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Influence of Heat Transfer Modelling on Phebus FPT1 Experiment Simulation Results

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ABSTRACT

Within the participation in the OECD International Standard Problem No. 46 the degradation phase of the Phebus FPT1 experiment was simulated with the MELCOR 1.8.5 computer code. The experiment provides the opportunity to assess the capability of systems-level severe accident modelling codes in an integral manner, covering core degradation through to the late phase, hydrogen production, fission products release and transport, circuit and containment phenomena, and iodine chemistry. The input model was developed strictly following the recommendations on noding for the reference case simulation provided in the ISP-46 specification report.

To be able to assess the capability of MELCOR to model the processes involved in the experiment, first the correct temperature conditions in the bundle have to be achieved. It turned out that the temperature conditions in the bundle are highly dependent on the adequacy of heat transfer modelling. The comparison of simulation results and experimental measurements showed that good agreement of thermal-hydraulic variables in the bundle can be achieved if the radiation inside the bundle and the heat losses through the shroud are correctly considered.

1 INTRODUCTION

The Phebus FP program [1] is investigating key phenomena involved in light-water-reactor severe accident sequences through a series of in-pile integral experiments. The Phebus facility, which is located at the "Institut de radioprotection et de surete nucleaire" (IRSN) in Cadarache, France, incorporates scaled-down representations of the reactor core, the primary circuit including the steam generator, and the containment. The facility thus provides prototypic reactor conditions, which allow the study of basic phenomena governing the releases, transport, deposition and retention of fission products. Phebus FPT1 [2], the second experiment in the series, was selected as the basis for the OECD International Standard Problem No. 46 [3]. The experiment provides the opportunity to assess the capability of systems-level severe accident modelling codes in an integral manner, covering core degradation through to the late phase (melt pool formation), hydrogen production, fission products release and transport, circuit and containment phenomena, and iodine chemistry.

The general objective of the ISP-46 is to assess the capability of computer codes to model in an integrated way the physical processes taking place during a severe accident in a pressurized water reactor, from the initial stages of core degradation through to the behaviour of released fission products in the containment. The codes are supposed to be used in a similar manner as they would be used for plant studies, employing standard models and options as far as possible, with representations of the facility in similar details as used for plant studies.

Within the participation in the ISP-46 the thermal-hydraulic, fuel degradation and aerosol phenomena, which occurred in the bundle and circuit part of the Phebus facility during the degradation phase of the Phebus FPT1 experiment were simulated with the MELCOR 1.8.5 computer code [4]. To be able to assess the capability of MELCOR to model the processes involved in the experiment, first the correct temperature conditions in the bundle have to be achieved.

In the paper the influence of the heat transfer modelling on the temperature conditions in the bundle are presented and discussed in comparison to experimental measurements.

2 EXPERIMENT

2.1 Phebus facility

The overall scaling factor of the Phebus facility test train is 1/5000 with respect to a 900 MWe pressurized water reactor [2]. On Figure 1 the schematic view of the essential part of the Phebus facility is presented.

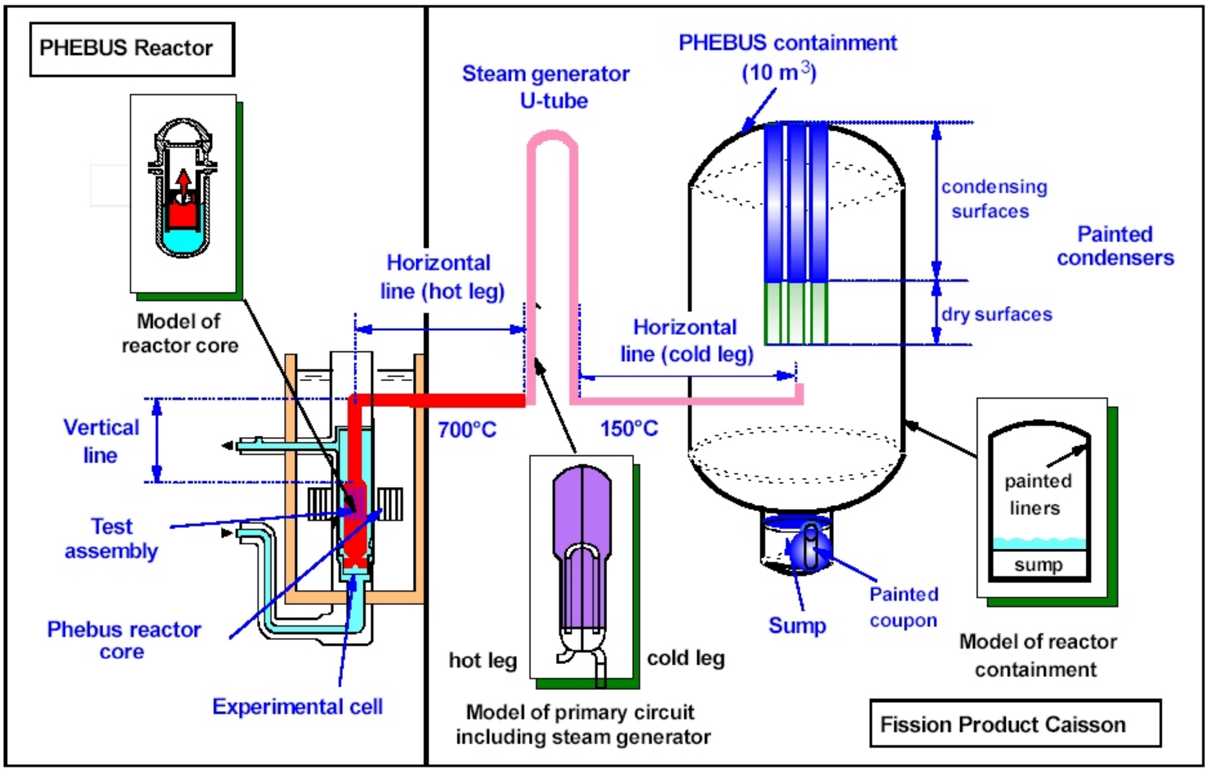

Figure 1: Schematic representation of the Phebus facility [2].

The degrading reactor core is represented by a 20 rod, 1 m high, test fuel bundle surrounded by an insulating ceramic shroud fitted inside a pressure tube (Figure 2). A rod simulating the reactor control rod system occupies the central position. The test device is inserted into a pressurized water loop, located at the centre of the 40 MW Phebus driver core. The upper plenum above the test fuel bundle is connected to an experimental circuit, including an inverted U-tube simulating a PWR steam generator. At the outlet of the circuit, the steam hydrogen mixture and radioactive aerosols are injected into a 10 m^3 vessel simulating the containment building of a reactor (cold leg break simulation). The containment vessel includes scaled painted surfaces and a water-filled sump to investigate iodine behaviour under realistic conditions.

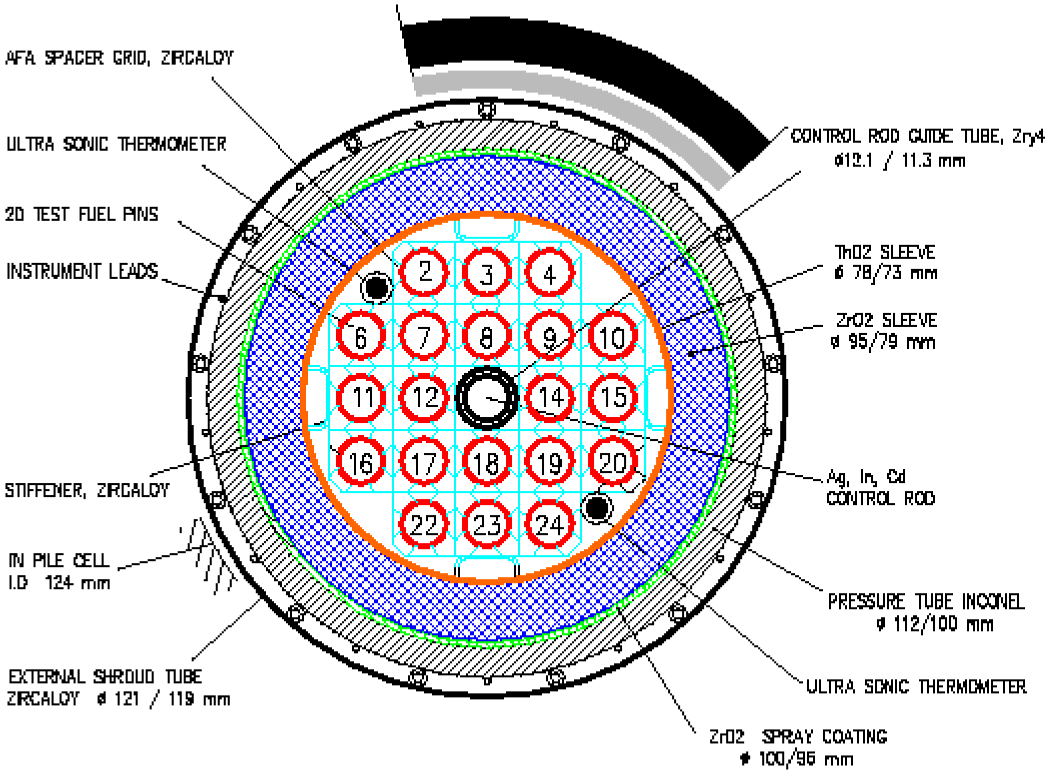

Figure 2: Radial configuration of the FPT1 bundle [2].

2.2 Experiment description

The FPT1 test bundle, which included 18 PWR fuel rods previously irradiated to an average burn-up level of 23.4 GWd/tU, two instrumented fresh fuel rods and one silver-indium-cadmium control rod, was pre-irradiated for ~7 days with an average bundle power of ~205 kW in the Phebus reactor before the experimental phase of the test itself in order to generate short-lived fission products in the fuel. After the pre-conditioning phase, a period of 36 hours was necessary to bring down reactor xenon poisoning, to dry the bundle using neutral gas and to establish the initial conditions. The experiment itself then began by injecting steam into the bundle and gradually increasing the core nuclear power.

The fuel degradation phase lasted about 5 hours, during which the inlet steam flow rate injected at the bottom of the test train varied from 0.5 to 2.2 g/s providing oxidizing conditions, while the bundle power was progressively increased from 0.65 kW up to 36.5 kW (Figure 3). The bundle degradation phase consisted of two main periods. The first one, devoted to the thermal calibration of the bundle and with measurement of the coupling factor between the experimental bundle and the driver core, lasted ~7900 s. During this period, the bundle power and the steam flow rate were increased step by step in order to check the thermal response of the bundle. The second period was the real temperature transient and degradation phase of the test, lasting from ~7900 s to ~17000 s. The degradation phase was specially devoted to the release of fission products, and bundle, structure and control rod materials in order to study their transport and retention in the experimental circuit.

After the degradation phase the experiment continued with the aerosol phase, the washing phase and the chemistry phase, which were not treated in the paper.

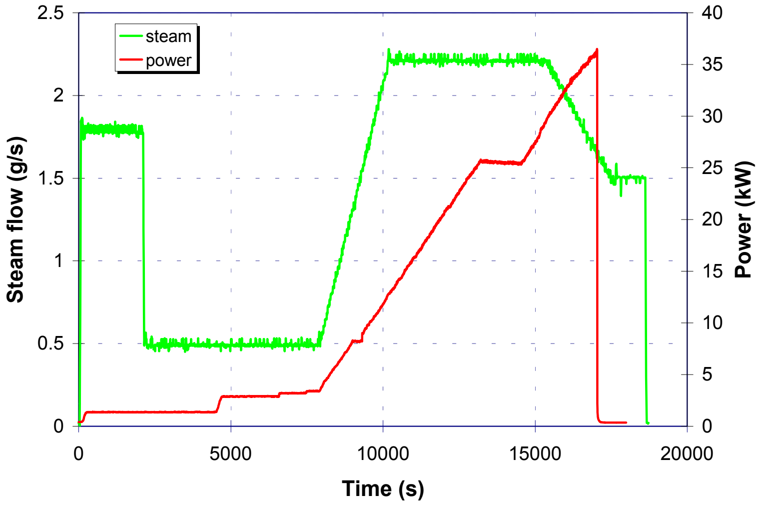

Figure 3: Inlet steam flow history and bundle power in FPT1.

3 MODEL DESCRIPTION AND SIMULATION RESULTS

The core nodalization of the bundle is presented on Figure 4. The control volumes are denoted with CV-xxx, the core cells with COR-xxx, and the heat structures with HS-xxxxx. The 11 axial levels in the heated length from level –7.987 m to level –6.987 m denoted with COR-x04 to COR-x14 were defined according to the ISP-46 specification [3]. The bundle was modelled with two radial rings. In the first radial ring there are the control rod, the control rod guide tube and the inner 8 irradiated fuel rods. In the second radial ring there are the outer 10 irradiated fuel rods, the 2 fresh fuel rods and the stiffeners. Since the fresh and irradiated fuel rods are both in the same core cells of the second radial ring they cannot be treated separately. Therefore in the input model only average properties of fresh and irradiated fuel rods could be considered and due to the same reason only average results could be calculated. As a supporting structure the fuel supporting plate and the two spacer grids were modelled, and as a non-supporting structure the control rod, the control rod guide tube, the stiffeners and the springs in the control and fuel rods. The support plate and two spacer grids were distributed in both radial rings according to the rings surface area. The shroud was considered as a heat structure.

At high temperatures the thermal radiation is an important mode of heat transfer within the core. In MELCOR the influence of the core geometry on the exchange of radiation between pairs of surfaces is taken into account with radiative exchange factors, determining the fraction of the total radiative energy leaving one surface, which would be in vacuum transferred to the other surface [5]. The value of radiative exchange factors is somewhat dependent on the core size and the nodalization. Because of the small size of the bundle in Phebus, each ring of the core nodalization contains only one layer of fuel rods. Thus, an "average" rod in a ring has a much better view of the adjacent ring than would be the case in a full-scale reactor core. In addition the fuel rods in the inner ring can see not only the fuel rods in the outer ring but also directly the shroud. Therefore the radiative exchange factor for radiation radially outward from the cell boundary to the next adjacent cell (default value: 0.25) has to be significantly increased.

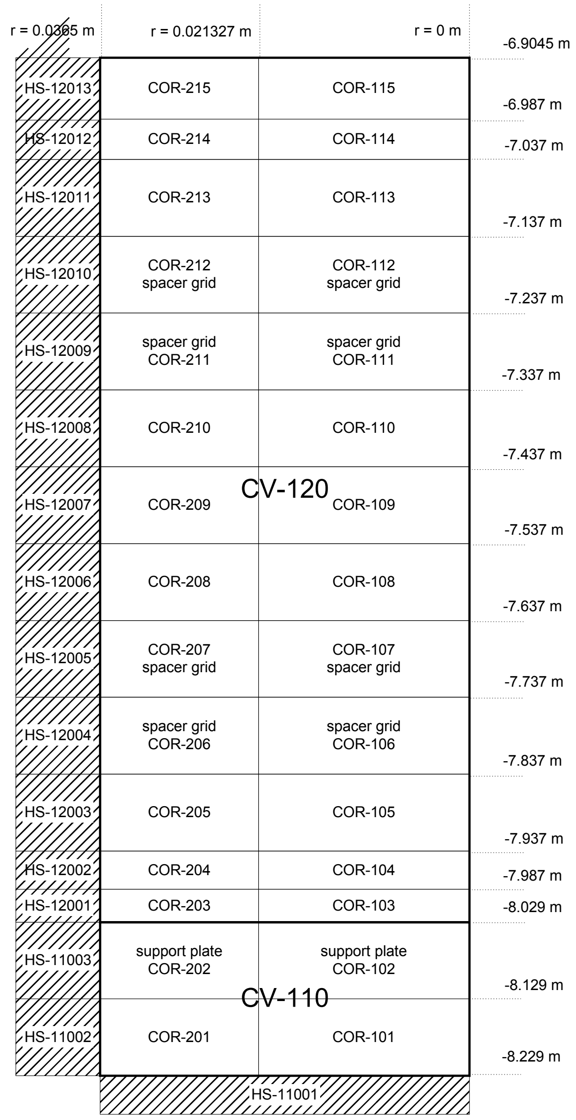

Figure 4: Core and heat structure nodalization of the bundle.

On Figures 5 to 7 the calculated temperatures of the shroud, clad and fuel are presented for different radiative exchange factors (0.25, 0.5, 0.75) in comparison with experimental measurements (FPT1). The fluctuations (Figure 6) or abrupt changes (Figure 7) in the experimental curves are due to the thermocouples failure. The abrupt fall in the calculated curves (Figures 6 and 7) indicates the component failure, since in MELCOR it is defined that the temperature of a nonexistent component is 0 K. As expected the temperature of the clad and fuel decreases when the radiative exchange factor is increased (Figures 6 and 7) since more heat is transferred by radiation. Consequently also the clad temperature peak caused by the zirconium exothermic oxidation reaction occurs at a later time (Figure 6). When the radiative exchange factor is increased the temperature curves move towards the experimental measurements, but also for the estimated value of the radiative exchange factor 0.75 the agreement still is not satisfactory.

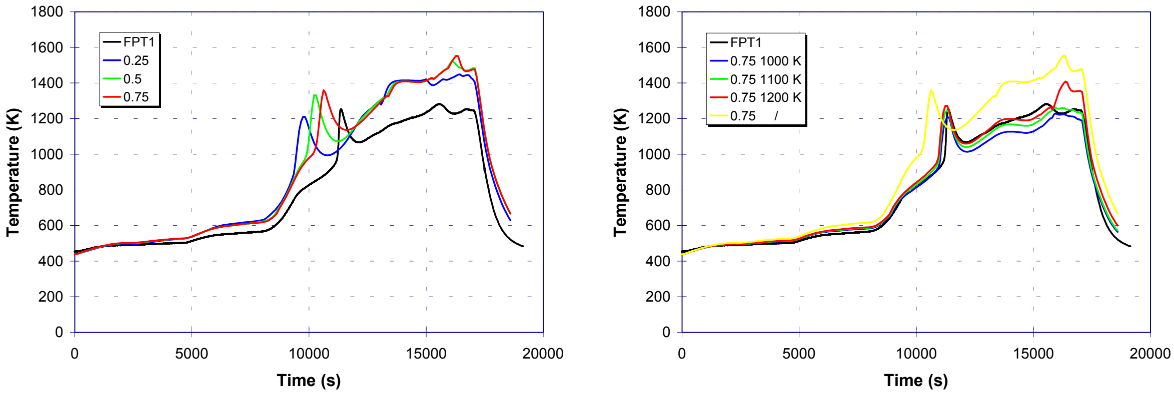

Figure 5: Inside shroud temperature at level 800 mm for different radiative exchange factors (left) and for different steam gaps closure temperatures (right).

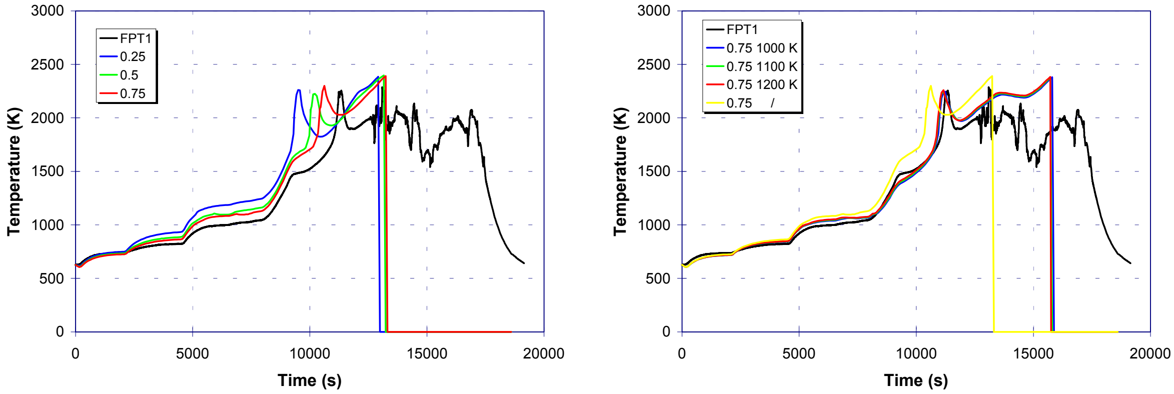

Figure 6: Clad temperature in outer ring at level 600 mm for different radiative exchange factors (left) and for different steam gaps closure temperatures (right).

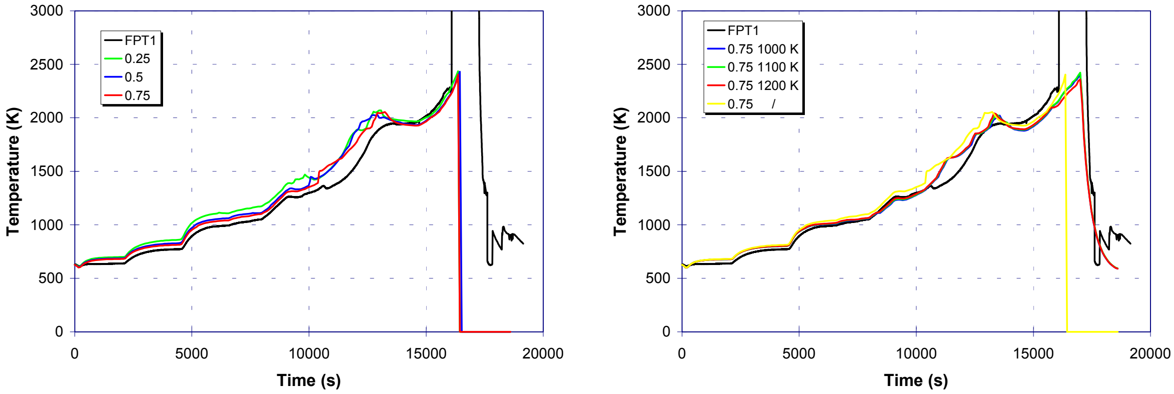

Figure 7: Fuel temperature in outer ring at level 300 mm for different radiative exchange factors (left) and for different steam gaps closure temperatures (right).

On Figure 5 we see that the calculated inside shroud temperature is overpredicted, what is an indication that the shroud heat conductivity could be underpredicted. Indeed, in the shroud there are two 0.5 mm thick steam gaps, between the ThO_2 and ZrO_2 sleeves and between the ZrO_2 sleeve and the ZrO_2 spray coating (Figure 2), which close during the heat up process due to the thermal expansion of the inner hotter sleeves, and consequently the shroud heat conductivity is significantly increased. Since in MELCOR it is not possible to simulate the closure of the two steam gaps directly, we decided to model the steam gaps closure with a temperature dependent effective steam gaps thermal conductivity

$$\lambda_{effective} = \begin{cases} \min\left(10\dfrac{\mathrm{W}}{\mathrm{mK}}, \lambda_{steam}\left(1-\dfrac{T-300\mathrm{K}}{T_{close}-300\mathrm{K}}\right)^{-1}\right) & \text{if } T < T_{close} \\ 10\dfrac{\mathrm{W}}{\mathrm{mK}} & \text{if } T \geq T_{close} \end{cases},$$

which is based on the assumption that the two steam gaps linearly close when the temperature rises from 300 K to T_{close}. On Figures 5 to 7 the influence of the steam gaps closure temperature T_{close} (1000 K, 1100 K, 1200 K, no gaps closure) on the simulation results is presented. We see that the steam gaps closure model significantly improves the simulation results, and that the results for the steam gaps closure temperature 1100 K are in nearly perfect agreement with the measured temperatures.

4 CONCLUSIONS

Within the participation in the OECD International Standard Problem No. 46 the degradation phase of the Phebus FPT1 experiment was simulated with the MELCOR 1.8.5 computer code. The input model was developed strictly following the recommendations on noding for the reference case simulation provided in the ISP-46 specification report.

To be able to assess the capability of MELCOR to model the processes involved in the experiment, first the correct temperature conditions in the bundle have to be achieved. The specifics of the Phebus bundle in comparison with a full-scale reactor core is that the Phebus bundle is much smaller, so the view between rods in adjacent core rings is much better, and that in the Phebus shroud there are two steam gaps, which close during the heat up process and consequently the shroud heat conductivity is significantly increased.

It turned out that the temperature conditions in the bundle are highly dependent on the adequacy of modelling of these specifics of the Phebus facility. Therefore a comprehensive parametric analysis has been performed, where the better view between rods in adjacent core rings has been considered with an increased radiative exchange factor and the steam gaps closure has been taken into account with a temperature dependent effective stream gaps thermal conductivity, where the steam gaps closure temperature has been varied. The comparison of simulation results with experimental measurements showed that good agreement of thermal-hydraulic variables in the bundle can be achieved if the radiation exchange factor for radiation radially outward from the cell boundary to the next adjacent cell is increased to 0.75 and the steam gaps closure temperature is set to 1100 K.

Acknowledgment

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5 REFERENCES

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