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Inherent Safety Characteristics of Advanced Fast Reactors

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Inherent Safety Characteristics of Advanced Fast Reactors

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Abstract. The study presents SFR transient performance for ULOF events initiated by pump trip and pump seizure with simultaneous failure of all shutdown systems in both cases. The most severe cases leading to the pin cladding rupture and possible sodium boiling are demonstrated. The impact of various features on SFR inherent safety performance for ULOF events was analysed. The decrease in hydraulic resistance of primary loop and increase in primary pump coast down time were investigated. Performing analysis resulted in a set of recommendations to varying parameters for the purpose of enhancing the inherent safety performance of SFR. In order to prevent the safety barrier rupture for ULOF events the set of thermal hydraulic criteria defining the ULOF transient processes dynamics and requirements to these criteria were recommended based on achieved results: primary sodium flow dip under the natural circulation asymptotic level and natural circulation rise time.

1. Introduction

Nowadays the one of the most important advanced NPP requirements is the safety requirement. NPP safety is a result of safety management, legal and engineering measures. Engineering measures employed so far include those that enhancing inherent safety performance of reactor. According to [1] «inherent safety refers to the achievement of safety through the elimination or exclusion of inherent hazards through the fundamental conceptual design choices made for the nuclear plant». It should be noted that inherent safety doesn't exclude the implementation of the active and passive safety systems in reactor design, but it rather ensures the reliance and diversity of reactor safety performance. The aim of the implementation of inherent safety principles in a reactor design is to reach such a safety level that there would be no combinations of transient initiating events that could violate the integrity of NPP safety barriers. In this case the initiating events could be both internal (any NPP system failure) and external ones (resulted from specific to NPP site impacts of natural phenomenon or human activity) including terrorism. According to [2] «a set of design extension conditions shall be derived on the basis of engineering judgement, deterministic assessments and probabilistic assessments for the purpose of further improving the safety of the nuclear power plant by enhancing the plant's capabilities to withstand, without unacceptable radiological consequences..». Thus a need arises to simulate such events and their consequences, to design additional engineer features and to provide their design-basis justification. That leads to increased timing budgets, physical resources and money supply required. The enhancing of inherent safety in advanced reactors designs makes possible to eliminate any beyond basis events on the early stage of conceptual design of reactor. Hence it would be not necessary to provide any additional safety management, to take any engineering measures with respect to beyond basis events on the stage of NPP operating.

2. ULOF transient analysis

The results of the inherent safety analysis presented in this article are obtained by using the one-dimensional DYANA code [3-6] for inherent safety analysis of fast liquid metal cooled reactors. Estimated sodium temperature and mass flow obtained from LOHS+LOF analysis via DYANA code [6] were in reasonable agreement with those obtained from PHENIX benchmark end-of-life test [7].

Under station blackout or loss of pump power supply conditions there is gradual reduction in primary sodium flow rate takes place due to pump trip. Pumps run-down time under all primary pumps trip conditions is sufficient to hold the temperature of the reactor components (fuel, cladding, primary sodium, reactor vessel, for LWR there are critical power ratio and steam-zirconium reaction margin) within acceptable limits and to remove reactor decay heat if reactor is scrammed. Besides, reactor design also includes auxiliary power supplies (batteries, diesel generators etc) providing primary pumps operating in the mode of decay heat removing (generally low flow rates about 5-6% of nominal value [8]). Natural circulation of primary sodium is developing if all power supplies failed. The most dangerous initiating event is pump seizure. Even single pump seizure may cause the excursion of acceptable temperature of fuel cladding.

ULOF transient dynamics depends not only on combination of initiating events but on the initial state conditions and parameters like initial power right before the accident, control rod position etc.

The results of ULOF transient analysis for fast sodium cooled reactor are presented in this chapter. MOX-fueled reactor 2800 MW of thermal power [9, 10] is under investigation. Seizure of all primary pumps (case A) and total loss of primary pumps power supplies (case B) are considered separately. Both accidents are under «without scram» and PDHRS system failure conditions. All secondary systems are normally operating. Initial state provides 100% nominal power.

Firstly, it is necessary to explore the conditions leading to violating of integrity of NPP safety barriers. There are 5 physical safety barriers for reactor under investigation (fuel matrix, steel cladding, reactor vessel and primary devices vessels, secondary devices vessels, containment). The safety barriers are termed through the acceptable temperatures (temperature criteria) of reactor critical components: fuel, cladding, primary sodium and reactor vessel. The values of all used temperature criteria are listed in table 1. The melting point is chosen for fuel temperature criteria because fuel melting causes increasing in gaseous fission products pressure under the cladding, besides the phase change gains the fuel swelling process. All these factors may cause the fuel cladding break. The value of cladding criteria is defined by the stress limits of fuel pin under the specific reactor conditions. The boiling temperature is set as the primary sodium criteria, because the sodium boiling can produce a high positive reactivity excursion due to the sodium void effect (if it is not negative). Finally the stress strain behavior of reactor vessel under the specific reactor conditions defines its temperature criteria.

Figures 1 and 2 illustrate the core components temperature excursion under cases A and B conditions accordingly. Case A is observed to be the most dangerous one (fig. 1) followed by cladding temperature unacceptable excursion on 8 sec. and sodium boiling onset on 15 s. of transient. Case B also initiates unacceptable cladding temperature excursion on 9 s. and sodium boiling onset on 15 s. of transient. This is very specific for ULOF transient to produce exceeding of cladding temperature criteria.

Table 1. Temperature criteria (Maximum acceptable temperatures of reactor critical components).

Component	Temperature criteria, K
Coolant	1153
Cladding	1073
Fuel	3023
Reactor vessel	1023

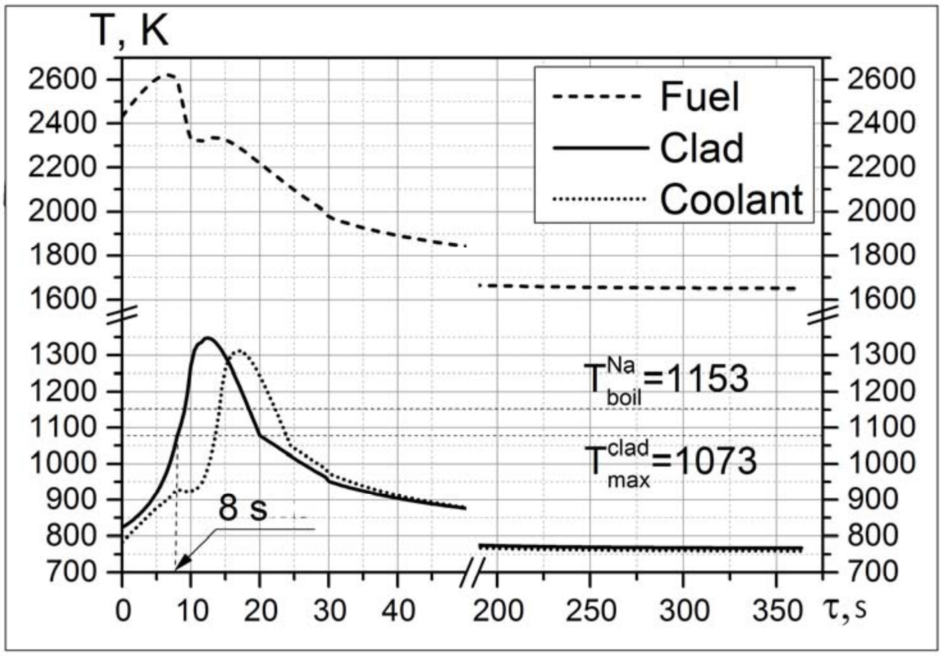

Figure 1. Peak temperatures of fuel, cladding and primary sodium under case A conditions.

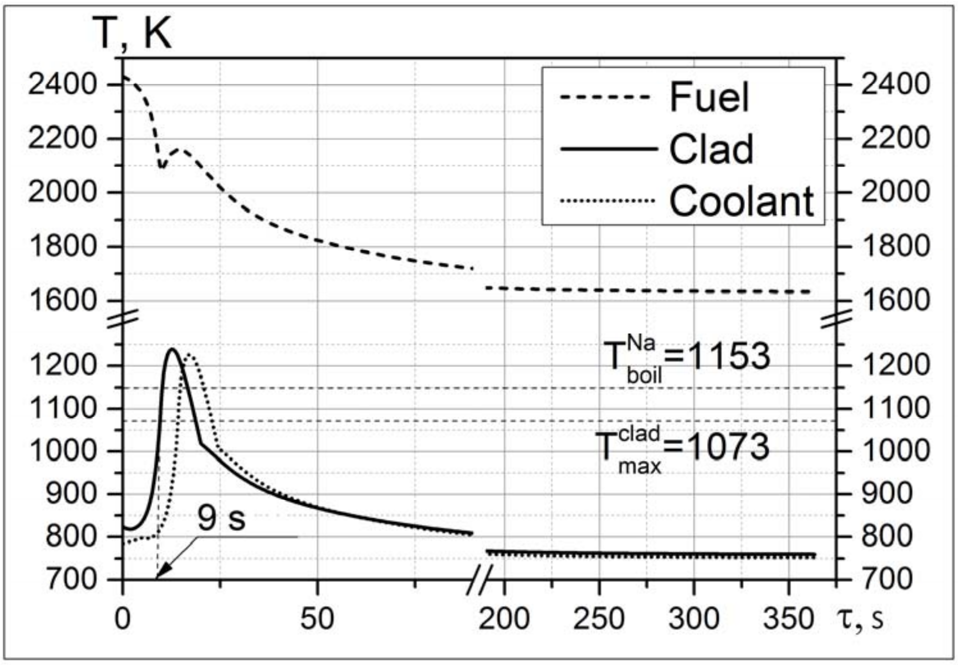

Figure 2. Peak temperatures of fuel, cladding and primary sodium under case B conditions.

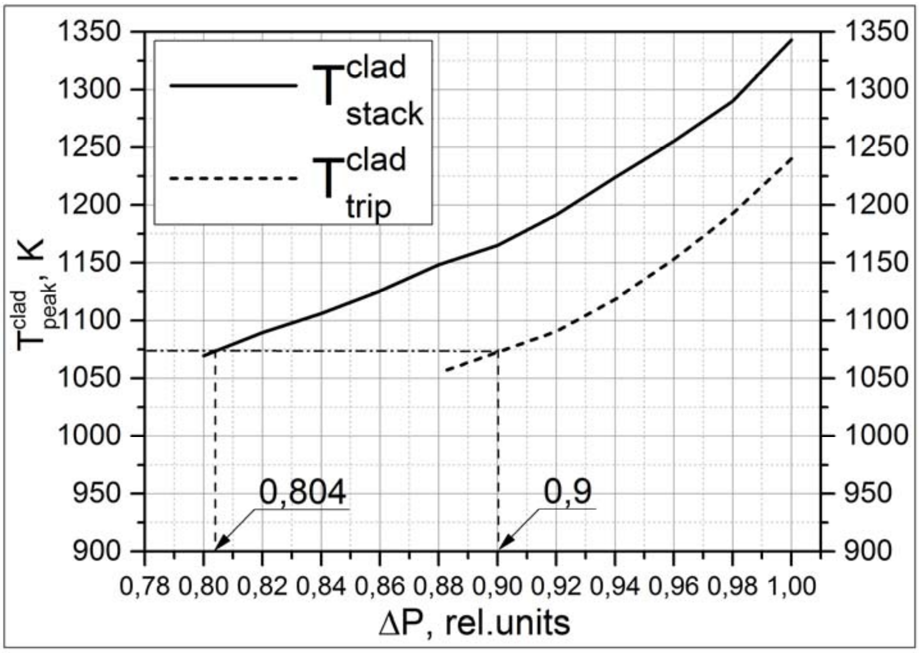

Figure 3. Peak temperature excursions under cases A and B conditions versus the pressure drop of primary circuit.

Next consider how do the values of some important reactor parameters impact on the peak temperature of the reactor components in term of the inherent safety.

The reducing of primary circuit pressure drop leads to the mitigation of ULOF transient. Temperature excursions are run down the acceptable values if primary circuit pressure drop reached $0.804\Delta P_0$ and $0.9\Delta P_0$ under cases A and B conditions accordingly (Fig. 3). To maintain the integrity of NPP safety barriers in terms of inherent safety of the reactor it requires the peak temperatures of the reactor components to stay within acceptable safety limits even under the most severe and low-probability conditions. In this work the most severe accident scenario is under the case A conditions. Fig. 4 illustrates that as the primary circuit pressure drop is reduced to $0.804\Delta P_0$ the reactor meets the requirement of safety barrier integrity under both case A and B conditions.

The safety barriers integrity conditions can be defined through the criteria characterizing the ULOF transient dynamics. The authors recommend such criteria as F_{NC} (natural circulation onset level), ΔF (coolant flow rate drop under the natural circulation onset level) and Δτ (time from coolant flow rate drop under the natural circulation onset level till natural circulation onset) (Fig. 5). Now to mitigate the ULOF transient the requirements to F_{NC}, ΔF and Δτ should be worked out.

The normalized primary sodium flow rate under case A conditions with reduced to $0.804\Delta P_0$ pressure drop is presented in fig 5. Referring to the fig. 5 recommended criteria values are shown in table 2. The peak cladding temperature is within acceptable limits, primary sodium boiling margin is 90º (fig. 4) if the requirements to the pressure drop and criteria are met.

The increasing of primary pump run-down time leads to the mitigation of ULOF transient under case B conditions. Temperature excursions are run down the acceptable values if run-down time reached the value of $1.8\tau_0$ (fig. 6). Only case B is considered because the increasing of primary pump run-down time under case A conditions obviously is not effective.

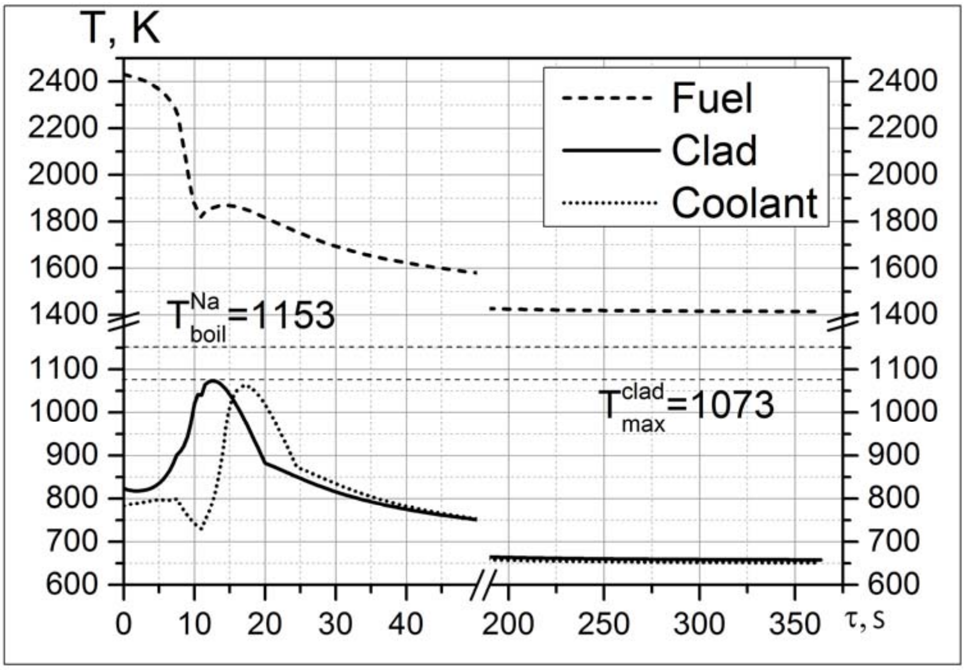

Figure 4. Peak temperatures of fuel, cladding and primary sodium under case A conditions with reduced primary circuit pressure drop.

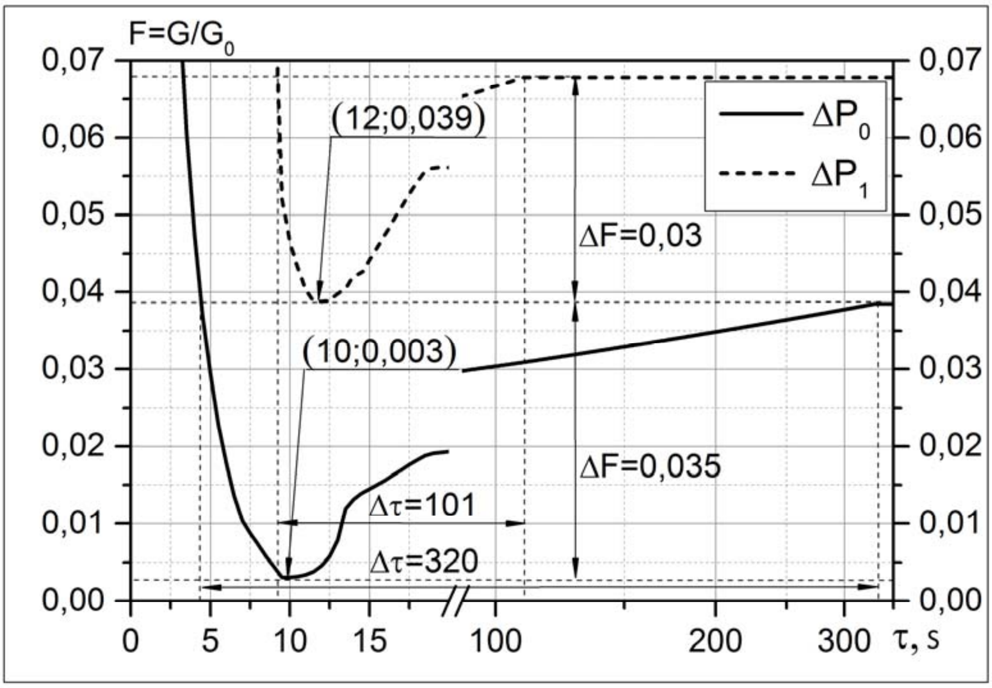

Figure 5. Primary sodium flow rate under case A conditions with reduced primary circuit pressure drop.

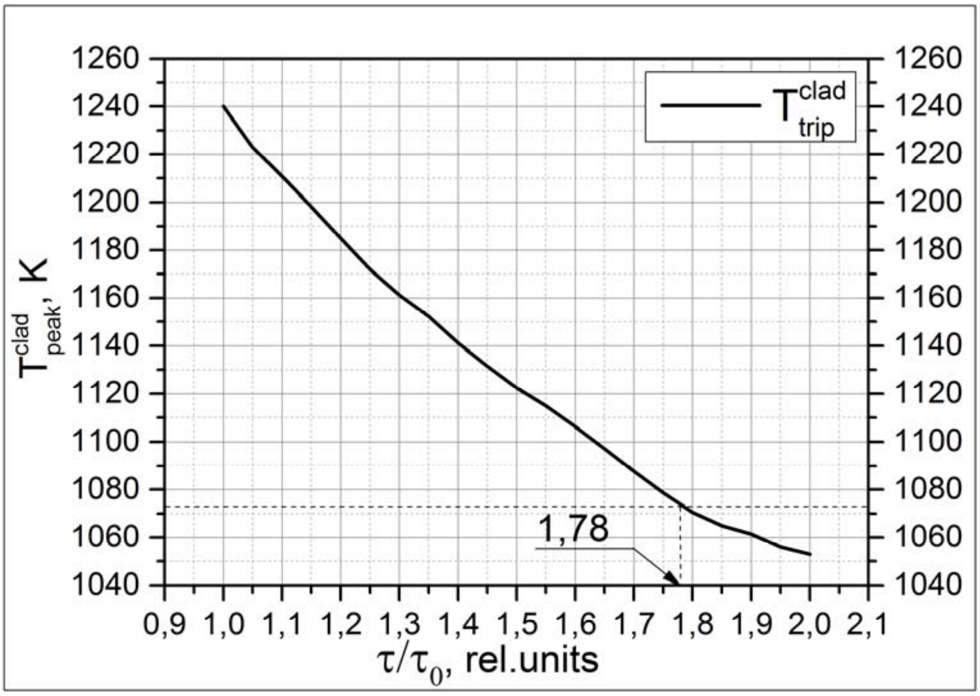

Figure 6. Peak temperature excursions under the case B conditions versus primary pump run-down time.

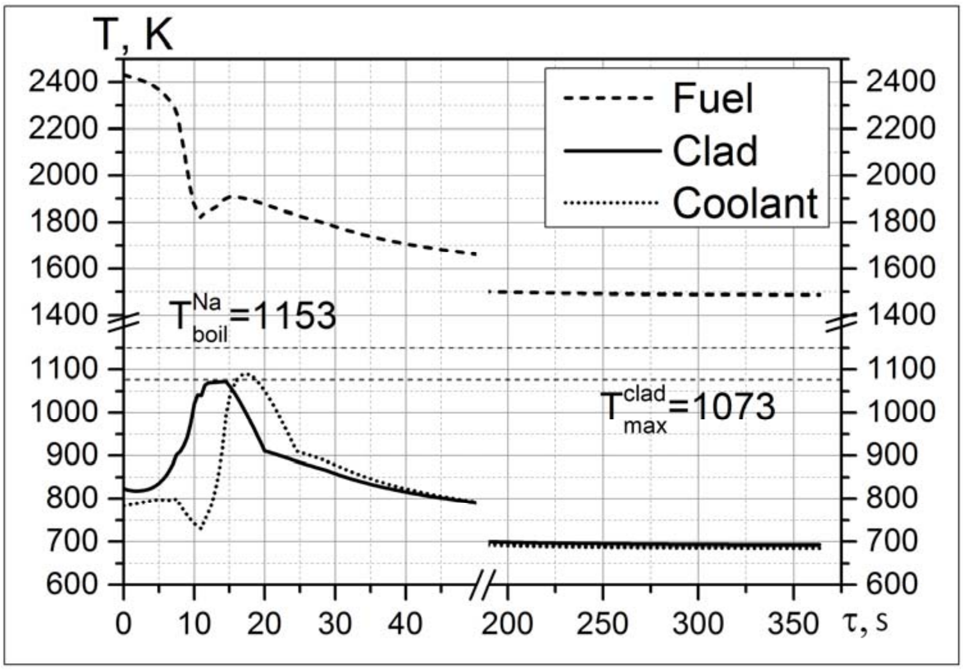

Figure 7. Peak temperatures of fuel, cladding and primary sodium under the case B conditions with increased primary pump run-down time.

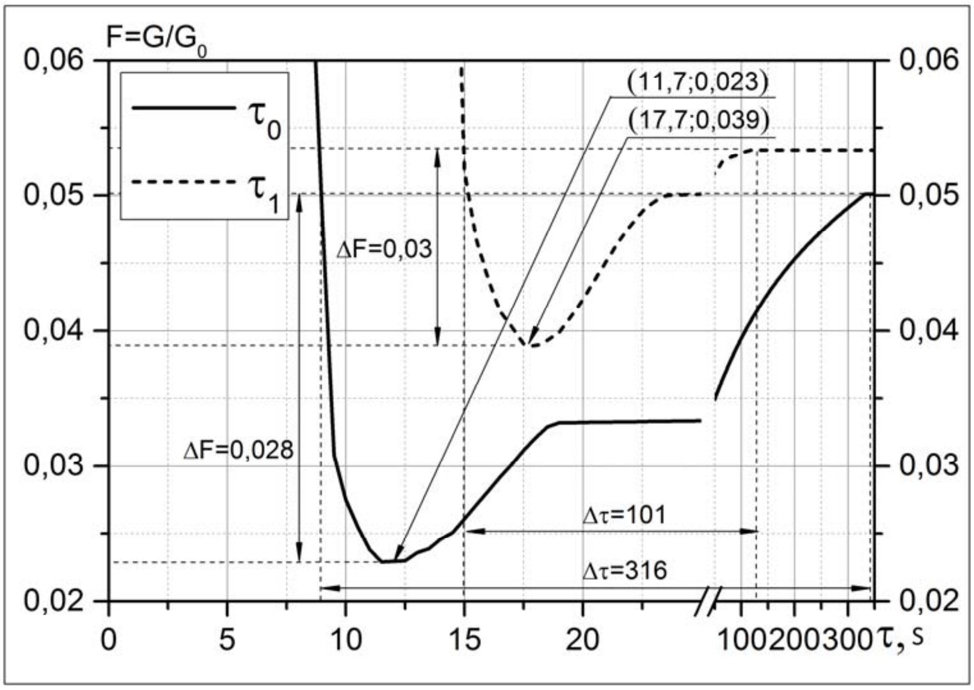

Figure 8. Primary sodium flow rate under case B conditions with increased primary pump run-down time.

Table 2. Requirements to the criteria characterizing the ULOF transient dynamics under case A conditions.

Criteria	Restriction
$\Delta\tau$	≤ 101 s.
ΔF	≤ 0,03 rel. units
F_{NC}	≥ 0,07 rel. units

Table 3. Requirements to the criteria characterizing the ULOF transient dynamics under case B conditions.

Criteria	Restriction
$\Delta\tau$	≤101 s.
ΔF	≤ 0,015 rel. units
F_{NC}	≥ 0,053 rel. units

The normalized primary sodium flow rate under case B conditions with encreased to $1.8\tau_0$ run-down time is presented in fig. 8. Referring to the fig. 8 recommended criteria values are shown in table 3. The peak cladding temperature is within acceptable limits, primary sodium boiling margin is 65° (fig. 7) if the requirements to the run-down time and criteria are met.

It should be noticed that integrity of NPP safety barriers is achieved under all investigated transient initiating events if the requirements to the criteria characterizing the ULOF transient dynamics are met.

3. Conclusion

ULOF transient performance analysis for pool-type MOX-fueled sodium fast reactor 2800 MW of thermal power is carried out. Two ULOF scenario cases were considered: all pumps seizure and all pumps trip. Both cases were followed by simultaneous scram and PDHRS failure. It was found out that the most severe case is all pumps seizure followed by exceeding of maximum acceptable fuel cladding temperature and possible sodium boiling.

The impact of various features on SFR inherent safety performance for ULOF events was also analyzed. The decrease in primary pressure drop and increase in primary pump run-down time were investigated. Performing analysis resulted in a set of recommendations to varying parameters in terms of enhancing the inherent safety performance of SFR under investigation. In order to exclude the safety barrier rupture for ULOF events the set of thermal hydraulic criteria characterizing the ULOF transient dynamics (fig. 5, 6) and requirements to them (tables 2, 3) were recommended based on achieved results: F_{nc} (natural circulation onset level), ΔF (coolant flow rate drop under the natural circulation onset level) and $\Delta\tau$ (time from coolant flow rate drop under the natural circulation onset level till natural circulation onset). To develop the refined requirements for the proposed criteria it is necessary to analyze SFR performance for ULOF, UTOP, ULOCA, ULOHS events and their overlaps coupled with uncertainty analysis. It is also necessary to take into account the heat removal through PDHRS even in a failure mode by heat-conductivity through the HX walls and to refine the acceptable temperatures of critical components of reactor with respect to reactor inherent safety.

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