FDS3 Simulations of Indoor Hydrocarbon Fires Engulfing Radioactive Waste Packages

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Abstract

The thermal environment of a hypothetical large indoor hydrocarbon pool fire is more complex compared to outdoor fires and can be more severe for engulfed objects. In order to analyze potential thermal environments for interim storage of spent fuel casks or low-level radioactive waste packages engulfed in pool fires numerical simulations with the CFD fire code FDS3 [1] were carried out for different storage configurations. In addition, data of indoor pool fire experiments were used to validate the model for this type of application.

A series of pool fire experiments under different ventilation conditions and varied pool surface (1 m² – 4 m²) inside a compartment of 3.6 m x 3.6 m x 5.7 m was conducted at iBMB (Institut für Baustoffe, Massivbau und Brandschutz) of Braunschweig University of Technology, Germany. The instrumentation included thermocouples, heat-flux and pressure gauges, bi-directional flow probes and gas concentration measurements. A mock low-level waste drum equipped with outside and inside thermocouples was positioned as an additional heat sink near the fire source. Two of these experiments have recently been used for benchmarking a number of fire simulation codes within the International Collaborative Fire Model Project (ICFMP). FDS3 simulations by GRS of some of the above mentioned experiments will be presented showing the ability of the model to sufficiently well represent the fire environment in most cases.

Further simulations were performed for hypothetical pool fire environments in interim storage facilities for German spent fuel transport and storage casks. The resulting temperature curves were then used for the thermo-mechanical analysis of the cask reaction performed by BAM (Bundesanstalt für Materialforschung und –prüfung, see corresponding conference paper by Wieser et al.). The FDS3 pool fire simulations show that the fire environment is strongly influenced by the ventilation conditions and cooling effects depending on the number and position of casks. For specific situations, which are beyond most typical accidental scenarios, thermal environments may be obtained being more severe than the standard 30 min 800°C fire.

1 Introduction

Following the terrorist attacks of September 11 2001, the German Federal Office for Radiation Protection (BfS) being the licensing authority for interim storage facilities decided to examine the consequences of a large aircraft attack on such facilities. At that time, licensing procedures for 17 new on-site interim storage facilities (12 large concrete buildings and 5 storage areas with mobile housings for the casks) were in progress. First, the potential radiological consequences for this kind of attack had to be assessed within these licensing procedures and afterwards similar investigations for the existing central interim storage facilities were on the schedule.

The new on-site facilities for interim storage of spent nuclear fuel are a consequence of the amended German Atomic Energy Act [2] including an agreement on the phase-out of nuclear power production in Germany. It also lays down the end of spent fuel transportation to reprocessing plants after June 2005 and the construction of on-site interim storage buildings in order to avoid spent fuel transports through Germany until a final repository for high level radioactive waste will be available. Transports to the already existing central interim storage buildings will mainly contain spent fuel from research reactors and high level waste from reprocessing plants.

There are two types of interim storage buildings: the STEAG-concept with one storage section chosen for NPP sites in the northern part of Germany and the WTI-concept for Southern Germany with a wall sub-dividing the building into two storage sections (see Fig. 1). The STEAG storage building has a wall thickness of approx. 1.2 m and a roof thickness of about 1.3 m, whereas the WTI building has a 0.7 - 0.85 m wall thickness and a roof thickness of approx. 0.55 m. The length of the storage section varies between 42 m and 70 m. The spent fuel elements are stored in dry transport and storage casks of CASTOR V/19 or CASTOR V/52 type in rows of 4 or 5 casks. These casks have a monolithic body of cast iron with a height of just under 6 m. Decay heat removal is assured by natural convection through side wall inlets and roof level outlets.

At the Neckarwestheim nuclear power plant, a special tunnel concept is intended. The two central interim storage facilities Gorleben and Ahaus are similar to the WTI building type, but with thinner walls and no separating center wall. The spent fuel storage section of the existing storage facility in Greifswald is similar to one section of the WTI-type interim storage building in Fig. 1.

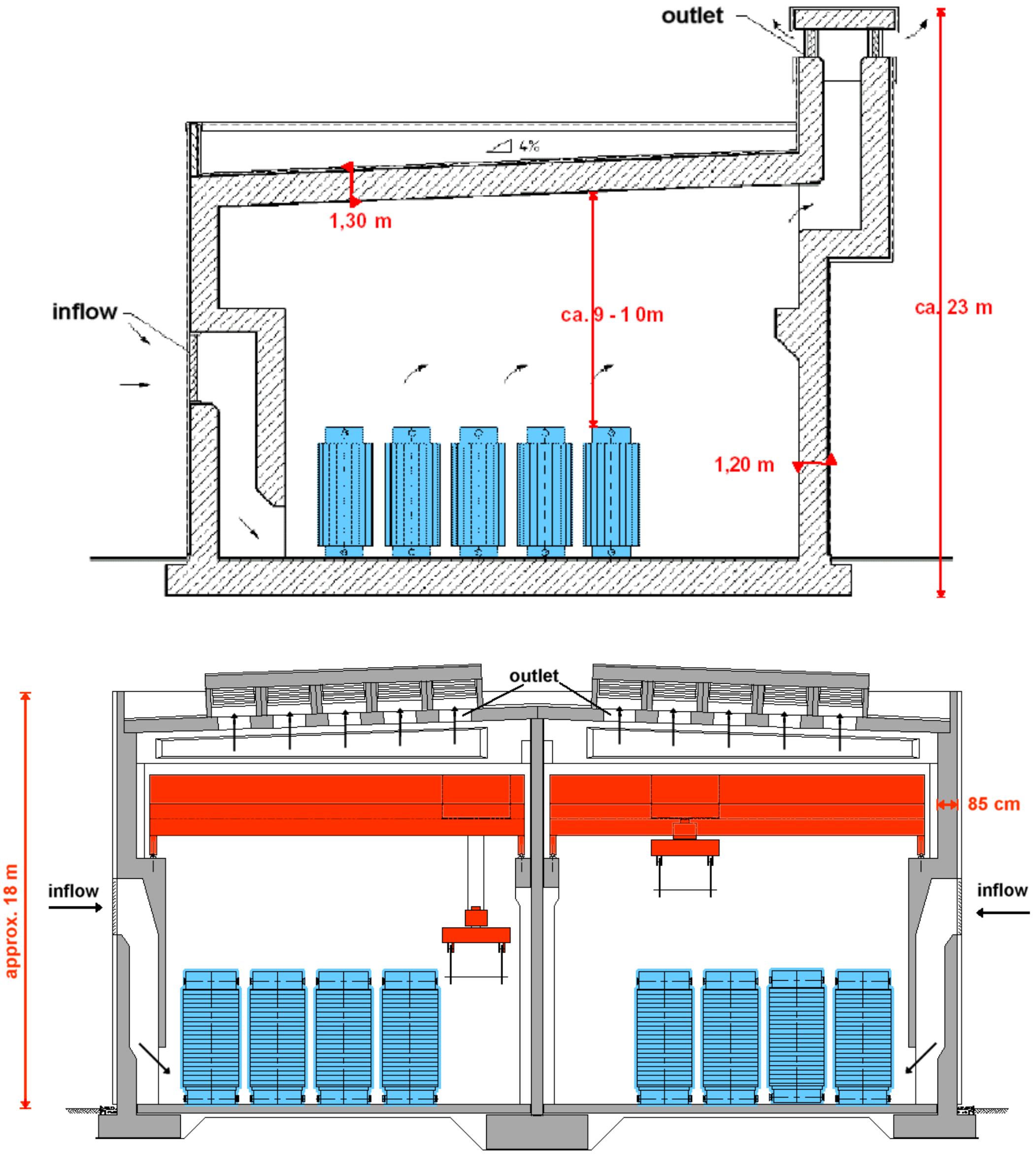

Fig. 1. Vertical cross sections of STEAG-type (top, without crane) and WTI-type (bottom)

The analyses of the impact consequences were performed for the Bundesamt für Strahlenschutz (BfS) by a consortium of experts from TÜV Hannover/Sachsen-Anhalt, Stangenberg and Partner Ingenieur GmbH (SPI, Bochum), Bundesanstalt für Materialforschung und –prüfung, (BAM, Berlin) and GRS. The major tasks of GRS were the examination of mechanical loads and the fire analysis. Fire temperature curves for site-specific worst case scenarios were then used as input for FEM analysis of cask performance by BAM (see corresponding conference paper by Wieser et al.) in order to check the possibility of radioactive release from the casks. Section 3 will give an example of the applied fire scenario analysis method and discuss some major findings but no specific scenarios.

2 Fuel Fire Experiments and Model Validation

From the early discussions of aircraft impact scenarios on interim storage facilities it turned out that a large spectrum of fire scenarios can occur depending on the impact scenario, the size and type of building. Depending on the building reaction a certain amount of jet fuel which is not burnt in the initial fuel spray fireball may enter the storage building either through existing ventilation openings or through additional openings originating from the aircraft impact [3]. In most cases, the airflow and fire pattern inside the building is too complex to use standard fire curves or zone models for a suitable fire scenario analysis. Hence, a computational fluid dynamics (CFD) fire model (FDS, Fire Dynamics Simulator [1]) was chosen for a more detailed fire analysis.

FDS3 (Fire Dynamics Simulator, version 3) is a freely available fire simulation code working on one or several coupled rectangular grids. Combustion may be handled as direct explicit calculation of combustion rates or with a mixing ratio approach, which is used for all simulations in this paper. Besides combustion, the model predicts flow, turbulence (LES approach), radiation and heat conduction. Fire analyses started with FDS2. When version 3 of FDS became available in the course of the project, also FDS3 simulations were included. The analyses presented in this paper will focus on FDS3 simulations. As information about the model validation was limited, some model validation and verification experiments had to be carried out to support the analysis for interim storage buildings. With the very recent release of FDS version 4 more information about the model validation is available [4].

Within the same general context, two series of fuel pool fire experiments (outdoor and indoor fires) were conducted at iBMB of the Braunschweig University of Technology, Germany. These experiments were chosen to validate FDS2 and FDS3 for jet fuel fire applications. The indoor experimental series took place in a compartment of 3.6 m x 3.6 m area and 5.7 m height (see Fig. 2). Ventilation conditions were varied between under-ventilated fires and optimum (near stochiometric) ventilation by opening or closing vents in the compartment wall and by controlling the fan system in the air outlet duct (see [5]). An additional outside hood above the main opening was used for experiments with natural ventilation in order to derive heat release rates from the oxygen consumption method.

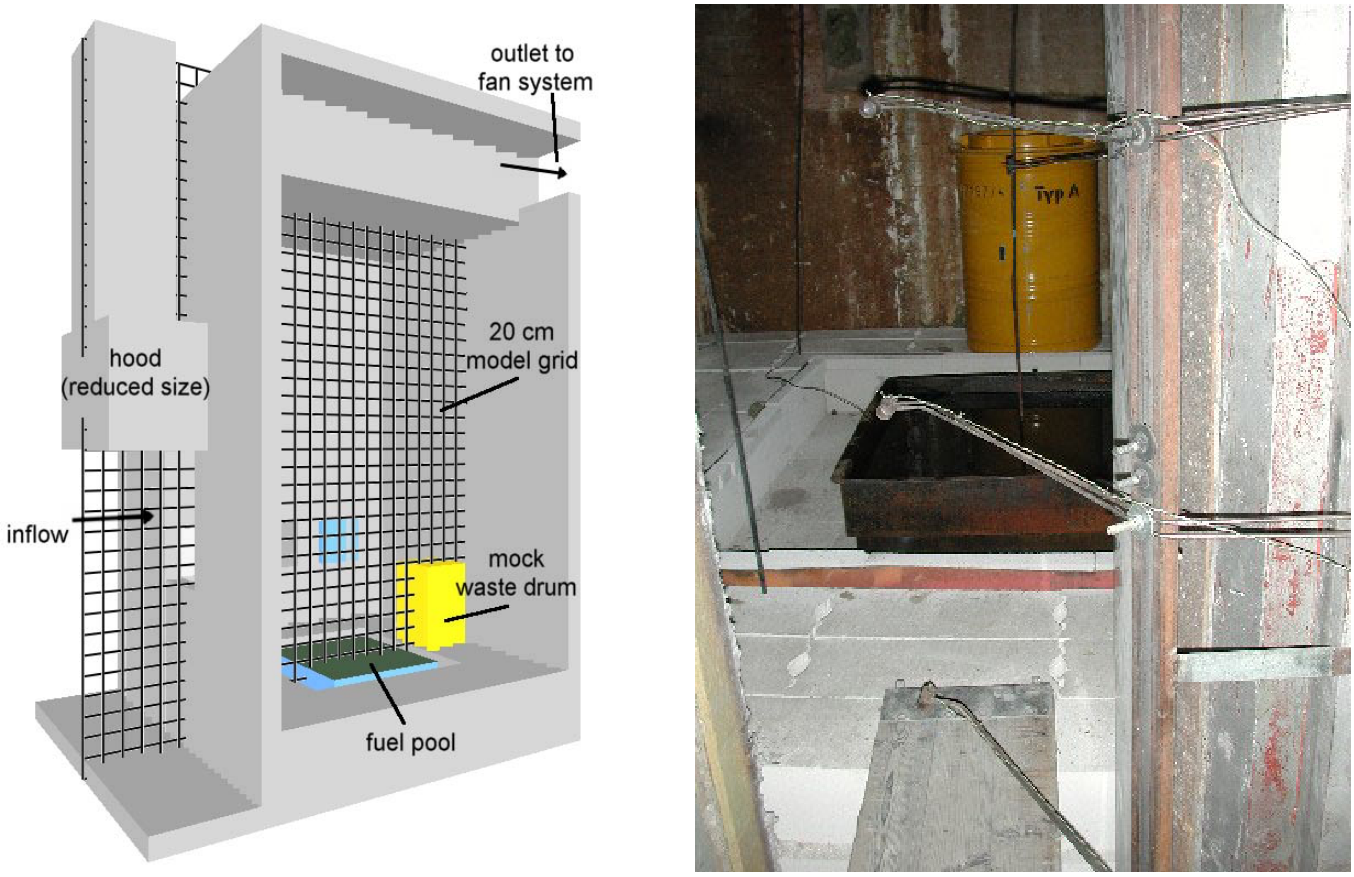

Fig. 2. Left: simplified experimental geometry in FDS3 with 2 m² pool and coarse grid resolution (front wall omitted), right: view through the inflow opening showing flow probes, a 1 m² pool and the mock waste drum

Thermocouples were located at 18 positions inside the compartment and at 16 surface positions on the light concrete wall and on different material specimens at the rear wall. The mock low-level waste drum included another steel drum with a concrete filling of the gap between both drums. The resin filling of the inner drum and the concrete were equipped with a grid of 18 thermocouples. Further instrumentation consisted of heat-flux and pressure gauges, bi-directional flow probes and gas concentration measurements. The fuel pool with an initial fuel thickness of 10 cm was located on a scale in order to record the fuel recession rate during the experiments.

Maximum flame temperatures inside the compartment varied between 700 °C and 1400 °C depending on the pool size and ventilation conditions, with highest values for experiments with forced ventilation via the exhaust fan system. Apart from short-term peak values, fuel recession rates varied between 4 and 6 mm/min. Initial simulations with FDS3 using the optional model feature of online fuel evaporation calculation showed unsatisfactory results. Therefore, in all following simulations with FDS3 fuel evaporation rates were prescribed as well as the exhaust duct flow in case of forced exhaust ventilation. Numerical experiments reported in [4] indicate that the performance of the evaporation model strongly depends on the grid resolution.

Fig. 3 shows simulated temperature curves above a 2 m² pool with forced exhaust duct ventilation using a coarse (20 cm) grid resolution. Simulated temperatures at 2.85 m and 4.7 m above the pool surface follow the observed temperatures fairly well, whereas simulated values at the lowest thermocouple are well below observations. Peak temperatures up to 1300 °C during the final increased evaporation of the thinned fuel pool are generally underestimated by the model. If a finer grid resolution of 10 cm is used in the lower and center part of compartment, the vertical temperature profile is better reproduced (see Fig. 4) and also the peak temperatures are near observations.

This dependency on the grid resolution is well known [4]. The deviation from an optimum grid resolution depending on the heat release rate is logged by the model, allowing the identification of potential need to refine the grid. On the other hand, an increased grid resolution by a factor of two approximately results in an increase of computational time by a factor of 16 (number of grid cells and reduced time step), which limits the grid refinement.

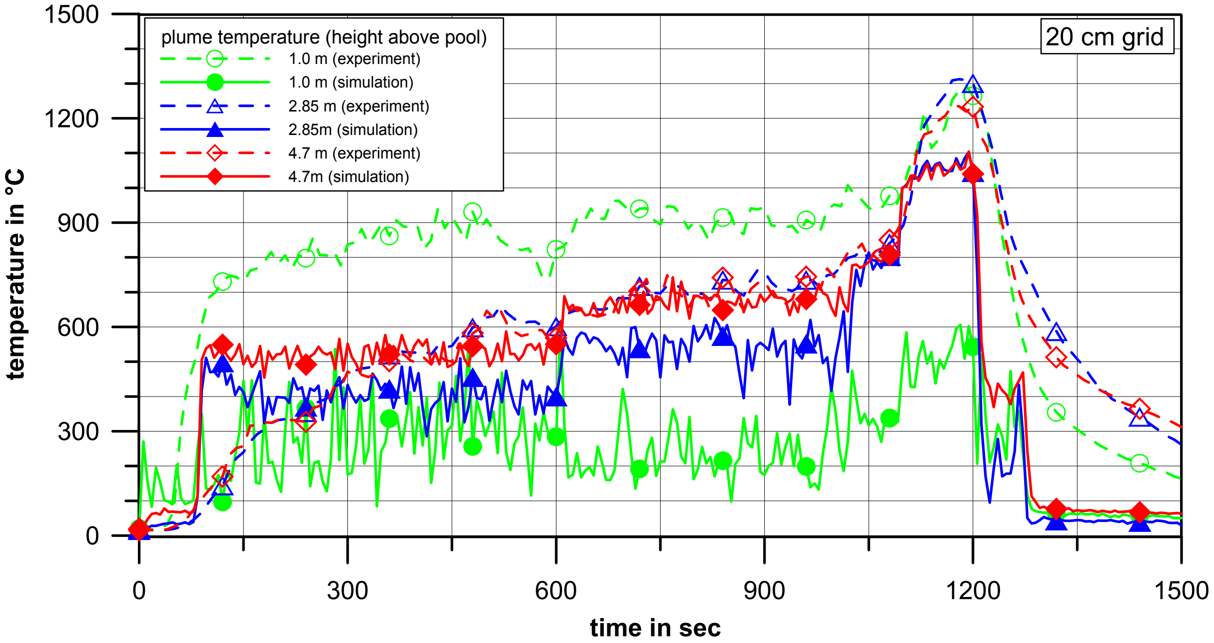

Fig. 3 Comparison of observed and simulated temperature curves at centered thermocouple positions above the pool surface (FDS3, coarse grid)

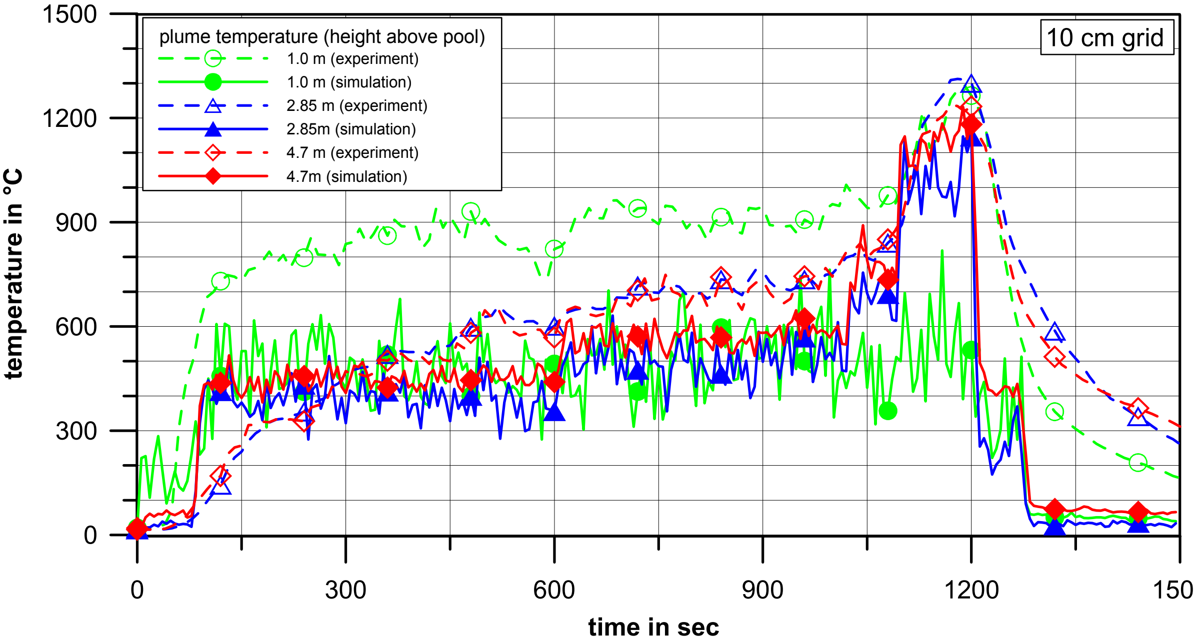

Fig. 4. Comparison of observed and simulated temperature curves at centered thermocouple positions above the pool surface (FDS3, fine grid)

Fig. 5 shows a comparison of the surface temperature curves for the backside light concrete wall and for the mock waste drum near the fire, which is represented in the model as a block of homogeneous material mix of steel and concrete. Apart from an underestimation of the short peak temperature phase and of the upper position drum surface temperature there is a good agreement between model and experiment. Overall, the model is able to reproduce the general pattern of the fire environment. Coarse grid simulations tend to underestimate temperatures and to distort the temperature pattern, particularly near the pool. Less satisfactory results were obtained for experiments with under-ventilated conditions. In addition, the level of agreement was slightly better in FDS3 than in FDS2. Having these uncertainties in mind, the model may be applied for the analysis of fuel pool fire environments.

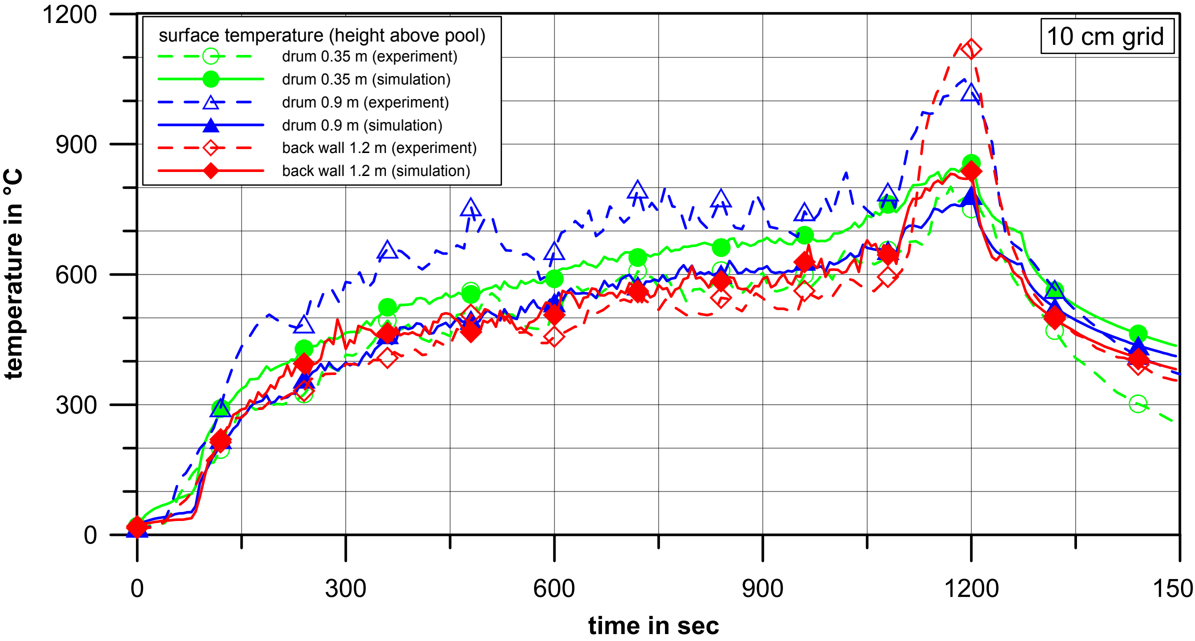

Fig. 5. Comparison of observed and simulated surface temperature curves of the mock waste drum and compartment wall (FDS3, fine grid)

Similar findings for FDS3 were obtained by NIST (National Institute for Standards and Technology) from semi-blind simulations of two of the above mentioned experiments (specification see [5]) within the International Collaborative Fire Model Project (ICFMP). In the frame of this project, up to now 5 benchmark exercises have been carried out with emphasis on nuclear power plant applications, starting with fires in cable rooms, followed by heptane and oil pool fires in large halls, combined sprayed fuel and cable fires, jet fuel pool fires and, last not least, special cable fires with fire propagation under different boundary conditions. The results of the first two benchmarks are documented in [6] and [7]; the other three benchmark exercises will be finished and documented in detail in 2005.

The coincidence between the FDS predictions and the measured values for the pool fires are sufficiently good, if the burning rate is known (i. e. semi-blind predictions). In case of completely blind calculations for under-ventilated conditions the predictions are not yet satisfactory due to sensitivity of the lower oxygen limit (LOL) value of the model. Furthermore, temperatures are overestimated for these conditions in case of applying special correlations (FDT, FIVE). The comparison of in total two completely blind and nine semi-blind simulations of jet fuel pool fires in the frame of the benchmark exercise no. 5 has demonstrated that the corresponding experimental series represents a useful addition to the validation matrix for fire simulation codes. Additional validation of the codes is necessary, on the one hand for ventilation controlled fuel pool fire scenarios within compartments with a large pool size in relation to the floor area, and, on the other hand, for specific cable fire scenarios, in particular, the simulation of fire induced cable failures and circuit faults. This future validation work will help to further improve the models and to reduce the need for pessimistic assumptions in scenario analysis applications.

3 Hydrocarbon Fires in Interim Storage Facilities

Hypothetical large hydrocarbon fires in interim storage facilities allow coarser grids compared to the validation simulations. On the other hand, the large extent of the buildings analyzed does not yet allow a representation of the complete building in FDS3 in case that the simulations have to be completed on a standard PC within a reasonable time period. Fire simulations in large buildings demand computer clusters as NIST has recently applied for the analysis of the WTC collapse [8] with the new parallel version FDS4. Hence, all model analyses were performed with building sections using appropriate boundary conditions to keep compatibility with the full fire environment.

First, the potential distribution of fire loads and debris inside the building was analyzed based on FEM analyses of the building reaction done by SPI. In a second step potential distribution of fire load and debris was analyzed. After digitizing the building, the fire loads and all obstacles, a pre-run with the model was carried out in order to find out the potential heat release rate based on the given ventilation condition. With this test, a pessimistic heat release rate and the respective fire duration was obtained considering the range of fuel burning rates observed, and avoiding the uncertainty of evaporation rates calculated by the model.

As an example, Fig.6 shows the model representation of a half intact rear part of a central interim storage building. The area around the casks is resolved with double (25 cm) grid resolution in order to guarantee a detailed representation of the fire engulfment. With this well resolved simulation a reference is given to assess the uncertainty of less time-consuming coarse grid simulations used for the purpose of scenario sensitivity analysis. Due to the large building floor area and the slight slope of the floor, the hypothetical fuel pool is present in the left part of the model only, continuously contracting to the left wall during the fire. Additionally, combustible debris from the aircraft is assumed to cover the floor. Following the pre-run, an average fuel consumption rate of 4 mm/min was chosen for the fuel pool.

Fig. 7 shows the resulting time series of simulated temperatures averaged around the cask lid level. After few minutes temperatures are continuously decreasing due to the shrinking of the jet fuel pool. Maximum temperatures are about 100 K lower when heat flux to the casks is taken into account, showing the mitigating influence of the large heat capacity of CASTOR casks. The analysis also reveals large differences in engulfing flame temperatures for different cask positions with highest values at the position opposite to the pool and to the air inflow. This difference is caused by the flow pattern inside the compartment, emphasizing the advantage of CFD codes relative to simpler codes like zone models.

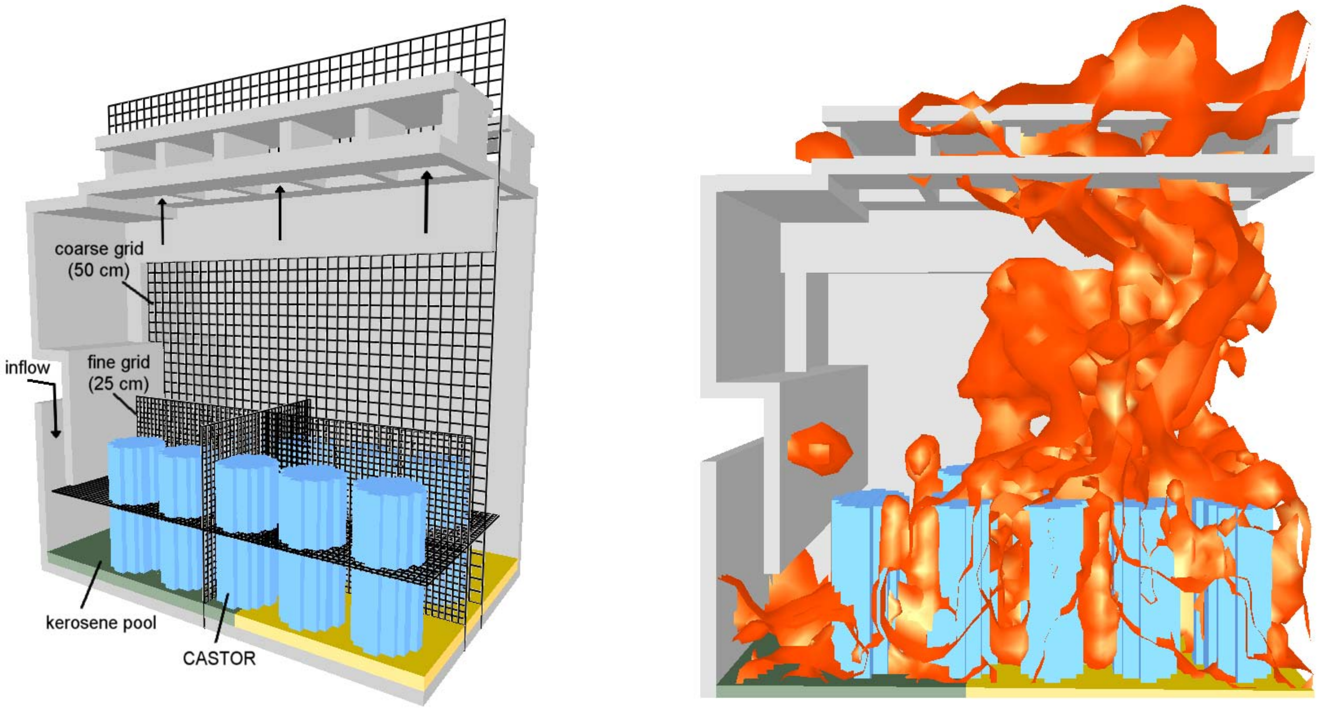

Fig. 6. Left: FDS3 Model representation of CASTOR casks in undamaged rear part of central interim storage facility (half), right: snapshot of FDS3 flame pattern 8 min after ignition

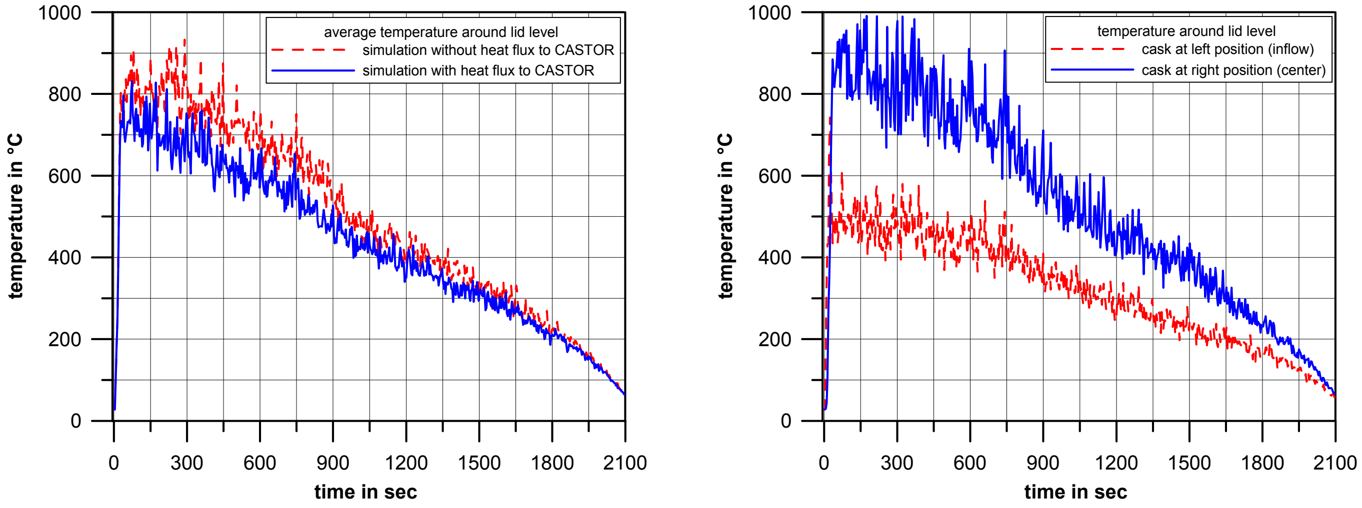

Fig. 7. Simulated temperatures in interim storage building engulfing cask lid level (left: influence of heat flux to casks, right: influence of cask position)

The fire scenario shown above does not exceed the standard IAEA 800°C fully engulfing fire scenario with 30 min duration. In other cases analyzed during the project, higher temperatures engulfing the casks were obtained for scenarios with larger pool sizes on flat floors or with better ventilation. In most of these cases with higher heat release rates, a coarse grid resolution of 50 cm is sufficient. Analyzed worst case jet fuel fire scenarios for on-site interim storage facilities have fire durations well below 30 min [9]. Nevertheless, engulfing peak temperatures for some casks may reach up to 1100 °C.

Factors reducing the severity of the fire scenarios are manifold. Depending on the resistance of the building not all fire loads present in case of an aircraft impact will enter the building. Particularly, parts of the jet fuel spraying out of ruptured tanks in case of an aircraft impact will burn in a large fireball outside the building. Openings for natural ventilation are not sufficient for an optimum ventilation of large pool fires inside the buildings, resulting in lower heat release rates than in open pool fires. As explained in the example, a large number of casks inside the building has a noticeable cooling effect on the fire environment. Furthermore, in some cases, special openings allow the drainage of fuel out of the storage building, limiting the potential fuel fire duration [9].

Subsequent FEM analyses performed by BAM have shown that none of the scenarios will cause a relevant decrease of leak tightness due to thermal impact. By the end of 2003 the licensing procedure for all planned on-site interim storage facilities has been finished.

4 Summary and Conclusions

Validation experiments with FDS3 have shown the ability of the model to sufficiently well represent pool fire environments in most cases. Compared to simpler fire models like zone models, FDS3 enables a detailed analysis of fire environments with complex geometry and flow pattern. On the other hand, commonly available computer resources limit the feasible number of model grid elements. When no computer clusters are available, these restrictions may only partly be overcome by limiting a fine grid resolution to the fire area or by taking advantage of symmetries and homogeneities of the fire environment.

Further validation and improvement of FDS3 and of other models involved in the ICFMP project is still needed. Furthermore, modeling of the pyrolysis and burning rates is still an unsolved problem for most of the fire simulation codes. The level of uncertainty found during the validation work has to be taken into account when applying FDS3 to analyze virtual fire scenarios.

The application of FDS3 to hypothetical jet fuel fires in interim storage buildings for spent fuel revealed a strong dependence of engulfing fire environments on ventilation conditions and on cask position. Simulated temperatures around casks do not exceed 1100°C. Some effects mitigating the severity of the fire engulfing casks are the large heat capacity of the casks, the limited ventilation or the limited jet fuel fire duration due to a large pool area or due to drainage openings. Time curves of engulfing fire temperatures derived from FDS3 simulations were used by BAM to analyze the thermal and thermo-mechanical performance of the casks, revealing no relevant decrease of lid seal leak tightness.

For future analyses a more realistic coupling of FDS3 and FEM simulations and an improved representation of objects in FDS3 would allow a reduction of pessimistic assumptions. However, a detailed validation of simulated fire pattern around obstacles would be necessary at first.

5 References

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