

Prevention of Early Containment Melt-Through during Severe Accident on WWER-1000, B-320 Light Water Reactor

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Abstract. An analysis was performed within PHARE Project BG 01.10.01 in 2003-2004 that has discovered a vulnerability of LWR WWER-1000, V-320 design consisting in early (up to one hour) containment melt-through via ionization chambers channels during severe accident. Based on this analysis, a separate project was started to find out the possibilities to retain the melt in the ionization chamber's channels and for prevention of early melt penetration and radioactive releases outside of the containment. An original engineering solution was developed, proposing ceramic plugs with a special design to be used for plugging the bottom of ionization chamber's channels in the reactor pit of WWER-1000, B-320. This technical solution was substantiated through analytical and experimental means. The analytical part consisted in using the NISA II FEM – DISPLAY III thermo-mechanical code for investigation of temperature and stress fields distributions within the plugs, when the corium falls over them.

Two experiments (hot and cold ones) were performed to prove the adequacy of the analyses for the proposed engineering solution, as well as the high temperature resistance and tightness of the ceramic plugs. This way the Design of WWER-1000, B-320 was enhanced against early containment failure during severe accident.

Finally, the solution was implemented on Units 5&6 of KNPP. All above works lasted as overall as of 4 years. The construction was patented.

Keywords: severe accident, early containment failure, ionization chambers channels, ceramic plugs.

Nomenclature

C_p	Heat capacity coefficient
T_L	Liquidus temperature
T_S	Solidus temperature
$T_{i(0)}$	Initial temperature (of the melt)
V	Volumetric generated power
W_{concr}	Weight percentage of the concrete
Z	Enthalpy
ε	Emissivity
λ	Thermal conductivity coefficient
ρ	Density
σ	Constant of Stefan–Boltzmann

Abbreviations

LWR	Light Water Reactor
RPV	Reactor Pressure Vessel
PSA	Probability Safety Analysis
KNPP	Kozloduy Nuclear Power Plant
WWER	Water-Water cooled Energy Reactor
IC	Ionization Chamber
LERF	Large Early Release Frequency
FEM	Finite Elements Method

1 Introduction

After the Reactor Pressure Vessel (RPV) break as an end of in-vessel phase of severe accident, the ex-vessel phase starts. The melt falling down into the reactor pit begins to ablate the concrete in both axial and radial directions. Such phenomena, called MCCI, is the most dangerous of the operating plants in the world from Generation II and III, as the accident in Fukushima has shown and promoted multiple investigations in this area, for example the SAR-NET Project in which Bulgaria has an input [1,2].

The axial melt-through towards of the internal ring ICs (Figure 1), which are situated at 145 mm (the first internal ring) from the wall of reactor pit, will bring the melt (mixed with ablated concrete) to the IC and fall down on

the bottom of the channels, that are plugged in the design of WWER-1000, V-320 by protective layer consisting in biological shield of cloth laminate, concrete and steel slabs below. There are also small holes through these layers and slabs for the cables of IC. The further ablation of the concrete and slabs would lead to melt-concrete penetration into the premise of IC below and outside the containment (Figure 2).

For WWER-1000, V-320 it was found, through PHARE BG 01.10.01 project, which analyses were made by using the CORCONE code [3], and have shown that the melt would ablate the side concrete wall of 145 mm thickness in about 45 min. after the melt release from RPV and would penetrate into IC channels. After that the melt very fast goes out of the containment through the concrete bottom of

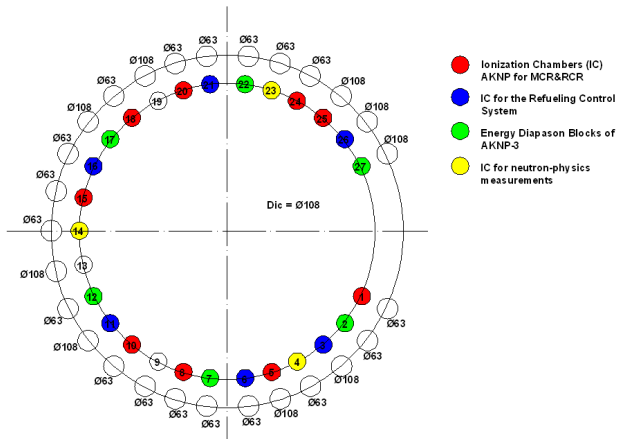


Figure 1. Layout of Ionization chamber (IC) channels in the concrete around the reactor pit.

IC channels. This phenomenon was called “early containment bypass of WWER-1000 during severe accident”. We prefer to call it “early containment melt-through”, because “containment bypass” has another meaning in terms of PSA – when exhausting radioactive steam-gas mixture from Primary circuit enters directly to the environment, e.g. in the case of steam generator tube rupture and stacked open steam-dump to atmosphere valve.

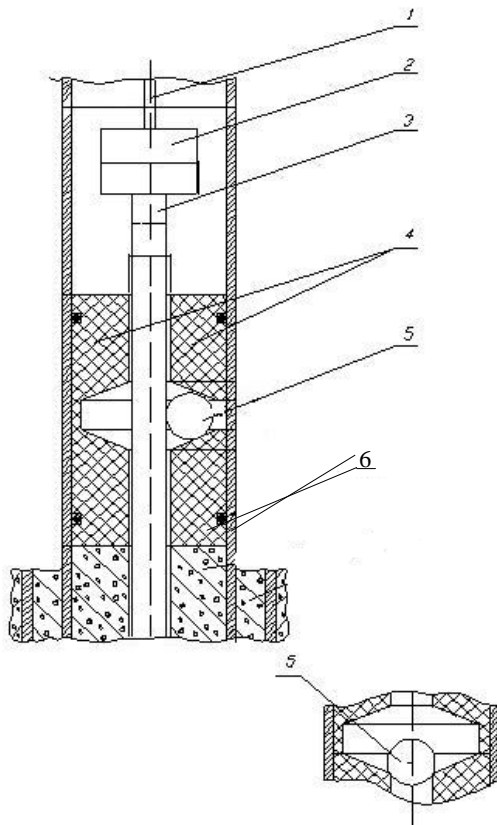


Figure 3. Plugging device of IC channel: (1) lifting cable for the ionization chamber; (2) ionization chamber; (3) powering cable for IC; (4) plug (TiC); (5) plugging ball (WC); (6) outside steel tube.

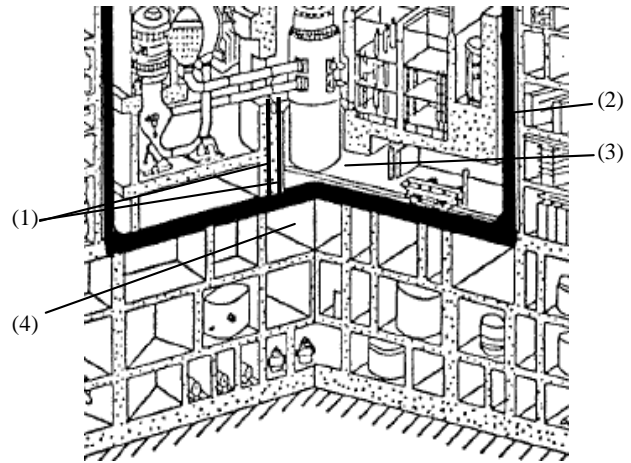


Figure 2. Layout of premises inside and outside the containment of WWER-1000 design: (1) ionization chamber (IC) channel; (2) containment wall; (3) reactor pit; (4) premise of the mechanisms for lifting IC.

To prevent the further penetration of the melt in the premise (4), the authors proposed a solution to plug the bottom of IC channels by plugs made from high-temperature-resistant materials (see below).

2 Engineering Solution for Plugging IC Channels

The engineering solution for plugging the IC channels is illustrated in Figure 3.

The plug (4) is designed to be made of Titanium Carbide, TiC, with melting point $T_{M \text{ TiC}} = 3170^\circ\text{C}$ and density $\rho = 4930 \text{ kg/m}^3$. The ball (5) is designed to be made of Tungsten Carbide, WC, with melting point $T_{M \text{ WC}} = 2870^\circ\text{C}$ and density $\rho = 15800 \text{ kg/m}^3$ [4]. The melting points of the above materials were chosen conservatively to be higher than the melting point of UO_2 .

The principle of operation of the plugging device consists in the following. During severe accident with discharging of molten corium in the reactor pit, the melt ablates the side concrete wall and mixed with concrete, falls down into the IC channels. The temperature of the melt is high enough to burn up the cable (3) and discharges the ball (5) (in normal conditions, the cable holds the ball). The ball, being almost twice heavier than the melt ($\rho_{\text{UO}_2} = 8740 \pm 200 \text{ kg/m}^3$ [5]), but mixed with ZrO_2 , other light metals and concrete the average density of the mixture decreases), falls over the central orifice (designed for the powering cable of IC) and plugs it without risk to emerge.

3 Analytical Work – Thermo-Mechanical Analyses

The thermo-mechanical analyses were done by simulation of the real process of penetrating of melt in IC channels. Finite-element models (FEM) were built, which include the proposed plugging devices and the adjacent parts that would be influenced as well – the internal steel tube of the channel, the outside steel tube, concrete of the containment wall, concrete to be filled in the clearance between

the two tubes, the biological shield below the plugs (made from Teflon by original Design) and the penetrating melt itself.

The CAD-CAM package of NISA II – DISPLAY III code was used to perform the FEM calculations by applying the updated HEAT-III module for phase transition and radiation heat transfer.

Taking into account the rotationally symmetry about the axis of IC channel' pipe (the plugging ball is over the central orifice (see Figure 3), the geometry of the construction and the adjacent parts and the same symmetry of the material properties and applied loads, FEM were developed by using 2D axisymmetric (pseudo 3D) elements, which are quadrilateral type with mid-side nod.

The thermo-mechanical analyses included consecutive solving of two connected tasks. First, the heat transfer task was solved to find out the temperature distribution, i.e. the temperatures for each point of the modelled object for characteristic moments of time. The second task was to find out the stress distribution for the chosen characteristic moments, taking for thermal loads the temperature distributions solved in the first task. Besides, additional mechanical loads as the weight of the melt-concrete mixture in the channel and pressure was considered for the calculations of the static strength of the system.

The general model scheme used for the thermo-mechanical analyses with description of the included modelled parts are shown in Figures 4 and 5 (for an IC internal pipe with $\varnothing 108 \times 6$).

The 2D axisymmetric solid FEM mesh used for the thermal resistance (thermal stability) analysis is shown in Figure 5 (for an IC internal pipe with $\varnothing 108 \times 6$).

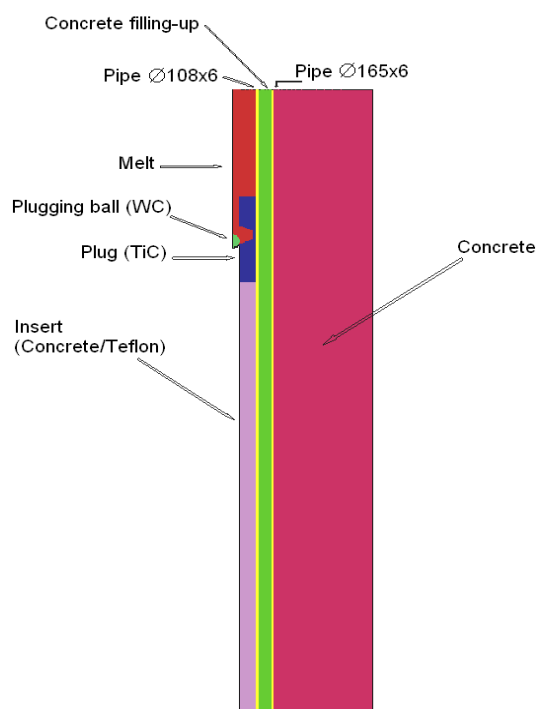


Figure 4. General FEM of Plugging device of IC channel.

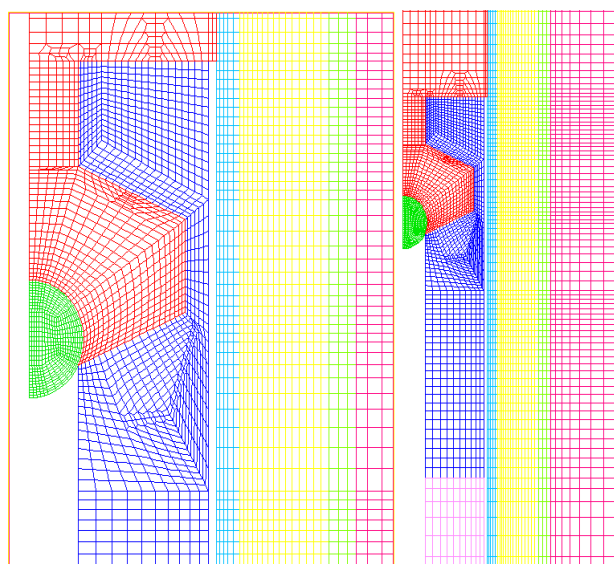


Figure 5. FEM mesh used in thermal-mechanical analyses of Plugging device of IC channel.

3.1 Initial and Boundary Conditions

An equal to maximum allowed design temperature of 150°C for the containment was postulated for all parts (nods) of the system as initial condition for the heat transfer task. The initial temperature of the melt was conservatively postulated as 2850°C , the specific volumetric power generated by the melt was chosen according to [1] as $V = 1.3 \text{ MW/m}^3$. The other parameters are taken from [5] and [6] and shown in Table 1.

Table 1. Parameters of the melt in IC channels

Parameter	Value	Parameter	Value
$T_{t(0)}$, $^{\circ}\text{C}$	2850	V , MW/m^3	8400
W_{concr} , %	6.7–15.8	ρ , kg/m^3	1.3
T_s , $^{\circ}\text{C}$	1250	C_p , J/kg.K	274–796
T_L , $^{\circ}\text{C}$	2650	λ , W/m.K	6.4–2.0–3.0
Z , kJ/kg	259.3		

For the clearance between the plug and the tube a process of radiation heat transfer was modelled using the Stefan–Boltzmann law $E(T) = \sigma \varepsilon T^4$. For the purposes of FEM calculations, the accepted value of the emissivity on the external cylindrical surface of TiC plug is $\varepsilon_{\text{TiC}} = 0.75$. Several sensitivity calculations were made for Teflon at conservative values $\varepsilon = 0.3$ and $\varepsilon = 0.5$, but also $\varepsilon = 0.99$ (black Teflon) and based on the obtained results, $\varepsilon_{\text{Teflon}} = 0.5$ was chosen. It was also accepted conservatively the lack of any convective cooldown of the plugging ball, the plug and the biological shield (insert).

3.2 Results

Fourteen characteristic nods in the FEM mesh were chosen to represent the heat-transfer process (Figure 6).

The temperature history of the representative 14 nods for the first 600 seconds is given in Figure 7a, while in Figure 7b it is shown for the first 24 hours.

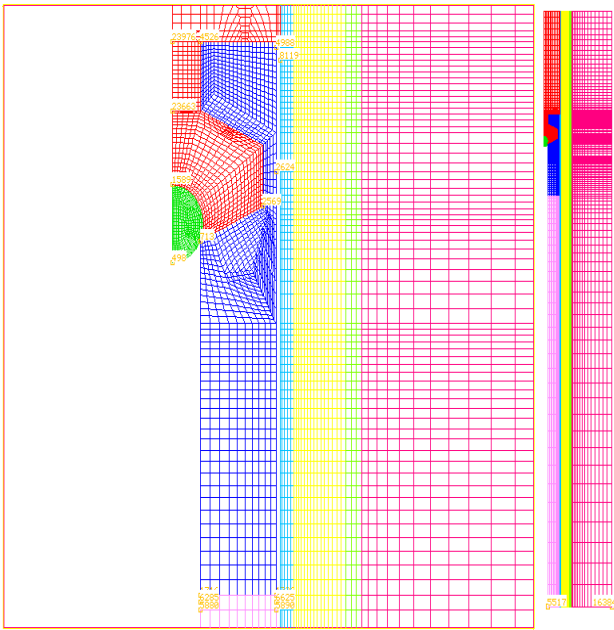


Figure 6. FEM mesh with location of 14 characteristic nodes.

In Figure 8a and Figure 8b the temperature distribution on FEM are shown for two characteristic moments.

The analysis of the results has shown that the thermal stability of all parts of the proposed device and adjacent components is assured.

The biological shield (insert) made in the original Design from Teflon has a margin of 30–35°C, what is very close to the error interval (10%) of the used module for thermal calculations – NISA HEAT III.

That is why the Teflon during the implementation process was replaced by a light concrete.

4 Experimental Works

Two experiments were performed to prove the operability of the proposed devices for plugging the IC channels under normal operation and severe accident conditions.

4.1 Cold experiment

The device (see Figure 3) was modelled in scale M=1:1, the plug and plugging ball made by steel, embedded in a steel tube $\varnothing 108 \times 6$ mm (as the largest type channel) and with a real IC powering cable.

The first aim of the cold experiment (at room temperature) was to prove that the plugging ball and the device as whole

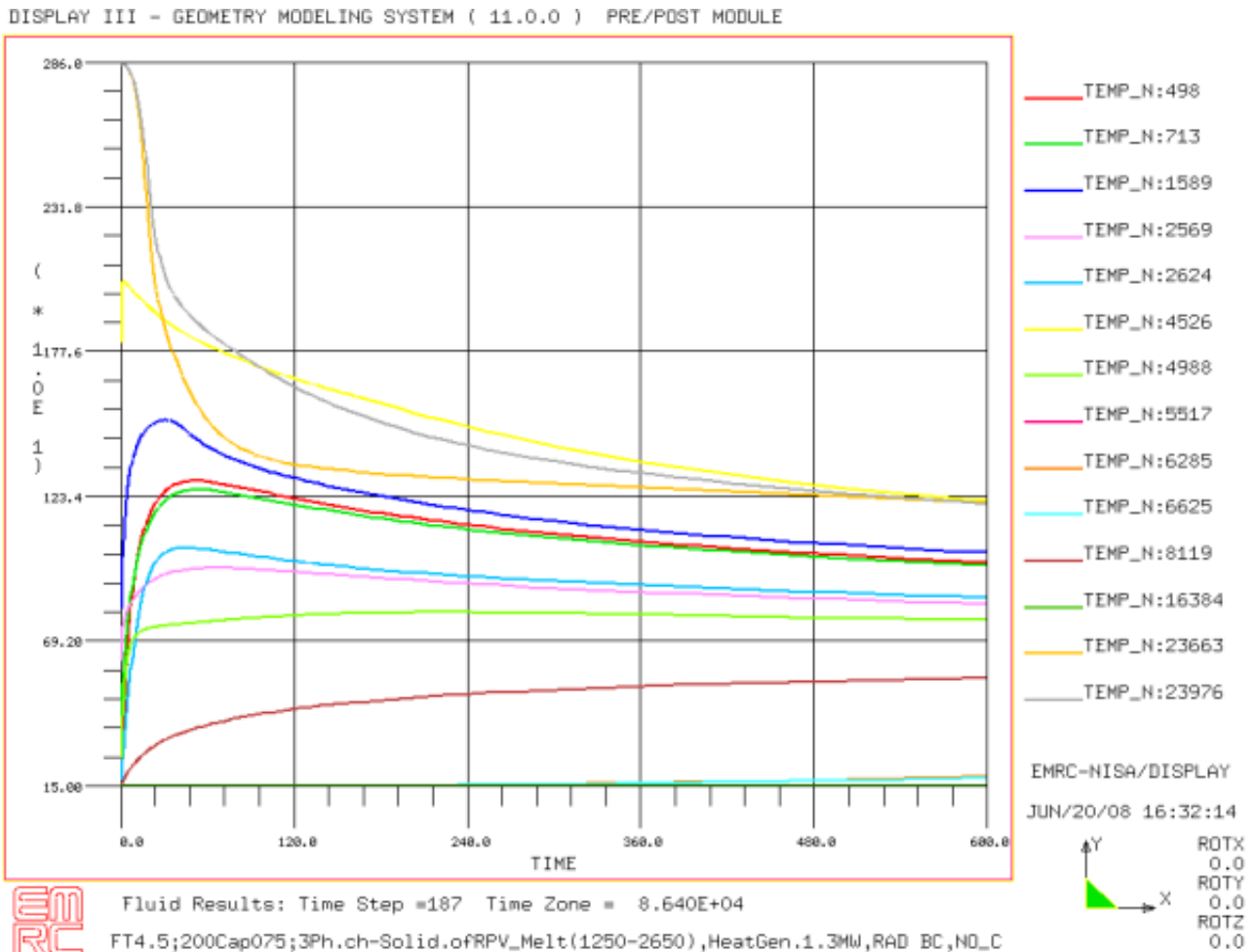


Figure 7a. Temperature development for period 0 ÷ 600 s of 14 characteristic nodes.

DISPLAY III - GEOMETRY MODELING SYSTEM (11.0.0) PRE/POST MODULE

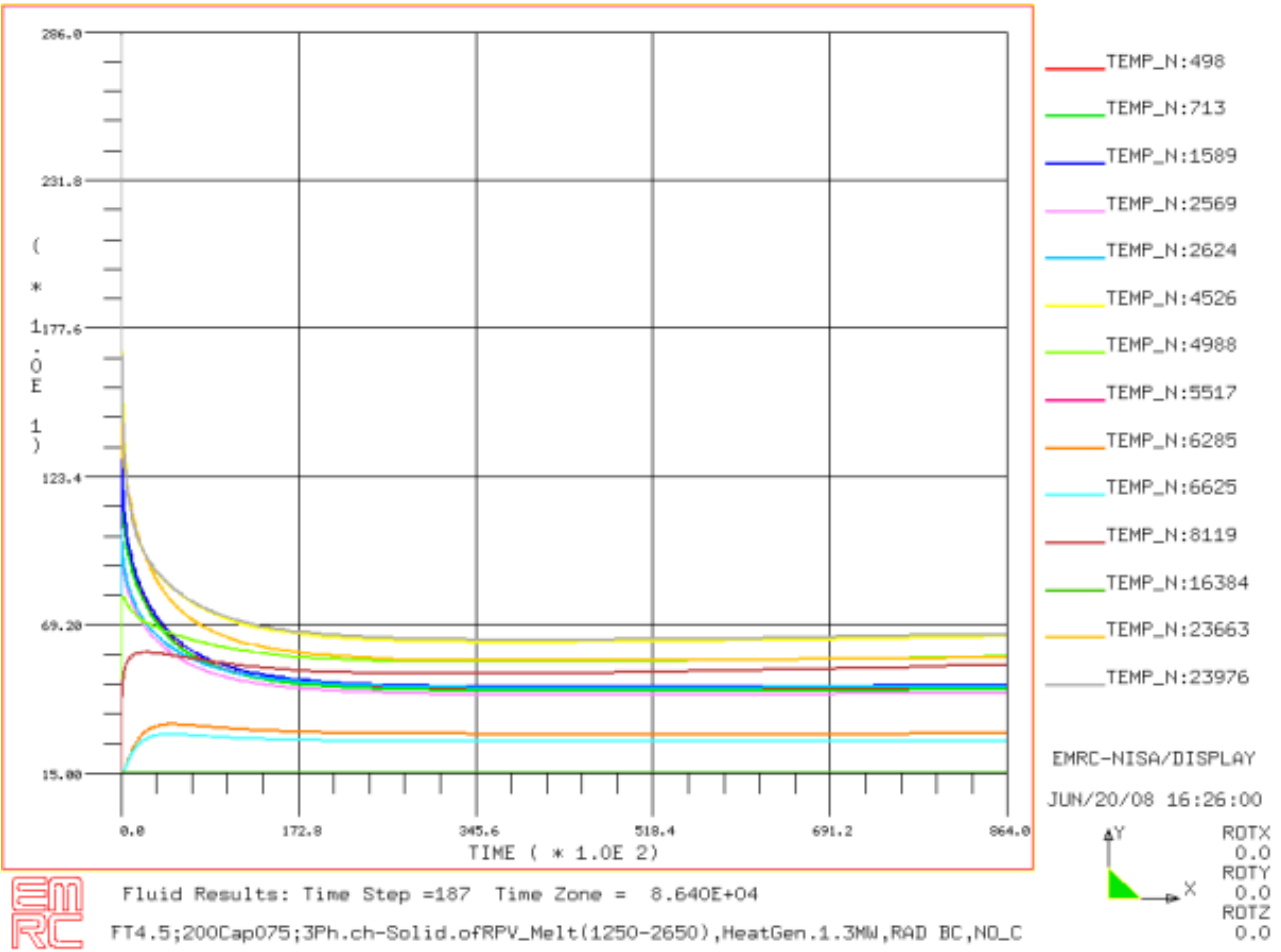


Figure 7b. Temperature development for period 0 ÷ 86400 s of 14 characteristic nodes.

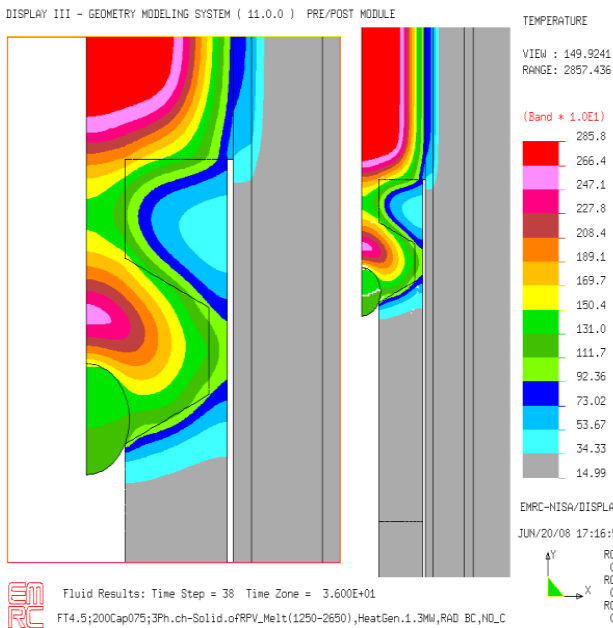


Figure 8a. Temperature distribution at 36 s.

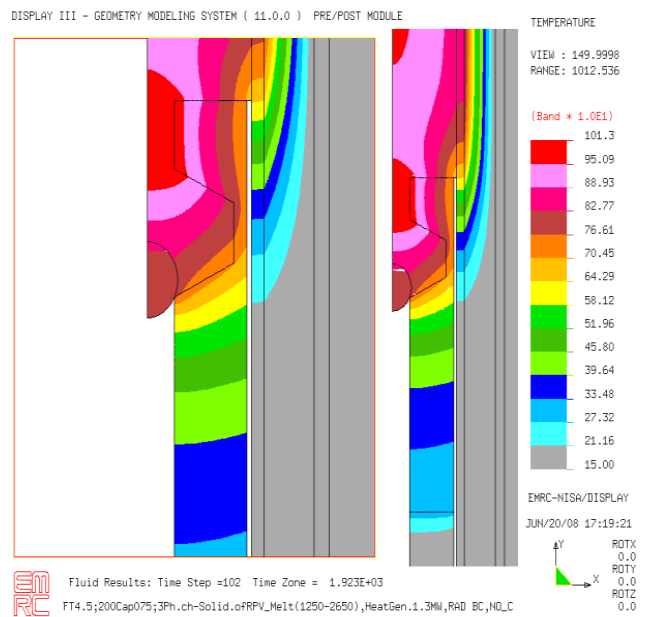


Figure 8b. Temperature distribution at 1923 s.

would not disturb the normal movement of the IC powering cable during normal operation (see Figure 3). The second aim of the cold experiment was to prove the plugging performance of the ball.

Accordingly, the experiment consisted in two phases. First, shifting up and down the cable and measuring the effort from the ball on the cable by digital dynamometer. The success criterion consisted in non-exceeding the theoretically calculated effort (13.9 kg) more than 10%. In Figure 9 the dynamo-graphs are presented. The greatest peaks are related to the initial pull-up/pull-down of the cable by the telpher, used for this experiment.

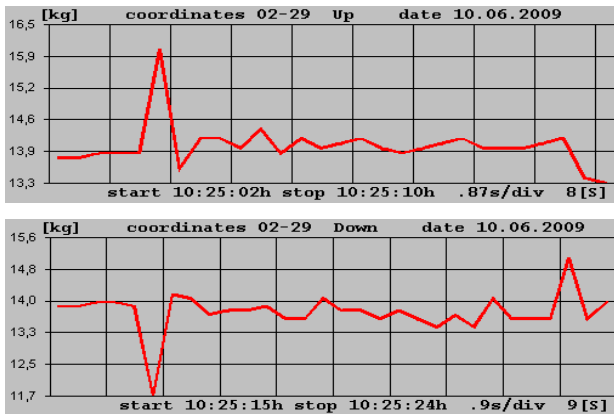


Figure 9. Dynamo-graphs of the cold experiment (phase 1).

In the second phase of the cold experiment, the cable was left to fall down under its own weight through the central orifice of the plug to see whether it would squeeze through its overall length, thus imitating the melting cut of the cable. The success criterion was that the cable must not hinder the ball to plug fully the orifice (see Figure 3), what happened indeed.

This way both phases of the cold experiment were successful.

4.2 Hot experiment

The purpose of the hot experiment was to use a melt simulant with similar thermodynamic properties as the real melt, to pour it down in a steel tube $\varnothing 108 \times 6$ mm with a plug (scale $M = 1:1$) and to prove that the melt will freeze in the clearance of 2 mm between the plug and the steel tube (see Figure 3) without penetrating below the plug.

The success criterion was the following: the melt, after pouring in the tube with the plug to freeze in the clearance within the height of the plug. For this purpose, a melt simulant was used consisting in mixture of Al and TiC in proportion 65:35 wt.%. The simulant was melted in an induction furnace at $T \sim 700^\circ\text{C}$. The estimated viscosity of the mixture, using [9], at this temperature is in the range of $\eta = 0.01\text{--}0.1$ Pa.s, which is consistent with the results in [6] and [1]. The calculated hidden phase transition heat of Al-TiC mixture is $\Delta H_f \approx 235.2$ kJ/kg, while for a mixture of 88% UO_2 +12%concrete (this proportion was calculated in [1]) is $\Delta H_{f_{\text{UO}_2+12\%\text{Concrete}}} = 228 \pm 13$ kJ/kg.

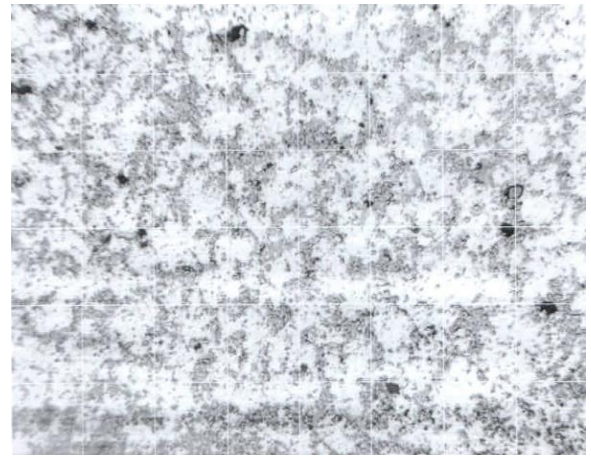


Figure 10. Metallographic picture of the melt simulant (zoom $\times 400$). The black spots are TiC, the white spots are Al, the grey spots are K-Al-F flux.

A flux K-Al-F (9.6 wt.%) was added to the simulant for better absorption (wettability) of TiC in the Aluminium, based on the information in [10-12]. A preliminary experiment with smaller quantities at the same proportions was performed to prove the good mixing of TiC and Al through metallographic analysis (Figure 10).

The melt was poured into the model tube, heated preliminary in a resistance furnace. It was found, after cooling down and cutting of the tube below the plug, that the melt was frozen (Figure 11) in the 2 mm clearance at 20 mm below of the upper surface of the plug.



Figure 11. Picture of the frozen melt in the clearance between the plug and the shielding tube.

Thus, the success criterion of the hot experiment was fully accomplished.

5 Implementaion Works

Some pictures of the mounting of the plugs at the bottom of IC channels of Unit 5 of KNPP is shown in Figure 12.



Figure 12. Mounting of the plugs at the bottom of IC channels on Unit 5.

The overall implementation process of mounting of the plugs lasted 2 years (performed during the annual outages) on Units 5&6 in 2013-2014 respectively.

6 Conclusion

The implementation of the proposed engineering solution resolve the problem with the early containment bypass – melt-trough for the Design of VVER-1000, B-320 in case of severe accident. It was assessed, within PSA Level-2 for Units 5&6 of KNPP, that the implemented plugs rise the time for retention of the melt from 1 hour to 36 hours, what time should be enough to implement the initial evacuation of the staff and population around KNPP within the highest level of the Emergency Plan of KNPP.

Such engineering solution is substantiated and implemented for the first time and contains know-how, what was the reason to patent it – (Patent No UA 107626/26.01.2015).

That is why it can be of interest for the other existing NPPs with VVER-1000 but also for other designs of existing reactors that can have ionization chamber channels close to the wall of their reactor pit.

Aknowledgments and Statements

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The metallographic investigation was conducted in the Technical University of Sofia.

The cold experiment was performed in KNPP, which provided the hall with telpher, dynamometric device and assisting staff. The hot experiment was conducted in the Aluminium factory “Alumina”, Pleven, Bulgaria, which provided all necessary I&C equipment, induction and resistance furnaces and crucibles.

The implementation work was performed by KNPP Plc. and Atomenergoremont Ltd. staff under the supervision

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