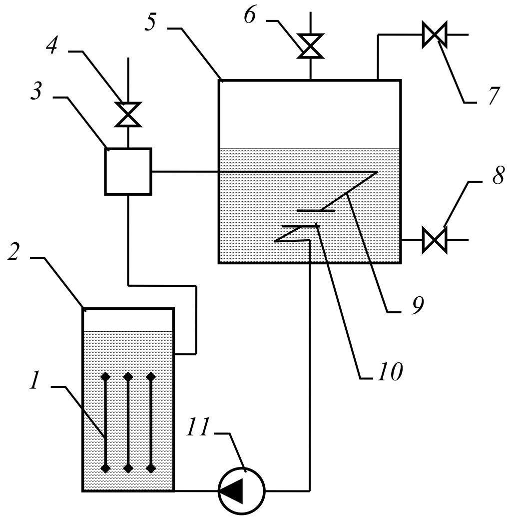

Fig. 1. Generalized diagram of the model of nuclear power plants with VVER/PWR:
1 – active zone; *2* – reactor vessel; *3* – pressure compensator; *4* – pressure compensator safety valve; *5* – steam generator; *6* – steam generator safety valve; *7*, *8* – insulation fittings of the 2nd circuit during an accident; *9* – heat exchange tubes of the steam generator; *10* – intercarrier leak; *11* – main circulation pump

5. The necessary conditions of a steam explosion can be determined according to the principle of thermodynamic instability (TDI) [5] – a simultaneous increase in the system (in this case, it is the steam volume of the reactor circuit/steam generator) *P* and mass (volume) *V* determines the conditions of the TDI.

6. According to the requirements of the accident management instructions in the accident process, the SG is isolated from the 2nd circuit for steam and feed water.

In this case, the conditions of steam pressure and explosion due to TDI in the steam volume of the reactor circuit/steam generator are required:

$$v_P = \frac{dP}{dt} > 0 \text{ and } v_V = \frac{dV_V}{dt} > 0\,. \tag{1}$$

Sufficient conditions for the occurrence of a steam explosion due to pulsed TDI:

$$v_P \geq (v_P)_{\text{cr}}\,, \tag{2}$$

where $(v_P)_{\text{cr}}$ – critical for steam explosion conditions pressure increase rate.

According to known experimental data on the parameters of the steam explosion obtained on model installations [5], the conservative estimate of $(v_P)_{\text{cr}} \approx 1.0$ MPa/s.

7. Energy power of a steam explosion (which determines the consequences of a steam explosion) [5]

$$N_e = \frac{d(PV_{\text{V}})}{dt} = V_V v_P + P v_V\,, \tag{3}$$

where V_v – vapor phase volume.

Taking into account the accepted provisions and assumptions, the equation of heat and mass balance in the reactor and steam generator during the accident with the CPO-ICL

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$$\frac{d(\rho_{VR}V_{VR})}{dt} = \Delta G_{VR}, \tag{4}$$

$$\frac{d(\rho_{VR}V_{VR}i_{VR})}{dt} = \Delta G_{VR}i_{VR}, \tag{5}$$

$$\frac{d(\rho_{LR}V_{LR})}{dt} = \Delta G_{VR} - G_T, \tag{6}$$

$$\frac{d(\rho_{LR}V_{LR}i_{LR})}{dt} = N_R - Q - \Delta G_{VR}(i_{VR} - i'_{LR} - i_{LR}), \tag{7}$$

$$\frac{d(\rho_{VG}V_{VG})}{dt} = \Delta G_{VG}, \tag{8}$$

$$\frac{d(\rho_{VG}V_{VG}i_{VG})}{dt} = Q + G_T i_R + \Delta G_{VG}(i_{VG} - i'_{LG} - i_{LG}), \tag{9}$$

$$\frac{d(\rho_{LG}V_{LG})}{dt} = -\Delta G_{VG} + G_T, \tag{10}$$

$$\frac{d(\rho_{LG}V_{LG}i_{LG})}{dt} = Q - \Delta G_{VG}(i_{VG} - i'_{LG} - i_{LG}) + G_T(i_{LR} - i_{LG}), \tag{11}$$

where:

ρ_{VR}, ρ_{VG} – Steam density in the reactor and steam generator;
V_{VR}, V_{VG} – Steam volume in the reactor and steam generator;
i_{VR}, i_{VG} – Specific enthalpy of steam in a reactor and steam generator;
ρ_{LR}, ρ_{LG} – Density of the liquid phase in the reactor and steam generator;
V_{LR}, V_{LG} – Volume of liquid phase in reactor and steam generator;
i_{LR}, i_{LG} – Specific enthalpy of the liquid phase in the reactor and steam generator;
G_{VR}, G_{VG} – Mass flow rate of vaporization in the reactor and steam generator;
N_R, Q – reactor power and heat removal in the volume of the steam generator;
G_T – mass flow rate of coolant in an intercircuit leak

$$G_T = \mu_T F_T \sqrt{\rho_{LR}(P_R - P_G)}, \tag{12}$$

where:

μ_T – cost coefficient in ICL;
F_T – ICL Cross-sectional area;
P_R, P_G – Pressure in the reactor and steam generator;
i'_{LR}, i'_{LG} – Specific enthalpy of liquid phase saturation in a reactor and steam generator.

Given:

$$V_{0R} = V_{LR} + V_{VR};$$

$$V_{0G} = V_{LG} + V_{VG};$$

$$\frac{d\rho}{dt} = \frac{d\rho}{dP}\frac{dP}{dt} = \frac{dP}{dt}a^{-2};$$

$$\frac{di}{dt} = \frac{di}{dP}\frac{dP}{dt} = \frac{dP}{dt}C_T.$$

After transformations of equations (4) – (12), we get a system of nonlinear equations:

$$\frac{dP_R}{dt} = v_{PR}(N_R, Q, P_R, P_G, i_{LR}, i_{LG}, F_T), \tag{13}$$

$$\frac{dV_{VR}}{dt} = v_{VR}(N_R, Q, P_R, P_G, i_{LR}, i_{LG}, F_T), \tag{14}$$

$$\frac{dP_G}{dt} = v_{PG}(N_R, Q, P_R, P_G, i_{LR}, i_{LG}, F_T), \tag{15}$$

$$\frac{dV_{VG}}{dt} = v_{VG}(N_R, Q, P_R, P_G, i_{LR}, i_{LG}, F_T)\,, \tag{16}$$

$$\frac{di_{LR}}{dt} = v_{iR}(N_R, Q, P_R, P_G, i_{LR}, i_{LG}, F_T)\,, \tag{17}$$

where:

V_{0R}, V_{0G} – "free" from structures internal volume of the reactor circuit and steam generator;

a – Speed of sound;

C_T – Isothermal heat capacity;

P_R, P_G – average pressure in the reactor circuit and the volume of the steam generator.

Thus, the necessary conditions for a steam explosion (1) in the reactor and in the volume of the steam generator:

$$v_{PR} > 0 \text{ and } v_{VR} > 0\,, \tag{19}$$

$$v_{PG} > 0 \text{ and } v_{VG} > 0\,. \tag{20}$$

Sufficient conditions for a steam explosion due to pulsed TDI:

$$v_{PR} \geq (v_P)_{cr}\,, \tag{21}$$

$$v_{PG} \geq (v_P)_{cr}\,. \tag{22}$$

Analysis of the obtained results

The analysis of the obtained dependencies (13) – (18) of determining the conditions of the steam explosion (19) – (22) of the CPO-ICL accident in the reactor/steam generator of the nuclear power plant with VVER/PWR established the following.

1. The most critical situation regarding a steam explosion in the reactor circuit under the following conditions:

$$N_R >> Q\,, \tag{23}$$

$$F_T \leq (F_T)_{cr} = \frac{N_R \big/ \sqrt{\rho_{LR}(P_R - P_G)}}{\mu(i_{VR} - i'_{LR} - i_{LR})}\,. \tag{24}$$

At $F_T > (F_T)_{cr}$ the ICL actually "performs" the safety function of preventing the destruction of the reactor vessel.

2. The necessary conditions for a steam explosion in the volume of a steam generator (20) can be realized in the entire range of ICL sizes, and sufficient conditions for a steam explosion as a result of a pulsed TDI (22) can be realized at $F_T > (F_T)_{cr}$.

3. Prevention of steam explosion conditions during an accident with CPO-ICL, VVER/PWR nuclear power plants can be based on additional qualification/modernization of the safety systems of the emergency feeding of the steam generator and the safety valves of the pressure compensator/safety valves of the steam generator/steam dispensing devices.

The qualification of pressure compensator/steam generator safety valves/steam discharge devices under steam explosion conditions can be based on a comparison of the time of inertial delay of opening the valve t_i and the propagation time of the steam explosion pulse t_d:

$$t_d \approx \frac{\max P - P_0}{(v_P)_{cr}}\,, \tag{25}$$

where:

P – Maximum permissible pressure of the start of reactor/steam generator destruction;

P_0 – operating pressure in the reactor/steam generator in normal operation.

Condition for successful qualification of pressure compensator safety valves/steam generator safety valves/steam discharge devices:

$$t_i < \frac{\max P - P_0}{(v_P)_{cr}}\,. \tag{26}$$

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At present, based on the lessons of the Fukushima accident, the following upgrades of the emergency system of the steam generator on NPP with VVER in the conditions of the accident with CPO have been introduced/are being implemented:

– mobile pumping units installed at the NPP industrial site;

– emergency feeding of the steam generator with natural circulation from the deaerator units of the turbine compartment (D-7).

Main limitations of the effectiveness of said systems for accident management with CPO:

– both systems are low-pressure and can feed the steam generator at a fairly low-pressure level in the steam generator volume. Therefore, in the conditions of an accident with CPO-ICL, these systems may not be effective enough for the entire duration of emergency processes;

– according to the lessons of the Fukushima accident, under extreme external conditions (flooding of an industrial site, fall of large/explosive objects, etc.), mobile pumping units may also be insufficiently efficient [5].

Therefore, approaches to modernizing the emergency feeding system of the steam generator, carried out by pumps with a steam drive from a steam generator, seem more promising [3, 4].

Conclusions

1. A deterministic method for determining the conditions and consequences of steam explosions in the process of accidents with complete de-energization and intercircuit leaks of nuclear power plants with WWER/PWR reactors has been developed.

2. The necessary conditions for steam explosions are determined on the basis of the principle of thermodynamic instability of systems – a simultaneous increase in pressure and mass in the steam volumes of the reactor and/or steam generator corresponds to the conditions of steam explosions. Determining parameters of the conditions of steam explosions – the rate of increase in pressure and vapor volume.

3. The consequences of steam explosions are determined by the energy power of steam explosions, which depends on the rate of increase in pressure and vapor volume.

4. On the basis of the developed method, the most critical situations regarding the conditions and consequences of steam explosions during an accident with complete de-energization and intercircuit leaks of nuclear power plants with WWER/PWR reactors were established.

The necessary and sufficient conditions for steam explosions in the reactor/SG have been established. In general terms, the expressions (21) and (22) correspond to the conditions under which the rate of pressure increase in the reactor/SG (depending on the current reactor power, current thermodynamic parameters in the 1st and 2nd circuits, the size of the intercircuit leak) exceeds the critical rate of inertial actuation of the reactor/SG safety valves, which are established by the technical documentation of the safety valves.

5. The necessary conditions for successful qualification for the opening of the reactor safety valves and steam generator, as well as the steam generator vaporizer devices in the conditions of steam explosions, have been established, namely, the flow rate of the coolant through the safety valves must exceed the mass rate of vaporization in the reactor core.

6. It is established that it is necessary to modernize the system of emergency replenishment of steam generator volumes for effective management of accidents with complete de-energization and intercircuit leaks of nuclear power plants with WWER/PWR reactors and prevention of conditions and consequences of steam explosions.

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