ВЕСТНИК НАЦИОНАЛЬНОГО ИССЛЕДОВАТЕЛЬСКОГО ЯДЕРНОГО УНИВЕРСИТЕТА “МИФИ”, 2019, том 8, № 4, с. 309–320

Comparing the Consequences Pressure Waves due to MCP pump stops and LOCA in VVER-1000

© 2019 г. Dina Ali Amer[a,#] and S. P. Nikonov[b,##]

[a] Alexandria University, Alexandria, 21526 Egypt

[b] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, 115409 Russia

[#]e-mail: Dina.amer@alexu.edu.eg

[##]e-mail: SPNikonov@mephi.ru

Received March 20, 2019; revised April 30, 2019; accepted May 14, 2019

Abstract—Consider the propagation of pressure waves in emergency situations on the equipment of the circuit for reactor VVER-1000. Here we discuss two situations: an instant rupture (10^{-4}) in the main circulation pipelines of the primary circuit with a double End Break (DEB) and instantaneous stop (10^{-4}) of the main circulating pump. The considered emergency situations are included in the list of different types of reports necessary for VVER safety justification [1]. As a model for investigation we chose the 3rd unit of Kalinin NPP (VVER-1000, model 320). All thermohydraulic and physics data for this are taken from the international stander problem Kalinin-3 [2, 3]. The first analysis for those emergency situations was made in works [4, 5]. For the calculations, the code of improved evaluation ATHLET [6] was used, which is included in the AC2 software package, officially obtained by the national research Nuclear University of MEPhI on the basis of a license agreement with Gesellschaft fur Anlagen-und Reaktorsicherheit (GRS) GmbH, Germany [7]. The ATHLET code is certified in Russia for calculations of stationary and transient regimes at reactors with water coolant [8].

We consider in detail the initial period of the accidents, because only at this stage we can observe the strongest amplitude and frequency of pressure fluctuations on NPP elements, which can lead to significant dynamic loads on the structural elements of these objects. This can be estimated either by: joint strength and hydrodynamic calculations, or it is possible to use the results obtained in this work as boundary conditions for the calculation of dynamic loads. The basic reason for the pressure waves in case of instant pump stop was the instant stop of the MCP. But in the case of instant rupture in the pipelines of the first circuit, the main reason is the instant boiling (superheated) of the coolant.

Keywords: VVER-1000, LOCA, Kalinin-3, MCP stop, LOCA, DEB, ATHLET, emergency situations

DOI: 10.1134/S2304487X19040023

1. A BRIEF DESCRIPTION OF THE CALCULATION CODE

The thermohydraulic system code ATHLET (Analysis of THermalhydraulics of LEaks and Transitions) was originally intended for analysis of the entire spectrum of the leak and transient analyses in PWR and BWR reactors. However, experience with it has shown that it can be successfully used to the full extent for Russian reactors such as VVER and RBMK. ATHLET consists of several basic modules that allow to describe different phenomena in the behavior of thermal hydraulic systems: thermal hydraulic module (TFD), heat exchange and thermal conductivity module (HECU), neutron-kinetic module (NEUKIN) to describe point and one-dimensional kinetics, module to describe the operation of the equipment (GCSM) and fully implicit module for numerical integration (FEBE). Also, other independent modules can be connected via the main interface. As all information about the program ATHLET can be find in its manual [6], so its description will not be included here.

Quite widely used capabilities of the ATHLET code for linking with various three-dimensional neutron-physical programs in the calculation of the spatial distribution of energy release fields and the spatial distribution of the coolant parameters in the reactor core (up to the sub-cassette), an example are the works [9–13].

2. THE DESIGN SCHEME OF THE SIMULATED POWER PLANT

The design scheme of the plant simulation presented below (Fig. 1) can be attributed to a group of

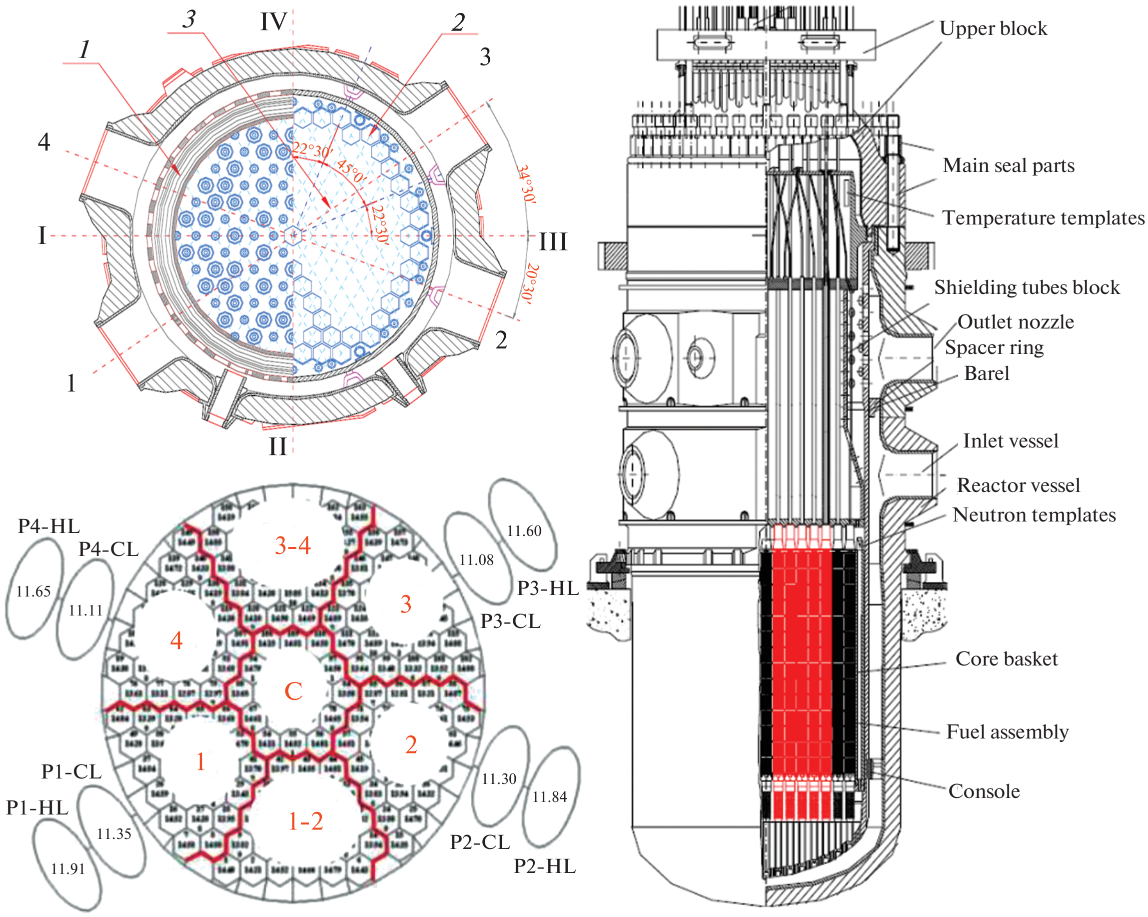

Fig. 1. To the upper left side there is a cross-section along the axis connecting leg. To the Bottom – the core partitioning scheme by seven groups of parallel hydraulic channels (six peripheral ones and central one) – To the right Reactor of Unit 3, Kalinin NPP ‘cross-section of in-core area’.

schemes for the analysis of the behavior of reactors of VVER-1000 type (model 320), which were developed for the code of ATHLET. The detailed description of the simulated power plant was included in [14].

In addition, the scheme of splitting the first circuit of the first loop (Fig. 2) is presented, which is used as an emergency loop when considering these transients. The scheme of splitting the first loop of the first circuit from the output (V-UP4) of the mixing chamber and to the input (V-DC0) of the reactor mixing chamber.

3. MAIN CHARACTERIZATIONS OF THE MODEL

The calculation was carried out with point kinetics, each of the seven selected reactor zones corresponded to a heat-generating element with averaged energy, obtained from the experimental transient state of the core of the standard problem Kalinin-3.

The value of the reactivity coefficients (Doppler, boron, density and temperature for the heat-transfer medium) correspond to the state of the core at the beginning of the experiment, the Kalinin-3 (126 effective day).

Figure 3 shows the model of the first circuit of the first loop, which is the same for other three circuits, except for pump. Also, the model for all components is the same in normal operation and emergency case, except for pump. The hydraulic behavior of a pump in the different states of operation is generally described by empirically developed sets of curves relating pump head and torque to the volumetric flow through the pump and the angular speed of the pump impeller. These curves are a four quadrant curves. Generally,

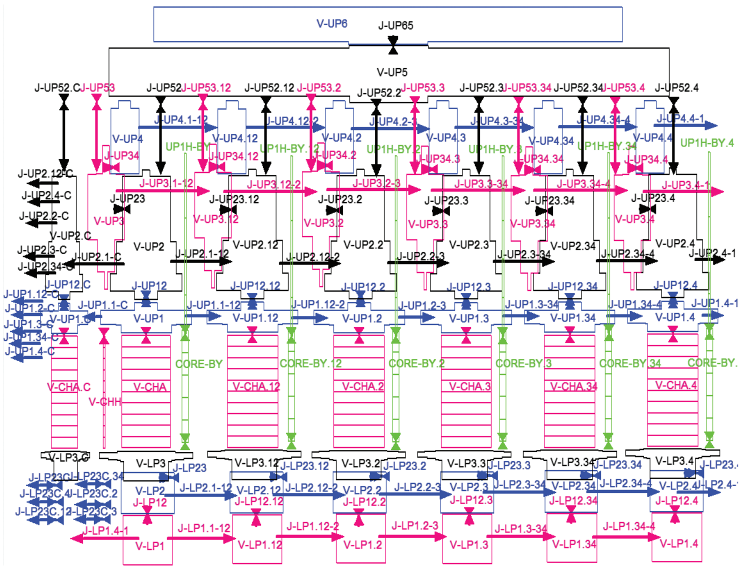

Fig. 2. Nodalization scheme of reactor objects in the primary circuit.

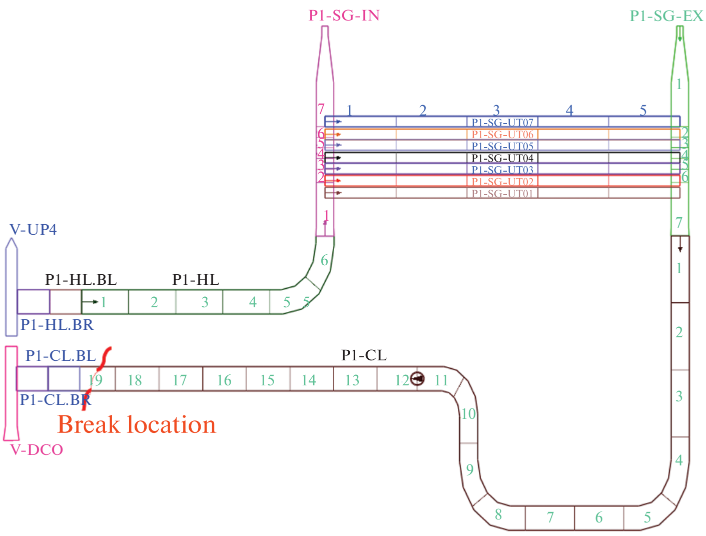

Fig. 3. The scheme of splitting the first circuit of the first loop.

they are supplied by the pump manufacturer for both the pump head and torque.

For each of the considered two emergency situations, will be mentioned the critical breakout models in the code, which is used in these calculations.

3.1. Instant Stop of the MCP

For normal operation, single phase homologous head curve and Single-phase homologous torque curve are used. But for simulating the pump stop, Pump Model with Speed Control and Single-phase homologous head curve are used.

3.2. LOCA

The BLASI block especially attached to the program ATHLET, where a one-dimensional nonequilibrium model is used. It is based on four conservation equations (water mass, steam mass, total energy, and total impulse) and allows to consider more detailed nodalization of the leak site.

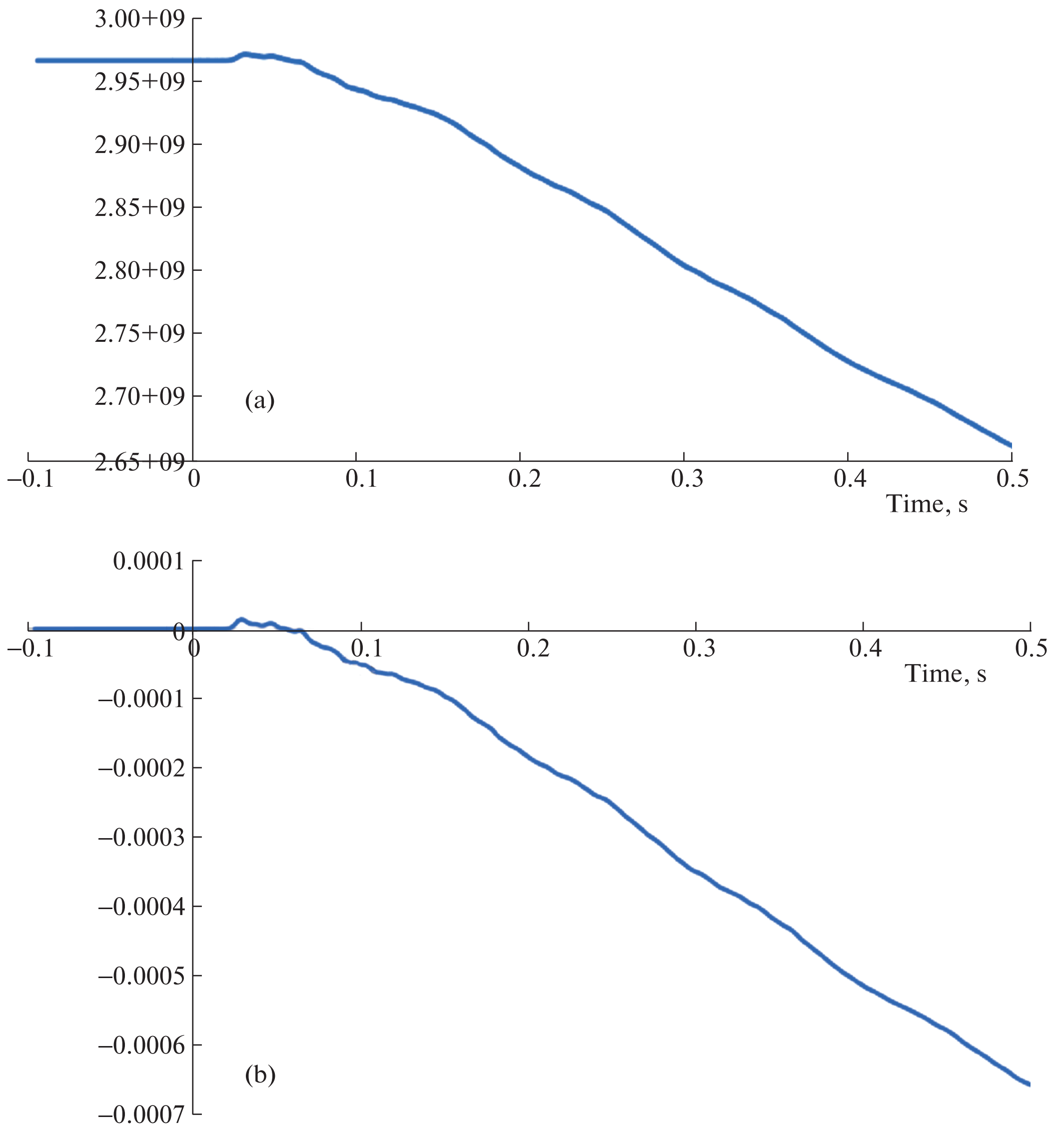

Fig. 4. a) Reactor Power in first 0.5 sec after emergency situation due to Instant Stop of the MCP. b) Reactor Total Reactivity in first 0.5 sec after emergency situation due to Instant Stop of the MCP.

4. RESULTS AND DISCUSSION

Starting with the reactor power, figure 4a and 4b show within the first 0.5 sec after the emergency due to MCP.1 stop, the reactor power and the reactor total reactivity have the same behavior as a direct rapid decreasing.

In case of LOCA, figures 5a and 5b show the same behavior for reactor power following its reactivity, but with a peak of increasing before 0.1 sec.

Figure 6 shows that in case of MCP stops, the average coolant temperature in the core rapidly in the a 0.5 second by more than 1 degree from 306.3 to 307.8. While in the case of LOCA, the increasing in coolant temperature in the core, which shown in Fig. 7, is higher, i.e. from 306 to 313°C.

Considering the average fuel temperature, Fig. 8 illustrates the decrease in fuel temperature within the first 0.5 sec by 2°C, comparing to figure 8 which shows the average fuel temperature in the case of LOCA by decreasing about 4°C within the same period of time.

In order to get a physical explanation for the previous behavior of power, reactivity and temperatures, it is necessary to follow the change in the coolant mass

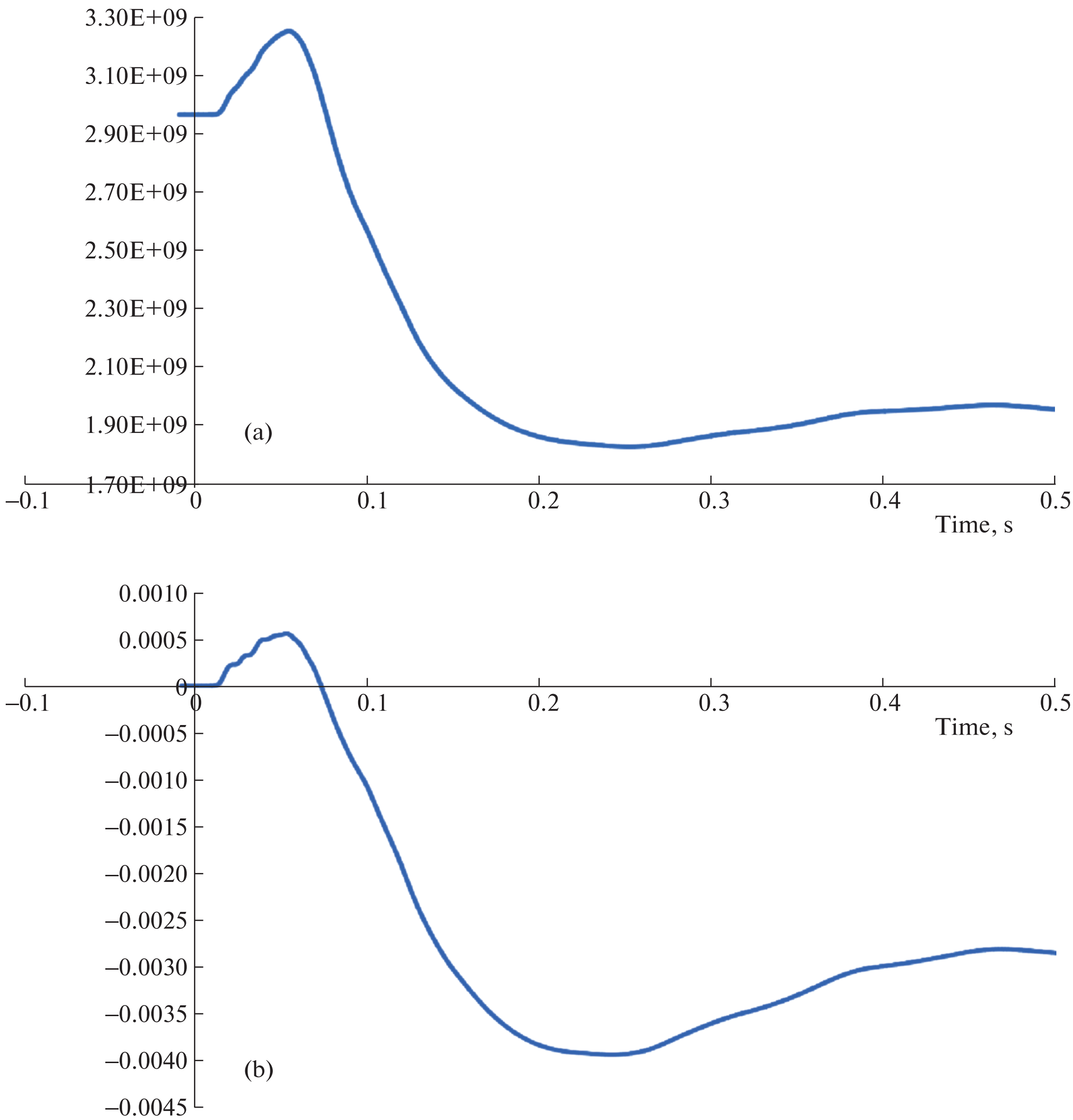

Fig. 5. a) Reactor Power in first 0.5 sec after emergency situation due to *LOCA*. b) Reactor Total Reactivity in first 0.5 sec after emergency situation due *LOCA*.

flow rate into and out from the core. Hence, Figs. 10 and 11 show the coolant mass flow rate into the core in the first 0.5 sec after the emergence due to instant stop of the MCP.1 and LOCA respectively from the 4 coolant loops. As expected, the decreasing rate is more rapid in case of LOCA than int MCP.1 stop from the first loop.

Observing also the coolant mass flow rate out from the core, Figs. 12 and 13 show it in case of MCP.1 stop and LOCA respectively. Comparing the two cases, it is obviously that in the case of LOCA the effect is extended to include the other three loops specially the fourth loop which is the closest – from the geometry point of view – to the emergency loop.1as shown before in Fig. 1.

Finally, it is important to consider the pressure difference as it is main parameter from the safety point of view. Figure 14 and 15 illustrate the pressure difference in the main components: reactor, core, MCP.1 and the steam generator. As a first observation the behavior change in a wavy way having ups and downs peaks. For

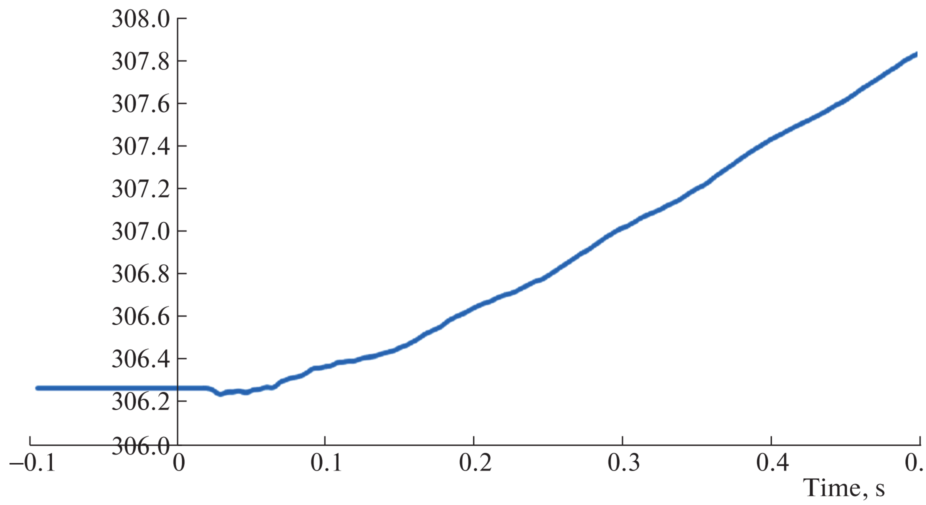

Fig. 6. Average Coolant Temperature in core in first 0.5 sec after emergency situation due to Instant Stop of the MCP.1.

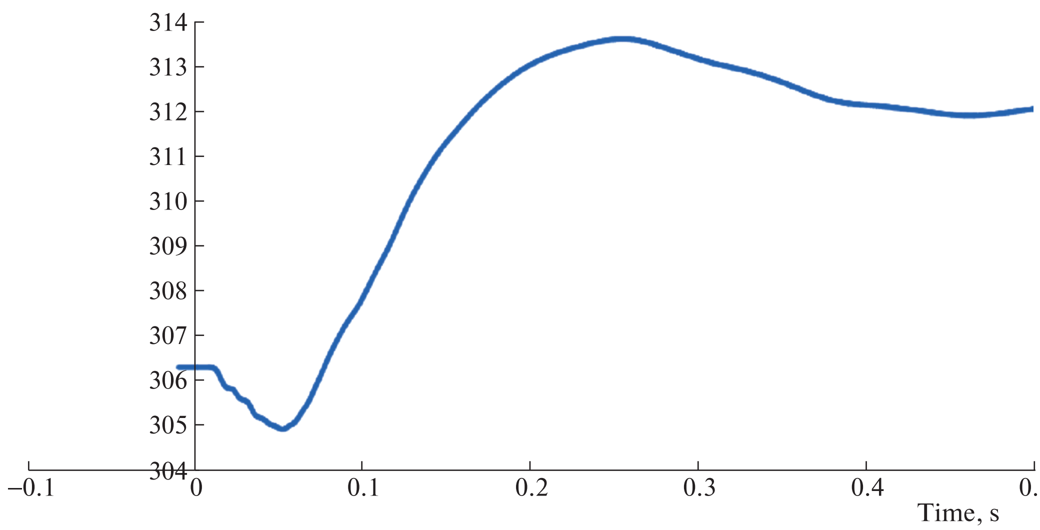

Fig. 7. Average Coolant Temperature in core in first 0.5 sec after emergency situation due to *LOCA*.

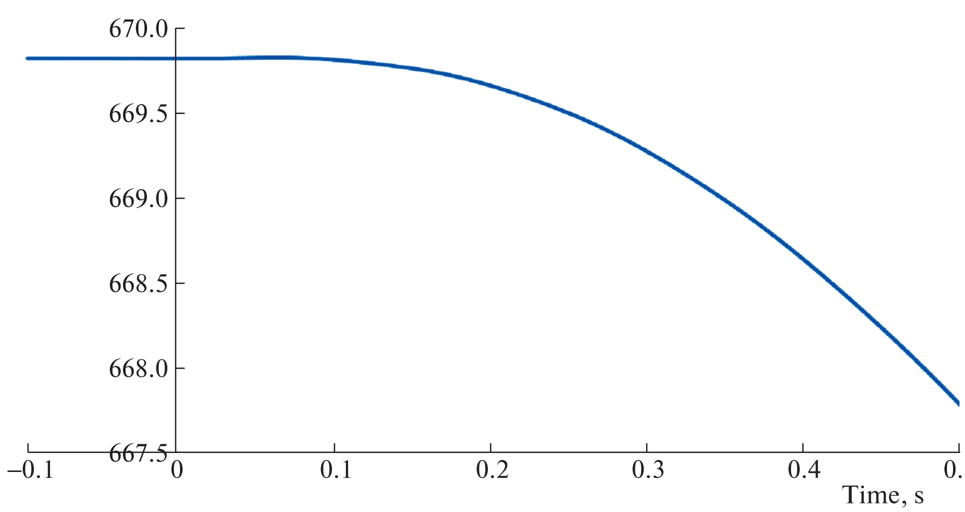

Fig. 8. Average Fuel Temperature in first 0.5 sec after emergency situation due to Instant Stop of the MCP.1.

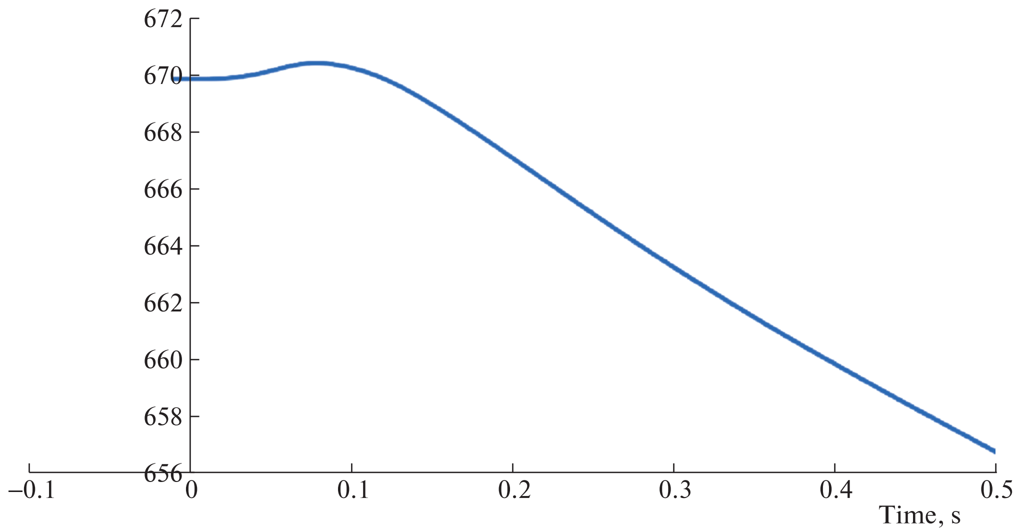

Fig. 9. Average Fuel Temperature in first 0.5 sec after emergency situation due to *LOCA*.

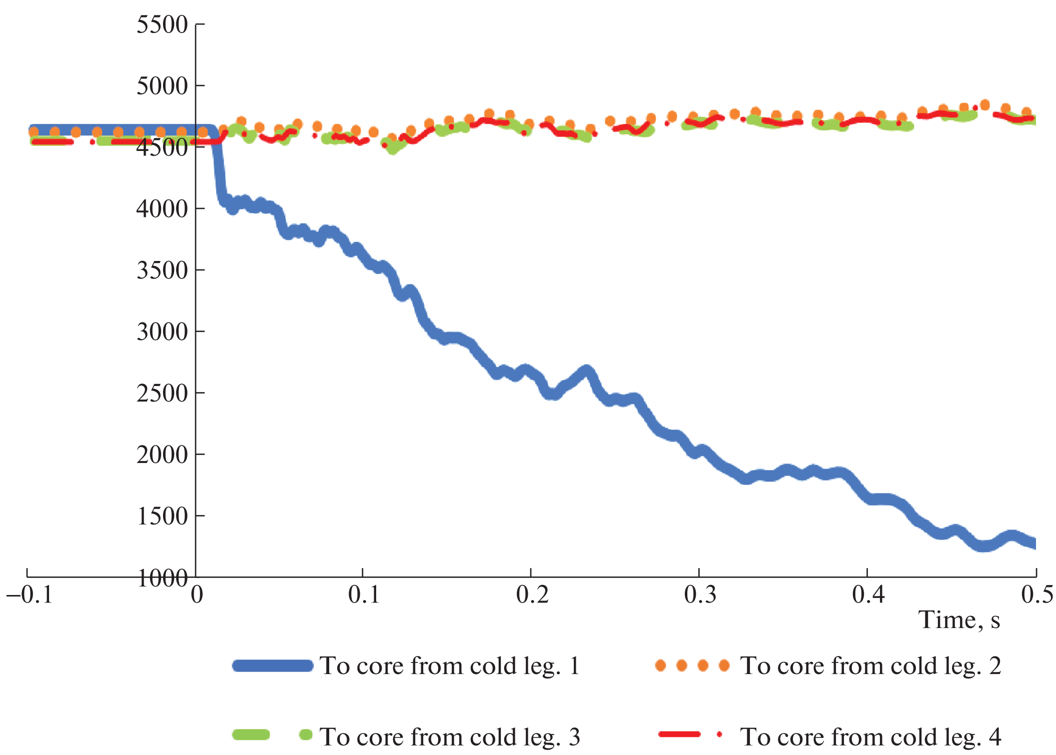

Fig. 10. Coolant Mass Flow Rate into the core from the four loops in first 0.5 sec after emergency situation due to Instant Stop of the MCP.1.

a second observation, the peaks are sharper in the case of LOCA then in the case of MCP.1 instant stop.

5. CONCLUSION

The details of the initial period of in the considered emergency situations shows a strongest amplitude and frequency of pressure fluctuations on NPP elements, strongest amplitude and frequency of pressure can lead to significant dynamic loads on the structural elements of these objects.

This can be estimated either by:

1) Joint strength and hydrodynamic calculations, or

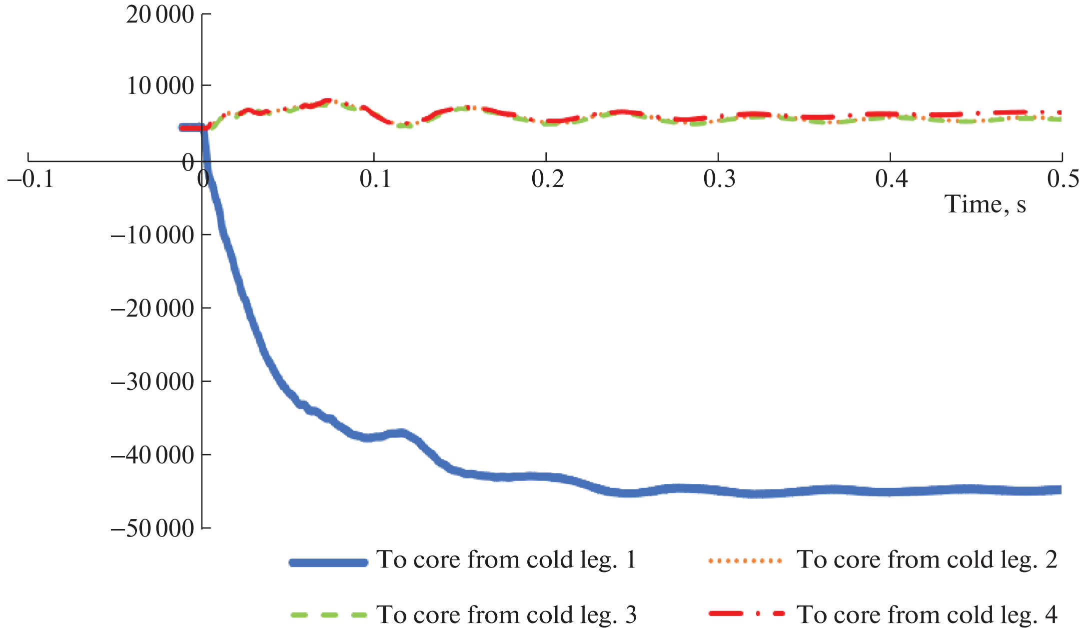

Fig. 11. Coolant Mass Flow Rate into the core from the four loops in first 0.5 sec after emergency situation due to *LOCA*.

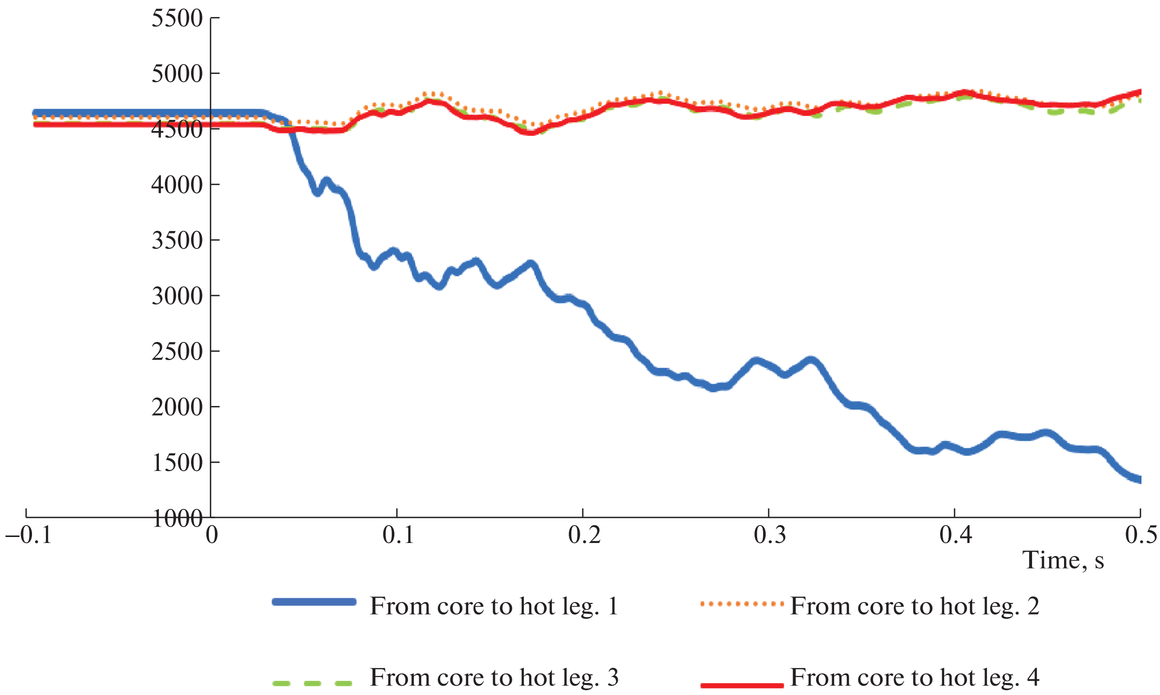

Fig. 12. Coolant Mass Flow Rate out of the core to the four loops in first 0.5 sec after emergency situation due to Instant Stop of the MCP.1.

2) It is possible to use the results obtained in this work as boundary conditions for the calculation of dynamic loads.

Comparing the two cases, MCP.1 instant stop and LOCA, the changes in all parameters are sharper and stronger in the case of LOCA than in the case of MCP.1 instant stop.

It is necessary to consider a similar process for the other MCPs specially the pump in 3rd circuit in which the pressurizer connected. In the safety case, emer-

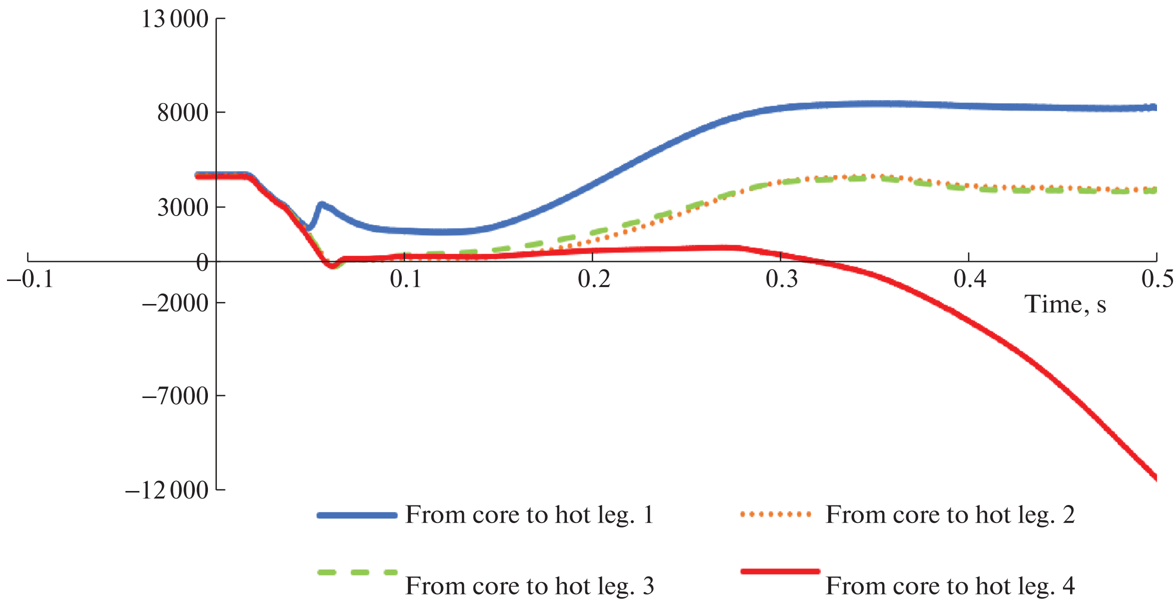

Fig. 13. Coolant Mass Flow Rate out of the core to the four loops in first 0.5 sec after emergency situation due to Instant Stop of the MCP.

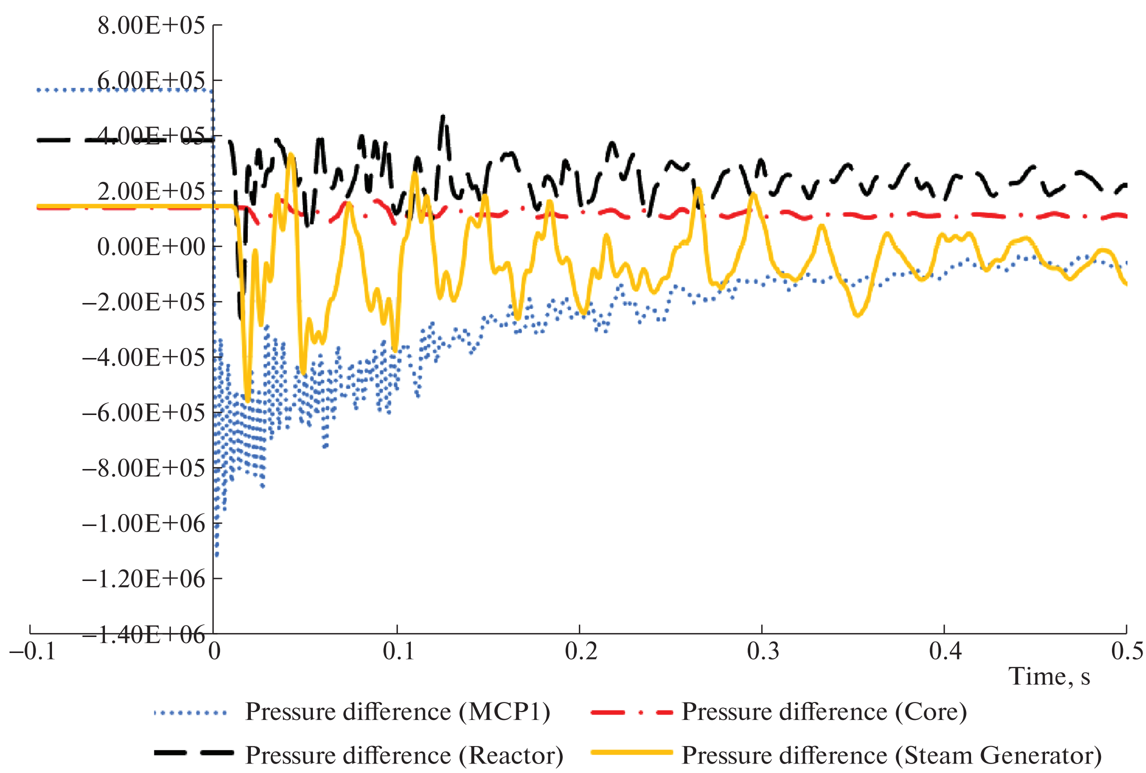

Fig. 14. Pressure Difference in Main Objects in first 0.5 sec after emergency situation due to Instant Stop of the MCP.1.

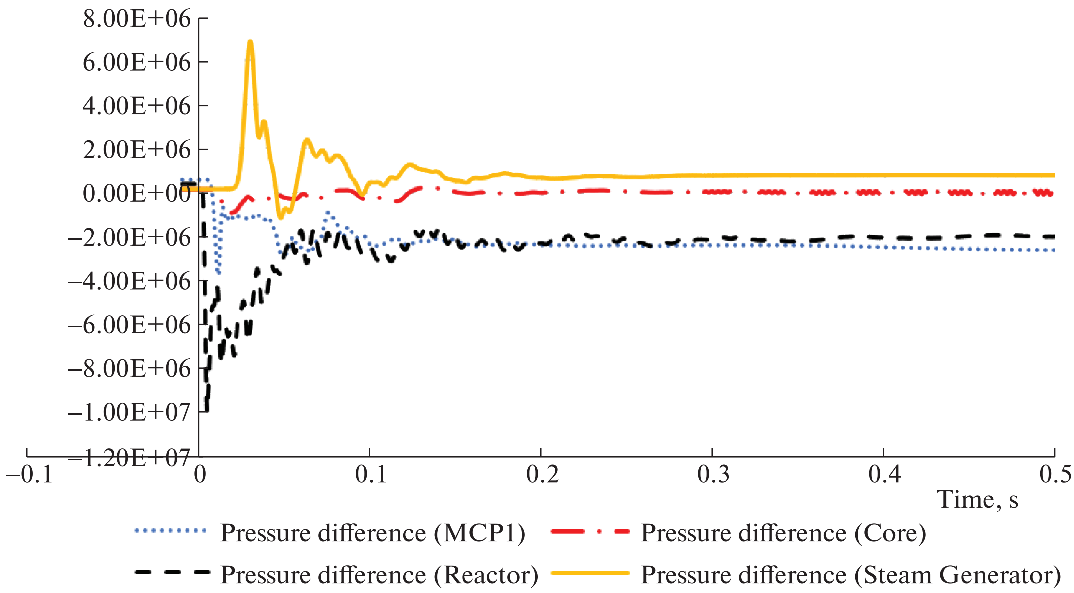

Fig. 15. Pressure Difference in Main Objects in first 0.5 sec after emergency situation due to *LOCA*.

gency situations are analyzed, which can also lead to significant pressure fluctuations in the first stage, in particular, these are accidents with instantaneous rupture of the main circulation pipeline.

So, the next step in the direction of analyzing the occurrence of pressure waves will be just the study of such accidents at breaks in different parts of pipelines, and MCP in the 3rd loop.

REFERENCES

1. PNAE G-1-036-95 (NP-006-98), Trebovanija k soderzhaniju otcheta po obosnovaniju bezopasnosti AS s reaktorom tipa VVER [Requirements to the contents of the report on safety justification of NPPs with VVER] (with amendment No. 1 dated 20.12.2005). In Russian.
2. Tereshonok V.A., Stepanov V.S., Ivchenkov V.V., Pitilimov V.A., and Nikonov S.P., Description of a transient caused by the switching-off of one of the four operating MCP at nominal reactor power at NPP Kalinin Unit 3, NEA/OECD, 2008.
3. Tereshonok V.A., Nikonov S.P., Lizorkin M.P., Velkov K., Pautz A., and Ivanov K., International benchmark for coupled codes and uncertainty analysis in modelling: switching-off of one of the four operating main circulation pumps at nominal power at NPP Kalinin unit, in *Proceedings of the 18th Symposium of AER on VVER Reactor Physics and Reactor Safety, Hungary, Eger, Oct. 6–10, 2008.*
4. Amer D. and Nikonov S.P., Pressure waves in the primary circuit of the VVER-1000 reactor at instant stop of the MCP, in *Proceedings of the Volga-2018 International conference for Young Scientists, Specialists and Post-Graduates on Nuclear Reactor Physics, September, 2018.*
5. Amer D. and Nikonov S.P., LOCA and pressure waves in the first loop of the VVER-1000 reactor, in *Proceedings of the 28th Symposium of AER on VVER Reactor Physics and Reactor Safety, Olomouc, Czechia, October 8–12, 2018.*
6. Austregesilo H., Deitenbeck H., Langenfeld A., Scheuer J., and Schoffel P., *ATHLET 3.1A, Programmer's Manual,* 2017.
7. Computer Code AC2, Code Certificate N0 17-01, Software License Agreement N0.L/M-03, 2017.
8. *Certification Passport Software No*. 350, 2014.
9. Grundmann U., Lucas D., and Rohde U., Coupling of the thermohydraulic code ATHLET with the neutron kinetic core model DYN3D, in *Proceedings of the International Conference on Mathematics and Computations, Physics and Environmental Analysis, Portland, USA, 1995,* vol. 1, pp. 257–263.
10. Panka I., Hegyi Gy., Maráczy Cs., and Keresztúri A., Uncertainties of the kiko3d-ATHLET calculations using the Kalinin-3 benchmark (phase II) data, in *Proceedings of the 25th Symposium of AER on VVER Reactor Physics and Reactor Safety, Balatongyörök, Hungary, 13–16 Oct., 2015.*
11. Nikonov S., Pautz A., and Velkov K., Detailed modeling of KALININ-3 NPP VVER-1000 reactor pressure vessel by the coupled system code ATHLET/BIPR-VVER, in *Proceedings of the International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering M&C 2011, Rio de Janeiro, RJ, Brazil, May 8–12, 2011.*
12. Romanenko V.I., Bachdanovich R.B., Bogdanova E.V., Nikonov S.P., and Tikhomirov G.V., Complex modeling of VVER-1000 fuel assembly using codes MCU/ATHLET, in *Proceedings of the 27th Symposium*

of AER on VVER Reactor Physics and Reactor Safety, Munich, Germany, Oct. 2017.

13. Nikonov S.P., Pham P., Romanenko V.I., and Tikhomirov G.V., Coupled neutronics thermohydraulic calculation of HPLWR fuel cell using codes MCU/ATHLET, in *Proceedings of the 27th Symposium of AER on VVER Reactor Physics and Reactor Safety, Munich, Germany, Oct. 2017.*
14. Amer D. and Nikonov S., Pressure waves in the primary circuit of the VVER-1000 reactor at instant stop of the MCP, *J. Phys.: Conf. Ser.,* 2018, vol. 1133, p. 012049.

Vestnik Natsional'nogo issledovatel'skogo yadernogo universiteta "MIFI", 2019, vol. 8, no. 4, pp. 311–322

Сравнение последствий волн давления при остановке ГЦН и LOCA в ВВЭР-1000

Дина Али Амер[1,2,*], С. П. Никонов[2,]**

[1] Александрийский университет, Александрия, 21526, Египет

[2] Национальный исследовательский ядерный университет "МИФИ", Москва, 115409, Россия

**e-mail: Dina.amer@alexu.edu.eg*

***e-mail: SPNikonov@mephi.ru*

Поступила в редакцию 20.03.2019
После доработки 30.04.2019
Принята к публикации 14.05.2019

Рассматривается процесс образования и распространения волн давления в первом контуре реактора ВВЭР-1000 при аварийных ситуациях. Анализируются две возможные аварии: мгновенный (10^{-4} с) разрыв главного циркуляционного трубопровода (ГЦТ) первого контура с двухсторонним истечением в разрыв (DEB) и мгновенная (10^{-4} с) остановка главного циркуляционного насоса (ГЦН). Рассматриваемые аварии включены в перечень различных видов отчетов, необходимых для обоснования безопасности ВВЭР [1]. В качестве модели для исследования выбран 3-й блок Калининской АЭС (ВВЭР-1000, модель 320). Все необходимые для расчетного исследования данные взяты из описания международной стандартной проблемы Калинин-3 [2–3]. Первый анализ выше указанных аварий был сделан в работах [4, 5]. Для расчетов использовался код улучшенной оценки ATHLET, который входит в программный пакет AC2, официально полученный Национальным исследовательским ядерным университетом "МИФИ" на основании лицензионного соглашения с компанией Gesellschaft fur Anlagen-und Reaktorsicherheit (GRS) GmbH, Германия [6, 7]. Код АТЛЕТ сертифицирован в России для расчетов стационарных и переходных режимов на реакторах с водяным теплоносителем [8].

В работе рассматривается начальный период аварий, поскольку только на этом этапе наблюдаются максимальные амплитуды и частоты колебаний давления в объектах АЭС, что может привести к значительным динамическим нагрузкам на конструктивные элементы этих объектов. Количественно динамическое воздействие можно оценить либо с помощью совместных прочностных и гидродинамических расчетов, либо можно использовать полученные в данной работе результаты в качестве граничных условий для расчета динамических нагрузок. Основной причиной возникновения волн давления в случае мгновенной остановки ГЦН является мгновенное изменение скорости потока, а при мгновенном разрыве ГЦТ первого контура – вскипание перегретого теплоносителя.

Ключевые слова: ВВЭР-1000, аварийные ситуации, LOCA, MCP stop, Калинин-3, ATHLET, двухстороннее истечение (DEB)

DOI: 10.1134/S2304487X19040023

СПИСОК ЛИТЕРАТУРЫ

1. ПНАЭ Г-1-036-95 (НП-006-98). Требования к содержанию отчета по обоснованию безопасности АС с реактором типа ВВЭР (с Изменением № 1 от 20.12.2005 г.).
2. *Tereshonok V.A., Stepanov V.S., Ivchenkov V.V., Pitilimov V.A., Nikonov S.P.*, Description of a Transient Caused by the Switching-off of One of the Four Operating MCP at Nominal Reactor Power at NPP Kalinin Unit 3, NEA/OECD, July, 2008.
3. *Tereshonok V.A., Nikonov S.P., Lizorkin M.P., Velkov K., Pautz A., Ivanov K.*, International Benchmark for Coupled Codes and Uncertainty Analysis in Modelling: Switching-off of one of the four operating main circulation pumps at nominal power at NPP Kalinin unit,

18th Symposium of AER on VVER Reactor Physics and Reactor Safety, Hungary, Eger, Oct. 6–10, 2008.

4. *Dina Ali Amer, Nikonov S.P.*, Pressure Waves in The Primary Circuit Of The VVER – 1000 Reactor At Instant Stop of The MCP, Volga-2018, International conference for young scientists, specialists and post-graduates on Nuclear Reactor Physics, September, 2018.
5. *Dina Ali Amer, Nikonov S.P.*, LOCA and pressure waves in the first loop of the VVER – 1000 reactor, 28th Symposium of AER on VVER Reactor Physics and Reactor Safety, Olomouc, Czechia, October 8–12, 2018.
6. *Austregesilo H., Deitenbeck H., Langenfeld A., Scheuer J., Schöffel P.*, ATHLET 3.1A, Programmer's Manual, March 2017.
7. Computer Code AC2, Code Certificate N0 17-01, Software License Agreement N0.L/M-03, 11 Sep. 2017.
8. Ростехнадзор, ФБУ "НТЦ ЯРБ", Аттестационный паспорт программного средства № 350 от 17.04.2014.
9. *Grundmann U., Lucas D., Rohde U.*, Coupling of the thermohydraulic code ATHLET with the neutron kinetic core model DYN3D. In: Proc. of Int. Conf. on Mathematics and Computations, Physics and Environmental Analysis, Portland (USA), 1995, vol. 1, pp. 257–263.
10. *Panka I., Hegyi Gy., Maráczy Cs., Keresztúri A.*, Uncertainties of the kiko3d- ATHLET calculations using the Kalinin-3 benchmark (phase II) data, 25th Symposium of AER on VVER Reactor Physics and Reactor Safety, Hungary, Balatongyörök, Oct. 13–16, 2015.
11. *Nikonov S., Pautz A., Velkov K.*, Detailed modeling of KALININ-3 NPP VVER-1000 reactor pressure vessel by the coupled system code ATHLET/BIPR-VVER, International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2011), ISBN 978-85-63688-00-2, Rio de Janeiro, RJ, Brazil, May 8–12, 2011.
12. *Romanenko V.I., Bachdanovich R.B., Bogdanova E.V., Nikonov S.P., Tikhomirov G.V.*, Complex Modeling Of VVER-1000 Fuel Assembly Using Codes MCU/ATHLET, 27th Symposium of AER on VVER Reactor Physics and Reactor Safety, Munich, Germany Oct. 2017.
13. *Nikonov S.P., Pham P., Romanenko V.I., Tikhomirov G.V.*, Coupled Neutronics Thermohydraulic Calculation of HPLWR Fuel Cell Using Codes MCU/ATHLET, 27th Symposium of AER on VVER Reactor Physics and Reactor Safety, Munich, Germany Oct. 2017.
14. *Amer D., Nikonov S.*, Pressure waves in the primary circuit of the VVER-1000 reactor at instant stop of the MCP. 2018 J. Phys.: Conf. Ser. 1133 012049.