Numerical – Experimental Research in Justification of Fire (Sodium) Safety of Sodium Cooled Fast Reactors

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Abstract. In report the main results of numerical and experimental studies aimed at justification of sodium fire safety of fast reactors with sodium coolant are presented.
The concept and composition of the sodium fire safety system in technological premises with sodium equipment are described.
The results of numerical and experimental research for fire safety systems efficiency in the premises of advanced fast reactor, tools to prevent sodium leakage in first loop and prospective sodium fire detection systems are presented.
The issue of jet outflow and spray burning of high-temperature sodium and related problem with increasing of the gas pressure in the room are considered. The results of the analysis and processing of French experiments on sodium spray burning are presented. The method is developed for the gas pressure raising calculation in the room based on the processing of experimental data.
The main experimental results with sodium flow through the defects in the pipeline under the insulation are presented. Based on this experimental data a possibility is shown for safe localization of the jet outflow and sodium spray burning with presence on pipelines and equipment the insulation and cladding.

Key Words: Fast Reactor, Sodium Leaks and Burning, Fire Safety, Numerical and Experimental Research

1. Introduction

Possible emergencies with sodium coolant leaks as a result of depressurization of loops of fast neutrons reactors are accompanied by sodium burning. The hazards of sodium fire are render negative influence on the personnel of nuclear station and the population, and also cause damage of the equipment and of building structures of sodium cooled fast reactor.
The hazards of sodium fire are: increasing the pressure and temperature of gas environment in emergency rooms, raise of building structures temperatures upon burning of sodium. Another hazard of sodium fire is spreading of sodium aerosols in the premises of the plant which are harmful to human health.
Fire safety with sodium leaks and burning on fast breeder reactors is represents a complex of the technical actions interfering occurrence and distribution of sodium fires in nuclear station and lowering an influence of sodium fires consequences on people and the equipment of NPP.
This paper contains the basic results of numerical and experimental research directed on increase the level of sodium fire safety for prospective reactors with sodium coolant, including the restriction of leaks level and sodium burning consequences and also the protection of premises with sodium equipment from the hazards of sodium fire.

2. The Concept and Composition of Fire Safety System of Sodium Cooled Fast Reactors

Below the main provisions of the fire safety conception of sodium cooled fast reactor are presented, based on the provisions of existing regulatory documents on fire safety of nuclear power facilities [1—3].

2.1.Fire Localization within Fire Zone

Walling fire resistance of fire zone must provide the location of the fire to complete free burnout of fire load (without taking into account impact on fire extinguishing agents). All sodium systems are located in separate rooms (fire zoning). Building structures (floor, walls, ceiling) are protected from the direct effects of sodium and thermal effects in the sodium fire by insulation and steel cladding. To limit the distribution of sodium aerosols beyond the fire zone room areas they are sealing.

2.2.Localization of Sodium Burning Consequences

Localization and removal from the premises of aerosol products of sodium burning at the sodium leakage are made with the active fire extinguishing systems – the special ventilation systems. While the sodium leak is localized the switching (or disabling) of ventilation system is occurs. The composition of the fire ventilation system provides filtration of air from sodium aerosols with the pre-treatment based on the battery of cyclones.

2.3.Suppression of Sodium Burning

To eliminate leaks and burning of radioactive sodium the primary circuit equipment of prospective fast reactors is expected to enclose in a durable safety vessel [4]. In the safety chamber volume between the main and safety reactor vessels the inert atmosphere is maintained and the sodium leakage control is located. The part of second circuit sodium pipelines is also has strength to atmosphere safety casing with an inert atmosphere and sodium leakage control systems. The suppression of possible sodium combustion is provided by passive tools. The flow out sodium enters the pallets with a hydraulic lock – the devices with lids of special design. Sodium burning is taken place almost only on the tops of the pallets. The volume of passive suppression sodium burning system (pallets with a hydraulic lock) is designed to accommodate the maximum possible amount of sodium.

2.4.Early Detection of Sodium Leaks and Burning

Detection of leaks and sodium burning in the early stage of the accident is provided by systems, which work at different physical principles and have a sufficiently high sensitivity and speed.

The operation principle of detection system with fault to the ground of electric heaters based on the creation the electrical contact between the heater and the wall of the pipeline when leaking sodium. The simultaneous loss of working and backup heaters is evidence of a sodium leak. Such systems are installed in all Russian fast reactors and showed high reliability and sensitivity.

In a second sodium loop for detection of sodium leaks and burning the smoke detection system is used based on smoke aspiration fire sensors VESDA [5]. The operation principle of the system is based on the change of optical density in controlled environment (air) in the

presence of sodium aerosols, which comes from the protected areas in the sensor. The signal is registered with the laser measuring system of the sensor.
Combustion of large amounts of sodium can be detected by monitoring the gas temperature and other technological parameters in premises with sodium equipment.

2.5.The Sodium Fire Safety System of Sodium Cooled Fast Reactor

Taking into account the main provisions safety concept the sodium fire safety system is formed, which includes the following elements:

- sodium leak and burning detection systems, which work based on different physical principles;
- passive localization system of spilled sodium within the fire area (emergency room);
- ventilation system performing localization and directional emission of sodium aerosols from the emergency room on a filtration system;
- sodium fire suppression systems (the pallets with a hydraulic lock, drainage fire extinguishing system), including a system of drainage.

3. Calculation Justification on Efficiency of Design Solutions to Ensure Fire Safety of Advanced Fast Reactor in Event of Any Sodium Leakage

3.1.Problem Statement and Initial Data

In justification of the technical solutions to ensure fire safety adopted in the project of prospective fast reactor the numerical studies of possible sodium leaks and burning consequences are performed. The numerical analysis of the sodium fires consequences was performed in some second circuit premises with sodium equipment for conditions of maximum design accident. The consequences of this accident are considered as a result of sodium leak through the defect (a round aperture) which occurs in equipment. The size of through defect corresponds to two thicknesses of the pipe wall or vessel. It was assumed that sodium leak detection (fire alarm) is triggered normally, for three minutes. The localization of sodium fire consequences in accident premises was performed by automatic / manual switching (or disabling) the regular ventilation systems. For localization of spilled sodium on the room floor the passive sodium fire suppression systems (the pallets with a hydraulic lock) was installed. The sodium burning on a horizontal surface formed by the tops of the pallets is considered.
To perform of the sodium fires consequences calculations in premises the upgraded version of a computer program BOX [6] named BOX2000 (developed in IPPE) was used.
The computer code BOX2000 allows to simulate the following basic processes associated with sodium fires:

- sodium leak and burning on some horizontal surface (pool fire);
- heat exchange in an emergency premise between the gas environment, building designs and sodium aerosols;
- a mass exchange of gases between an emergency premise and other premises due to work and switches of ventilation systems;
- change of gas masses and sodium aerosols in an emergency premise due to their sedimentation on building structures and also work of ventilation systems.

3.2.Main Requirements for Operation Condition of Sodium Fire Safety System

Fire safety for premises with sodium equipment of fast reactor must be provided with the following requirements of the sodium fire system operation conditions:

- in terms of building structures strength in premises the maximum temperature on concrete surface on the floor, walls and ceiling is taken within +100 ° C;
- to ensure the acceptable working conditions of ventilation systems elements the temperature of air removed by ventilation from premises should not exceed 370 ^{0}C;
- to guarantee the integrity of building structures (based on the integrated strength of liner and reinforced concrete structures) the vacuum and the excess pressure in fire zones must not exceed 1000 Pa.

3.3.The Results of Calculation Researches and the Main Conclusions

The calculation results showed the deviation of the estimated parameters (pressure and temperature of the gaseous medium, the temperature of concrete surface on the floor) from the maximum allowable values in a number of premises. For problematic areas recommended the following additional technical solutions to ensure the sodium fire safety:

- increase the insulation thickness on the floor;
- introduction of the special operation algorithm of ventilation system while the sodium fire occurs: when the computed gas temperature in the room reaches the specified value when ventilation system is disconnected from the emergency room.

With the additional technical solutions the principles used in the design of fire safety system provides localization and suppression of sodium fire in considered premises of the prospective fast reactor for conditions of maximum design accident.

4. Experimental Studies of the Steel Foil Insulation Effectiveness

4.1.Experimental Facility, Methodology and Objectives of Experimental Studies

Experimental work to assess the possibility of using the steel foil insulation blocks to keep the primary sodium leakage from the safety vessel of fast reactor was carried out on facility of IPPE, which included vacuum gas, the container of sodium and the sodium connecting pipe between the container and investigated vertical and horizontal steel foil insulation blocks. Sodium container and sodium feed line is equipped with electric heating and insulation. On each insulation block the temperature measuring system was mounted. To localize the possible sodium leakage through defects under each insulation block the pallets was installed.

The sequence of experiments was the follows. The sodium container, connecting pipe and insulation blocks were heated to a predetermined temperature. Further, by supplying of inert gas (argon, nitrogen) from the receiver in the experimental setup a necessary pressure was created and maintained constant during each experiment. Supply of sodium to the insulation block with the specified flow rate was carried out by opening the valve on the connecting pipe.

Controlled parameters during the experiments was the pressure, temperature and the level of sodium in container, the temperature inside steel foil insulation and outer casing of insulation around the place of sodium leak, the air temperature and humidity in the experimental box.

By the processing of experiments the nature of flow sodium under isolation and outside it was investigated under the given experiments conditions (postulated size defect and the temperature of leaking sodium). The temperature status of steel foil insulation block was studied at different temperatures of flowing sodium. The impossibility of jet expiry and spray sodium burning at a given defect size was studied and inability of sodium burning at the temperature lower than 180°C is tested.

4.2.Design of the Steel Foil Insulation Blocks

The cut of the Steel Foil Insulation Blocks is presented in figure 1.
The blocks consist of a package of stainless steel sheets (pos. 1), the sheets in the pack are arranged with a certain gap of the flat and corrugated sheets alternation. On the outer surface of the blocks is the stainless steel liner (pos. 2), which is welded to the attachment points of the blocks to a safety case (pos. 3). Due to the stepped arrangement of the vertical blocks joints overlaps the gap between adjacent blocks. The gaps between the blocks on the outside overlaps with trims or overlap welding the exterior cladding units to seal the outer surface of the insulation relative to the reactor shaft.

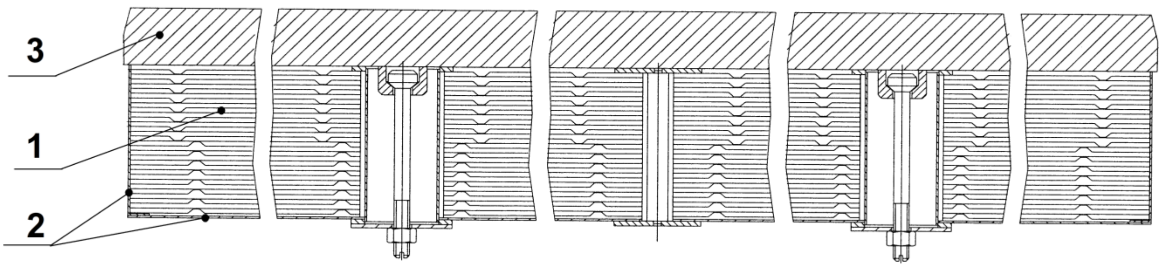

FIG 1. The cut of the Steel Foil Insulation Blocks.

4.3.The Results of Experimental Researches

During the experiments all blocks of steel foil isolation confirmed its efficiency as insulation. But the insulation steel foil blocks cannot perform the function of holding the sodium flow through a defect in the simulator of safety case under the given experimental conditions. During the experiments the jet expiration and sprayed fire of leaked sodium was not observed.

5. Numerical research of leak detection system effectiveness based on smoke aspiration fire sensors VESDA

5.1.Initial Preconditions and the Object of Research

To confirm the efficiency of sodium leaks detection system based on VESDA type sensors the numerical analysis disruption of normal operation with depressurization of the pipeline and sodium burning in second loop technological room on fast reactor. The leak and sodium combustion consequences the premises were considered as a result of crack in the second loop pipeline. Some assumptions of this disruption scenario are similar to the parameters of maximum design accident discussed in section 3. As independent failure from the initial event the operator error was accepted (the operator do not promptly switched the regular ventilation in premise to emergency exhaust ventilation).
The aim of this work is to assess the efficiency (performance) of the detection system and the choice of the most appropriate placement of sampling sites air samples from the protected areas on the sensitive element of the detector.
Numerical research were performed with use of computer code BOX-3D developed by IPPE.
The computer code BOX-3D allows to simulate the following processes in 3D-geometry within the premises of sodium cooled fast reactors:

- the heat source action due to the heat release from the equipment and sodium burning;
- the mass source action due to the sodium aerosols release from the burning area;

- geometrical characteristics of a considered premise, including the gas environment, burning area and building structures;
- mass exchange and sedimentation of sodium aerosols on building structures and air lines of ventilation systems.

5.2.Calculation Research Results

From the result of numerical research for the disruption of normal operation regime was found that the sodium aerosols concentration in 30 seconds after a leakage of sodium (taking into account the response time of the sensor after 90 seconds) reaches a value of ~1 mg/m^3 (given the sensitivity of the system) not only on the surfaces of building structures and vent channel, but also inside the gas volume of the room.
Thus for the accident conditions accepted the sampling duct of leak detection system VESDA at any point in the space of the second loop fast reactor premise will fix sodium leaks for the time below the predetermined speed of the leak detection system (3 minutes).

6. Analysis and Processing of Experimental Data of Sodium Spray Burning

6.1.The Main Objectives of Analysis and Processing of Experimental Data

The first objective is to obtain the calculated equations to simulate the process of sodium spray burning in fast reactor technological rooms based on the results of the analysis and processing of experimental data.
The second is use the analytical equations for upgrading the computer code BOX2000 (calculation of parameters on sodium burning process) in terms of modeling the sodium spray fire process together with pool sodium fire.
The third is the application French experimental study of the sodium spray burning for computer code BOX2000 verification.

6.2.Review of Experimental Data for Sodium Spray Burning

The analysis of sodium spray burning processes combined with an increase of gas pressure and temperature is made on the basis of numerous experiments with dispersion of sodium in experimental boxes. These experiments was conducted by the French experts and presented in the references [7—9].
Initial conditions and results of the most representative experiments, and also the parameters calculated on the basis of these data are given in article [10].
The basic conclusion from the analysis of experimental data is that under the given experimental conditions the spraying of sodium that flowing through defect at the air accompanied by quick (no more than 110 seconds) increasing of gas pressure in experimental boxes to unacceptably high values (up to 333 kPa).

6.3.Equation for Estimating the Pressure Rise (First Peak) with Free Sodium Jet Spraying in the Air

The ratio of sprayed sodium D is determined on the basis of the following precondition: the heat released from sodium burning is spent on growth of gas pressure in box due to air heating. The equation of heat balance (heat from the sodium burning required to increase the pressure of the gaseous medium).
The equation of heat balance for air growth pressure definition in box can write in following kind:

$$F \times \tau_m \times D \times q = V \times \gamma \times C_p \times T_o \times P_m^{exc}, \quad (1)$$

Where F – the sodium flow rate, kg/sec; τ_m – the time at which the pressure reaches its maximum value, sec; $q = 11{,}3\ MJ/kg\ Na$ – the heat of sodium burning; V – the volume of the chamber, m^3; $\gamma = 1{,}2\ kg/m^3$ – air density at initial temperature; $C_p = 1{,}005\ kJ/(kg \cdot K)$ – the air heat capacity; T_0 = 300 K – the initial air temperature, P_m^{exc} – maximum excess pressure.
The right part of balance is received from the equation of ideal gas. From equation (1) after substitution of the known data we shall receive the formula for definition of the ratio of sprayed sodium D:

$$D = 3{,}26 \cdot 10^{-7} \times V \times P_m^{exc}/(F \times \tau_m). \quad (2)$$

In equation (2) maximum excess pressure in box P_m^{exc} is set in Pa.

7. The Problem Decision with Fast Growth of Gas Pressure at the Sprayed Flow out of Sodium Jet

Operating conditions of pipelines and equipment with sodium at fast reactors are essentially different from the conditions realized in experiments [7—9].
One of essential differences is the presence of electric heating systems at almost sodium systems, pipelines and the equipment of fast reactors. These systems are intended for heating and maintenance the given temperature of sodium in process of operation. Besides for decrease the thermal losses from heated pipelines and equipment an electric heaters of pipelines and the equipment are covered by thermal insulation. For protection against mechanical damages above the insulation a metallic protective casings are installed.
The opportunity of safe localization and exception of conditions for the sodium spray burning may be confirmed by results of experimental researches with sodium leakages through defect in the pipeline beneath thermal insulation executed in IPPE. The basic results of researches are given in works [11, 12].
The experimental setup consists of a working section, sodium tank and gas receiver. The working section was made in a form of horizontal tube made of 0Kh19N10T steel with length 780 mm, external diameter 145 mm and walls thickness 5 mm. On the top of the pipe a defect was created – a round opening 2 to 10 mm in diameter in order to simulate upward outflow. The ends of the tube were plugged. Sodium was fed from a sodium tank along the tube to defect. Sodium flow was created by feeding inert gas from the receiver into the sodium tank. Electric heaters were arranged on the surface of the working section and the sodium system; on the working section heat insulation of prescribed thickness with or without facing was arranged on top of the heaters. The setup was placed in a 220 m^3 process box, which made it possible to visually observe through an observation window the outflow and fuming of the box.
The experiments were performed in the following order. The sodium, sodium pipeline, and working section were heated to a prescribed temperature. The required pressure was created by feeding gas into the sodium tank; sodium was fed into the working section beneath the thermal insulation with a prescribed flow rate by rapidly opening a valve. The following were recorded during the experiment: the indications of thermocouples arranged near the defect, at distance 100 mm to the left and right of the defect, and in air at height 250 mm above the defect as well as the flow rate, the time at which sodium was introduced, and the gas pressure in the sodium-feed tank.

The main result of these experiments is that the sodium flows inside the tube in a gap between the heaters and thermal insulation and flows down into the bottom part of the working section. It flows into the room, without splashing, in the form of intermittent streams and large drops. Burning starts at leak sites, and then the flame propagates along the surface and continues onto the floor of the box.
At presence the equipment and pipelines without thermal insulation (electromagnetic pumps, pulse tubes of devices of the control etc.) in the technological scheme of fast reactor second loop the dispersion of leaked sodium may be excluded by installation the screens on a way of possible sodium leaks (for example, cooling of the electromagnetic pump in the channel formed by the screen). In some cases, when screens using is complicated and parameters of sodium leakage and its dispersion do not represent danger, it is possible to allow the sodium spray burning and take into account its consequences.

Conclusion

Based on requirements of regulatory documents on fire safety the concept and composition for sodium fire safety system in technological premises of perspective fast reactor are generated.
Numerical researches of possible failures consequences with a sodium leak and burning in perspective fast reactor confirmed efficiency of the accepted technical decisions on localization of sodium burning consequences and protection of premises against dangerous fore factors for conditions of maximum design accident.
Experimental results of steel foil insulation blocks confirmed their efficiency as thermal insulation. However the insulation blocks of the given design are not capable to keep the sodium flowing out through defect in the simulator of the safety case. During the experiments the jet flow out and sodium spray burning was not observed.
The numerical researches confirm the effectiveness of sodium leaks detection system based on VESDA type sensors. It is shown that installation of the leak detection system VESDA sampling duct at any point in air space of the second loop fast reactor premise for disruption of normal operation will fix the sodium leak for smaller time, than required for a leak detection system (3 minutes).
The experimental data analysis on sodium spray burning has shown rapid growth (in some ten seconds) of the gas pressure in tight box up unacceptably high values (for some hundred kPa). The rapid gas pressure growth is connected to the instant opening of systems with sodium equipment without the thermal insulation and its jacket, and also with a high dispersion ratio of liquid coolant. As a result of the experimental data analysis and processing on sodium spray burning sodium the analytical equation for an estimation of the gas pressure growth (the first peak) are received.
The analysis of experiments with instant opening of defects beneath thermal insulation and its jacket under the close conditions has shown, that conditions for sodium jet formation and sodium dispersion then it flows through thermal insulation and burns on a box floor does not exist, thus the appreciable increase of the gas pressure in box was not observed. Thus, based on analysis of experimental data complex the opportunity for safe localization of sodium spray burning is shown at presence on pipelines and equipment the thermal insulation and its jackets with thin-walled not tight casings.

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