Nonlinear Dynamics and Applications

27

Nonlinear Dynamics and Applications

Minsk
2021

Proceedings of the Twenty-eight Anniversary Seminar NPCS'2021
in memory of Prof. V.I. Kuvshinov
May 18-21, 2021, Minsk, Belarus
Fractals, Chaos, Phase Transitions, Self-organization

Editors
V.A. Shaparau
A.G. Trifonov

Volume 27
2021

Minsk "Pravo i Ekonomika" 2021

Nonlinear Dynamics and Applications

Minsk
2021

Proceedings of the Twenty-eight Anniversary Seminar NPCS'2021
in memory of Prof. V.I. Kuvshinov
May 18-21, 2021, Minsk, Belarus
Fractals, Chaos, Phase Transitions, Self-organization

Editors
V.A. Shaparau
A.G. Trifonov

Volume 27
2021

Minsk "Pravo i Ekonomika" 2021

УДК 53(061.3)
ББК 22.3(Англ.)
Н72

Nonlinear Dynamics and Applications : Proceedings of the Twenty eight Anniversary Seminar NPCS’2021, Minsk, May 18-21, 2021 = Нелинейная динамика и приложения : труды XXVIII Международного семинара, Минск, 18-21 мая 2021 г. / редкол.: В. А. Шапоров [и др.]; под ред. В. А. Шапорова, А. Г. Трифонова; Объединенный институт энергетических и ядерных исследований – «Сосны» НАН Беларуси. – Минск : Право и экономика, 2021. – 544 с. – ISBN 978-985-552-976-8.

УДК 53(061.3)
ББК 22.3(Англ.)

Редакционная коллегия:
В. А. Шапоров, А. Г. Трифонов, Л. Ф. Бабичев

ISBN 978-985-552-976-8

© Государственное научное учреждение «Объединенный институт энергетических и ядерных исследований – «Сосны» НАН Беларуси», 2021
© Оформление. ИООО «Право и экономика», 2021

Научное издание

Nonlinear Dynamics and Applications : Proceedings of the Twenty eight Anniversary Seminar NPCS’2021, Minsk, May 18-21, 2021 = Нелинейная динамика и приложения : труды XXVIII Международного семинара, Минск, 18-21 мая 2021 г.

Технический редактор *В.Г. Гавриленко*

Подписано в печать 27.08.2021 Формат 60x84$_1$/8 Бумага офсетная
Печать цифровая Усл.печ.л. 68,03 Уч.изд.л. 68,4 Тираж 75 экз. Заказ 3974
ИООО «Право и экономика» 220072 Минск Сурганова 1, корп. 2 Тел. 8 029 684 18 66
Отпечатано на издательской системе Gestetner в ИООО «Право и экономика»
Свидетельство о государственной регистрации издателя,
изготовителя, распространителя печатных изданий, выданное
Министерством информации Республики Беларусь 17 февраля 2014 г.
в качестве издателя печатных изданий за № 1/185

ISBN 978-985-552-976-8

9 789855 529768

Nonlinear Dynamics and Applications. Vol. 27 (2021) 519-532

Comparative Analysis of Severe Accidents (Small- and Large-Break Loss-of-Coolant Accident) for a VVER-1200 Reactor

A.G. Lukashevich*, D.A. Bortnik, E.G. Vashetko, V.V. Gilewsky
Joint Institute for Power and Nuclear Research – "Sosny"
of the National Academy of Sciences of Belarus,
220109 Minsk, PO box 119, BELARUS

The ASTEC integral code is used to simulate severe accidents in the frame of the deterministic safety analysis of nuclear power plants. The goal of this work is a comparative analysis of severe accidents for a small leak of DN 80 mm and a large leak of DN 850 mm in the cold leg of the primary circuit of a VVER-1200 reactor with a failure of active ECCS.

PACS numbers: 02.70.–c, 24.10.Nz, 28.41.AkQ
Keywords: ASTEC code, severe accident, modeling, safety analysis

1. Introduction

The development of nuclear energy makes ever more stringent requirements for ensuring the safety of nuclear power plants. When justifying safety, it is customary to divide possible radiation accidents into design basis ones, for which the design defines initiating events and end states and provides safety systems that ensure the limitation of their consequences to the limits established for such accidents, and beyond design basis caused by unaccounted for initiating events or accompanied by additional compared to design basis accidents, failures of safety systems or erroneous decisions of personnel, which can lead to severe damage or to melting of the core and release of radioactive fission products outside the reactor containment.

A severe accident leading to core melting may result from extremely unlikely cases of overlapping initiating events (rupture of primary circuit pipelines, complete blackout, etc.) and independent failures of the corresponding safety systems. However, due to extremely severe radiation and socio-economic consequences, severe accidents can make a significant contribution to the total risk from NPP operation.

After severe accidents at the TMI nuclear power plant, USA in 1979, at the Chernobyl nuclear power plant in 1986 and at the Fukushima-1 nuclear power plant, Japan in 2011, the analysis of the consequences of severe accidents and ways of limiting them became one of the components of the safety design justification.

The ASTEC (Accident Source Term Evaluation Code) integral code aims at simulating a hypothetical severe accident in a nuclear water-cooled reactor, from initiating event to the possible radioactive release outside the reactor containment [1-2].

---

*E-mail: alexey.lukashevich@gmail.com

2. General characteristics of small- and large-break loss-of-coolant accident with the failure of active ECCS

Accidents with a loss of coolant at the initial stage have the following features:

- in the first circuit, a decrease in pressure begins due to the release of the coolant into the break;
- a drop in the flow rate of the coolant along the primary circuit causes the formation of steam in the core, leading to a decrease in the power due to the negative steam effect of reactivity;
- after the emergency protection is triggered (the signal depends on the scenario), the reactor power is reduced to the level of residual energy;
- the main circulating pumps (MCP) are shut down due to a complete blackout or according to the setting (depending on the scenario);
- from the side of the secondary circuit, the steam generator (SG) is cut off from the turbine (shut-off control valves are closed), as a result, with small leaks, the pressure in the SG increases, depending on the size of the leak, the quick-acting pressure reducing plant of air discharge to the atmosphere or turbine bypass valve response setting can be reached;
- the consumption of normal steam generator make-up is reduced as a result of stopping the feed electric pumps or in accordance with the operation of the feed water regulator.

Uncompensated coolant outflow from the primary circuit leads to gradual dehumidification and heating of the core. Since in the simulated scenarios the failure of the active part of the ECCS is assumed (as a result of complete blackout or as an additional failure), the emergency replenishment of the core is carried out only from the passive ECCS with a flow rate determined by the pressure in the primary circuit. The response time and duration of operation of the ECCS hydroaccumulators depends on the rate of pressure drop of the coolant.

At the stage of the combined flooding of the core, the conditions for cooling the fuel assemblies are improved, the level in the core is partially restored. After the drainage of the ECCS hydroaccumulators, the flow of water into the primary circuit stops, and the mass of the coolant in the primary circuit and the level in the core again begin to decrease.

The upper sections of the fuel elements are drained, the deterioration of the conditions for heat removal from the fuel elements leads to heating of their cladding at a rate of 0.8 ... 1.5 K / s. The heating front moves from top to bottom, in accordance with the decrease in the level. When the fuel element cladding reaches a temperature of 1200 K, the zirconium-steam reaction intensifies, as a result of which the cladding temperature escalates, and the hydrogen content increases in the core. As the temperature of the fuel elements increases, the gas pressure under the cladding of the fuel elements begins to increase, which leads to their rupture. Steam access inside the fuel rods leads to bilateral oxidation of the cladding and a further increase in their temperature.

At some point, the heated part of the core is completely drained. Due to the sufficiently effective heat exchange by radiation, the temperature of the steel elements reaches the melting point (1700 K). The mass of the melt moves down into the zone of the fuel assembly supports, where a significant mass of the coolant remains, and causes intense boiling of the coolant. An increase in the steam flow rate through the core leads to additional oxidation of the fuel element cladding.

When the temperature of the cladding reaches 2250 K, the accident turns into the stage of destruction of the core. The melt (fuel cladding, fuel and structural materials) moves down into the area of the core support grid. After the destruction of the support spacer grid, the melt and debris of the core enter the zone of the core support grid, again causing violent boiling of the coolant. At the moment the hot material enters the lower plenum of the reactor, the pressure in the reactor vessel rises. After draining the lower plenum, the melt fills all the free space bounded by the in-vessel shaft. Further, through penetration of the wall of the in-vessel shaft occurs in the region of the core support grid. The melt falls on the bottom of the reactor vessel. Due to the heat flux from the layer of superheated steel formed during the separation of the corium in the lower plenum of the reactor, the reactor vessel rupture occurs.

3. Initial data and calculation of the stationary nominal state of the reactor installation

Table 1 shows the main parameters of the reactor plant in the nominal state.

Table 1 – the main parameters of the reactor plant in the nominal state

Parameter	Value
Thermal power of the reactor, MW	3200
Coolant flow through the reactor, m^3 / h	88000
Coolant pressure at the core exit, MPa, absolute	16,2
Coolant temperature at the reactor inlet, ° C	298,2
Steam pressure in the steam header of the steam generator, MPa	7,0
Feed water temperature, ° C	225,0

The calculation of the stationary nominal state of the reactor plant is carried out to bring the values of a number of important parameters to the nominal values that ensure the operation of the NPP in normal mode. These calculations are performed for convenience at negative times. The calculation starts at t = –5000, and ends at t = 0. Time t = 0 is the beginning of the emergency scenario.

Figures 1–2 show the calculation results for a stationary nominal operating mode in the ASTEC program code.

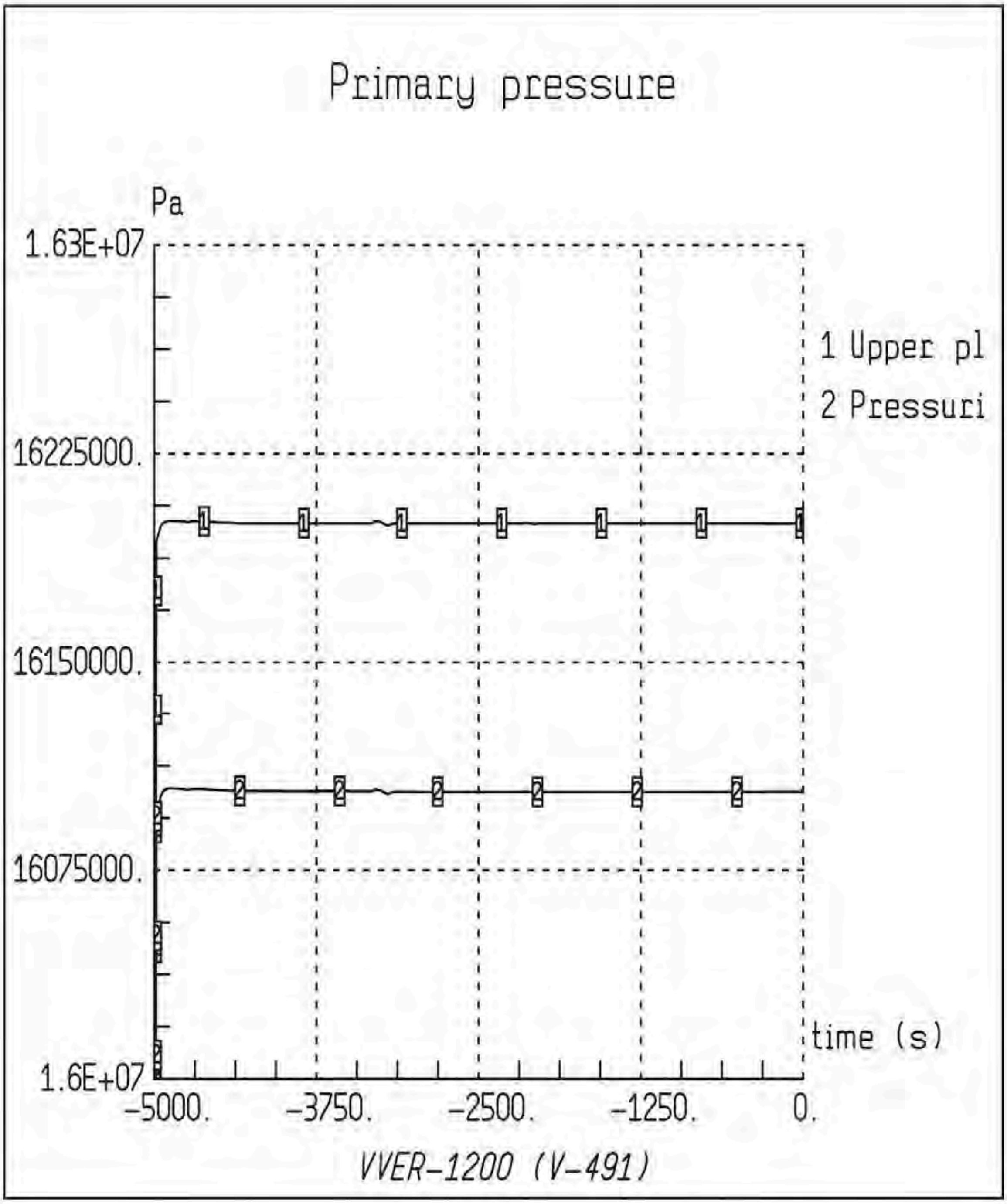

Figure 1 – Pressure in the pressurizer and the upper plenum of the reactor in a stationary nominal state

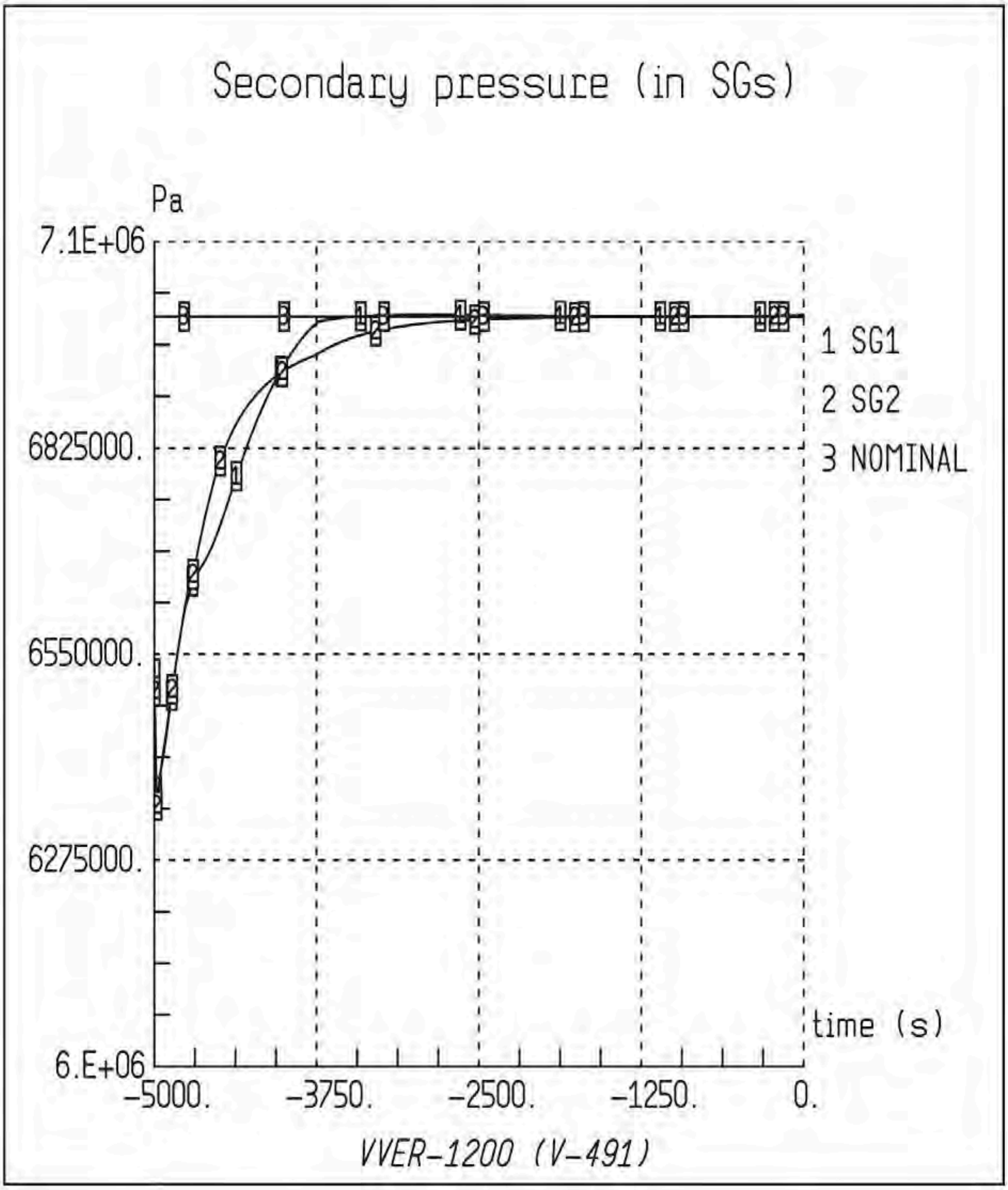

Figure 2 – Pressure in steam generators in stationary nominal state

4. Calculation of a severe accident with a small leak in the cold leg of the primary circuit

Let us consider an accident with a small leak of DN 80 mm in the cold leg of the primary circuit of a VVER-1200 reactor with a failure of active ECCS

Figures 3–6 show the calculation results for a small leak in the cold leg of the primary circuit in the ASTEC program code.

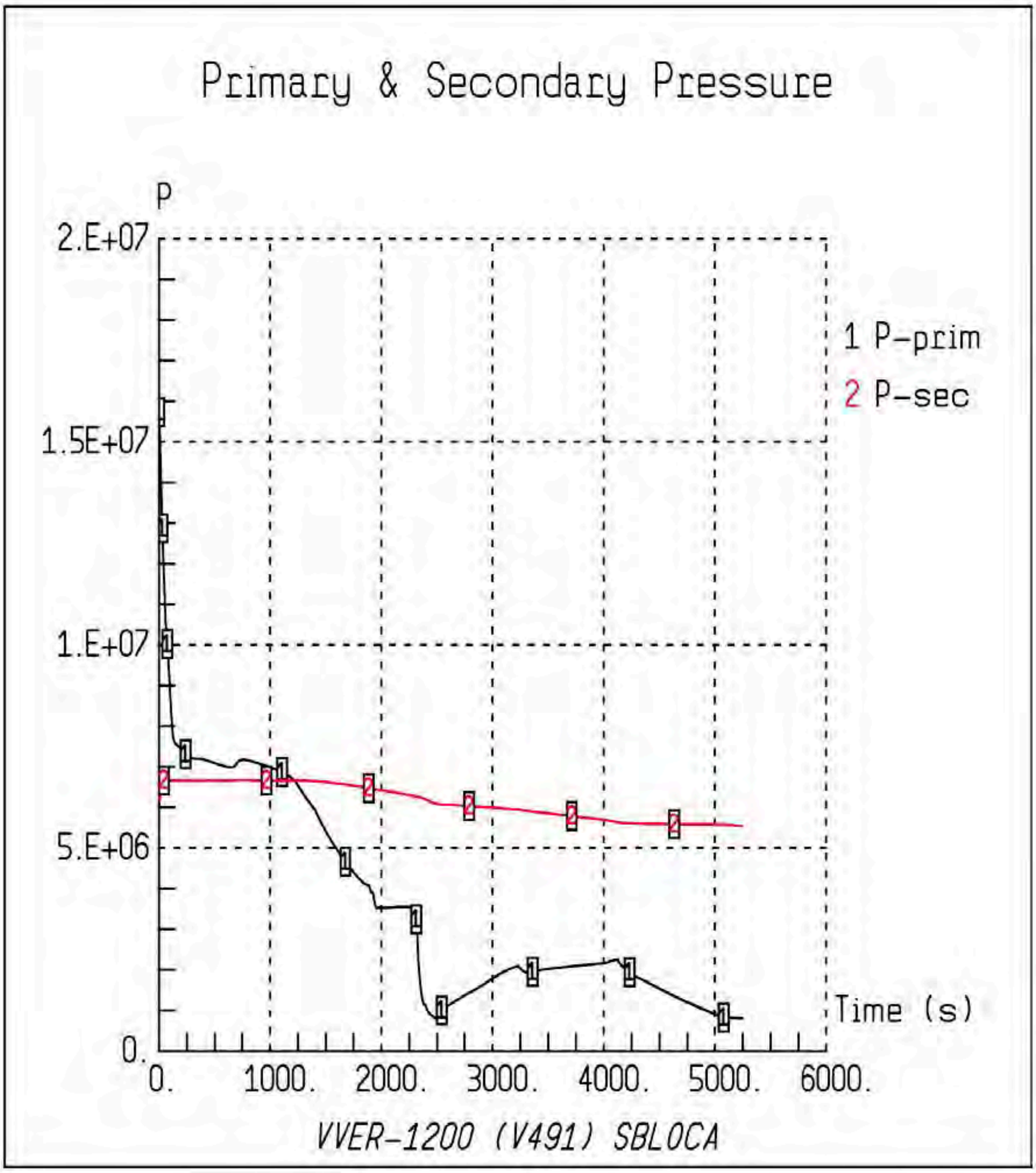

Figure 3 – Pressure in the primary and secondary circuits of a nuclear power plant in an accident with a small leak

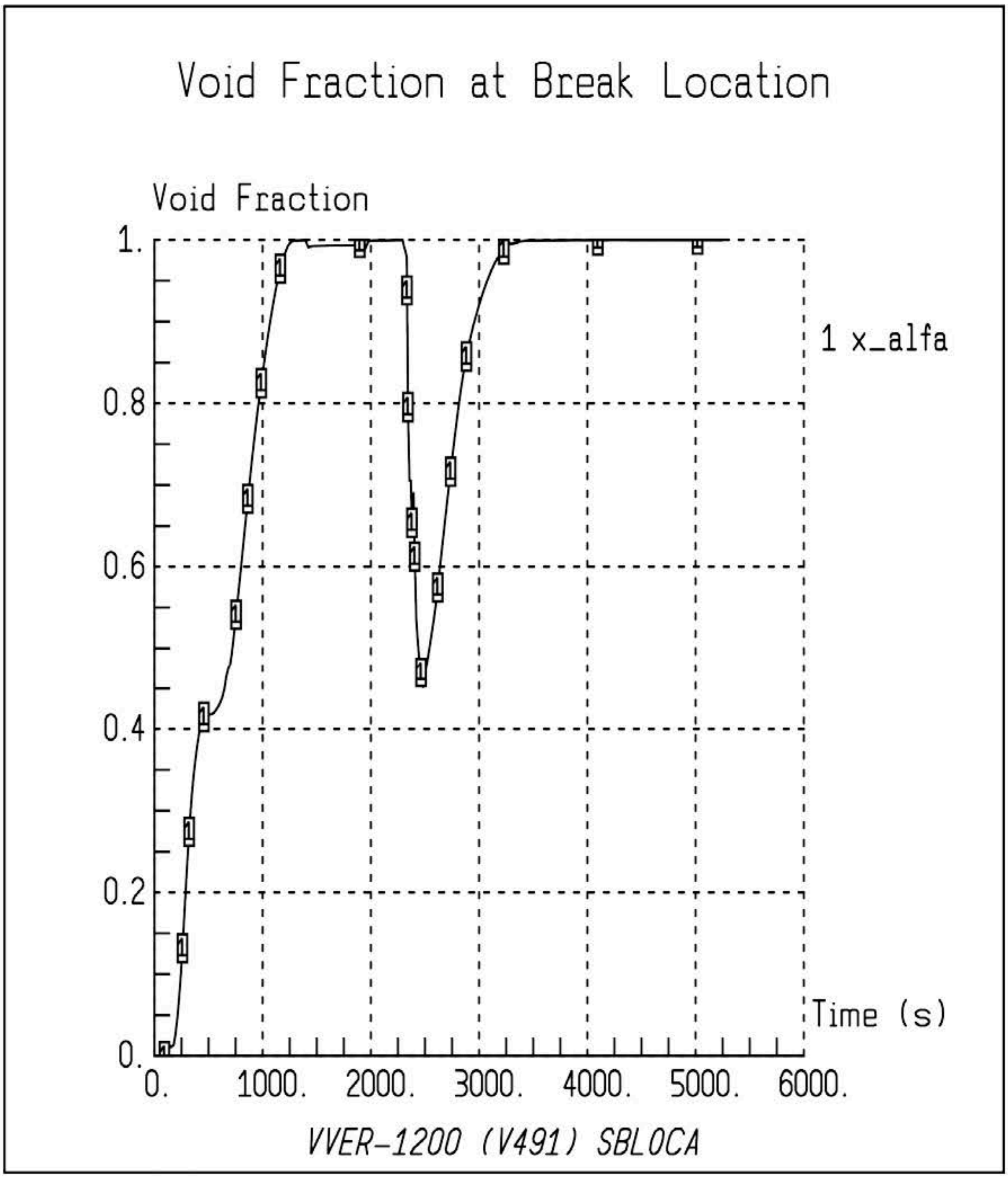

Figure 4 – Steam volume fraction at the location of a small leak

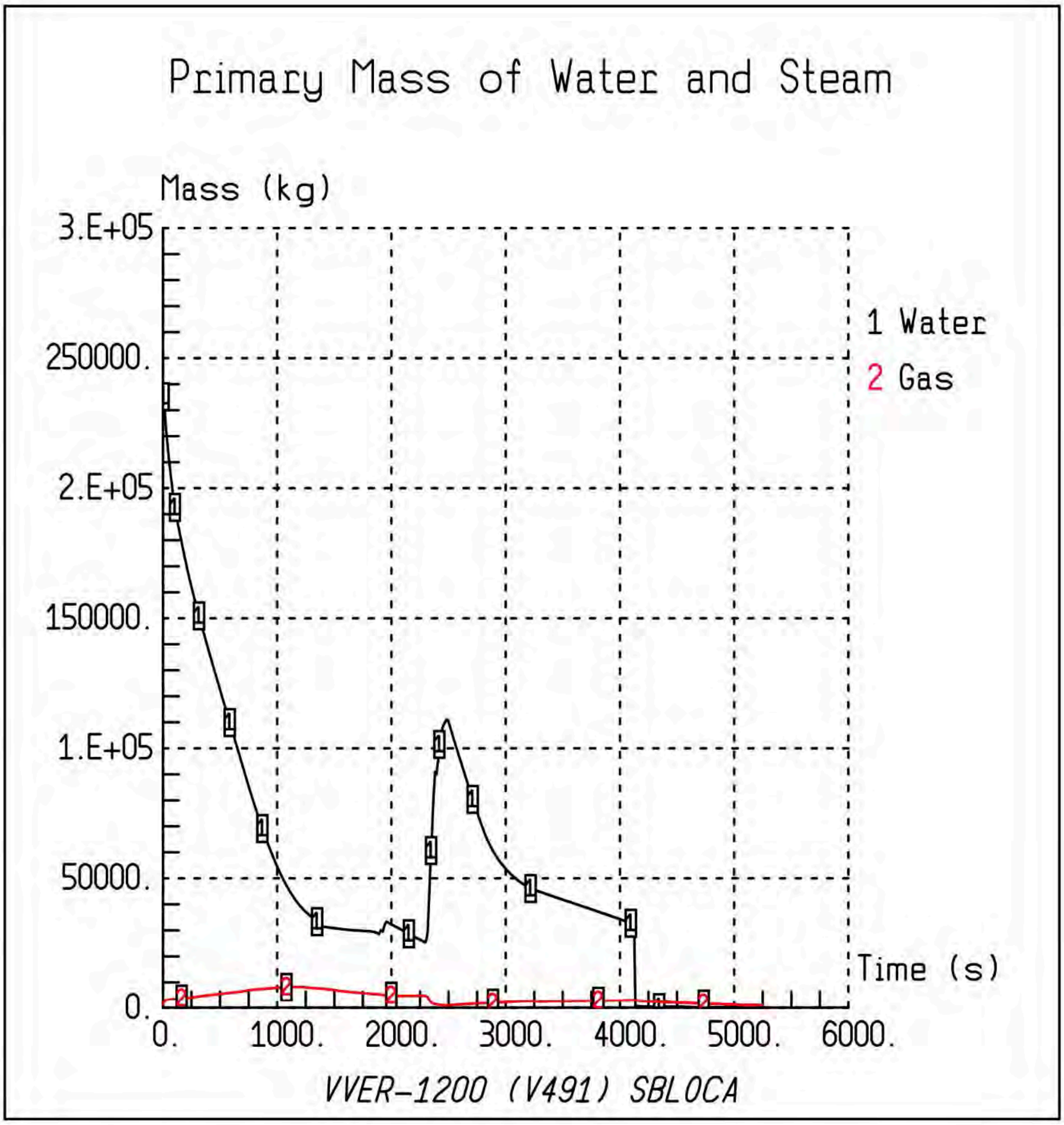

Figure 5 – Mass of water and steam in the primary circuit of a nuclear power plant in an accident with a small leak

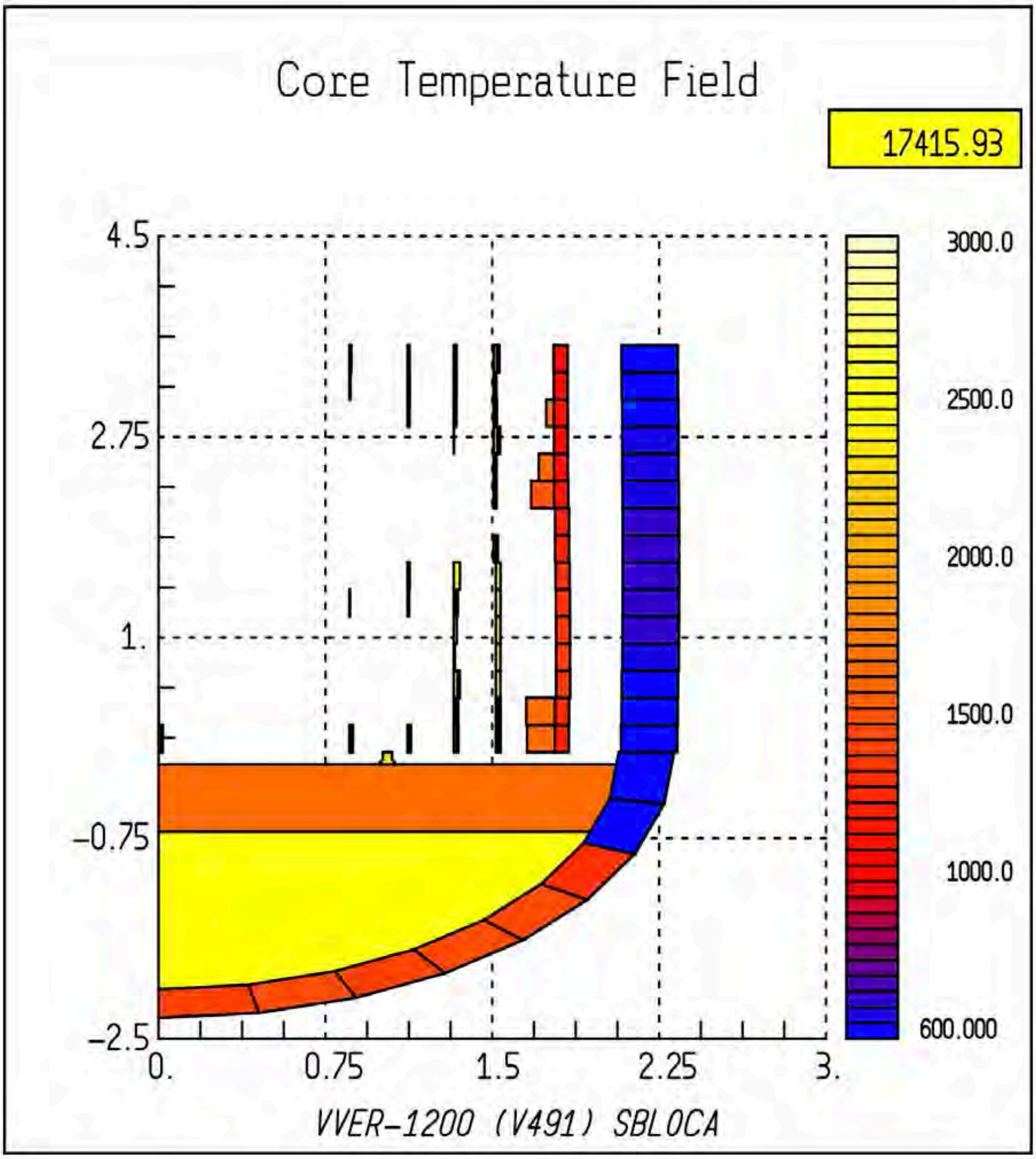

Figure 6 – Temperature values in the reactor core with a small leak at the time t=17415 s

5. Calculation of a severe accident with a large leak in the cold leg of the primary circuit

Let us consider an accident with a large leak of DN 850 mm in the cold leg of the primary circuit of a VVER-1200 reactor with a failure of active ECCS.

Figures 7–11 show the calculation results for a large leak in the cold leg of the primary circuit in the ASTEC program code.

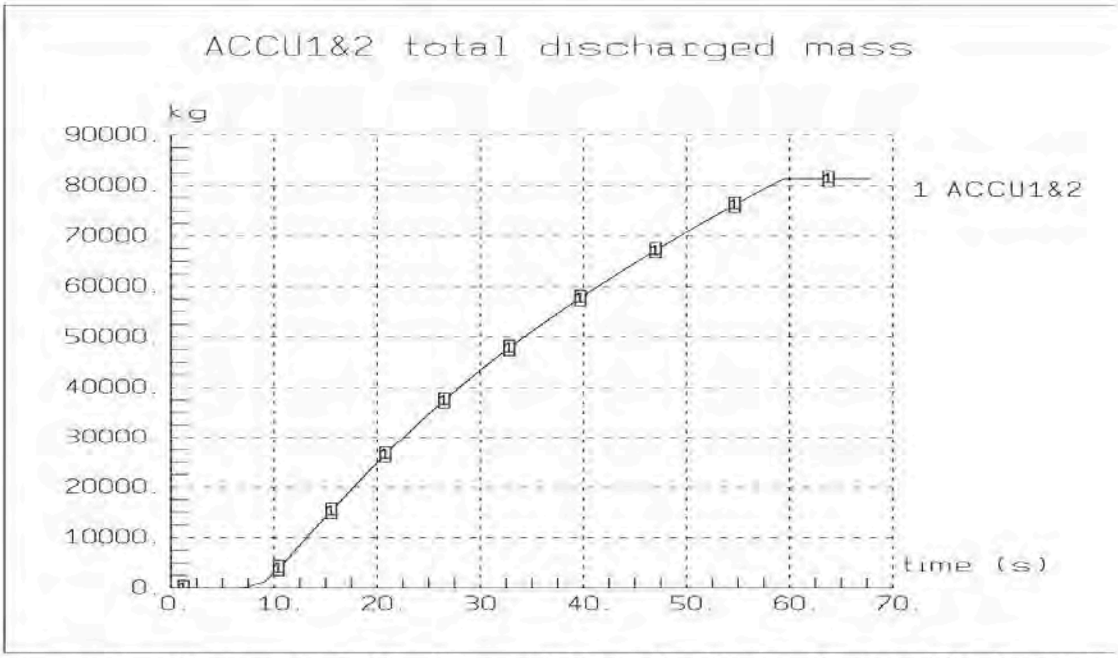

Figure 7 – The amount of water used from the first and second hydroaccumulators during an accident with a large leak at the time 67 s.

At the time 59 s, the hydroaccumulators are disabled according to the condition “Level in ECCS hydroaccumulators less than 1.25 m”.

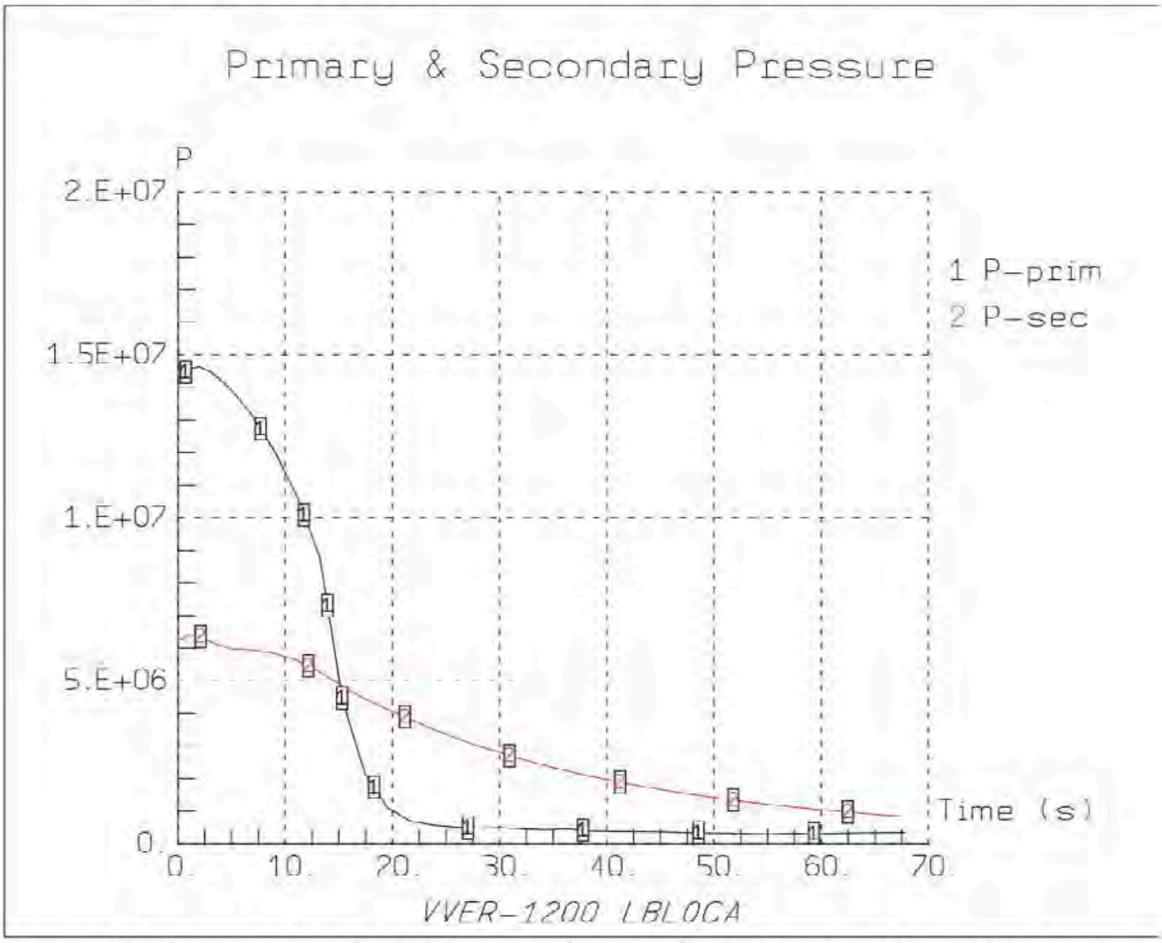

Figure 8 – Pressure in the primary and secondary circuits of a nuclear power plant during an accident with a large leak at the time 67 s

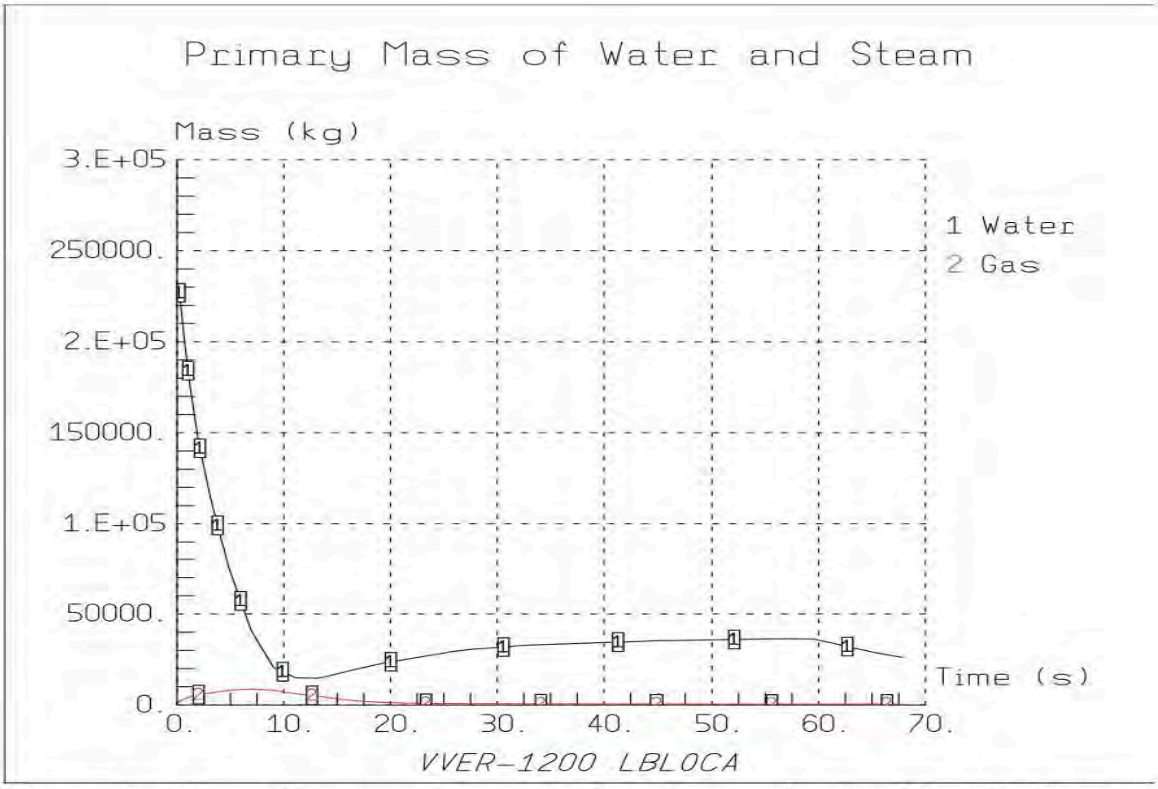

Figure 9 – Mass of water and steam in the primary circuit of the NPP in case of an accident with a large leak at the time 67 s

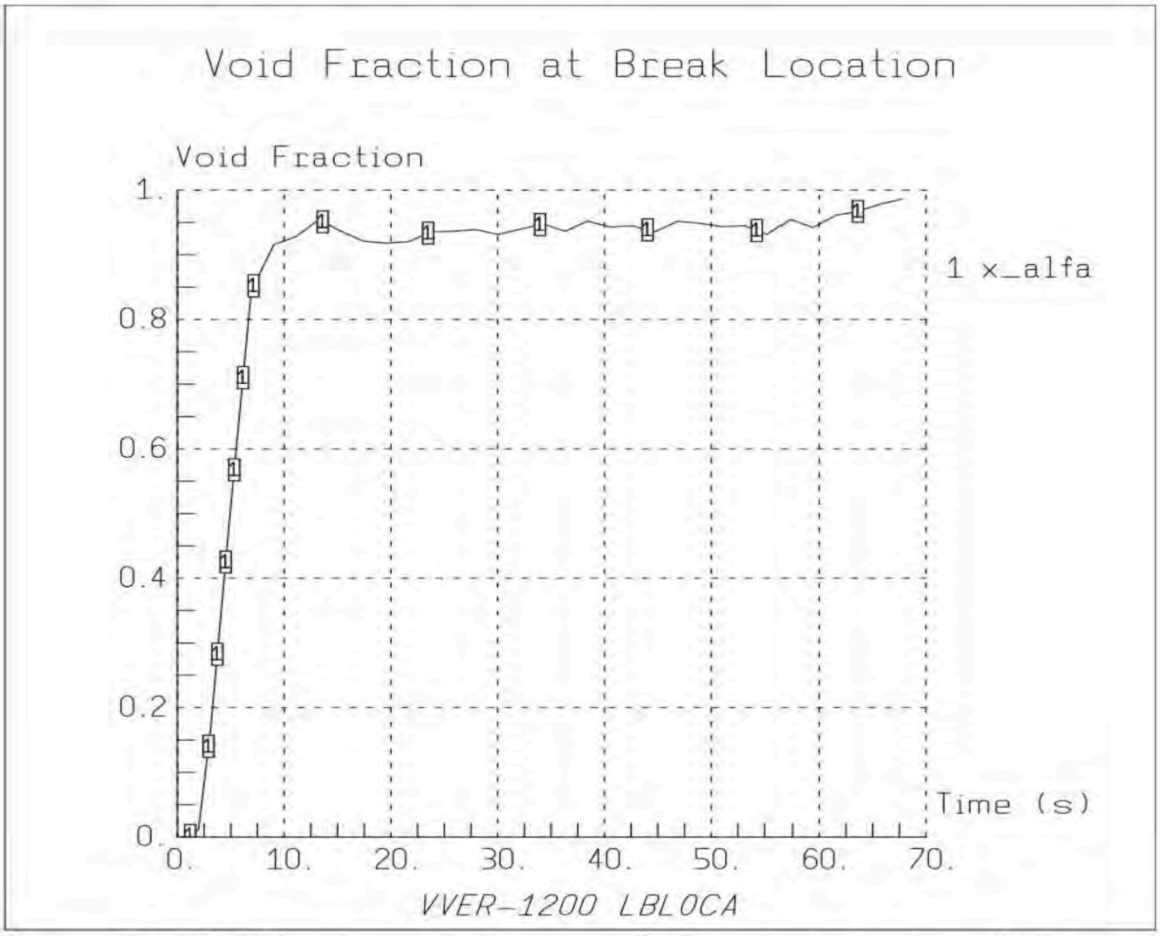

Figure 10 – Void fraction at the location of a large leak at a time of 67 s

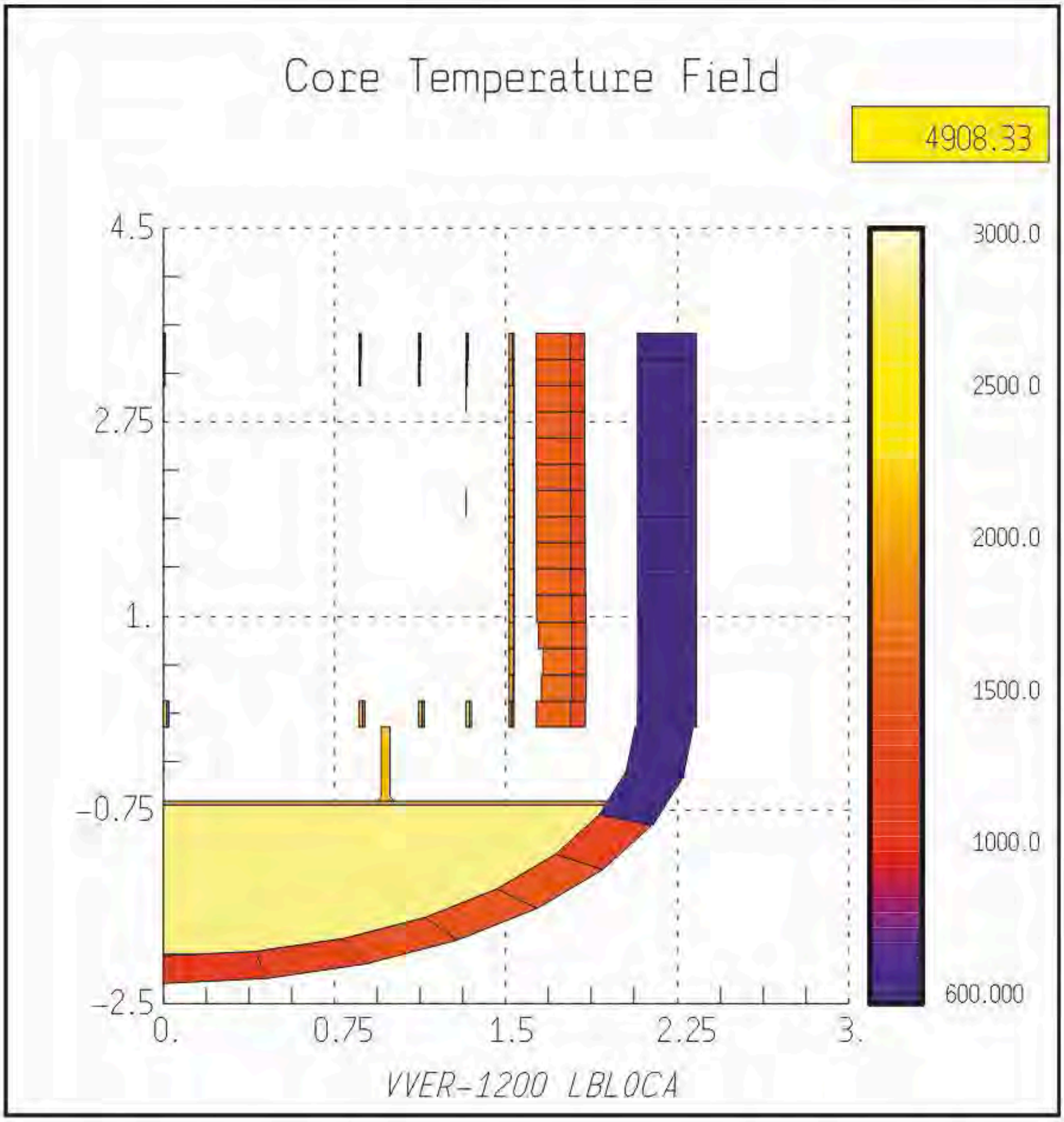

Figure 11 – Temperature values in the reactor core with a large leak at time t=4908 s

6. Comparative analysis of severe accidents (small- and large-break loss-of-coolant accident) for a VVER-1200 reactor

Table 2 shows the chronological sequence of events for a small leak of DN 80 mm and a large leak of DN 850 mm in the cold leg of the primary circuit of a VVER-1200 reactor with a failure of active ECCS based on the results of calculations using the ASTEC software.

Table 2 – Chronological sequence of events for a small leak of DN 80 mm and for a large leak of DN 850 mm with failure of active ECCS

Event	**Start conditions, blocking conditions, or triggering action**	**Time, s**	
		Small leak DN80	**Large leak DN850**
the reactor installation is operating at rated power level	The initial state	0,0	0,0
Instant leak DN80 / DN850	The initial state	0,0	0,0
Failure of all pumps of the emergency injection system and the sprinkler system	Postulated failure	0,0	0,0
Start feeding boron solution from ECCS hydroaccumulators	Reactor outlet pressure less than 5.90 MPa	1350,0	7,0
End of ECCS hydroaccumulators discharge	Decrease in level in ECCS hydroaccumulators less than 1.25 m	2 500,0	59,43
Start of hydrogen generation	Heating up the core	4 232,1	149,1
Intensification of the steam-zirconium reaction, the beginning of the destruction of the fuel element cladding	Exceeding the temperature of the fuel element claddings of the design limit 1 200 ° C	5154,0	414,9
The beginning of the flow of the melt into the lower plenum of the reactor	Heating up the core	8202,8	1 202,8
Diagrid collapse	Core melting and collapse	13 200,0	1 920,0
Start of materials falling into the core catcher	Destruction of the reactor vessel	17 416,0	4 908,0

7. Conclusion

The total release of hydrogen under the containment during the course of the accident, a small leak of DN 80 mm with the failure of active ECCS was 490.6 kg, the destruction of the reactor vessel occurs at a time of 17 416.0 s, the melt outlet from the reactor vessel is 110 154.0 kg.

The total release of hydrogen under the containment at a large leakage of DN 850 mm was 81.4 kg, the destruction of the reactor vessel occurs at the moment of time 4,908.0 s, the melt outlet from the reactor vessel is 72,388.0 kg.

A comparative analysis of accidents with a small DN 80 mm and large DN 850 mm leakage of the primary coolant and with the failure of active ECCS showed that as a result of a rapid loss of coolant in an accident with a large leak, less explosive hydrogen is formed. Due to the higher rate of the process of melting and destruction of the core, the peripheral part of the structures does not have time to get into the melt, and the exit of the melt from the reactor vessel with a large leak is also less than with a small one. However, the speed of the process with a large leak leaves much less time for decision-making.

The results obtained can be used in the analysis of other severe beyond design basis accidents with a loss of coolant and as a basis for the further development of ASTEC models for a VVER-1200 reactor, for example, in order to simulate the release of fission products during a severe accident, to simulate containment, and other tasks.

Acknowledgements

This work was supported within the framework of event 11 "Development and creation of a system of scientific and technical support for the Ministry for Emergency Situations in the field of nuclear and radiation safety" of subprogram 6 "Scientific support for the development of nuclear energy in the Republic of Belarus" of the State program "Science-intensive technologies and equipment" for 2016 - 2020 years.

References

[1] Chatelard P., Reinke N., Arndt S., Belon S., Cantrel L., Carénini L., Chevalier-Jabet K., Cousin F., Eckel J., Jacq F., Marchetto C., Mun C., Piar L., “ASTEC V2 severe accident integral code main features, current V2.0 modelling status, perspectives”, Nuclear Engineering and Design, 272 (June 2014), p.119-135.

[2] Chatelard P., Belon S., Bosland L., Carénini L., Coindreau O., Cousin F., Marchetto C., Nowack H., Piar L., Chailan L, “Main modelling features of ASTEC V2.1 major version”, Annals of Nuclear Energy, vol.93 (July 2016), pp.83-93.