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Qualification of Compensatory Test Methods Involving Pressure Increase in the VVER Containment System

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In general, containment leakage testing of nuclear power plants with VVER reactors by elevated pressures using the compensatory leakage detection method (CLDM) can be performed at pressures and pressure increase rates higher than those stipulated by the regulations using the absolute pressure method (AP method). Elevated pressures and pressure increase rates under certain conditions can violate safety limits of the containment systems and/or decrease the reliability/life of containment structures and equipment. These factors determine the need to qualify the CLDM to promote conditions for reliability and safety. A non-stationary thermodynamic model of the qualification conditions for CLDM testing of the containment was developed. The criteria for CLDM qualification conditions are the maximum allowable pressure and pressure increase rate during testing. The CLDM condition for recording leakage in the containment is pressure stabilization in the containment systems. Based on the developed CLDM thermodynamic model, it was established that the containment leakage rate is determined by the flow rate of air entering the containment systems and by the thermodynamic state of the air inside and outside the containment systems. The established qualification conditions were used to determine conditions for the minimum recorded leakage sizes within CLDM and the maximum allowable ambient air flow rates and test duration. A prerequisite for justifying the qualification and implementation of the CLDM is to revise/amend regulatory and technical requirements for the maximum allowable pressure and pressure change rate in the containment systems and for the conditions for disconnecting containment systems passive heat removal systems (if any) during testing.

Keywords: containment system, qualification, testing.

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Introduction

The urgency of improving the regulations for high-pressure testing (HPT) of containment integrity (CI) at nuclear power plants (NPPs) with VVER reactors is determined by the following main reasons:

insufficient justification of the HPT frequency and duration;

insufficient validity of HPT methods for leakage recording.

Currently, the regulatory and operational documentation [1], [2] establishes annual CI HPT. It should be noted that the terms of the CI HPT meet the conditions of a "small" accident. Under these conditions, structures of the NPP containment systems (CS) are under increased dynamic loads that can significantly affect the reliability/life of CS components. In addition, containment CI HPT is always on the critical path of scheduled outages of VVER units, and the duration of containment leakage tests reaches up to two days [3], [4].

For example, according to the feasibility study of the Energoatom Company's "Program for Increasing the Installed Capacity Factory" [3], a 10-day reduction in the duration of scheduled outages in the entire industry is equivalent to commissioning a new VVER-1000 unit.

At the same time, according to the experience of the United States, France, Japan, the Czech Republic, Finland and other countries, the frequency of outages is determined as every 3-10 years [3]. The justification for this outage frequency is usually based on the experience in operation and testing, as well as on the results of safety analysis using risk-based methods.

Canada, France and other countries have also developed approaches for continuous monitoring (without CI HPT in scheduled maintenance) over the containment condition [3].

In the operational programs of CI HPT for NPPs with VVER-1000, leakage rates are determined indirectly by changes in thermodynamic parameters [2].

Scheduled CI HPT outages are performed at relatively low pressures (no more than 0.1 MPa), and the coolant leakage rate is determined using the equation of thermodynamic state justified only by ideal gas conditions.

As a result, these provisions of the regulatory method for CI HPT lead to a relatively longer duration and insufficient correctness of the calculated estimates of the containment leakage flow rate.

Thus, the issues of improving the regulations for the CI HPT at NPPs with VVERs are relevant both for ensuring the reliability and safety and improving operational efficiency.

Analysis of literature sources

Paper [3] presents a risk-based method for predicting the need for CI HPT based on the experience of previous tests, individual for each power unit, and assessing the probability of violating the regulatory conditions for the acceptability of containment leakage for the tests to be performed.

However, the general shortcomings of probabilistic methods due to the uncertainty of the calculated estimates [5] and the use of leakage cost data obtained by the regulatory indirect method [2] determine the need for further improvement of the methods for justifying the frequency of CI HPT outages.

Paper [4] presents an analysis of the experience in conducting HPT within NPP VVER-1000 containment leakage inspection, based on which the authors consider the following:

insufficient validity of the duration of the HPT involving the regulated indirect absolute pressure method (AP method) [2];

insufficient validity of the AP method itself, based on the equation of the thermodynamic state of the ideal Mendeleev-Clapeyron gas.

Therefore, [4], [6] proposed an alternative compensatory leakage determination method (CLDM) based on the establishment of leakage parameters by the balance of the controlled incoming air flow and the air leaking from the CS.

Key assumptions and assumptions of CLDM

1. The fact of establishing the balance between the controlled (measured) incoming flow and the flow out of the CS is recorded when the pressure in the CS is stabilized during the test and there is no flow in the control vessel systems.

2. To reduce the test duration and ensure isothermal exchange processes in the CS, a relatively accelerated ("fast") air intake from the CS environment is provided.

3. To verify the results of the CLDM, the results of the regulatory AP method are taken into account.

The following comments are necessary regarding the main assumptions of CLDM.

1. In the absence of coolant leaks (or rather insignificant leaks), pressure stabilization in the CS under certain conditions of the CLDM test may lead to violations of the maximum allowable pressure limit in the VVER-1000 CS (0.5 MPa) established by regulatory and operational documentation.

2. The CLDM assumption that the flow rate (G_0) from the environment and the leakage rate (G_o) when the pressure in the CS is stabilized is not sufficiently justified, since the leakage rate also depends on the thermodynamic state and compression of the air in the CS and the leakage capacity. Therefore, in general, the values of (G_0) and (G_o) can differ significantly when pressure is stabilized in the CS.

3. The accelerated (intensive) filling of the CS with external air and the corresponding increase in pressure during leakage tests also has limitations in terms of reliability and safety. The intensive pressure increase in the CS actually corresponds to the conditions of the initiating event with increased dynamic loads on the CS structures (containment, reinforcement, etc.) and can significantly affect the reliability and final service life of these structures under certain conditions.

4. The verification of the CLDM test results with the test results of the regulatory AP method is also insufficiently justified, since the test conditions of these methods (maximum pressure, pressure change rate, etc.) may differ significantly.

During the modernization of containment systems at NPPs with VVERs, stable pressure and temperature of the air-steam environment in the CS are maintained by a **passive heat removal system (PHRS)**. The PHRS ensures stable constant pressure in the CS in normal operation, emergencies and CLDM testing, regardless of the presence and/or size of a coolant leak.

The PHRS is classified as a confining safety system and disconnection of the PHRS during testing requires additional justification to ensure safe conditions.

Goal and objectives of the work

The goal of the work is to justify the criteria and conditions for CLDM qualification in accordance with the requirements for ensuring the effectiveness of testing and reliability and safety of CS.

To achieve the goal of the work, the following tasks are necessary.

1. Develop a thermodynamic model for CLDM qualification.

2. Analyze the qualification conditions for CLDM based on the thermodynamic model.

Thermodynamic model of CLDM qualification

Main provisions and assumptions.

1. Criteria (parameters) for the CLDM qualification:
   maximum allowable pressure of containment leakage testing P_{cr};
   maximum allowable rate of increase in pressure of containment leakage tests $P_{cr}^{'}$.
2. Qualification conditions of the CLDM

$$P < P_{cr}, \tag{1}$$

$$\frac{dP}{dt} < P_{cr}^{'}, \tag{2}$$

where *P* is the pressure in the containment vessel; *t* is the time.

Qualification criteria P_{cr} and $P_{cr}^{'}$ must meet the regulatory requirements for confining safety systems [7].

3. The volume of air in the CS (V_o) is modeled by the average thermodynamic parameters (pressure, temperature). The average air temperature in the CS (T_o) during the tests [4] is assumed to be constant.

The equation of the mass and heat balance of the volume V_o in the unsteady-state mode of air supply from the environment [5] is as follows:

$$V_o \frac{d\rho_o}{dt} = G_a(t) - G_o(t), \tag{3}$$

$$V_o \frac{d(\rho_o \cdot i_o)}{dt} = G_a(t) \cdot i_a - G_o(t) \cdot i_o(t), \tag{4}$$

where ρ_o is the air density in the CS; $G_a(t)$ is the mass flow rate of the air supply from the environment controlled by the flow meter; $G_o(t)$ is the mass flow rate in the coolant leakage; i_o and i_a are the specific enthalpy of air in the environment and in the CS.

Mass flow rate in the containment leakage [8]:

$$G_o(t) = \mu \cdot F_T \cdot \sqrt{\rho_o(t) \cdot \left[\left(P_o(t) - P_a\right)\right]}, \tag{5}$$

where *μ* is the leakage capacity parameter (flow coefficient) [8]; F_T is the equivalent cross-sectional area; P_o, P_a are the air pressure in the CS and the environment.

Initial conditions:

$$P_o(t=0) = P_{oo}; i_o(t=0) = i_o(P_{oo}, T_o). \tag{6}$$

After transforming the mass and heat balance equations (3) and (4), we obtain:

$$\frac{dP_o}{dt} = \frac{G_a \cdot i_a - G_o \cdot i_o}{V_o\left[\rho_o \cdot di_o / dP_o + i_o \cdot d\rho_o / dP_o\right]}. \tag{7}$$

The condition for compensation of incoming and outgoing air at the end of the overpressure test (t_T) [4]:

$$\frac{dP_o}{dt}(t = t_T) = 0. \tag{8}$$

Then the leakage rate follows from (7) and (8):

$$G_o(t_T) = G_a(t_T) \cdot i_a / i_o. \tag{9}$$

Thus, in general, the actual flow rate can differ significantly from the controlled flow rate coming from the environment.

Taking into account the qualification condition (1) and the equation of air movement in the leakage (5), the permissible area of the determinable leakage size of the CLDM is given by:

$$F_T > \frac{maxG_a \cdot i_a}{i_o \cdot \mu \cdot \sqrt{\rho_o \cdot (P_{cr} - P_a)}}. \tag{10}$$

A priori, HPT CLDM does not know about the presence of a air leakage in the CS. Therefore, the qualification conditions (1) and (2) should be analyzed for the maximum allowable flow rate of incoming air $(maxG_a)$ and the minimum flow rate in the leakage $(G_o \approx 0)$.

In these boundary conditions, equations (3) and (4) after transformations become:

$$V_o \cdot a_o^{-2} \cdot \frac{dP_o}{dt} = maxG_a, \tag{11}$$

$$\frac{dP_o}{dt} = \frac{maxG_a \cdot i_a}{V_o\left[\rho_o \cdot di_o / dP_o + i_o \cdot a_o^{-2}\right]}, \tag{12}$$

where $a_o = \sqrt{dP_o / d\rho_o)}$ is the speed of sound in the air of the CS.

Then the qualification conditions (1) and (2) with $maxG_a$, taking into account (11) and (12), become:

$$t_T < a_o^{-2} \cdot V_o \cdot \left(P_{cr} - P_o\right) \cdot maxG_a^{-1}, \tag{13}$$

$$maxG_a < V_o \cdot \left[\rho_o \cdot di_o / dP_o + i_o \cdot a_o^{-2}\right] \cdot i_a^{-1} \cdot P_{cr}^{'}. \tag{14}$$

The qualification conditions (13) and (14) of $maxG_a$ determine the maximum allowable flow rate of air entering the CS and the duration of the HPT in the established regulatory requirements for the maximum allowable pressure and pressure change rate.

Analysis of the results obtained

Analysis of the results from CLDM qualification (10), (11), (13), and (14) for the containment leakage tests allows the following comments:

1. When pressure in the CS is stabilized and the compensation condition (8) is met, the leakage flow rate is determined by the current flow rate of the incoming air and the thermodynamic state of the air outside and inside the CS (9); in general, the values of G_o and G_a can differ significantly.

Taking into account the heat and mass exchange processes between the air coming from the environment and the air in the CS, the differences between G_o and G_a decrease, and in the limiting case, when $i_o = i_a$, it follows that $G_o = G_a$.

2. The minimum size of the containment leakage (10) that can be registered by CLDM is determined by the incoming air flow rate, the thermodynamic state of the air outside/inside the CS, as well as the maximum allowable pressure in the CS during testing and the leakage capacity.

3. Qualification conditions for CLDM by the maximum permissible test duration (13) and air flow rate in the CS (14) depend on the qualification criteria (P_{cr} and $P_{cr}^{'}$), air volume in the CS (V_o), and thermodynamic state of air in the CS.

4. Qualification and practical implementation of the CLDM into operation determines the need to revise/supplement the regulatory requirements for the leakage test programs for CS by:

maximum allowable pressure in the CS during testing;
maximum permissible rate of pressure increase in the CS during testing;
conditions for disconnecting the PHRS (if any) during testing.

Conclusions

1. A non-stationary thermodynamic model of the qualification conditions for CS CLDM testing was developed. Criteria for the qualification conditions of CLDM are the maximum allowable pressure and the pressure increase rate during testing. The condition for recording the CLDM flow rate in the CS leakage is the stabilization of pressure in the CS.

2. Based on the developed thermodynamic model of CLDM, it was established that the leakage flow rate is determined by the flow rate of air entering the CS controlled by the flow meter, as well as the thermodynamic state of air inside and outside the CS.

3. Based on the established qualification conditions, conditions for the minimum recorded leakage rates of the CLDM and the maximum allowed ambient air flow rates and test duration were determined.

4. A necessary condition for justifying the qualification and implementation of the CLDM is the revision/supplementation of regulatory and technical requirements for the maximum allowable pressure and pressure change rate in the CS during testing, as well as conditions for disconnection during testing of passive heat removal systems from the CS (if any).

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Питання кваліфікації компенсаційних методів випробувань підвищенням тиску в системі герметичного огородження ВВЕР

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Випробування на герметичність захисної оболонки ядерних енергоустановок з водо-водяними енергетичними реакторами підвищенням тиску компенсаційним методом визначення витоку (КМВВ) загалом може здійснюватися при тисках та швидкості збільшення тиску більше, ніж передбачено регламентом методом «абсолютного тиску» (АР-метод). Підвищені тиски та швидкість збільшення тиску за певних умов можуть порушити межі безпеки системи герметичного огородження (СГО) та/або призвести до умов аварійної ситуації, та/або до зменшення надійності / ресурсу конструкцій та обладнання СГО. Ці фактори визначають необхідність кваліфікації КМВВ забезпечення умов надійності та безпеки. Розроблена нестаціонарна термодинамічна модель умов кваліфікації випробувань КМВВ герметичності захисної оболонки. Критерії умов кваліфікації КМВВ – гранично допустимий тиск та швидкість збільшення тиску під час випробувань. Умова реєстрації КМВВ витрати у витоку захисної оболонки – стабілізація тиску в СГО. На основі розробленої термодинамічної моделі КМВВ встановлено, що витрата у витоку захисної оболонки визначається контрольованою витратоміром витратою повітря, яке надходить в СГО, а також термодинамічним станом повітря всередині і зовні СГО. На основі встановлених умов кваліфікації визначені умови для мінімально реєстрованих розмірів витоку КМВВ, а також гранично допустимих витрат повітря з навколишнього середовища та тривалості випробувань. Необхідна умова обґрунтування кваліфікації та практичного впровадження КМВВ – перегляд/доповнення нормативно-технічних вимог до гранично допустимих під час випробувань тиску та швидкості зміни тиску в СГО, а також умови можливості відключення під час випробувань систем пасивного відведення тепла від СГО (у разі їх наявності).

Ключові слова: випробування, кваліфікація, система герметичного огородження.

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