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SEVERE ACCIDENT MANAGEMENT AT NPP-2006 REACTOR PLANTS (LENINGRAD NPP-2)

V. G. Sidorov, V. O. Astafieva, Yu. V. Krylov, K. S. Titov,
V. O. Kukhtevich, S. E. Semashko, and A. G. Mitryukhin

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The article examines measures involved in severe accident management for NPP-2006 reactor plants based on the Leningrad NPP-2 prototype and their substantiation using deterministic analysis and special computer codes. The results obtained during the analysis should be considered in the development of severe accident management guidelines for these reactor plants in terms of the composition and priority of management actions.

The present article demonstrates the management of severe accidents at reactor plants of the NPP-2006 type based on the Leningrad NPP-2 prototype.

Severe accidents associated with the melting or partial destruction of the nuclear fuel at an NPP are possible with the failure of safety systems designed to remove heat from the reactor plant. For NPP-2006 reactor plants for which the Leningrad NPP-2 is a prototype, the containment passive heat removal system (C PHRS), as well as the system of passive heat removal from the reactor through steam generators (SG PHRS), remove heat even under conditions of complete power supply failure. Under such conditions, the main events representing the risk of a severe accident involving reactor core meltdown include leaks from the primary circuit into the containment circuit in the event of safety systems not compensating for the loss of the coolant.

In accordance with NPP safety requirements [1, 2] for accidents involving significant damage to the fuel, it is necessary to provide measures for minimizing radiation exposure to personnel, population, and environment. In accordance with the defense-in-depth concept, actions associated with the management of severe accidents begin at the fourth level after diagnosing the transition of an accident into the severe stage. In such cases, a significant proportion of management measures is accomplished by the operator manually.

Prior to the transition of an accident to the severe stage, the actions of NPP personnel are primarily oriented towards averting severe damage to the fuel in the core and spent fuel pool. The main task at this stage of accident management is to feed the spent fuel pool and primary circuit. In order to feed the reactor, it is necessary to restore the operability of the equipment in the systems supplying water to the primary circuit. As an alternative to the design systems, the cooling of spent fuel can be performed using external water reserves located at the site. For this purpose, the NPP-2006 designs of reactor plants provide for a separate independent system with an autonomous power supply.

Following the transition of an accident to the severe stage, actions to mitigate its consequences must be carried out. For accidents with primary circuit leaks, the main tasks consist in the localization of radioactive materials inside the containment and steps for decreasing radioactive emissions into the atmosphere. Severe accident management involves:

– protection of the containment from physical influences that can lead to loads that violate its integrity and tightness;

– transfer of the NPP to a controlled state in order to prevent damage to the containment and implement preventive measures to reduce radiation exposure;

– transfer of the controlled NPP to a safe state for minimizing radiation consequences.

Atomenergoproekt, St. Petersburg, Russia; e-mail: vgsidorov@atomproekt.com. Translated from Atomnaya Énergiya, Vol. 133, No. 3, pp. 144–150, September, 2022. Original article submitted September 12, 2022.

TABLE 1. Containment Hazards and Means for Their Prevention for NPP-2006 Reactor Plants

Physical phenomenon	Safety barrier hazards	Averting the safety barrier violation
Detonation/combustion of combustible gases in the containment	Action of the temperature and pressure from the side of the containment medium	Measures for averting detonation involving operation of the passive hydrogen removal system
Intra-vessel steam explosions	Containment action following rupture of the reactor vessel due to an increased pressure of the primary circuit	Internal properties of equipment, measures to exclude water supply to the superheated zone
High pressure in the primary circuit in the case of the reactor vessel destruction	Direct heating of the containment due to the heat exchange with the dispersed melt after the destruction of the reactor vessel	Internal properties of equipment, availability of passive heat removal systems of the primary circuit, pressure reduction in the primary circuit
Uncontrolled nuclear reaction	Action on the containment following a rupture of the reactor vessel due to an increase in the pressure of the primary circuit	Internal properties of equipment, measures to exclude the water supply to the core
Violation of the heat removal from the containment to the final absorber	Slow static loading by internal pressure	Application of a special containment heat removal system
Melt removed from the reactor vessel and spent fuel pool	Melting of structures upon contact with the fuel melt	Retention of the melt outside the reactor vessel using the molten core catcher; alternative fuel cooling in the spent fuel pool

A controlled state following a severe accident is characterized by the stabilization or steady decline of all containment medium parameters in the absence of hazards associated with the violation of preserved safety barriers. The transition of an NPP to a safe state following a severe accident is established when the following conditions are provided:

– the melt is reliably localized and hardens, having a stable or reduced temperature;

– the heat from core fragments is removed and transferred to the final absorber;

– the configuration of nuclear fissile materials is such that the effective neutron multiplication factor is below 1;

– the pressure in the containment is sufficiently low that emissions of fission products into the atmosphere are almost absent.

The transition to a safe state can be carried out as soon as the functioning of necessary systems have been restored. The achievement of a safe state after a severe accident for NPP-2006 reactor plants is possible by restoring the cooling of the containment medium and suppressing the existing sources of vaporization (molten core catcher, spent fuel pool). Severe accident management implies the protection of safety barriers against physical phenomena characteristic of severe accidents. Since the main safety barrier in severe accidents consists in the containment, the protection of such barriers following the transition of an accident to the severe stage becomes a priority.

Table 1 summarizes physical phenomena hazardous to the containment, along with measures for averting or mitigating them, realized within the framework of the NPP -2006 design of reactor plants.

Deterministic analysis was performed to justify the severe accident management measures.

Deterministic analysis of severe accidents. The deterministic analysis of severe accidents is performed using certified computer codes:

SOKRAT-V3/KUPOL-M software package for combined modeling of severe accidental processes in the containment, as well as intra-circuit processes;

HEFEST-EVA software module (included in the SOCRAT-V3 code) for calculating physical and chemical processes in the molten core catcher);

LIMITS-V and FIRECON codes for analyzing combustion conditions in the containment;

TDMCC code for criticality analysis.

The results of the deterministic analysis are used to assess the fulfillment of special severe accident criteria. The fulfillment of the acceptance criteria is a prerequisite of not exceeding the normative limit emissions from the containment established for severe accidents. The provided criteria were developed for NPP-2006 reactor plants based on the requirements of domestic regulatory documents, IAEA recommendations, and the experience of the NPP computational substantiation.

For severe accidents, the following acceptance criteria are used:

– the concentration of a gas mixture in the containment should not reach an explosive (detonation) value;

– the interaction of the melt with the water should not result in damage to the building structures of the containment due to peak pressure increase;

– the destruction of a vessel under the thermal effect of a melt at a high pressure should be avoided. The value of 2 MPa has been selected as the maximum permissible pressure for the moment of the reactor vessel destruction in accordance with the recommendations of [3];

– damage to the containment under the direct influence of fuel melt must be excluded;

– the parameters of the containment medium must ensure its integrity and standard operation of accident management systems. The maximum permissible parameters are selected based on the strength analysis of the containment building structures under the influence of various internal loads;

– the subcriticality of the destroyed and molten core, as well as that of the molten core catcher, shall be ensured. NPP-2006 reactor plant designs assume that subcriticality is ensured by an effective neutron multiplication factor of no more than 0.95 [4].

Let us consider some particular aspects of organizing accident management measures relevant for NPP-2006 reactor plants.

Primary circuit water supply for averting reactor core destruction. At the initial stage of an accident prior to its transition to the severe stage, the operator must employ all possible means to prevent its transition to the severe phase. When it is possible to restore the feed of the primary circuit, water must be supplied to the reactor prior to the diagnosis of significant core damage. The possibility of this supply is determined by restoring the operability of the systems supplying water to the primary circuit. After the beginning of the core heating, the water supply into the primary circuit can lead both to positive and negative consequences. In order to make a decision about water supply into the overheated core, it is necessary to evaluate hazards that can lead to possible damage to the containment.

The effectiveness of measures for preventing the significant destruction of the reactor core during the restoration of the primary circuit feed depends on the time interval from the beginning of the core heating to the water supply and on the flow rate of the supplied water. Containment tightness hazards include increased synthesis of hydrogen, the possible loss of fuel-water system subcriticality upon partial or complete core destruction (this can lead to an uncontrollable nuclear reaction), as well as the impossibility of intra-vessel retention of the melt in the case of its extensive area formed due to the absence of the special technical equipment for the external cooling of the reactor vessel. If the hazards connected with the risk of the containment damage are significant, then attempts to localize the damaged core inside the reactor vessel should be abandoned to prioritize extra-vessel localization in the molten core catcher.

The hazards were analyzed using SOKRAT/V3, KUPOL-M, and LIMITS-V severe accident codes. An example of the analysis for an accident with the break of the main circulating conduit and the failure of high- and low-pressure emergency core cooling systems (HP ECCS and LP ECCS) is shown in Fig. 1. The accident scenario assumed that the operator succeeds in restoring the operability of one HP ECCS channel at the beginning of the core heating and supplying the water to the primary circuit. This accident scenario examined the water supply upon reaching a temperature above the core of 400, 500, 600, 650, 700, and 800°C.

According to the calculations, core flooding that causes no hazard of violating the containment integrity is possible before the core is heated up to 650–750°C. The limit temperature above which the core destruction cannot be prevented without significant damage depends on the beginning of the water supply and the flow rate of the primary circuit feed from the restored safety system.

Following core draining, fuel rod claddings are rapidly heated and the operator has a little time (for significant leaks – 10 min) to make a decision about water supply to the primary circuit after the beginning of heating. Accordingly, when supplying the borated water to the destroyed core, the risk associated with operator error is high. Based on the analysis, it is recommended that an increase in the above-core temperature over 650°C be determined as a signal for prohibiting water

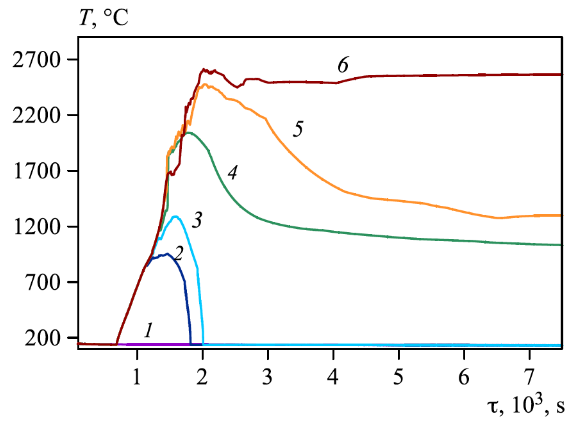

Fig. 1. Maximum temperature of fuel rod claddings in the core during the water supply at the above-core temperature of 400 (*1*), 500 (*2*), 600 (*3*), 650 (*4*), 700 (*5*), and 800°C (*6*).

supply into the primary circuit. After reaching this temperature, the operator may not supply the water to the core. At the same time, it is necessary to take measures that exclude the possibility of resuming the water supply. In order to prevent the unauthorized start-up of water supply systems, the corresponding pump control units will be dismantled.

Diagnostics of the accident transition to the severe stage. In accordance with conventional international practice, the transition of an accident to the severe stage is diagnosed from the indications of temperature sensors above the core when a certain value is exceeded. The limit temperature of starting the management of a severe accident is defined by the characteristics of equipment and by the composition of the measures used by NPP personnel to manage severe accidents. For NPP-2006 reactor plants (Leningrad NPP -2, Astravets NPP, Paks-2 NPP (Hungary), El-Dabaa NPP (Egypt), Xudabao NPP, 7th and 8th power units of Taiwan NPP (China)), this temperature is located in the interval of 400–650°C.

Hydrogen safety in severe accidents. Detonation in the containment accommodations represents the most complex problem, requiring the introduction of special management measures in the case of severe accidents at NPP-2006 reactor plants. In order to achieve a reduction in the hydrogen concentration, catalytic recombiners are used. In accordance with the specifications, these enter the base operating mode slowly and have limited productivity. The power of recombiners is selected in such a way as to ensure the oxidation of the entire hydrogen mass released into the containment within a certain time interval. However, under the conditions of severe accidents following the intensification of the steam–zirconium reaction at the temperature of zirconium fuel rod claddings above 1200°C, calculations show the rapid peak ejection of hydrogen resulting in its high concentration in accommodations.

According to the analysis, in the absence of special management measures affecting the hydrogen concentration in the accommodations, a dangerously explosive concentration of combustible gases can be formed adjacent to the location of a leak in the primary circuit during severe accidents with small coolant leaks. For NPP-2006 reactor plants, this problem is aggravated by a large containment volume and the operation of passive heat removal systems for decreasing the vapor concentration. For example, Fig. 2 depicts a cartogram illustrating the possibility of hydrogen detonation in an accident with a small coolant leak in the primary circuit having a conditional diameter of 40 mm from the primary circuit cold leg of the El-Dabaa NPP reactor plant upon the simultaneous failure of emergency core cooling systems. The cartogram represents the calculated volumes of the KUPOL-M code, where the possibility of detonation after the beginning of a severe accident is evaluated using the LIMITS-V code. The calculations demonstrate the detonation hazard in the boxes of steam generators and the accommodations adjacent to them.

The solution of this problem requires a change to be effected in the ratio of hydrogen and oxygen concentrations in containment accommodations. This can be achieved either by increasing the steam quantity in the containment though a decrease in its condensation or organizing an additional supply for inertization. For this purpose, it is necessary to turn off the sprinkler system in those scenarios where such systems are operational. In this case, as calculated estimations have shown, the design criteria of dose loads established for a DEC accident scenario are not violated with the invoking of the SOCRAT-V3/KUPOL-M code. The corresponding actions on turning off the sprinkler system are provided at the diagnosed severe accident hazard following the failure of the primary circuit feed. However, according to the calculations, this single

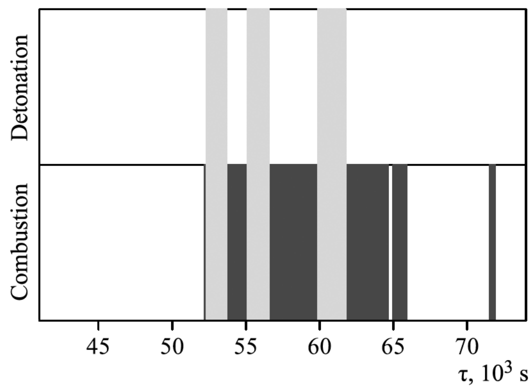

Fig. 2. Combustion and detonation conditions of the CD 40 leak accident upon the emergency safety system failure.

action is insufficient for the scenarios of accidents with small coolant leaks. The additional supply of steam can be organized by limiting the heat removal from the secondary circuit by turning off the passive heat removal system through the steam generators (SG PHRS) and fast-acting atmospheric reducing units (FAAR). Calculations have shown the effectiveness of this measure in preventing the formation of detonating hazardous mixtures.

At the same time, such management measures lead to an acceleration in the development of an accident and its transition to a severe stage. A more optimal management option involves the forced discharge of hydrogen formed in the primary circuit into the accommodation of a large volume removed from the accommodation with the leak. This measure, which is performed after the diagnosed transition of an accident to the severe stage, decreases hydrogen concentration in the accommodations near the leak localization. NPP-2006 reactor plants can use two discharge options: either to the central hall of the reactor building located above steam generator boxes, or into the accommodation of conduits and reinforcement, which is located under steam generator boxes. For the Paks-2 and El-Dabaa NPPs, the option with the discharge of the steam–gas medium from the primary circuit into the dome space was selected. In this case, the discharge is carried out from the pressurizer header using a special system. In severe accident scenarios involving the failure of the heat removal through the secondary circuit, an additional discharge of the primary circuit medium excludes high pressure in the reactor vessel at the moment of its destruction.

The behavioral modeling of combustible gases in the containment with the attraction of the severe accident codes showed the effectiveness of the accepted technological solution for providing hydrogen safety at the average and small leaks of the primary circuit: the zone of detonation conditions completely disappeared, while the combustion zone decreased.

For the 7th and 8th power units of Taiwan NPP and Xudabao NPP, for which Leningrad NPP-2 is also a prototype, the discharge of the primary circuit medium is performed into the accommodation of the reinforcement, located under the boxes of steam generators. Calculations proved the effectiveness of the accepted technological solution (Fig. 3). The analogous technological solution is planned to be realized at Leningrad NPP-2.

Recommendations for operator actions in severe accident management. The sequence and priority of severe accident management tasks performed by operating personnel are set out in the form of procedures in the Severe Accident Management Guidelines. They also contain a set of criteria that determine the containment tightness hazard, requiring an immediate response and a change of priority in terms of management procedures.

Using deterministic analysis, the following recommendations can be given regarding the development of severe accident management procedures (SAMP) and serious threat management procedures (STMP) for NPP-2006 reactor plants in terms of the composition and priority of management actions:

– for the SAMP “Preventing the transition of the accident to the severe stage,” which has the highest priority, in term of its exit point, the maximum temperature, limiting operator actions when implementing this procedure, as well as measures aimed at eliminating an unauthorized water supply after this point. For NPP-2006 reactor plants, this point currently corresponds to the above-core temperature, at which the transition of the accident to the severe stage is diagnosed;

– following the transition of an accident into the severe stage, the elimination of possible combustible gas detonation in the containment is the greatest priority. The relevant actions of the operator to prevent the formation of detonation hazardous gaseous mixtures should be reflected in the SAMP as having a high priority;

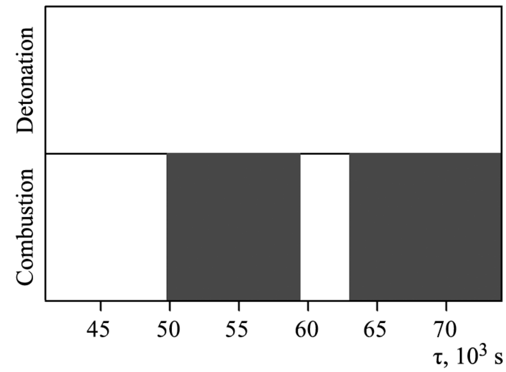

Fig. 3. Combustion and detonation conditions of the CD 40 leak accident upon the failure of active safety systems at the presence of management actions on averting the detonation of combustible gases.

– following the transition of an accident to the severe stage, the operator must ensure that the pressure in the primary circuit constitutes no danger to the containment and implement the SAMP "Reducing the pressure in the primary circuit." The commencement of this procedure corresponds with the diagnostics of the transition of an accident to the severe stage;

– further, it is required to carry out actions aimed at the long-term localization of the melt – according to the SAMP "Ensuring the safe retention of the melt in the molten core catcher". To do this, the operator must ensure the reliable additional cooling of the catcher wall by opening the valves on the lines connecting the shaft and the pit. This action diversifies the cooling of the wall by means of water entering the shaft from the floor of steam generator accommodations. Next, the operator must trace the actuation of passive water supply valves and, if necessary, supply the water from the intra-vessel revision shaft to the surface of the melt; after the beginning of a severe accident at the design functioning of the containment passive heat removal system, the overpressurization hazard is absent and no obligatory operation of the sprinkler system is required. At this stage, the main task of the operator is to guarantee the necessary water level in the reserve tanks of passive safety systems from external sources after their draining;

– the minimization of radioactive emissions into the atmosphere according to the SAMP "Reducing the emission of fission products" is carried out by the operator through the supply of alkali to the pit using a special system at the diagnosed beginning of a severe accident to bind iodine radioactive isotopes;

– at the later development stage of an accident, it is necessary to decrease the containment pressure to the atmospheric level in order to reduce ejection from the containment. As the calculation analysis shows, this action is effective only at the restored operability of the sprinkler system and the suppression of vaporization in the spent fuel pool and molten core catcher. In the case of a severe accident, the sprinkler system can be started only after achieving a low concentration of hydrogen in the containment (below the ignition limit of 4%). When the sprinkler system operates, it is necessary to monitor the hydrogen concentration and prevent it from exceeding 4%.

Conclusion. The management measures developed for NPP-2006 reactor plants ensured compliance with the design safety criteria established for severe accidents. Their implementation in the NPP-2006 designs for reactor plants requires appropriate adjustments to the Severe Accident Management Guidelines in terms of the composition and priority of severe accident management procedures.

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