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EFFECIENCY OF SIMULATING DECAY HEAT IN THE CORIUM OF A NUCLEAR REACTOR BY THE OHMIC HEATING METHOD

Most commonly, in consequence of a severe accident at a nuclear power plant (NPP) followed by a meltdown of the reactor core, corium is formed. Decay heat is one of the features of it and highly affects the thermal field of the entire corium. Thus, taking into account the decay heat is a central to physical modeling of severe accidents. For this reason, methods for simulating decay heat must meet at least two requirements of physical modeling: intensity and uniformity of heating throughout the entire volume of the melt.

This paper provides studies on the efficiency of using ohmic heating as a method for simulating decay heat in a corium prototype during experiments at the LAVA-B test-bench. Melt heating data using an ohmic heater was obtained by computer modeling based on a software package ANSYS. To assess the efficiency of using ohmic heating, the obtained calculation parameters were compared with the parameters of other existing methods for simulating decay heat in the melt under similar conditions, such as induction heating and plasmatron heating.

Key words: corium, LAVA-B test-bench, decay heat, ANSYS, ohmic heating method.

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Ядролық реактор кориумындағы қалдық энергияны омдық қыздыру әдісімен имитациялаудың тиімділігі

Әдетте, реактордың белсенді аймағының балқуымен бірге жүретін атом электр станциясында (АЭС) ауыр апат салдарынан кориум – балқыған ядролық отын реактордың құрылымдық материалдарымен әрекеттескенде пайда болатын күрделі қоспа – пайда болады. Оның сипаттамаларының бірі – бүкіл кориумның жылу өрісіне айтарлықтай әсер ететін қалдық энергия бөлу болып табылады. Демек, қалдық энергия шығынын есепке алу ауыр апаттарды физикалық модельдеу процестерінде шешуші рөл атқарады. Осы себептен қалдық энергияны имитациялау әдістері физикалық модельдеудің кем дегенде екі талабына сәйкес келуі керек: балқыманың бүкіл көлеміндегі жылудың қарқындылығын қамтамасыз ету және біркелкі таралу.

Бұл мақала LAVA - Б сынақ стендіндегі эксперименттер кезінде корум прототипінде ыдырау жылуын модельдеу әдісі ретінде омдық қыздыруды пайдаланудың тиімділігі туралы зерттеулерді ұсынады. Омдық қыздырғышты пайдаланып балқыманы қыздыру туралы деректер ANSYS бағдарламалық қаптамасына негізделген компьютерлік модельдеу арқылы алынды. Омдық қыздыруды пайдаланудың тиімділігін бағалау үшін алынған есептеу параметрлері ұқсас жағдайларда балқымада ыдырау жылуын модельдеудің басқа да бар әдістерінің параметрлерімен салыстырылды, мысалы, индукциялық қыздыру және плазматронды қыздыру процесстері.

Түйін сөздер: кориум, ЛАВА-Б қондырғысы, қалдық энергия, ANSYS, омдық қыздыру әдісі.

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Эффективность имитации остаточного энерговыделения в кориуме ядерного реактора методом омического нагрева

Как правило, в следствии возникновения тяжелой аварии на атомной электростанции (АЭС), которая сопровождается расплавленеим активной зоны реактора, образуется кориум – сложная смесь материалов, когда расплавленное ядерное топливо взаимодействует с конструкционными материалами реактора. Одним из его характеристик является остаточное энерговыделение, что достаточно сильно влияет на тепловое поле всего кориума. Следовательно учет остаточного энерговыделения играет ключевую роль в процессах физического моделирования тяжелых аварий. По этой причине методы имитации остаточного энерговыделения должны соответствовать как минимум двум требованиям физического моделирования: интенсивности и равномерности нагрева по всему объему расплава.

В данной работе изучается эффективность применения омического нагрева, как метода имитации остаточного энерговыделения в прототипе кориума во время проведения экспериментов на установке ЛАВА-Б. Данные нагрева расплава при применении омического нагревателя были получены методом компьютерного моделирования на базе програмного комплекса ANSYS. Для оценки эффективности применения омического нагрева было проведено сравнение полученных параметров расчета с параметрами других существующих способов имитации остаточного энерговыделения в расплаве при аналогичных условиях, таких как, индукционный нагрев и нагрев плазматронами.

Ключевые слова: кориум, установка ЛАВА-Б, остаточное энерговыделение, ANSYS, метод омического нагрева.

Introduction

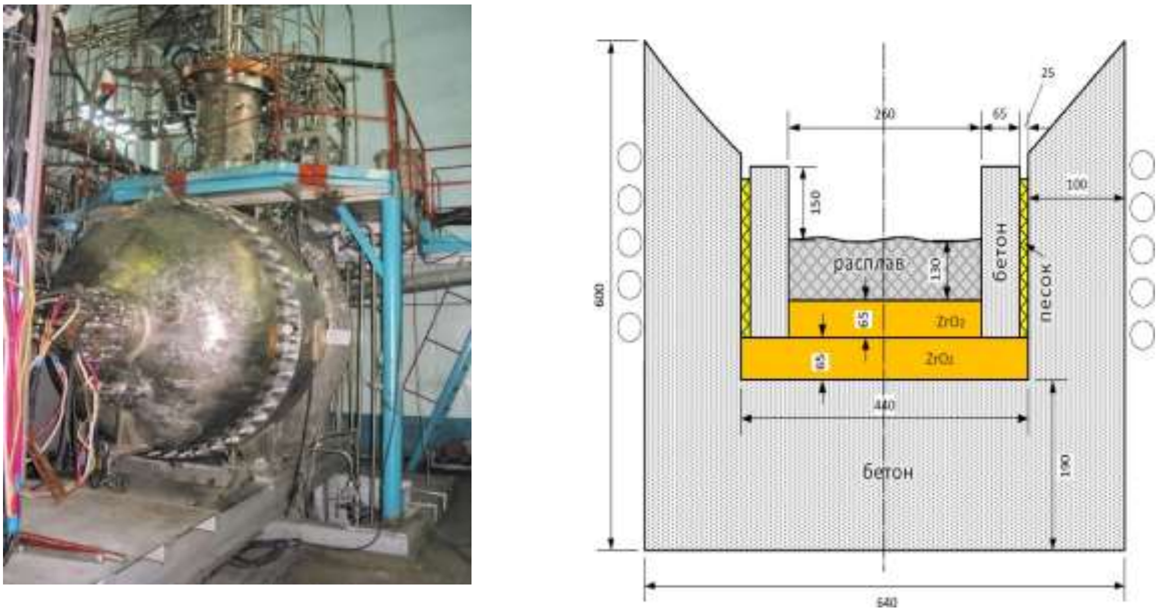
As it is known, during a severe accident at a NPP, the reactor core melts and a corium is formed, consisting of a mixture of the reactor core and structural materials. Decay heat is a feature of corium, which is described by long-term heat release, even after the cessation of radioactive decay in the melt [2]. This occurs due to the transition of fission product nuclei to a more stable state, as a result of which a significant amount of energy is released. Hence, when conducting experiments on physical modeling of severe accidents at NPPs, it is important to take this feature into account, since it affects the overall thermal field of the melt.

There are several experimental installations in the world that simulate the decay heat in a corium prototype (a mixture of uranium dioxide natural enrichment, zirconium oxide, zirconium and steel). The purpose of such experimental installations is the same - to study the nature of interaction between corium prototype (corium) and the structural materials of the melt trap. However, methods for simulating decay heat are different. Thus, at the installation of a series of NEA-MCCI experiments, the principle of direct passage of electric current through the melt was used as a simulator of decay heat, and the experimental test-benches VULCANO , LAVA-B, VESTA, VESTA-S, BETA, COMET, COMETA, SICOPS use induction heating. Along with this, in a series of MOCKA experiments , the decay heat was modeled using the reaction of thermite mixtures [3-7].

Research object and methods

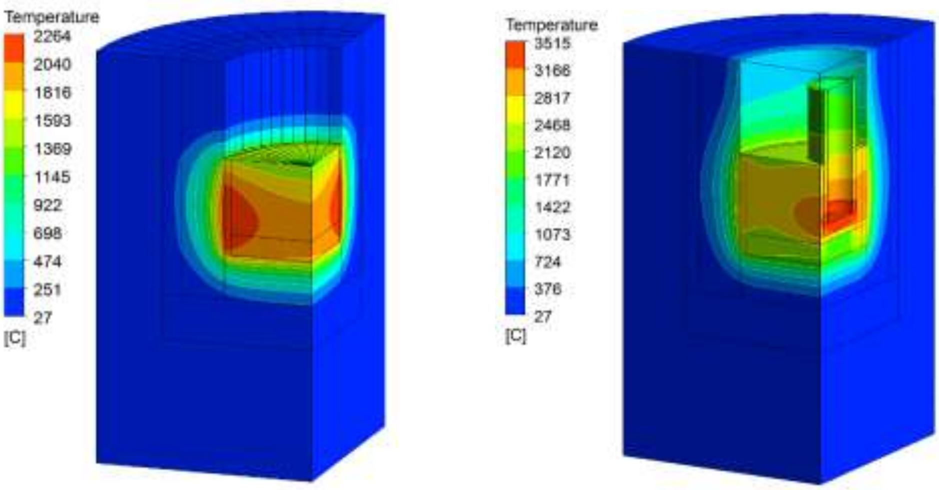
Of the settings listed above, it is necessary to note the LAVA-B test-bench [8], which is operated at the Institute of Atomic Energy Branch of the Republican State Enterprise “National Nuclear Center Republic Kazakhstan” and provides the opportunity to conduct experiments with a corium prototype. The external view of this device is shown in Figure 1 (a). The test-bench consists of two main parts - an electric melting furnace (EMF), in which a burden with a volume of up to 60 kg is melted using the induction method, and a melt receiver (MR), into which the melt from the EMF is poured from a height of about 1.7 meters. The MR is an experimental section with an internal volume of 5.3 m^3, in which a melt trap with thermocouples is installed. Constructive scheme of melt trap with refractory blocks is shown in Figure 1 (b).

This test-bench was used for conducting experiments to study the interaction between corium and structural elements of the reactor (reactor vessel, containment shell, etc.). Depending on the specifics of the experiment, induction and plasmatron heating methods were used to simulate the heat decay in the melt [9-10]. Using computer modeling in the ANSYS software package, the heating parameters of the melt and trap elements were determined for each method (Fig. 2).



a) b)

Figure 1 – External view of the LAVA-B test-bench (a) and melt trap diagram (b).



a) b)

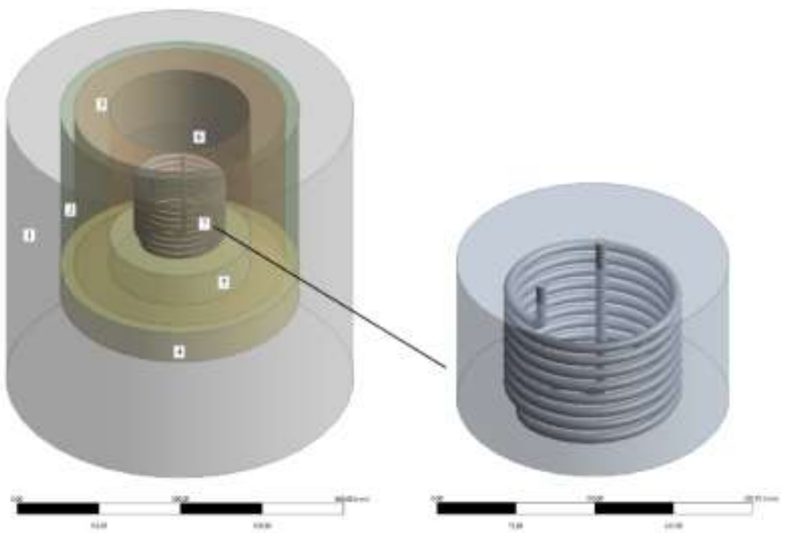
Figure 2 – Temperature field of the melt trap model with induction (a) and plasmatron (b) heating methods

The results of computer modeling showed that the plasmatron heating method, although it helps to achieve higher temperatures, however, creates a large temperature gradient throughout the entire volume of the melt, heating it locally at the location of the plasmatrons. The induction method creates a more uniform heating pattern, and at the same time, due to the skin effect, for the most part, only the side surface of the corium is heated [11] . In addition, the heating temperature of the melt directly depends on the skin effect, the thickness of which depends on the inductor power. It turns out that to heat the melt to a certain temperature using the induction method, it is needed a more powerful source of electricity than is required for other methods. As is evident, both methods have some disadvantages and are not always suitable for conducting experiments with corium, where the key factor is creating uniform heating throughout the entire volume of the melt and achieving a high temperature. Thus, it would be impossible to study the interaction between corium and melt trap materials, where parts of the trap be made of electrically conductive materials. In addition, with the materials of the reactor vessel bottom model, the use of the induction method as a way to simulate the decay heat in the melt would also be impossible, since the inductor will heat not only the melt, but primarily all parts of the melt trap and the bottom model, thereby distorting the thermophysical parameters of the experiment.

In [12], a comparative analysis of all known methods for simulating decay heat in a corium prototype was implemented . It has been shown that one of the optimal methods is ohmic heating.

The purpose of this study was to determine the efficiency of using the ohmic heating method as a simulator of decay heat in a prototype corium in comparison with induction and plasmatron methods. To achieve this goal, the computer modeling method was chosen as the main tool.

The thermophysical model for calculations was created in the ANSYS software based on the design of an experimental melt trap (see Fig. 1 (b)), which was used in one of the experiments at the LAVA-B test-bench. A specially designed ohmic heater was used as a thermal heating simulation method. Figure 3 shows a computer model of a melt trap with such a heater.



1, 3 - concrete, 2 - sand, 4.5 - zirconia disks, 6 - corium, 7 - tungsten heater.

Figure 3-View of a computer model of a melt trap with an ohmic heater

The heater parameters are presented in Table 1.

It should be noted that one of the main advantages of a spiral heater is that its geometric parameters can be changed depending on the specifics of the experiment to provide the desired heating pattern scenario.

Table 1 - Parameters of the spiral heater

Options	Values
Diameter of tungsten wire spiral, mm	10
Length, mm	2497.3
Internal radius of the spiral, mm	94
Number of turns	8
Surface area, mm ^{3}	$1.3804*10^5$
Volume, mm ^{3}	$3.4473*10^5$

To compare the chosen method of simulating decay heat with the above studies of the efficiency of using plasmatron and induction heating methods, the dimensions and materials of the trap, as well as the initial conditions and all other parameters will be identical:

- Initial corium temperature: 2511 ℃;
- Melt composition: uranium dioxide (UO_2) -33 kg, zirconium (Zr) -15 kg, zirconium dioxide (ZrO_2) -3 kg, steel 12X18H10T -9 kg;
- Heater power: 35 kW;
- Heating time: 30 minutes;

The thermophysical parameters of corium and tungsten are presented in Tables 2 and 3, respectively.

Table 2 - Thermophysical options of corium [9]

Temperature, K	Heat capacity J/kg·K	Thermal conductivity, W/(m·K)	Density, kg/m^3
373	326.25	12.63	5451
573	357.4	11.66	5420
773	380.6	11.67	5387
1073	390.7	12.23	5342
1273	398.7	13.5	5299
1573	412.8	14.6	5243

Table 3 - Thermophysical options of tungsten [13]

Temperature, K	Heat capacity J/kg·K	Thermal conductivity, W/(m·K)	Density, kg/m^3
300	132.4	162.8	19260
500	138.3	145.9	19210
700	141.9	130.2	19150
900	145.7	120.2	19100
1200	152.2	113.5	19010
1400	157.1	111.2	18950
1600	162.5	110.1	18890
1800	166.0	109.0	18820
2000	174.7	108.3	18720
2200	181.6	107.2	18620
2400	189.1	106.8	18520
2600	197.6	107.4	18420
2800	207.0	108.8	18320
3000	217.8	107.5	18220

Results of computer decay heat modeling in the melt at the LAVA-B test-bench

Based on the results of computer modeling, data on the thermal field of the trap and melt were obtained when using an ohmic heater as a method for simulating decay heat in the corium. The maximum and minimum temperatures of the melt when heated by the ohmic method were 2748℃ and 2443℃ respectively.

As Figure 4 shows, the temperature field of the corium is distributed evenly throughout the entire volume. The maximum and minimum temperature indicators of the melt when heated by the ohmic method were 2721 ℃ and 2486 ℃ respectively.

To compare the intensity and uniformity of heating of the melt when using an ohmic heater, plasmatron and induction methods for simulating decay heat, a comparison was made of the distribution of temperature values over the melt cross section for each of the methods (Figure 5).

Figure 5 shows that during ohmic heating of the corium, the difference in temperature of the melt in the center and near the walls of the trap is relatively small (about 300 ℃), and the distribution pattern of the thermal field of the corium melt more uniform compared to the data of plasmatron and induction heating. In addition, the temperatures achieved by ohmic heating are significantly higher than those achieved by induction heating. In addition, by changing the internal radius of the heater, it is possible to obtain a more uniform temperature field (temperature distribution in the volume of the corium).

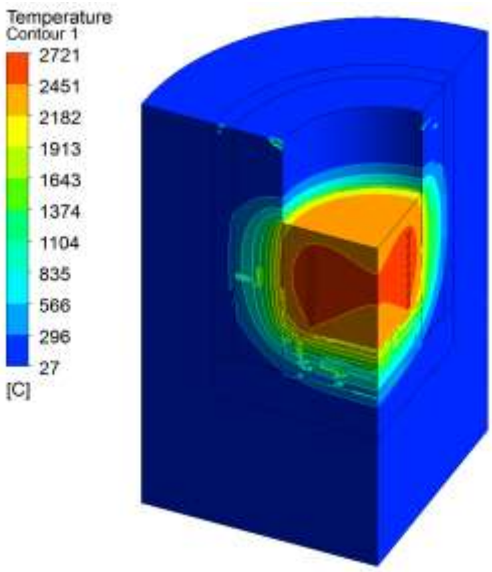


Figure 4 - Temperature field of the MR when heated by the ohmic method

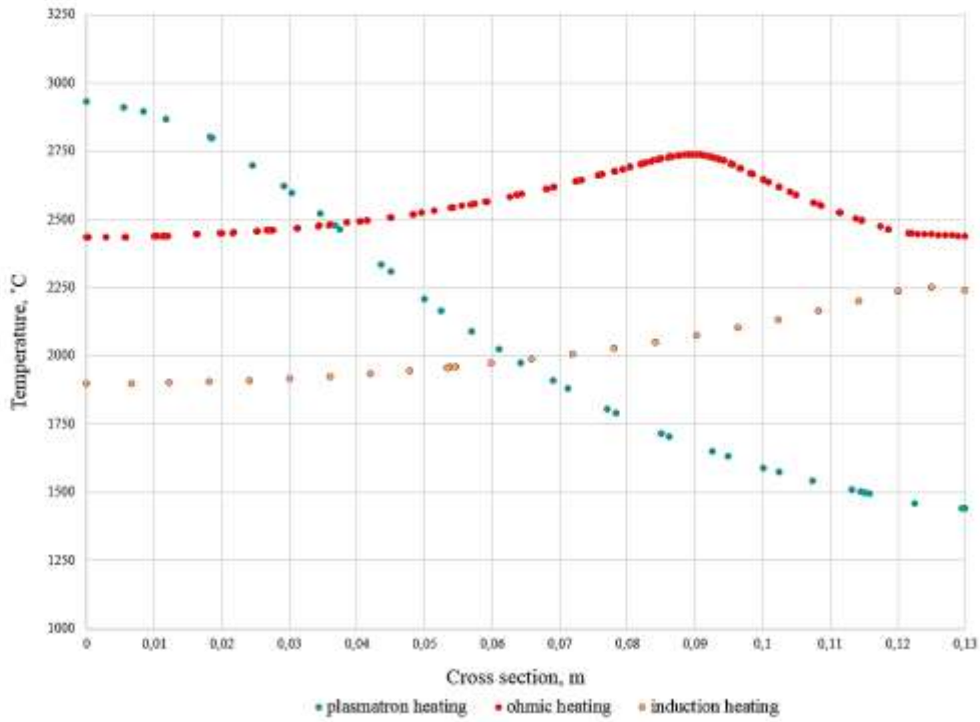


Figure 5 - Graph of distribution of temperature values in the melt when heated by plasmatron, ohmic and induction methods [10]

Figure 6 presents a graph of changes in corium temperature values (average over volume) over 30 minutes when the melt is heated by the ohmic method. Over a heating period of about 8 minutes, the average temperature drops to a critical level of 2244 °C. The sharp temperature drop can be explained by the process of heat transfer from the melt to the walls of the trap, which are at room temperature before draining it from the EMF. In such a short time, the corium prototype melt does not have time to receive a large amount of heat from the heater due to its low thermal conductivity. Further, according to the calculation results, a uniform increase in the average temperature is observed to 2352 °C in 22 minutes.

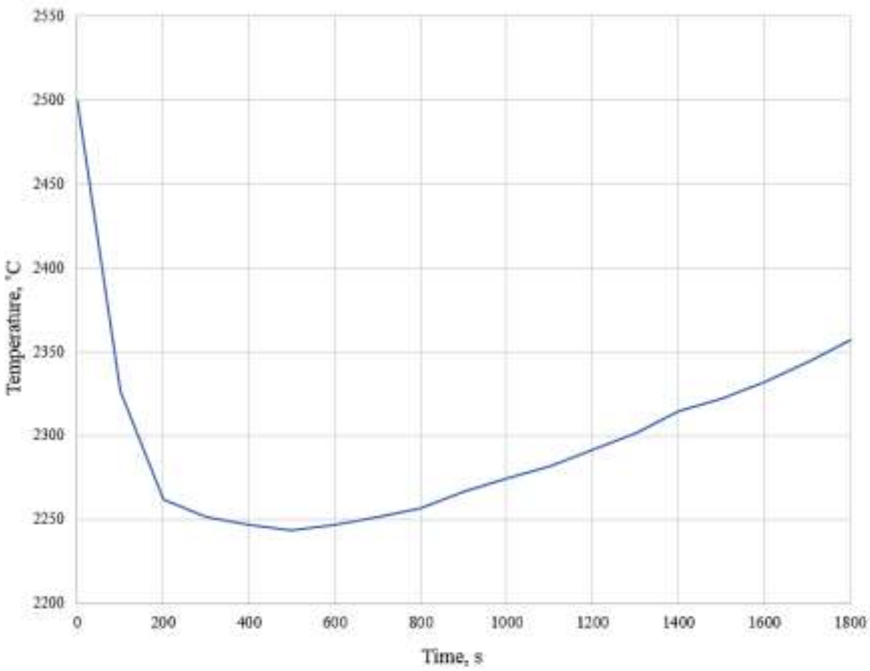


Figure 6 - Graph of changes in the volume-averaged temperature of the corium during ohmic heating

Conclusion

This paper presents the results of computer modeling in the ANSYS software of the process simulating decay heat in the corium at the LAVA-B test-bench using the ohmic heating method. The distribution of the thermal field in the volume of the melt has been established. In comparison with plasmatron and induction heating methods, the study shows the efficiency of using ohmic heating to simulate the decay heat in the corium when studying the processes of an beyond the vessel accident at a NPP when the corium is localized in a melt trap. The calculation results showed that when an ohmic heater (spiral shape) is used to simulate decay heat, the melt is heated more uniformly compared to induction and plasmatron methods.

An important advantage of the ohmic method is the variability of the heater design. Due to its variability, the ohmic method can be used in many experiments to simulate a severe accident at a NPP, since it allows one to change the nature of melt heating, changing the geometric parameters of the heater and its location in the trap

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References

1 Morales J.P. World major nuclear accidents and their negative impact in the environment, human health and public opinion //International Journal of Energy, Environment and Economics. – 2013. – Vol.21. – P.1-23.

2 Vasiliev Yu.S. Studies of the consequences of severe accidents of water-cooled nuclear power reactors under the COTELS project // Bulletin NNC RK. – 2022. – V.1. – P.5-17.

3 Fink J. K., Thompson D. H., Spencer B. W., Sehgal B. R. Aerosol and melt chemistry in the ACE molten core-concrete interaction experiments//High Temperature and Materials Science. – 1995 – Vol.33(1). – P.51-76.

4 Journeau C., Piluso P., Haquet J.F.Two-dimensional interaction of oxidic corium with concretes: The VULCANO VB test series//Annals of Nuclear Energy. – 2009. – V.36. – P.1597-1613.

5 Farmer M.T., Kilsdonk D.J., and Aeschlimann R.W. Corium Coolability under Ex-Vessel Accident Conditions for LWRs // Nuclear Eng. Technology. – 2009. – Vol. 41. – P.575-602.

6 Miassoedov A., Cron T., Gaus-Liu X., Palagin A., Schmidt-Stiefel S., Wenz T. LIVE experiments on melt behavior in the reactor pressure vessel lower head //8th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics. Pointe Aux Piments, Mauritius. – 2011. – P.793-801.

7 Kim H.Y., An S.M., Jung J., Ha K.S., Song J.H. Corium melt researches at VESTA test facility //Nuclear Engineering and Technology. – 2017. – Vol. 49. – P.1547-1554.

8 Bekmuldin M.K., Ganovichev D.A., Akayev A.S. Issledovaniye teploizolyatsionnykh svoystv korpusa priyema rasplava eksperimental'noy ustanovki LAVA-B//Vestnik NYATS RK. – 2019. – Vol.1. – P.66-71. (In Russ.)

9 Toleubekov K.O., Khazhidinov A.S., Akayev A.S. Modelirovaniye induktsionnogo nagreva pri imitatsii ostatochnogo energovydeleniya v koriume pri vzaimodeystvii s zharoprochnymi materialami //Vestnik NYATS. – 2021. – Вып.1. (In Russ.)

10 Baklanov V.V., Zhdanov V.S., Malysheva Ye.V. Eksperimental'noye issledovaniye protsessov pri uderzhanii rasplava koriuma v korpuse reaktora (INVECOR) //Vestnik NYATS RK. – 2009. – Vyp.1(37). – P.55-66. (In Russ.)

11 Toleubekov K.O., Baklanov V.V., Akayev A.S., Bekmuldin M.K. Modeling the process of decay heat imitation in the corium at the «Lava-B» facility //Recent Contributions to Physics. – 2022. – Vol.2 (81). – P.97-105.

12 Skakov M.K., Baklanov V.V., Nurpaissova G.S. Analysis of methods for simulating the decay heat in corium when modeling a severe accidents at nuclear power plant //Eurasian Physical Technical Journal. – 2024. – Vol.21, N.1 (47). – P.57-66.

13 Zinov'yev. V.Ye. Teplofizicheskiye svoystva metallov pri vysokikh temperaturakh //Metallurgiya. – 1989. – Tom 20, vyp.3. (In Russ.)

References

1 J.P. Morales, International Journal of Energy, Environment and Economics, 21, 1-23 (2013).

2 Yu.S. Vasiliev, Bulletin NNC RK, 1, 5-17 (2022).

3 J.K. Fink, D.H. Thompson, B.W Spencer and B.R. Sehgal, High Temperature and Materials Science, 33(1), 51-76 (1995).

4 C. Journeau, P. Piluso and J.F. Haquet, Annals of Nuclear Energy, 36, 1597-1613 (2009).

5 M.T.Farmer, D.J. Kilsdonk, and R.W Aeschlimann, Nuclear Eng. Technology, 41, 575-602 (2009).

6 A. Miassoedov et al., Proc. of the 8th Int. Conf. on Heat Transfer, Fluid Mechanics and Thermodynamics

(Pointe Aux Piments, 11 – 13 July, 2011), p.793-801
7 H.Y. Kim, S.M. An, J. Jung, K.S. Ha and J.H. Song, Nuclear Engineering and Technology, 49, 1547-1554 (2017).
8 M.K. Bekmuldin, D.A. Ganovichev and A.S. Akaev, Bulletin of the National Scientific Center of the Republic of Kazakhstan, 1, 66-71 (2019). (In Russ.)
9 K.O. Toleubekov, A.S. Khazhidinov and A.S. Akaev, Bulletin of the National Nuclear Center of the Republic of Kazakhstan, 1 (2021). (In Russ.)
10 V.V. Baklanov, V.S. Zhdanov and E.V. Malysheva, Bulletin of the National Scientific Center of the Republic of Kazakhstan, 1(37), 55-66 (2009). (In Russ.)
11 K.O. Toleubekov, V.V. Baklanov, A.S. Akaev, and M.K. Bekmuldin Recent Contributions to Physics, 2(81), 97-105 (2022).
12 M.K. Skakov, V.V. Baklanov, G.S. Nurpaissova, Eurasian Physical Technical Journal, 21, 57-66 (2024).
13 V. Ye. Zinoviev. Thermophysical properties of metals at high temperatures, (Metallurgy, 1989). (In Russ.)

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