COMPREHENSIVE CFD ANALYSES CONCERNING THE SERIOUS INCIDENT OCCURRED IN THE PAKS NPP, SPRING 2003

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Abstract

On 10-11th April, 2003, a serious incident occurred in a special fuel assembly cleaning tank, which was installed into the service shaft of the 2nd unit of the Paks NPP of Hungary. As a consequence of the incident, most of the 30 fuel assemblies put into the cleaning tank have seriously damaged. At the Institute of Nuclear Techniques, Budapest University of Technology and Economics, several CFD investigations were performed concerning the course of the incident, the post incidental conditions and the recovery work.

The main reason of the incident can be originated from the defective design of the cleaning tank which resulted in the insufficient cooling of the system. First, the CFD calculations, with which the thermal-hydraulic deficiencies of the design were revealed, are presented in this paper. This investigation clearly showed how as strong temperature stratification could develop inside the cleaning tank that it was able to block the coolant flow through the fuel assemblies.

After the blocking of the flow, the coolant started to boil, and the assemblies became uncovered. The temperature of the surfaces of the fuel assemblies rose above 1000 ºC. With the aid of the radiative heat transfer model of the CFX-5.6 code, the surface temperatures and also the heat transfer between the shrouds of the assemblies and the inner surface of the cleaning tank mantle were analyzed.

When the cleaning instrument got opened the fuel assemblies suffered a serious thermal shock and the assemblies highly damaged. For better understanding of the post-incident state inside the cleaning vessel and for serving as a basis for the safety analyses of the cooling systems, other detailed 3D thermal-hydraulic calculations were performed. These calculations also serve as a basis for the recovery work.

The recovery work is planned to be started in the close future. During this work, the service shaft will be operated in a low-coolant-level operational mode. The operators of the damaged fuel removing equipments will work standing on a platform which will be placed into the service shaft just above the surface of the coolant. Therefore protecting the workers against unnecessary personal doses is a very important task. Therefore, the vertical distribution of the contamination in the service shaft was estimated for different operational and incidental scenarios with a wide parameter-study performed with a 3D CFD model.

All calculations were performed with different types of CFX codes.

1. Construction and operation of the cleaning instrument

The cleaning vessel was a double-mantled closed tank as it can be seen on the left side of Figure 1. It was installed into the so-called service shaft which located next to the spent fuel pool. 30 fuel assemblies could be placed in the tank, which were positioned by the bottom support plate and the upper positioning plate. The foot parts of the fuel assemblies were positioned into the seats of the bottom support plate. The coolant entered the cleaning vessel via four nozzles into the lower elliptical part under the lower support plate. From the elliptical bottom, the coolant reached the fuel assemblies through the bores drilled into the seats of the bottom support plate.

In accordance with the original concept, the coolant would have flown up through the assemblies and after leaving them, it would have flown down among the assemblies to the outlet nozzles. However, there are 12 small perforations with a diameter of 9 mm on the shrouds of all regular (i.e. not follower) fuel assemblies at the top of the foot part (see the right side of Figure 1).

The cleaning instrument had various operating modes. During the cleaning process ("C" operational mode), the mass flow of the coolant was 250 t/h. Due to the turbulence and the impulse of the flow, the pressure drop through these perforations was high enough that most of the coolant flow went through the assemblies in this operational mode. But in the course of the operating mode "B" (after the "C" operational mode), when the coolant mass flow was decreased to 20 t/h, it was doubtful whether most part of the coolant flowed directly to the outlet nozzles through the perforations without reaching the active part of the assemblies. This option was not investigated during the design of the cleaning tank.

2. Summary of the incident

At 16:40, 10th April, 2003, the cleaning process of the sixth batch of assemblies had been just finished. From this time, the cleaning instrument was cooled by 20 t/h coolant mass flow according to the "B" operating mode. This operational mode continued for hours because the reactor building crane was busy with other operation and was not able to remove the cover of the cleaning instrument. At 19:20, the water level in the spent fuel pool rapidly increased. The subsequent investigations showed that this time the coolant temperature in the cleaning vessel reached the saturation, and boiled away [1]. At 21:53, the noble gas detectors gave an alarm signal. At 02:15, 10th April, the vessel cover was removed and radioactive release to the environment through the stack of the reactor building was experienced. At the same time, the water level decreased in the spent fuel pool. According to the change of the level, about 5 m^3 of cold water flowed into the cleaning vessel. It is clear, that previously this volume was filled with steam and the assemblies were uncovered. The following visual examinations in the vessel showed, that most of the fuel had suffered heavy damage, and some fuel pins broke into pieces due to the corrosion and the thermal shock [2][3]. Figure 2 shows the course and the stages of the incident.

3. CFD investigations of the early stage of the incident

First, the CFD model is presented with which the first stage of the incident, from 16:40 to 19:00, was investigated. During this period one-phase flow was in progress. The model (See Figure 3) was developed with the code CFX-5.5.1. It contains the following components of the cleaning vessel:

- The internal mantle of the cleaning vessel and the lid.
- The lower elliptical part of the cleaning vessel.

The four coolant inlet nozzles inside the elliptical bottom with the baffle plates above them.

- The lower support plate with the 30 bores.
- The upper positioning plate.
- The two outlet nozzles.
- The 30 fuel assemblies with six perforations at the bottom part of them.

The fuel assemblies were modelled as 320 cm high hexagonal prisms with a cylinder cut out from it. These drilled hexagonal prisms were cut out from the flow domain. The radius of the cylinder was chosen to obtain an equivalent flow cross section. Instead of the 12 perforations of 9 mm in diameter, six perforations of 13 mm in diameter were built into the bottom part of the assembly's model. The flow resistance inside the fuel assemblies was modelled by a sufficiently set volumetric force which was based on previous measurements.

3.1. Development of flow-blocking temperature stratification in the cleaning vessel

The calculations showed that even without any heat source in the model, the by-pass flow reaches 12% in the "B" operational mode of 20 t/h coolant mass flow. Taking into account a heat source of 350 kW, the results show that as strong temperature stratification develops that it is capable to increase the amount of by-pass mass flow as it can be seen on the left side of Figure 5. Although the calculation was terminated after 4000 seconds because of convergence problems, these results clearly show that the maximum temperature would reach the saturation temperature (~120 ºC) within approximately two hours (see the right side of Figure 5). After 4000 seconds the by-pass reaches 71%; the maximum temperature reaches 81 ºC. It means that meanwhile the temperature increased 50 ºC in the vessel; the difference between the inlet and outlet temperatures was only 8 ºC.

4. Calculations on the radiative heat transfer in the uncovered cleaning vessel

In the period between 19:20, 10th April and 02:15, 11th April, the coolant boiled away, and the temperature could exceed 1000 ºC in a short time as the level of the corrosion showed it clearly in the post-incident investigations. On the other hand, after this fast heating up, the temperature became stable at a certain level. Since the radiative heat transfer is nearly proportional to the fourth power of the maximum temperature in case of high temperature differences, it appeared to be evident that during this period of the incident, the radiative heat transfer became the dominant way of cooling the fuel assemblies in the cleaning vessel.

For investigating this period, Monte-Carlo radiative heat transfer calculations performed with a model developed using the code CFX-5.6. With this model, the temperature fields on the surfaces of the fuel assembly shroud were stated with the assumption that the heat was removed purely by radiation. With the model that contained a 60º segment of the cleaning vessel, an extensive parameter study was performed with different temperatures of the inner surface of the cleaning vessel and different values of emissivity of both the vessel inner surface and the assembly shroud surfaces taken into account. The results of the calculations showed quite good agreement with the post-incident video records. Generally summarizing the lessons learned from these calculations the following can be stated:

- The maximum temperatures of the shrouds depend very slightly on the temperature of the inner wall of the vessel. So, without exactly estimating the inner wall temperature, the maximum temperatures coming from the radiation calculations would be sufficiently accurate.

- On the other hand, the maximum temperatures and the temperature distribution depend very strongly on the emissivity of both the assembly shrouds and the inner wall of the vessel. In case presuming 800 ºC for the inner wall temperature and emissivity of 1.0 for all surfaces, the maximum temperature of the shrouds was given to be 1070 ºC. Supposing that the emissivity of the shrouds and the inner wall is 0.125, the results showed a maximum temperature of 1322 ºC. In case of 100 ºC inner wall temperature and emissivity of 0.125, the maximum temperature was derived to be 1235 ºC.

5. CFD study of the post-incident state of the damaged cleaning vessel

In order to much better understand the post-incident state inside the cleaning vessel and to serve as a basis for the safety of the cooling systems detailed thermal-hydraulic calculations were performed with the code CFX-5.6. These calculations also serve as a basis for the recovery work. It was a special problem that the geometrical and physical properties of the debris were not exactly known. Therefore the debris was modelled by a special porosity model [4]. The uncertainties come from unknown data were decreased by a rather extensive parameter study.

5.1. Geometry of the CFX model

At the Paks NPP, a survey was performed with video camera on the content and geometry of the debris at the bottom of the cleaning tank in March, 2004 [2][3]. The developed geometry – based on these video surveys – can be seen in Figure 7. The intact parts of the assemblies were modelled as hexagonal prisms. The flow domains in the assemblies are modelled as cylinders cut from these hexagonal prisms. The cross-section of these cylinders is equal to the real cross-section of the flow inside the assemblies. The damages were modelled as missing parts. The whole model geometry contains the cleaning tank itself without the cover, the elliptical bottom part of the cleaning tank and the upper part of the service pool.

5.2. Boundary conditions and other parameters

The cleaning tank had a separate cooling loop of 20 t/h mass flow forced by a submersible pump. This cooling loop enters the cleaning instrument at the elliptical bottom and the coolant flows into the assemblies through bores in the bottom positioning plate, into which the assemblies were positioned. Neither the possible displacements from these positions nor the perforations at the bottom of the fuel assemblies were modelled. From the opened cleaning tank the coolant could flow freely to the service tank. The coolant inlets' temperature was 24 ºC for all cases.

Different heat power density values could be set for six different assembly groups and for the debris. Setting the heat source in the elliptical bottom was also possible for modelling occasionally dropped fuel debris into this part of the cleaning tank.

For the bottom part of fuel pin bundles the resistance was set to ξ=20, for the top parts to ξ=100. The debris is real porous media, the inside flow is low and laminar and the flow resistance is derived from Darcy's law:

$$-grad\ P = \frac{\mu}{K} \cdot U$$

where P is the pressure, μ is the dynamic viscosity, K is the permeability and U is the velocity of the medium. Since the permeability of the debris was not known, this parameter was a subject of extensive parameter study. During this study, the permeability of the debris was set in the range of 10^{-7}-10^{-10} m^2. Analytical calculations based on literature showed that hypothetical debris consisting of pure fuel pellets has a permeability of 10^{-7}-10^{-8} m^2. More compact porous media like pure gravel or porous sandstone or coarse grain sand has a permeability of 10^{-9}-10^{-10} m^2 [4].

5.3. The parameter study

During the calculations, extensive parameter study of 18 different parameter set configurations was performed. The alphanumerics of the twelve configurations that did not result in boiling are shown in Figure 8. The following parameters were set in these configurations:

- There were calculations of states immediately after the incident, and also for states of later date. Alphanumeric symbols "APR" or "NOV" refer to the calculations for April 11, 2003 or November 30, 2003 respectively. The heat sources were calculated both in a realistic and a conservative way considering the maximum linear heat power of the hottest assembly as the linear heat power for all parts of all assemblies. Alphanumeric symbols "REAL" or "CONS" refer to these two approaches.
- Different calculations were performed considering the submersible pump of the cleaning tank operating or being stopped. Alphanumeric symbols "PON" or "POFF" refer to the state of this pump.
- Some of the calculations were run with consideration of debris dropped into the elliptic bottom of the cleaning tank. These calculations have alphanumeric symbol "DEB".
- Alphanumeric symbols "P07", "P38", "P08", "P59", "P09" or "P10" refer to the debris permeability value of 10^{-7}, $3*10^{-8}$, 10^{-8}, $5*10^{-9}$, 10^{-9} or 10^{-10} m^2 respectively.

5.4. Results of the post-incident calculations

The calculations for configurations P09_APR_CONS_PON, P10_APR_CONS_PON, P09_NOV_REAL_PON, P10_NOV_REAL_PON, P09_NOV_CONS_PON and P10_NOV_CONS_PON gave results of temperature values over the boiling point. It means that in the case when the permeability of the debris is 10^{-9} m^2 or less, the coolant turns to boiling for all cases. For the other configurations, the characteristic maximum temperature results can be seen on Figure 8.

The results showed clearly that the hottest point can be found inside the debris for all cases. The assemblies are well cooled for all cases. In the assemblies which are highly damaged in low levels, the flow changes its direction after switching off the pump of the cleaning tank (calculations signed by "POFF") and this way, the coolant gets to the elliptical bottom through these truncated assemblies, and flows up through the more intact fuel bundles. It means that stopping of the submersible pump six month after the incident was not critical from the viewpoint of the cooling of the assemblies. In the case when debris was presumed to be in the elliptical bottom, the temperature field changed very slightly.

6. CFD study on the damaged system during the recovery work

During the recovery work, the service shaft will be operated in a low-coolant-level operational mode. Since the operators of the damaged fuel removing equipment will work standing on a platform just above the surface of the coolant of decreased level, protecting them against unnecessary personal doses is a very important task. From this viewpoint, the coolant of the service shaft plays double role.

First, the few meters high layer of coolant between the working platform and the damaged fuel is an important part of the biological shielding for the workers. On the other hand, due to the considerable amount of radioactive contamination dispersed into the coolant, it is also a source of radiation. Therefore, the vertical distribution of the contamination in the service shaft is a very important question during different operational modes of the cooling and purification systems. For answering this question, a complex 3D CFD model of the damaged cleaning tank, the service shaft with decreased level and the residual heat removing and cleaning systems has been developed. The model can be seen in the left side of Figure 9. The model contains the following elements:

- The so-called TV shaft which is used for controlling the service shaft by camera during normal operation.
- The inlet and outlet chunks of the redundant service shaft cooling systems. Usually they are referred to with their alphanumeric symbols: TG01D001 and TG01D002.
- The so-called protective flange at the top level of the cleaning tank. This flange will be the holder instrument for the hermetic containers into which the debris and the fuel assembly fragments will be placed. The model does not contain the hermetic containers. Another function of the protecting flange is preventing the debris from dropping into the bottom part of the service shaft.
- The cleaning tank with the upper positioning plate. As it can be seen in Figure 9, the assembly positioning holes are blocked except one of them. The debris and the damaged fuel assemblies inside the cleaning tank were modelled as porous medium.
- During the recovery work, the cleaning tank will be cooled by a so-called autonomous cooling system (see Figure 9). The outlet of the autonomous cooling system was modelled as a chunk at the proper level in the TV shaft. The autonomous cooling system feeds back the coolant at the bottom of the cleaning tank.
- The model contains the mechanical filter which will be installed into the protective flange. This filter feeds the coolant from above the protective flange below it.

6.1. The investigated configurations

With the CFX model a wide parameter study was performed. In the course of this study calculations for 16 different parameter set configurations were run. The configurations and the alphanumerics of them can be seen on the right side of Figure 9 and the quasi state configurations on Figure 10. The following different connections and parameters were set for these configurations:

- The “A” connection is the normal recovery operational connection. The cleaning tank is cooled by the autonomous cooling system and the purification system works with a mass flow of 40 t/h.
- In the “B” connection, the purification system is out of operation. With these transient calculations the increase of the contamination in time was investigated.
- The “C” and the “D” connections are the incidental connections when both the cleaning tank and the service shaft are cooled by the TG01D001 loop of 110 t/h mass flow. In case of the “C” connection the purification system works with a mass flow of 20 t/h, in case of the “D” connection it stops.
- In case of natural circulation in a large water tank the difference between the inlet temperatures of different coolant loops has large significance. For the “A” connection, the coolant fed back by the cooling system and the purification system enters the model via different inlet boundaries.

For the “A20”, “A18”, “A22” and “A30” configurations, the inlet temperature of the coolant fed back by the purification system was set to be 20 ºC, 18 ºC, 22 ºC and 30 ºC respectively. The coolant fed back by the autonomous system enters the model with an inlet temperature of 20 ºC. For the “B”, “C” and “D’ configurations, all inlet temperatures were set to be 20 ºC.

- MFOUT marks that the mechanical filter is switched off. MF90 marks that the mechanical filter works with an efficiency of 90%. Normally, the efficiency is not known therefore it was modelled to be 0% – marked with “MF0”.

6.2. Results of the CFD study on the damaged system during the recovery work

The results showed that for the “A” and “C” configurations quasi-stationary states develop. The most characteristic numerical results are shown in Figure 10. The results showed:

- The contamination concentrations are rather sensible for the inlet temperatures in case of the “A” configurations. In case of the purification system charges back coolant of equal or lower temperature than the autonomous cooling system, the highest average concentration can be experienced on the coolant surface (“A18” and “A20”). Due to the stable temperature stratification in the service shaft, the bottom part remains rather uncontaminated. In this case, the results are rather insensible of switching on or off the mechanical filter of 0% purification efficiency. In case the mechanical filter purifies the coolant with an efficiency of 90%, the average contamination decreases significantly.
- In case of the purification system charges back coolant of higher temperature than the autonomous cooling system (“A22” and “A30”) the contamination concentrations are much higher for both the whole domain and the upper part of the service shaft. On the other hand, since the highly contaminated coolant that leaves the cleaning tank spreads along the protective flange, the surface average contamination is lower than it was experienced for the above valued case.
- In case of the incidental cooling (“C”), in spite of the fact that the purification system works, the contamination in the whole domain increases continuously during even a 10 hours long transient, before the quasi-stationary state develops.

The performed transient calculations also showed the contamination growth rates in time for the configurations without the purification system functioning (“B” and “D”).

On the basis of these result the extra doses for the workers can be estimated for different cooling connections, and different sources of radioactive contamination dissolving into the water.

Summary

On 10-11th April, 2003, a serious incident occurred in a special fuel assembly cleaning tank, which was installed into the service shaft of the 2nd unit of the Paks NPP of Hungary. As a consequence of the incident, most of the 30 fuel assemblies put into the cleaning tank have been seriously damaged. At the Institute of Nuclear Techniques, Budapest University of Technology and Economics, several CFD investigations were performed concerning the course of the incident, the post incidental conditions and the recovery work.

In the paper, both the damaged instrument, the course of the incident, the different CFD models, calculations and results are presented.

References

[1] A. Aszódi, I. Boros, A. Csige, G. Légrádi: Thermal-hydraulic analysis of the incident in the Paks NPP on 10th April 2003, 13th Symposium of AER on VVER Reactor Physics and Reactor Safety, Drezda, Germany, 2003., pp. 737-754, ISBN 963-372-630-1

[2] T. Parkó, G. Bóna: Structure of the damaged fuel in the cleaning tank of unit 2, preliminary assessment, Paks NPP, Hungary, 23.03.2004

[3] T. Parkó: Degree and locality of the damage of the fuel in the cleaning tank, Paks NPP, Hungary, 23.03.2004

[4] A. Aszódi, G. Légrádi: CFD analysis of the damaged cleaning tank thermo-hydraulics, Proc. 14th Symposium of AER on VVER Reactor Physics and Reactor Safety, p.615-628, Espoo, Finland, September 13-17, 2004, ISBN 963-372-631 X

Figures

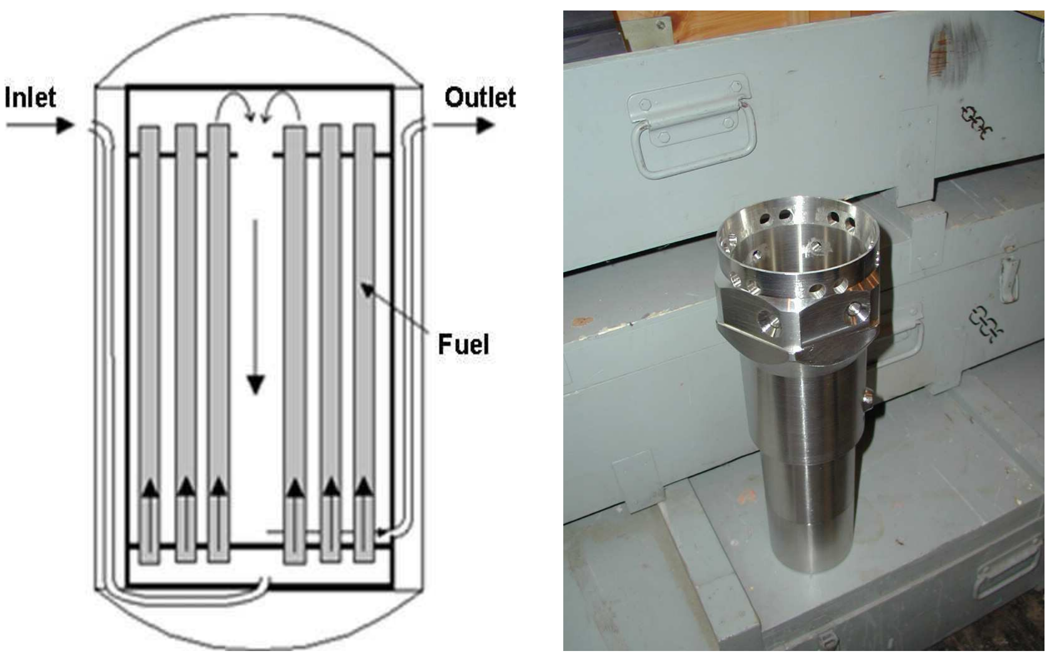

Figure 1: The scetch of the cleaning vessel (left) and the foot part of a working assembly (right). The 12 perforations, 2 perforations for all six plates of the shroud can be seen at the top part of it.

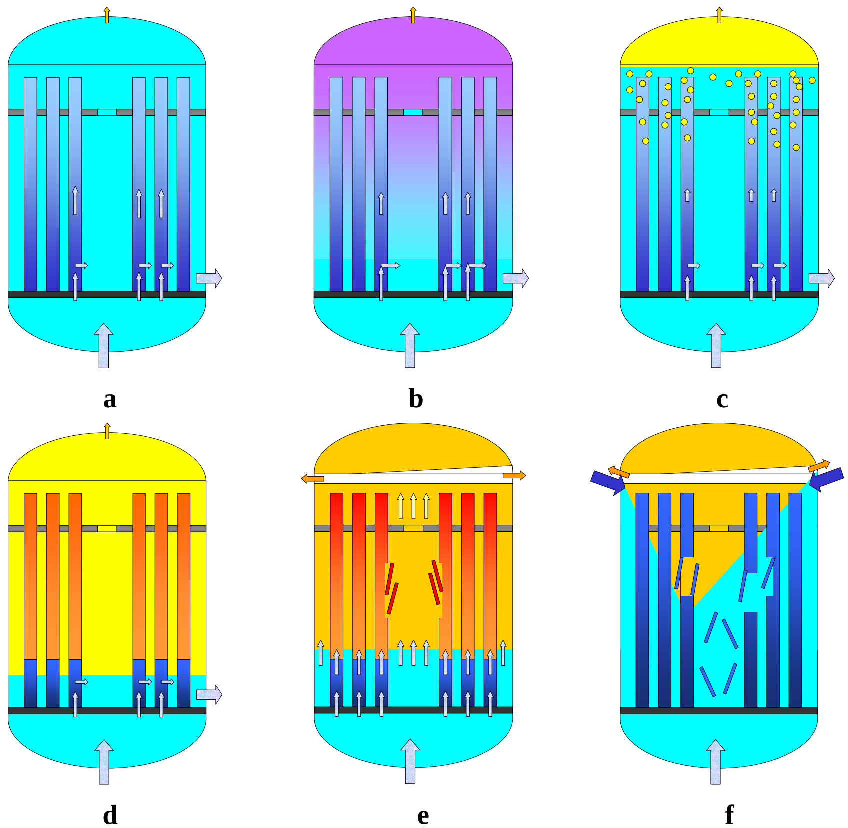

Figure 2: Main stages of the incident: a-b: temperature rises and temperature stratification develops at the beginning; c-e: boiling blocks the flow, the steam pushes the water out, overheating of the assemblies, blasting and oxidation of the fuel pins; f: opening of the cover and flooding of the cleaning tank

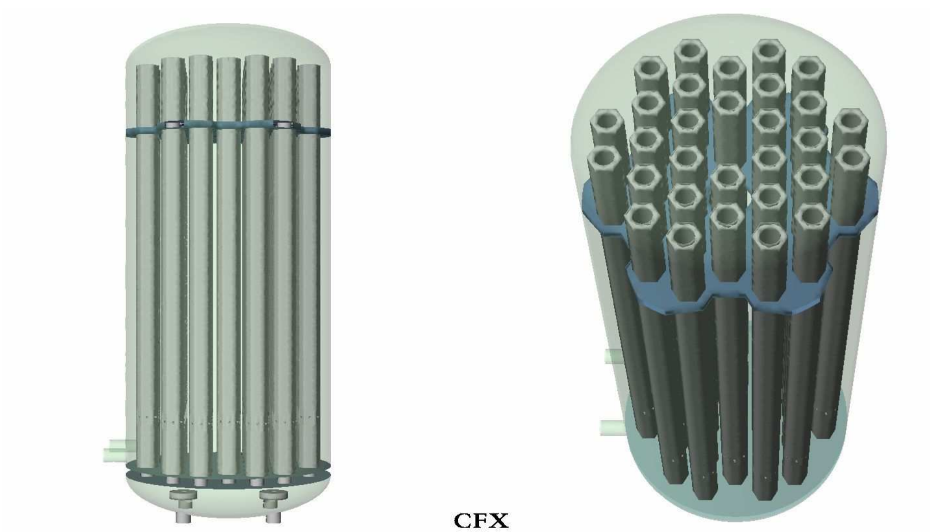

Figure 3: The CFX model of the intact cleaning vessel

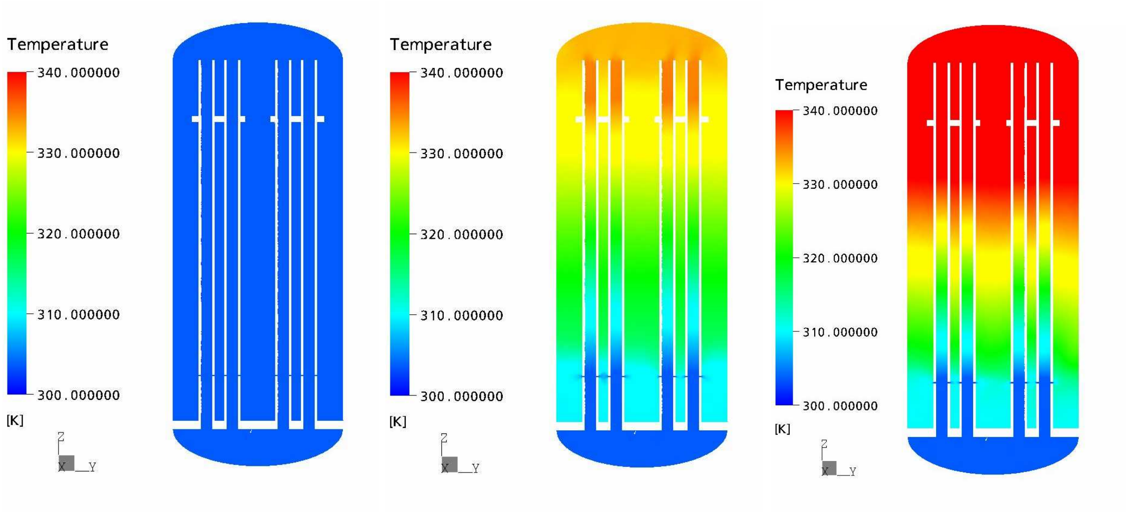

Figure 4: Temperature fields in the cleaning vessel during the operational mode "B" transient at 0, 2000 and 4000 seconds

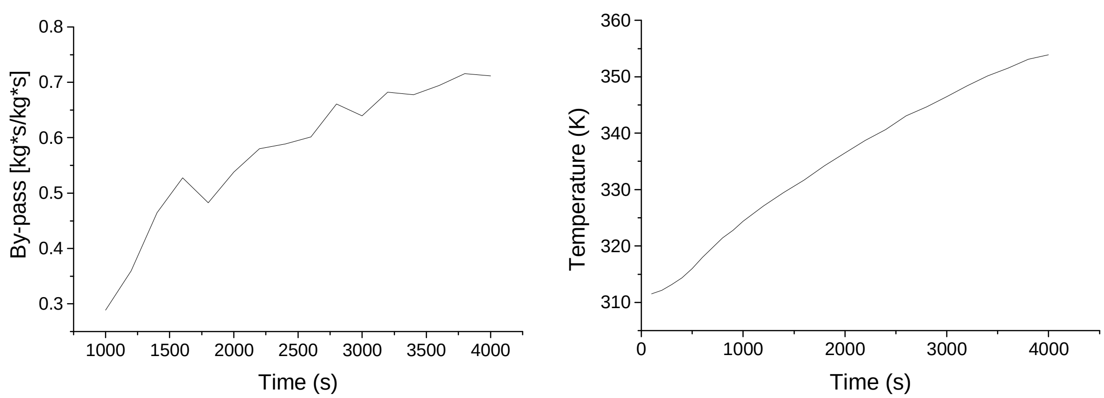

Figure 5: By-pass ratio (left) and maximum temperature (right) during the operational mode "B" transient

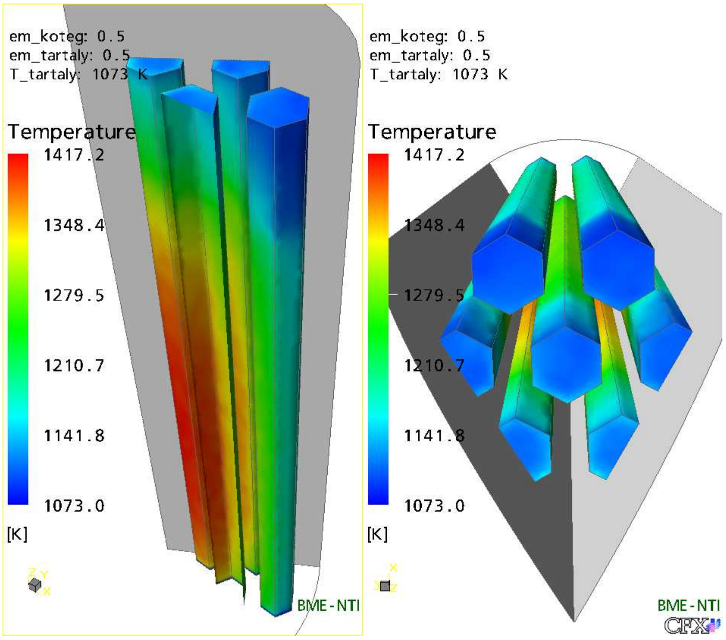

Figure 6: Computational results for the radiative heat transfer inside the cleaning vessel, calculating by the following parameters: Temperature of the vessel=800 ºC, emissivity of both the vessel and the assembly's shrouds: 0.5

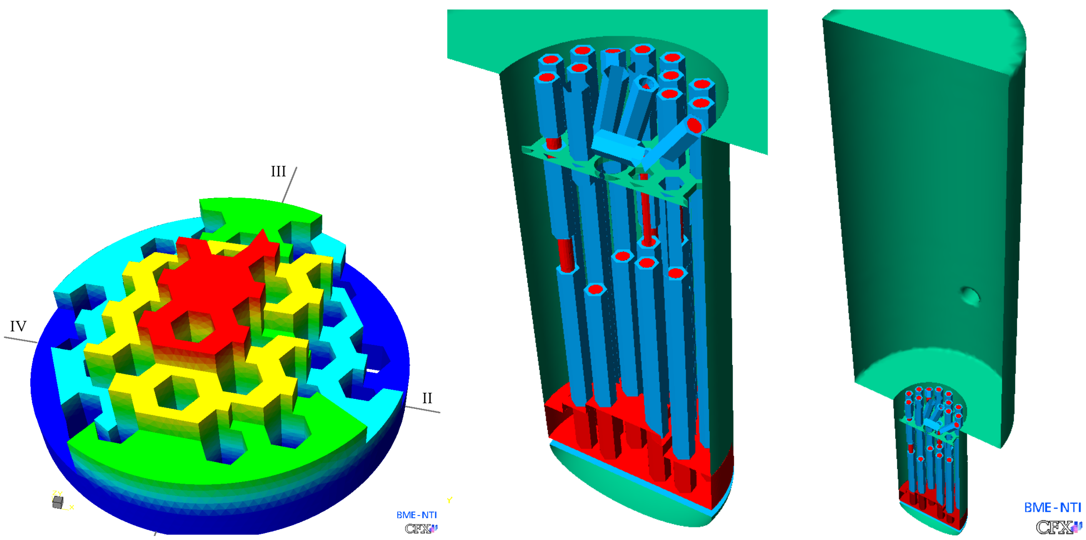

Figure 7: The CFX geometry of the debris at the bottom of the cleaning tank (right), the damaged assemblies (center) and the whole model geometry, for the post-incident calculations

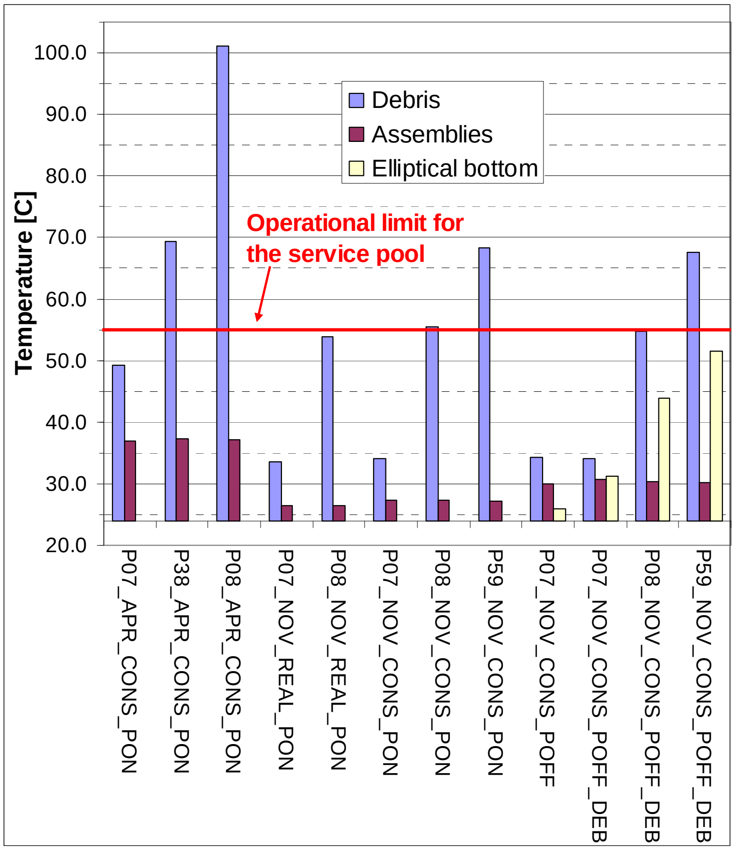

Figure 8: Maximum temperatures in the debris, in the assemblies and in the elliptical bottom for the post-incidental calculations

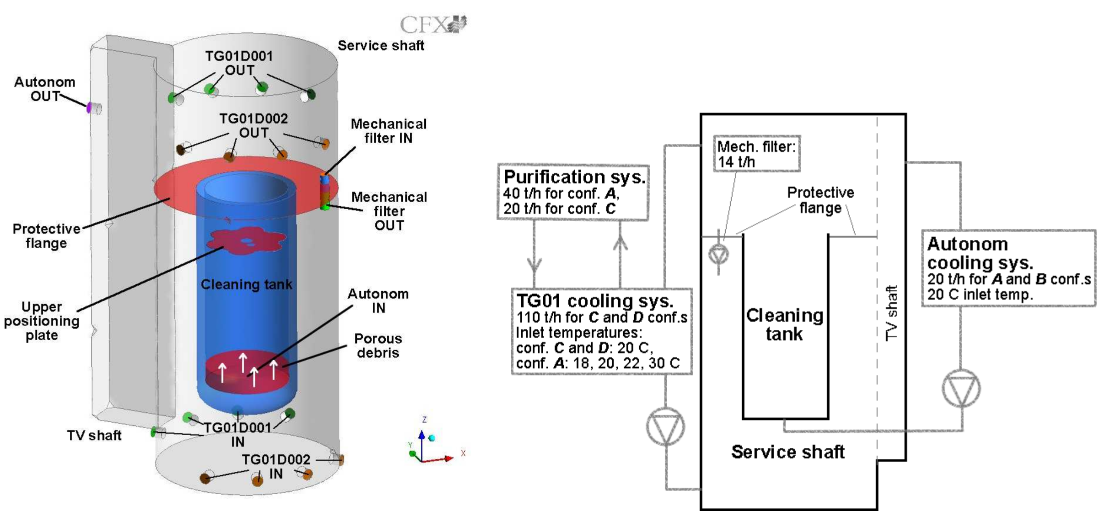

Figure 9: CFX geometry model of the damaged cleaning tank and service shaft of decreased coolant level (left) and the investigated connections and configurations (right)

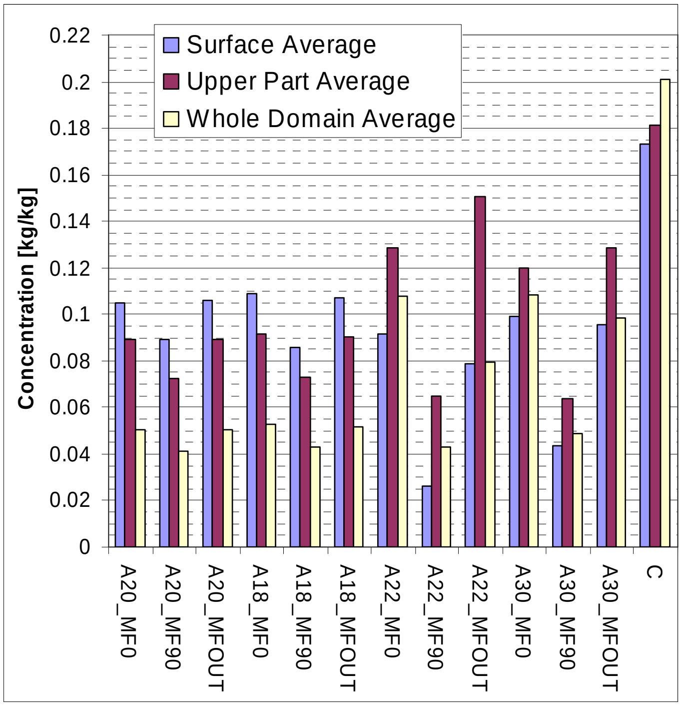

Figure 10: Results for the quasi-stationary configurations of the CFX calculations on the damaged cleaning tank and service shaft of decreased coolant level during recovery
The calculations were run for a normalized contamination source of 1 kg/s inside the cleaning tank. Therefore the normalized results have a dimension of kg/kg