

Sensitivity of WWER-1000 LB LOCA Analysis Results to Initial and Boundary Conditions

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1. Introduction

Concept of safety margins /1/ in relation to some plant parameters (especially, those indicating the integrity of physical barriers on the radioactivity release paths) plays an important role in a NPP safety assessment. The existence of margins gives the assurance that the plant is safe under all design basis conditions including the postulated accidents. Safety margin can be defined as relation (expressed in physical units) between maximum permissible value of a certain plant parameter (safety limit, exceeding of which leads, for instance, to safety barrier failure or to unacceptable physical phenomenon) and actual value of this parameter.

In many cases, maximum permissible values and/or actual values are not known with sufficient precision, hence safety margin can not be exactly quantified. Therefore in most cases so called conservative approach is being used now in design practice to assess plant safety in relation to design basis transients and accidents. Its major components are conservatism of acceptance criteria characterising safety and conservatism of analysis that gives plant parameters to be compared with acceptance criteria.

Acceptance criteria conservatism is determined by the fact that they are stipulated by regulatory body with some margin in relation to the relevant safety limits (i.e., in relation to the parameter values that would really result in the safety barrier failure or unacceptable physical phenomena). Conservatism of the analysis is expressed, in particular, by treating the boundary and initial condition uncertainties so as to be sure that the plant parameter values obtained by the accident analysis are more adverse than those that would be reached actually should the accident really occurs.

Accordingly, safety margin is understood in practice as the difference between conservative analysis result and acceptance criterion for the relevant plant parameter (for example, in relation to the maximum cladding temperature in LOCA). In this interpretation, larger safety margin would mean more safe plant. In particular, if safety margin falls to zero, the plant's safety level would turn out unacceptable. In fact, such conclusion can be subjective from the technical viewpoint, at least - due to two reasons.

Firstly, as mentioned above, the acceptance criteria are always assigned with some margin in relation to the real safety limits. Therefore even decreasing safety margin to zero (for example achieving of PCT value 1200°C in LOCA analysis) does not necessarily mean the achieving of safety limit, i.e. that the plant safety is not ensured. Secondly, it is implied during analysis of design basis accidents that conservative analysis is deterministic, i.e. it gives the maximum possible parameter values to be compared to acceptance criteria. Actually, when treating the uncertainties, e.g. for initial conditions, the relevant numerical values assumed as maximum possible involve (implicitly or explicitly) some probability of non-exceeding just these numerical values.

Therefore numerical value of safety margin obtained in accident analysis essentially depends on what probability of realisation of initial condition more adverse than value assumed in calculation was considered as acceptable in this analysis or in this design. In case of boundary conditions (for instance, break location, configuration of the operable safety system, plant status before accident, and so on), the problem seems even more complicated since it is more difficult to assess probability of realisation of a given boundary condition set.

In this paper, sensitivity of WWER-1000 LB LOCA analysis results in relation to some typical boundary and initial conditions is considered. For some initial conditions quantifiable in relation to the

probability of the numerical values, their effect on the calculated safety margins for PCT and local cladding oxidation in the core hot spot is considered.

It should be taken into account that results given in present paper do not relate to any specific WWER-1000 unit. The purpose of the calculations was comparative assessment of boundary and initial conditions effect on results characterising acceptance criteria fulfilment. Therefore initial data assumed for calculations (including ECCS configuration) may not represent the design features of an operating or being designed WWER-1000 unit.

2. TRAP program package

Thermalhydraulic safety analysis of design basis accidents and transients for WWER units are conducted using TRAP program system that was developed in EDO Gidropress. First versions of the programs included in this complex were developed more than 30 years ago. Since then TRAP system is being permanently modernised and extended. Code validation had been permanently conducted beginning the first versions. For this purpose, own EDO Gidropress' experiments, data of start-up work and real incident on NPP with WWER, experiments carried out on domestic and foreign facilities were used.

Codes of TRAP system took part successfully in several international standard problems being organised both by IAEA and OECD/NEA. As example, Fig.1 shows results of blind calculation for international standard problem ISP-27 organised on BETHSY experimental facility in France. It is seen that blind calculation using DINAMIKA code (one of the major codes of TRAP complex) has predicted the experimental results much better than the most of calculations by ATHLET, RELAP and CATHARE codes.

According to new requirements of Russian safety standards, the TRAP program system in its last version (TRAP-97) has passed through the certification procedure. In the frame of this procedure, independent experts of GAN RF have carried out the in-depth examination both of TRAP codes themselves and its validation report. As the result of this comprehensive assessment, TRAP-97 program system and its main constitutive parts (DINAMIKA-97 /2/ and TECH-M-97 /3/) have received the GAN RF certificates that allow usage of TRAP-97 for thermalhydraulic calculations of transients and accidents for WWER reactor plant safety assessments.

The results given in the present paper were obtained by TECH-M-97 code. Fig.2 shows the reactor plant nodalization used for these calculations. This nodalization represents both WWER-1000 configuration and typical ECCS configuration. The nodalization depicted in Fig.2 is a typical one for the design analysis of LB LOCA events. It is noted however that the adequacy of the nodalization to be used for each specific plant design is being proved by preliminary evaluation.

3. Effect of boundary conditions

According to the requirements of the safety normative documents, the boundary conditions should be set up taking into account all dependent failures. Besides, one independent failure of any one element of any safety system should be assumed (single failure principle). Therefore, the preliminary consideration of sensitivity to boundary conditions is required for deterministic analysis. The most conservative accident scenario subject to comprehensive thermalhydraulic analysis to prove fulfilment of acceptance criteria established for this accident is determined on the sensitivity studies mentioned above. The results that allow to estimate the sensitivity of significant LB LOCA parameters (PCT and local oxidation) to some boundary conditions are presented below.

Effect of passive ECCS configuration

There are four ECCS tanks of 60 m³ each at WWER-1000 reactor plant. Tanks are connected directly to the reactor chambers via check valves - two tanks to the reactor collection chamber (RCC) and two - to the reactor pressure chamber (RPC). According to single failure principle, it is required to consider

possibility of anyone tank failure. Therefore there are two possible combinations of operable tanks relating to water supply to the reactor: (1) 2 tanks to RPC and 1 tank to RCC; (2) 1 tank to RPC and 2 tanks to RCC. The most adverse combination of mentioned two ones shall be considered in the licensing LB LOCA analysis.

The calculation results of the cold leg double-ended break at the reactor inlet are shown in Fig.3. It is seen that «1 tank to RPC and 2 tanks to RCC» configuration gives more adverse result in sight of the core hot spot temperature condition. In particular, higher PCT during phase after the first peak means that possible local oxidation for «1 tank to RPC and 2 tanks to RCC» scheme will be more adverse compared to «2 tanks to RPC and 1 tank to RCC» scheme. Therefore «1 tank to RPC and 2 tanks to RCC» configuration is usually assumed in the LB LOCA licensing analyses for WWER-1000. It should be noted however that the conservatism of this assumption for each specific design must be justified by preliminary evaluation.

Effect of active ECCS configuration

Typical scheme of active ECCS at WWER-1000 unit provides for water supply from low pressure pumps (LPP) to the reactor chambers (via ECCS tanks pipes) and to one or two loops (depending on reactor plant design). According to single failure principle, it is required to consider possibility of failure of any one LPP (for four-channel scheme it is necessary also to assume that any one channel is inoperable due to repair). Therefore there are several possible combinations of the operable LPP channels in relation to water supply to the primary circuit. Accordingly, the most adverse combination must be assumed for the LB LOCA licensing analysis.

As an example, Fig.4 shows the effect of two operable LPP combinations on the core hot spot temperature: (1) LPP supply to the reactor and to the intact loop; (2) LPP supply to the reactor and to the damaged loop. It is seen that scheme (2) gives more adverse result in sight of the core hot spot temperature condition. In particular, higher PCT during phase after the first peak means that possible local oxidation for scheme (2) will be more adverse compared to (1) scheme. Therefore the operability of LPP supplying water to the damaged loop is usually assumed in the LB LOCA licensing analyses. As far as the rest LPPs are concerned, the possibility of single failure is assumed there (for four-channel ECCS the repair of one train is assumed as well). It should be noted however that conservative ECCS configuration assumed for licensing analysis must be justified by preliminary evaluation for each specific design.

Effect of blowdown coefficient

The first cladding temperature peak takes place during the first few seconds of accident when departure from nucleate boiling occurs in core hot spot. The causes of the heat transfer crisis are sharp drop of primary pressure and coolant flow rate. In case of cold leg rupture, core flow rate reduction results from the main coolant pump (MCP) stop and coolant discharge via the break. Therefore the usual practice is to vary the reactor discharge coefficient in the range 0,6-1,0, trying to obtain the earliest and the most complete coolant flow stagnation in the core. The worst discharge coefficient is used then for detail licensing analysis.

Fig.5 shows the effect of blowdown coefficient on the core hot spot temperature conditions. Calculations have been carried out for three values of the blowdown coefficient (0,6, 0,8 and 1,0) from the control volume modelling reactor inlet nozzle (control volume 68 in Fig.2). The discharge coefficient has weak influence on the first peak of the maximum cladding temperature (difference for various coefficients is about 2.5%). For coefficient 0.8, the cladding temperature during phase after the first peak is obviously higher than for 1.0 and 0.6 coefficients (averaged temperature over 0-400 s period is 315°C, 363°C and 351°C for 1,0, 0,8 and 0,6 coefficients, respectively). This means that possible local oxidation for 0.8 coefficient will be higher than for 1.0 and 0.6 coefficients.

Therefore the blowdown coefficient is assumed in most cases as 0.8 for licensing WWER-1000 LB LOCA analyses. It should be noted however that conservative coefficient is determined for each

specific design by preliminary assessments (both in sight of maximum cladding temperature and local oxidation).

4. Effect of initial conditions

Deterministic accident analysis for the plant licensing has to be carried out conservatively in relation both to the boundary conditions (assuming possible safety system failures) and to the initial conditions (assuming uncertainties of parameters being used as input data). Effect of some boundary conditions on the core temperature for LB LOCA was discussed in Section 3 of present paper. The purpose of the results given below is to demonstrate the influence of some initial conditions to the core hot spot temperature during a WWER-1000 LB LOCA.

Effect of maximum linear power

Both design power peaking factors coefficients and various uncertainties (e.g., related to measurement and control of the reactor power, inaccuracy of core physics calculations, fuel rod geometry, fuel enrichment, etc) are to be taken into account conservatively while assigning initial linear power in the most powered fuel rod. All these uncertainties are assumed as realized simultaneously in one hottest fuel rod by means of the relevant power peaking factor; the hot channel for TECH-M-97 code is then arranged consisting of a certain number of these hottest fuel rods.

Uncertainties related to neutron-physics calculation inaccuracy, fuel rod geometry and enrichment are assigned by multiplication design power of hot fuel rod to so-called engineering margin coefficient. Engineering margin coefficient is calculated statistically, and its numerical value for accident analyses is assumed for 3σ interval. This means that the power of the hottest fuel rod used for accident analysis is conservative with probability not less than 98,86%. The above approach gives for WWER-1000 the maximum linear heat rate as 448 W/cm. Using this value, design safety analyses are carried out and the requirements to the core power distribution control under normal operation are determined.

Fig.6 depicts the effect of maximum linear heat rate on the core hot spot temperature conditions. Calculations have been carried out using two values of initial linear heat rate, namely 448 W/cm and 417 W/cm. The last value corresponds to the engineering coefficient value being conservative with the probability not less than 95%. This confidence level is usually considered as acceptable for the technical applications. In particular, the most significant acceptance criterion for the safety analysis of the anticipated operational occurrences is absence of departure from nucleate boiling in core hot spot with probability not less than 95% (besides, the frequency of such transients is much more than for LB LOCA). It is seen from Fig.6 that maximum linear heat rate effects significantly not only on the first peak temperature maximum but on core hot spot temperature conditions during subsequent accident phase (and hence on local oxidation).

Effect of pellet-cladding gap conductivity

The conductivity of gas gap between fuel pellet and cladding determines initial fuel temperature. Since the heat removal from fuel rod to coolant is terminated practically at the moment of pipe break, the fuel rod cladding temperature rises due to heat accumulated in fuel. Therefore the first cladding temperature maximum depends on the initial fuel temperature and hence on the gas gap conductivity.

The gas gap conductivity depends mostly upon the gap size, that is difference between outer pellet diameter and inner cladding diameter. Design tolerances for these parameters are such, that maximum and minimum possible gaps differ nearly two times. Of course, the gap value at the core hot spot for LB LOCA design safety analysis is assumed as maximum over range of tolerance (in spite of the fact that statistic treatment of the pellet and clad manufacturing data gives extremely low probability to have such a large gap). The conductivity is calculated for this maximum gap value and then is decreased in order to take into account fuel densification and probable uncertainties of the conductivity correlation itself. The conductivity defined in this way determines initial fuel temperature very conservatively and hence effects on the core hot spot temperature conditions.

Fig.7 exhibits impact of gas gap conductivity on core hot spot temperature mode. Calculations have been carried out using two values of gas gap conductivity: (1) according to approach adopted now for design safety analyses as described above, and (2) conservative with probability at least 95%. One can see that gas gap conductivity significantly effects both on the first temperature maximum and on the core hot spot temperature conditions during subsequent accident phase (and hence on local oxidation).

Effect of residual heat

Residual heat has significant effect on the core temperature conditions during phase after the first temperature peak when core is essentially emptied and heat removal from fuel rods is constrained by low heat transfer coefficient to the overheated steam. In design LB LOCA analysis, the decay heat is set up as function of time using a standard correlation (for instance ANSI-79) assuming infinite time of the on full power operation. In addition, correlation inaccuracy is considered conservatively for 3σ interval, i.e. for the probability not less than 99,86%.

Fig.8 shows effect of residual heat value on the core hot spot temperature conditions. Calculations have been carried out using two curves of residual heat: (1) according to the approach adopted now for design safety analysis, and (2) conservative with probability not less than 95%. As one can see, residual heat has significant effect on the cladding temperature after the first peak (during reflood phase) and hence on the local oxidation. In particular, no significant oxidation should be expected in case of (2) since the cladding temperature during the accident is less than steam-zirconium reaction limit.

5. Conclusion

When substantiating the WWER reactor plant safety, an extended analysis is accomplished to find such a combination of initial and boundary conditions, that ensures conservatism of the analysis results in sight of parameters characterising the meeting of the acceptance criteria for specific design basis accidents. To this end, a great number of preliminary calculations are carried out at the first design phase using system thermalhydraulic codes developed in EDO Hidropress and certified by national regulatory body.

On the examples of some initial and boundary conditions being used for LB LOCA licensing analysis, high level of conservatism has been demonstrated as applied to the assessment of basic acceptance criteria meeting for this accident: maximum cladding temperature and maximum local oxidation. The results obtained have shown that calculated LB LOCA consequences can be significantly decreased if more technically reasonable conservatism for possible uncertainties is used, at least in relation to some initial and boundary conditions.

References

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- 3 Программа для ЭВМ. Расчет параметров первого контура при разрывах трубопроводов «ТЕЧЬ-М-97». Методика расчета. 862407.00466-019001. ОКБ «Гидропресс», 1998 (Паспорт аттестации ГАН России №112 от 02.09.99).

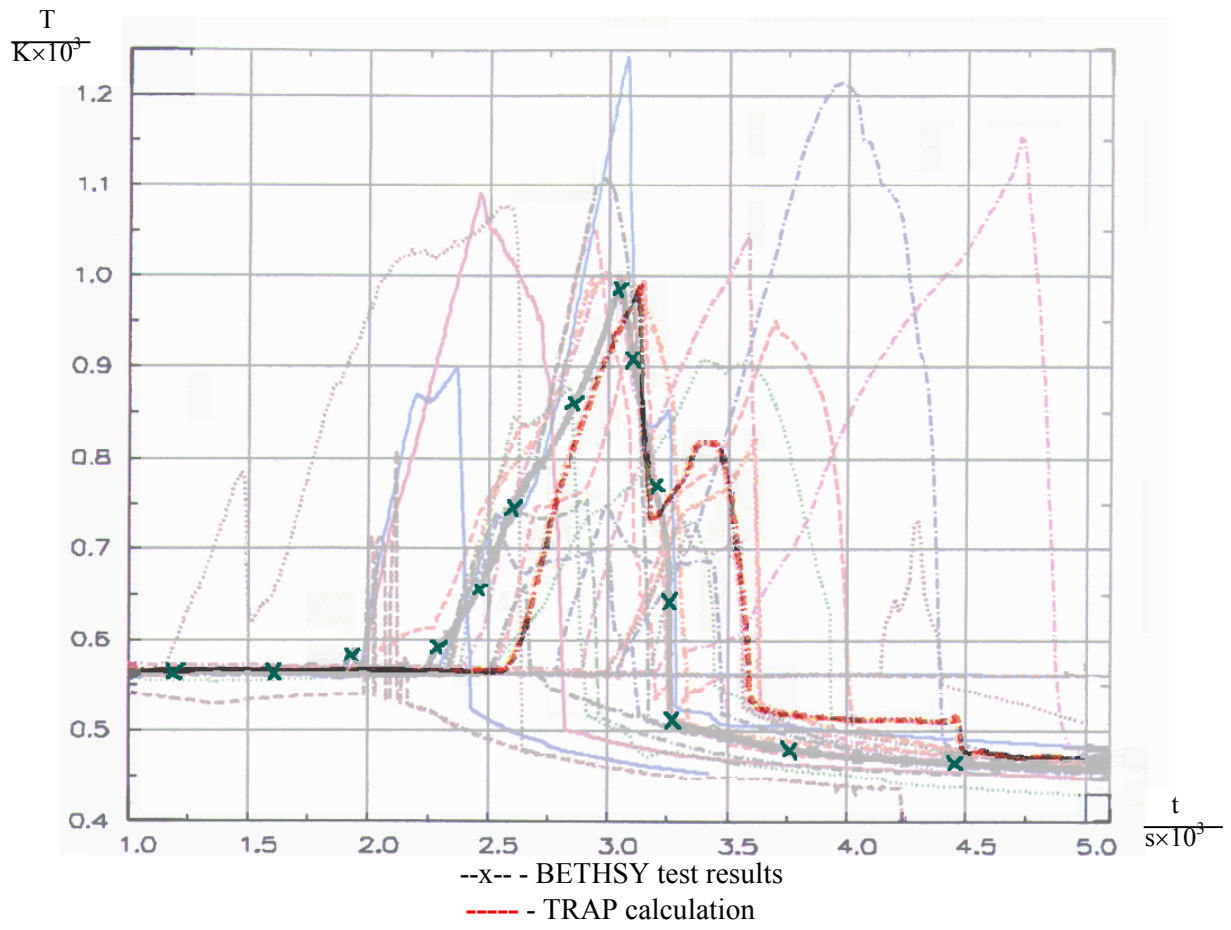


Fig.1. ISP-27 blind calculation results.

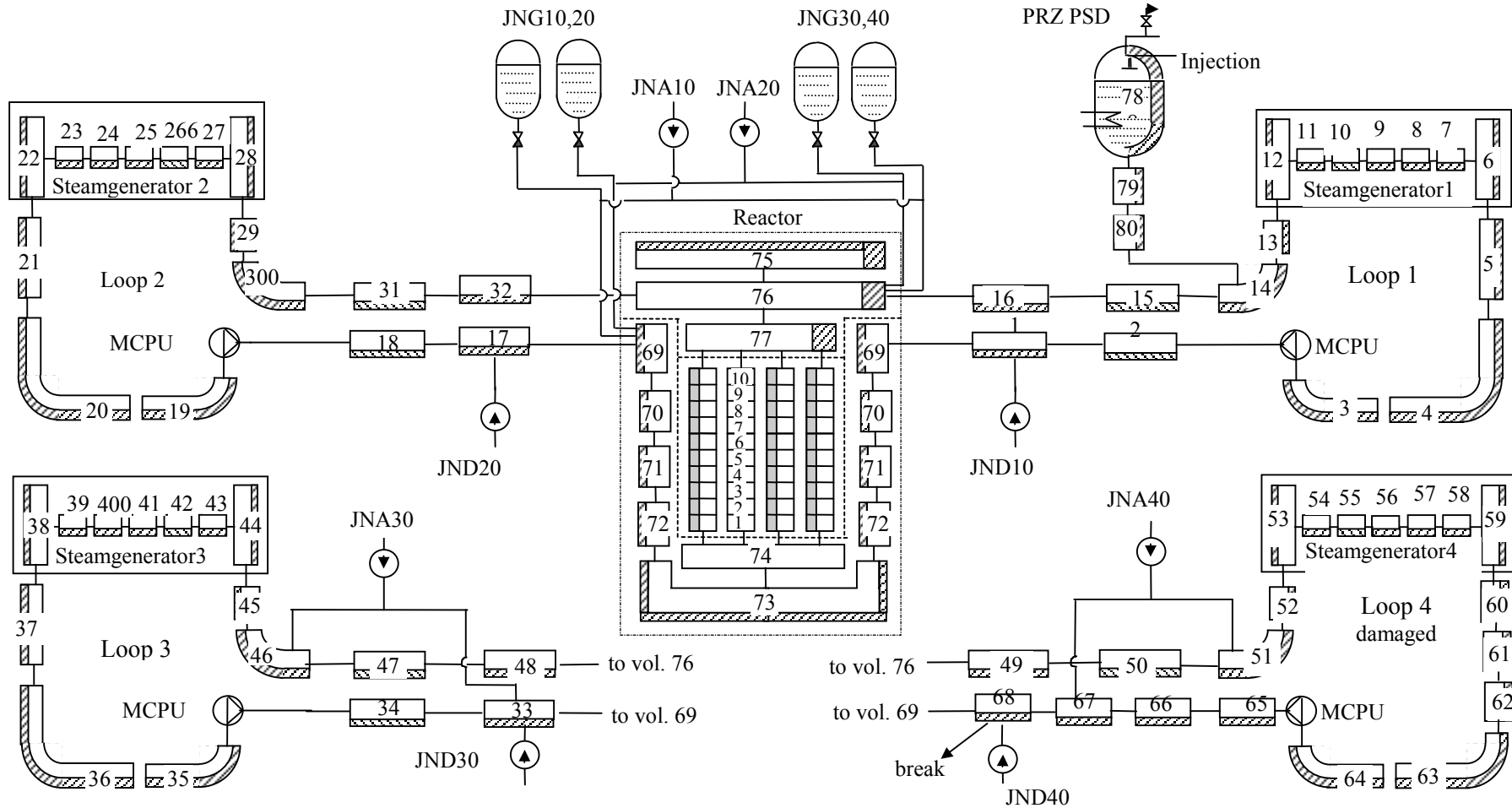


Fig.2. Typical WWR-1000 nodalization for TECH-M-97 code

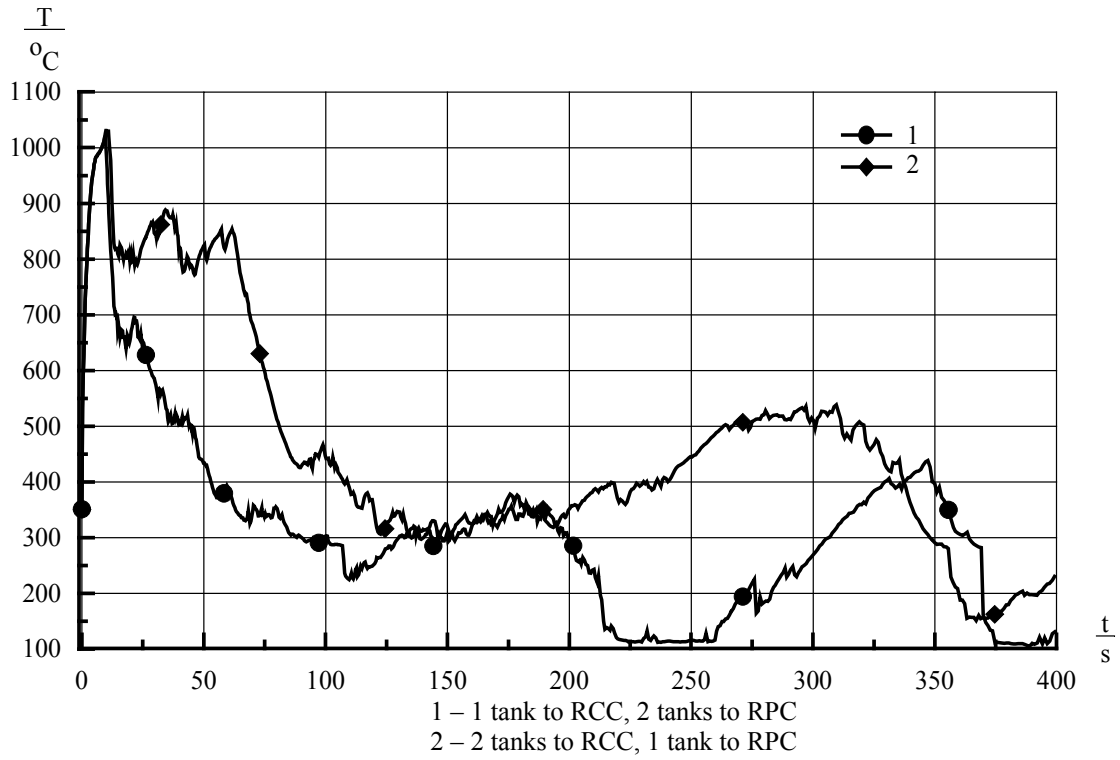


Fig.3. Effect of passive ECCS configuration.

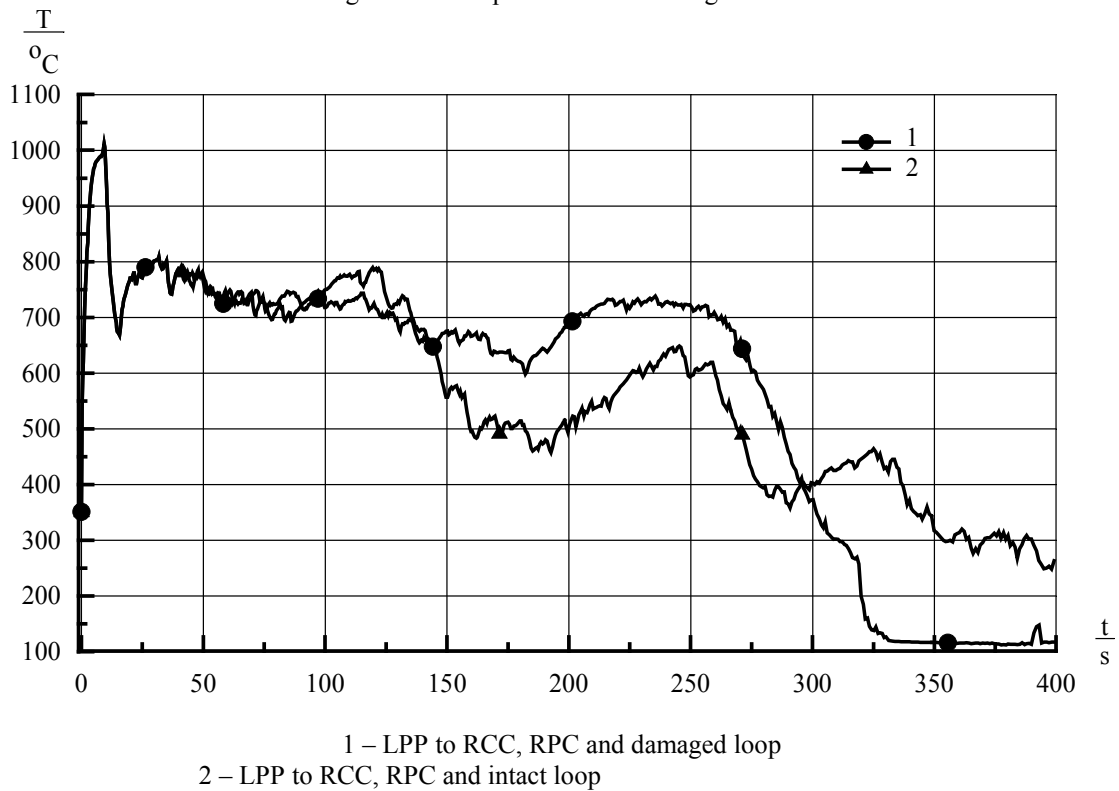


Fig.4. Effect of active ECCS configuration.

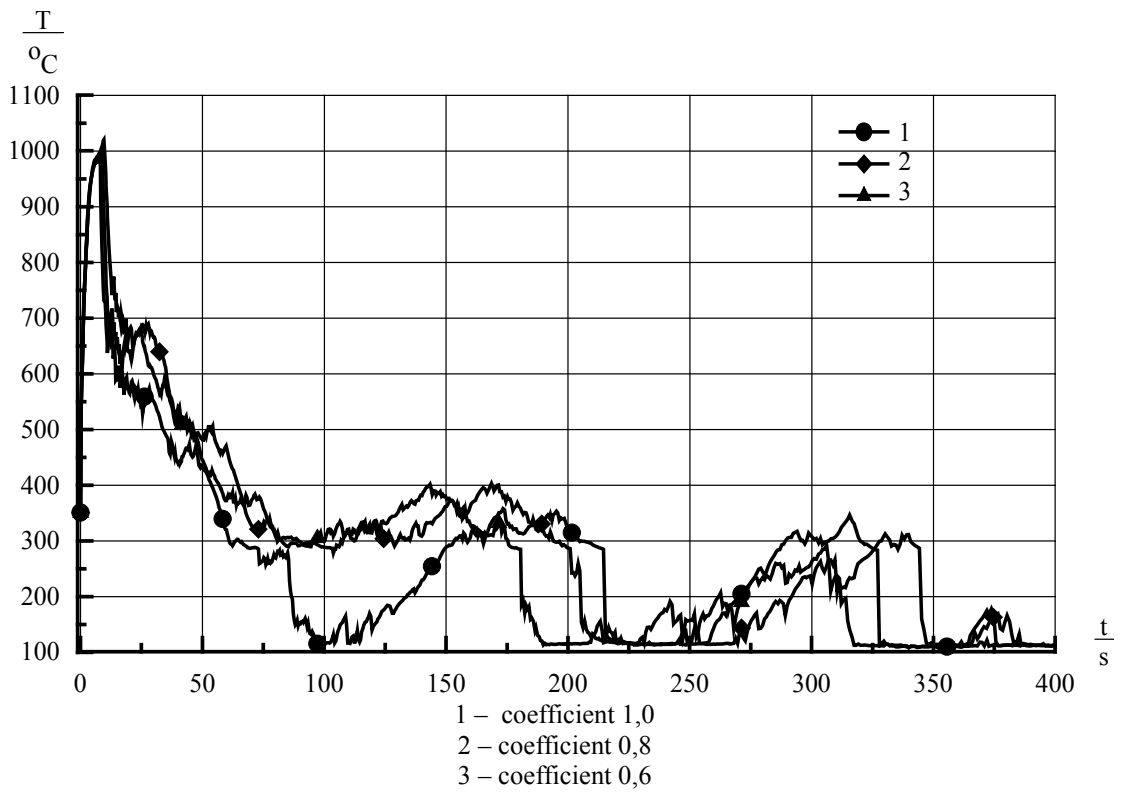


Fig.5. Effect of blowdown coefficient.

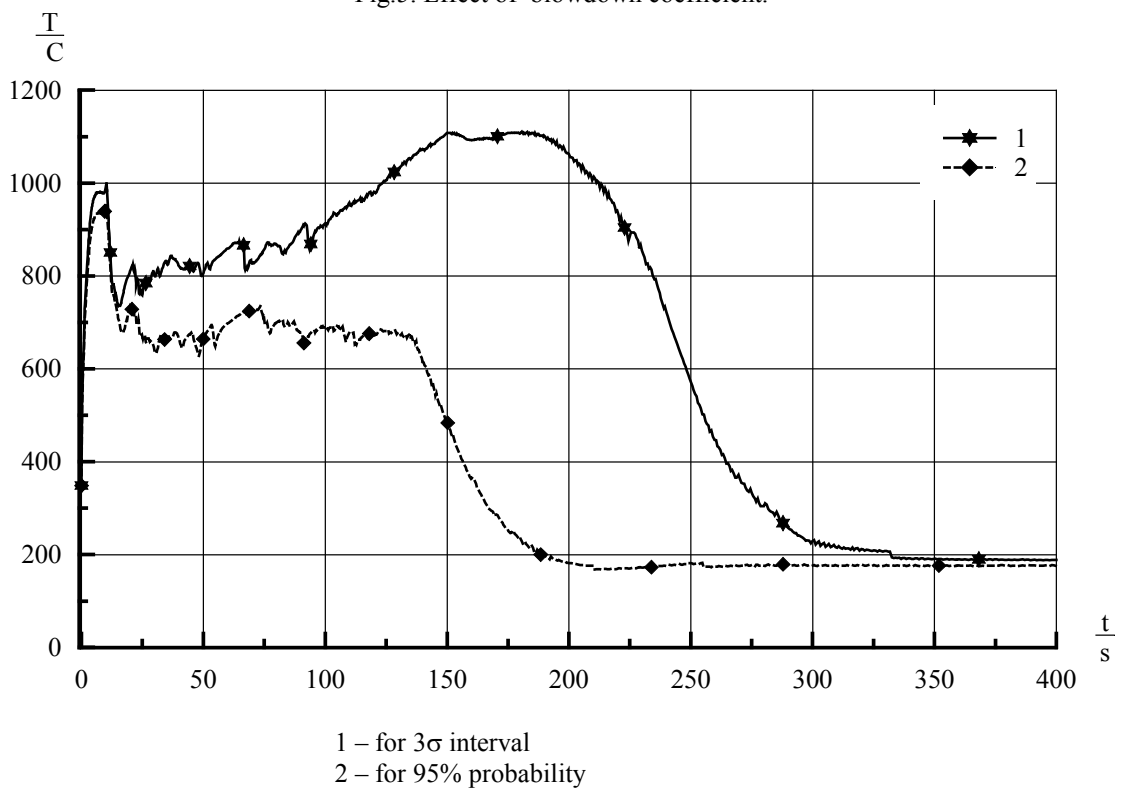


Fig.6. Effect of linear heat rate.

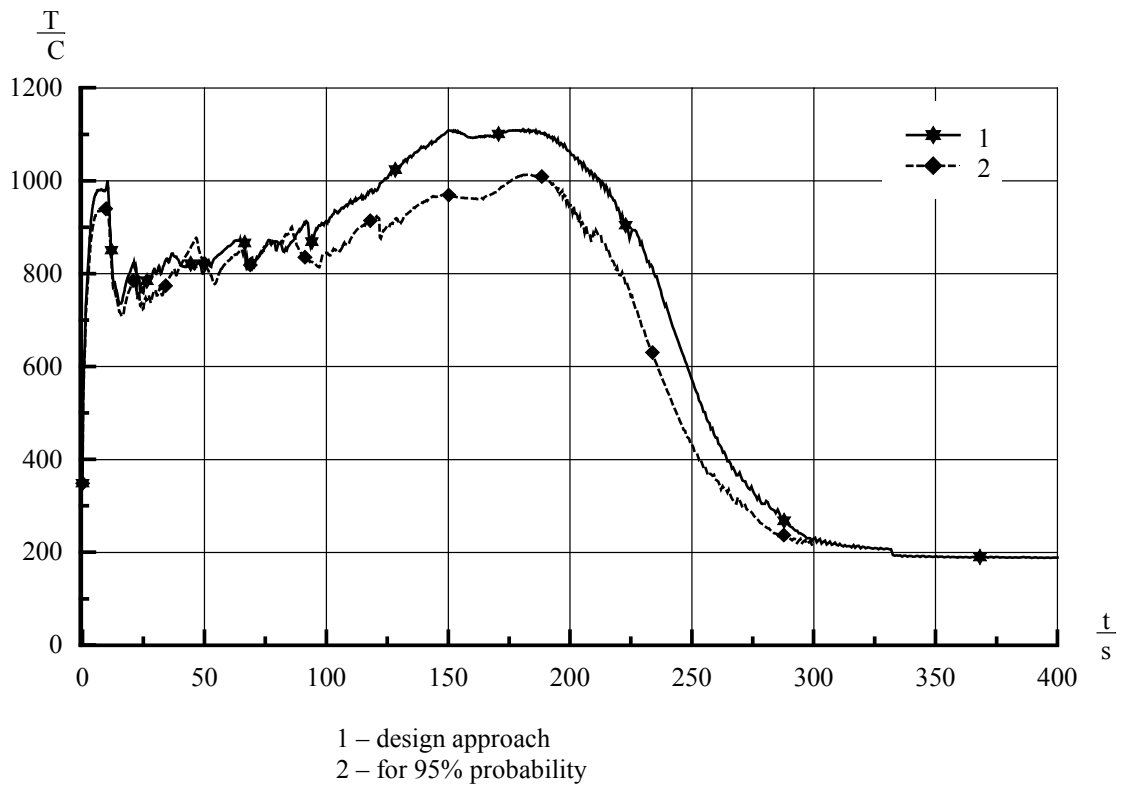


Fig.7.Effect of gas gap conductivity.

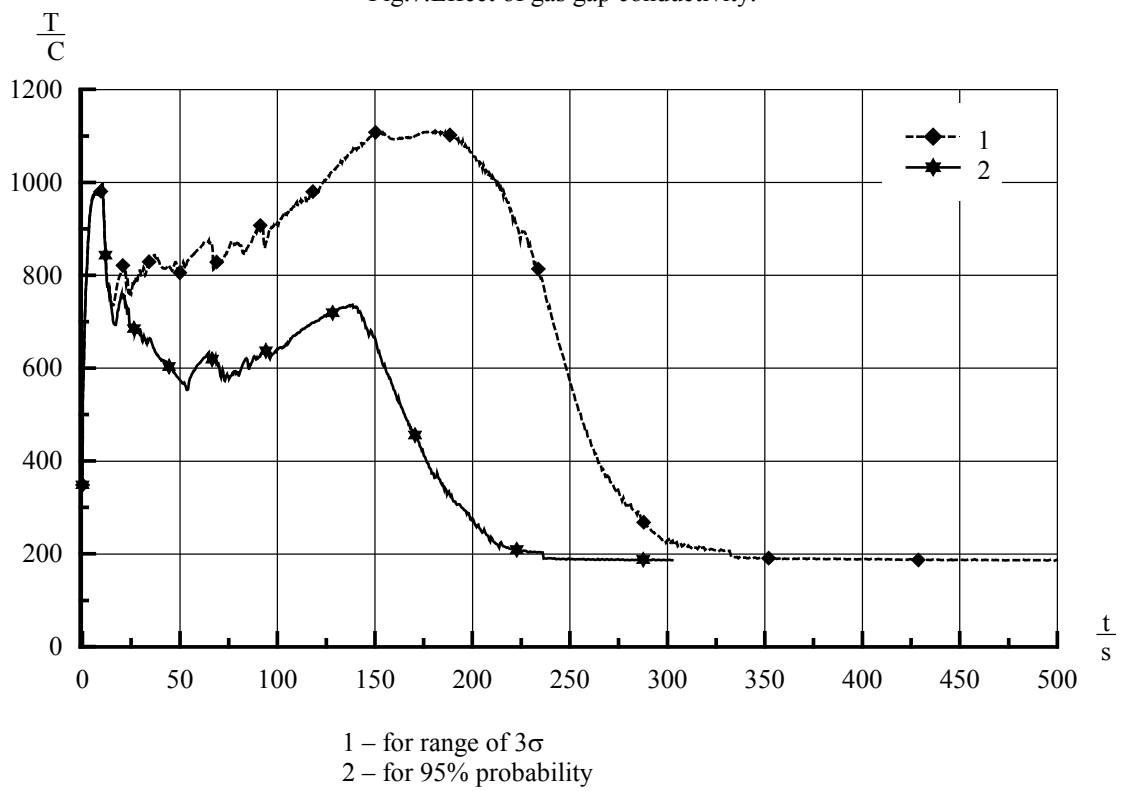


Fig.8. Effect of residual heat.