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ANALYSIS OF CONSEQUENCES OF AN AIRPLANE CRASH ON UNDERGROUND RADIOACTIVE WASTE STORAGE BUILDINGS

PART II: COMPUTATIONAL FLUID DYNAMICS FIRE ANAYLSIS

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ABSTRACT

A hypothetical Military Aircraft Crash (MAC) onto the underground radioactive waste storage buildings of the Nuclear Power Plant Gösgen was studied. Based on the structural analysis of the MAC impact, a CFD-based fire analysis is performed in this paper. A reference MAC-induced building roof hole-size and a mass of kerosene entering the buildings were inferred from the structural analysis and used in the fire analysis of the radioactive waste storage buildings and a reference geometric configuration of the stainless steel barrels containing bituminised radioactive waste. A mesh analysis led to the choice of a fine mesh in the compartment where the MAC occurred, and coarser meshes elsewhere. The CFD fire analysis showed that the fire duration and combustion gas temperatures depend strongly on the hole size and whether the building doors are closed or left open. In addition, the fire dynamics was found to be complex, involving turbulent mixing of air, fuel, and combustion gases, chemical reactions, ventilation and buoyancy effects, and pool fire flame expansion. In addition, the mechanical and thermal resistances of the barrels provide further barriers to a possible bitumen and radioactive waste burning, preventing radioactive releases into the environment. This conclusion is supported by several parametric and sensitivity case studies.

INTRODUCTION

NPP Gösgen has evaluated a hypothetical MAC impact on the underground low and intermediate level radioactive waste (LLW and ILW) storage buildings and the resulting kerosene fire and radiological consequences. The MAC is expected to create a breach (a “hole”) in the roof of the buildings and project debris and kerosene from the aircraft into the buildings. The buildings contain stacks of stainless steel (SS) barrels filled with bituminized radioactive wastes. Figure 1 shows the configuration of the LLW building with waste barrels stacked in the compartment considered for the fire analysis. The “transparent” volume drawn above the stacks of barrels denotes the hole in the roof of the building considered for the fire analysis. Figure 2 shows the configuration of the ILW building where barrels are not stacked above the floor but are rather placed on a hexagonal grid of wells constructed inside the basemat of this building. The wells interested by the fire analysis are located beneath of the blue square area, which represents the assumed spreading area of kerosene. Each channel may contain up to four barrels positioned one on top of the other and the wells are sealed with a thick SS cover. The rectangular volume sketched above the kerosene area denotes the hole in the roof of the building created by the MAC.

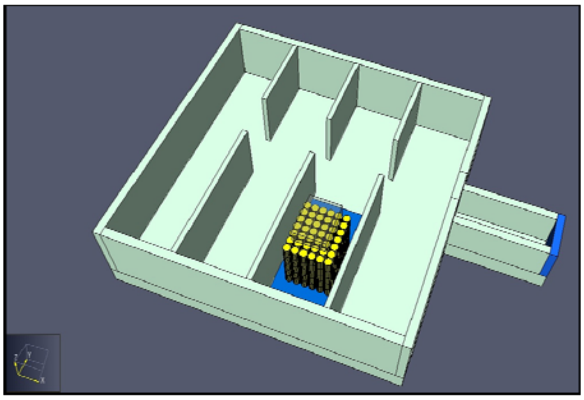

Figure 1: Configuration of the LLW building and of the compartment considered for the fire analysis

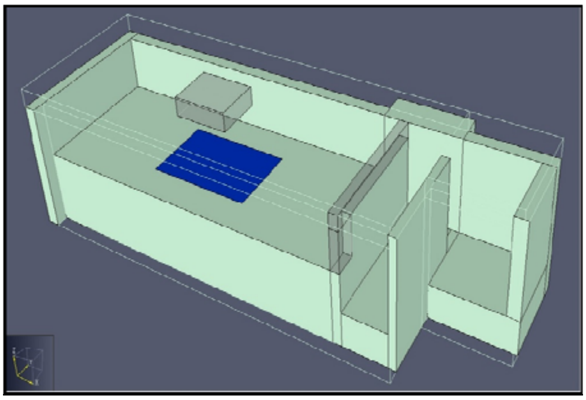

Figure 2: Configuration of the ILW building and the blue area considered for the fire analysis.

The key questions here are the impacts of the kerosene fire and the potential damage to the LLW and ILW waste barrels that could lead to a bitumen fire and consequent release of the radioactive materials embedded in the bitumen.

The evaluations of the mechanical and thermal impacts of a MAC on the ILW and LLW buildings and their radiological consequences have been performed in two stages. First a detailed, realistic structural analysis of the impact of a MAC on the ILW building was performed providing best estimate analysis of the hole size and shape, debris amount, kerosene mass entering the building, and the resultant speeds of aircraft and debris. This study is presented in the Part I of the paper. The results of these analyses provided the input for detailed fire analysis based on a Computational Fluid Dynamics (CFD) methodology, which are discussed in the current Part II.

These questions were addressed by conducting simulations of the kerosene fires that could be produced in the LLW and ILW buildings from kerosene entering the buildings during the MAC. Two reference cases for the LLW and ILW building fires, respectively, were established as limiting conservative cases and additional 17 cases were defined to study parametrically the effects of variables such as roof hole size and mass of kerosene as well as the various possible geometric configurations of the potentially following bitumen fires.

SCOPE OF THE WORK

The scope of the work was set such that to gain a deeper insight into the fire mechanism involved in the LLW and ILW building fire events. This includes:

- CFD simulations of the reference scenarios for the LLW and ILW building fires with the reference kerosene mass and hole size with realistic assumptions on the geometric configuration of the combustible materials in the buildings.
- Parametric CFD sensitivity studies for the amount of kerosene available for burning using a reference impact hole.
- Parametric CFD sensitivity studies for the hole size present in the roofs.
- CFD simulations of the reference scenario of the LLW building with alternative conservative geometric configurations of the combustible materials.

The goal is to provide the information on fire duration, maximum temperatures reached, and the expected number of barrels that may be damaged leading potentially to radiological releases.

METHODOLOGY

The fire analysis starts with the 3D geometry generation step, followed by a mesh analysis. An optimal mesh level was sought using meshing studies on a significant part of the geometry of the LLW building and combustible materials. Selection of the mesh size was performed not only on the basis of the mesh analysis study, but also considering the so called 'fire characteristic size', which is an indicator for optimal mesh size. Three level of meshes were analysed: coarse ($\Delta x = \Delta y = 0.20$ m, $\Delta z = 0.20$ m), medium ($\Delta x = \Delta y = 0.10$ m, $\Delta z = 0.10$ m), and fine ($\Delta x = \Delta y = 0.05$ m, $\Delta z = 0.10$ m). The fine level mesh was used for all the full-geometry CFD simulations of the reference cases and parametric studies, involving 1'824'580 cells in the LLW building.

Before performing the CFD simulations, the geometrical configuration and the boundaries of the simulation volume were defined and the combustible materials (kerosene and bitumen) and the locations where the fire would develop or can extend to, have been introduced in the models. The elements initiating the fire, the state of the openings in the buildings, the building ventilation conditions, were set as well as the pressure or velocity boundary conditions (including leaks at boundaries). To reduce the simulation times, the buildings were subdivided into sub-blocks with similar number of meshes. In the regions where combustible materials were present, fine mesh was used, while in the other regions of the building coarser mesh was considered to be reasonably good enough for fire simulations in large empty volumes.

Finally, examining the computed heat releases, the temperature distributions and the thermal properties of the SS barrels and other materials present in the buildings the consequences of the fire were established.

Fire Model for LLW Building

If the waste barrels reach a sufficiently high temperature, or if they have been damaged by the MAC and the bitumen has been exposed to flames or high temperature gases, a bitumen fire could follow the kerosene fire. Three bitumen geometric configurations have been chosen for the fire-exposed bitumen from the upper two layers of barrels located in the compartment impacted by MAC, which are assumed to be severely damaged by aircraft and or debris:

- **Cylindrical geometry —** Hypothesizing in an unrealistic, extremely conservative way that the skin of SS barrels has been completely removed from around the solid bitumen volume that it contained, the surface of the bitumen contained in the upper two layers of barrels is then exposed to the high temperature gases from the kerosene fire and can be ignited and burn.
- **Lower box geometry —** The bitumen of the two upper layers of barrels, after a long heating time would melt, escape from the barrels, and flow down in the intra-barrel spaces and get solidified there, forming an ideal box. This bitumen can burn on the external surfaces of the box exposed to the high-temperature Kerosene fire gases.
- **Flat geometry —** The bitumen of the two upper layers of barrels would melt and flow down fast and form a flat layer on the floor of the compartment. This bitumen would burn at its upper surface on the floor of the compartment, located below the kerosene layer due to the difference in density between kerosene and bitumen. In this case, schematically, the bitumen fire is initiated only when the fire of kerosene layer fire ends.

Moreover, it is assumed that other compartments of the LLW building are empty, the doors of the LLW and ILW buildings are closed by default, there is no air leakage into the building from doors, the plant is under station black out conditions, therefore the ventilation and the sprinkler systems are not available.

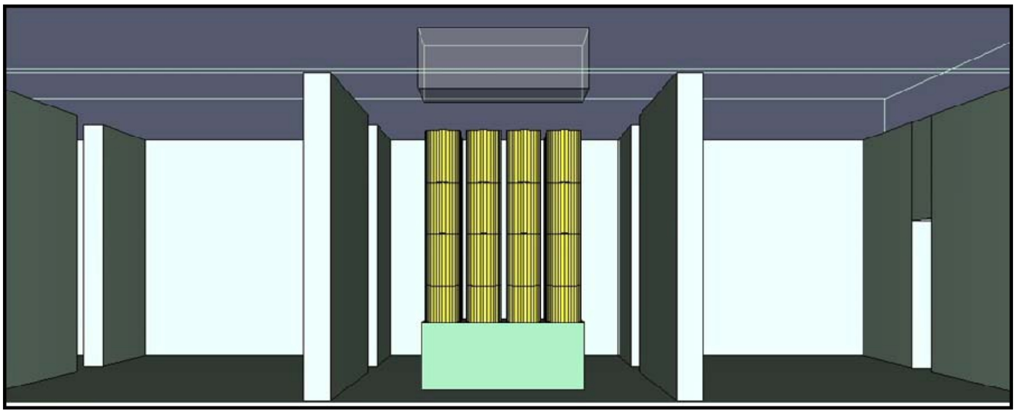

Figure 3: Geometry used for the Box Bitumen fire model cases

In all cases, a bitumen fire can be initiated only when the compartment temperature is above the burning temperature of bitumen (294°C) and only if the oxygen volume fraction is at the level at which bitumen can burn (controlled by stoichiometric reactions), and that the bitumen vapour volume fraction in the air close to the bitumen surface is between the lower and upper limits of flammability of bitumen.

Fire Model for ILW Building

The earlier realistic MAC impact analysis has produced a hole size of about 8 m^2, with the military airplane remaining stuck in the hole. This means that the effective open hole size could be considered to be smaller; this aspect is examined via the parametric test cases.

The MAC propels a mass of kerosene and debris from the roof to the ILW hall floor. It appears that the direct exposure of the SS barrels located inside the wells in the thick concrete slab below the hall floor, to the debris from the MAC and to the following high-temperature combustion gases from the kerosene fire can be realistically excluded. The wells have thick covers protecting them. Therefore, it was assumed that the 800 kg of kerosene entering the building would spread only in a limited area of 24 m^2, as the floor of the ILW hall is not flat due to the concave covers of the wells that can collect liquid.

In light of the discussion above, a realistic but still conservative geometric configuration for the kerosene fire would be a kerosene pool of about 4 cm depth on the floor without any debris layer.

Software

The CFD code known as Fire Dynamics Simulator (FDS, 2015), developed by the National Institute of Standards and Technology (NIST, USA) and VTT Technical Research Centre of Finland, was used for the fire simulations. FDS is a versatile software aimed at solving practical fire protection engineering problems and also providing a tool for fundamental fire dynamics and combustion studies. FDS models can predict smoke, temperature, carbon monoxide, and other substance concentrations during fires. It has been used to address fire consequences for the safety analysis of nuclear power plants (2007, 2006).

Input decks for the FDS are generated with PyroSim Software. PyroSim (2016) is a graphical user interface for the FDS, which allows easily to include a building CAD design and all necessary user inputs in the model, and post process results.

The verification and validation evaluations showed that the new models, features and improvements produce the expected results within the acceptability range provided by the authors and benchmarks.

HIGHLIGHTS OF THE CFD FIRE ANALYSIS RESULTS

This Section focuses on the analysis of the results of the two main reference scenarios: the first is related to the LLW building (with a closed door), case T1, and the second is the reference case for the ILW building, case T2. The parametric studies' results will not be presented in this papers.

LLW Building Reference Scenario - Case T1

A small fraction of the kerosene surface (the blue area in Figure 1) is ignited manually to start the fire and to perform the simulations. The summary of important, characteristic fire results is provided in Table 1. A comparison between FDS simulation duration and theoretical duration (evaluated by dividing the total mass by the product of the burning area and the reference mass loss rate, 0.037 kg/m2/s) showed that the simulation of the fire had lasted longer than the theoretical fire duration. That is mainly due to the fact that the simulations are oxygen controlled. The availability of oxygen depends on natural ventilation, the oxygen concentration, and burning reaction types and rates.

Table 1: Case T1 – Summary of results

Mass of burned Kerosene [kg]	Fire duration [m:s]		Released Energy [MJ]		Temperature [°C]
	Simulation	Theoretical	Simulation	Theoretical	Max
187.16	13:27	08:03	4.909	8.048	859

The ideal, complete combustion of the Kerosene delivers a higher energy release (theoretical value) than the FDS results. The difference is linked to the reactions involved in the FDS fire simulations and the resulting combustion products (CO_2, CO, H_2O, Soot …). The history of oxygen consumption and that of the important combustion product generation are presented in Figure 4. The corresponding heat release rate versus time is shown in Figure 5. As the heat release rate increases, the oxygen concentration rapidly decreases. This trend is inverted at 102 s when the fire intensity diminishes drastically. The oxygen concentration starts recovering slowly, while the heat release rate is reduced very fast at about 200 s and then slowly goes to zero, reaching zero at 807 s. Figure 4 shows also the fast CO_2 build up between 0 and 200 s. The drastic reduction of oxygen concentration and fast CO_2 build up are the main two reasons for the heat release reduction and fire suppression at 807 s.

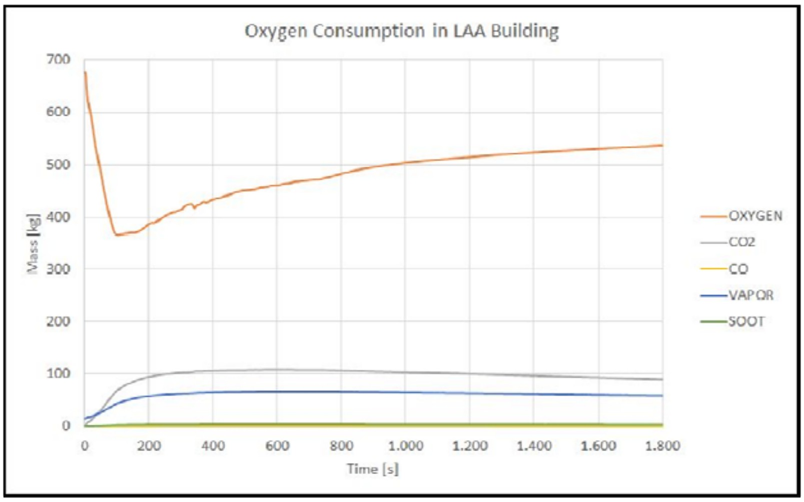

Figure 4 Case T1 - Oxygen consumption and combustion product build-up

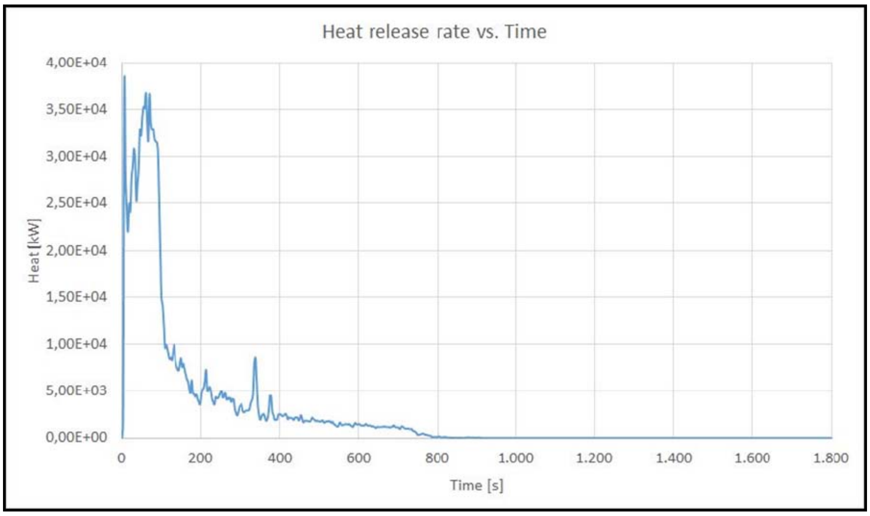

Figure 5 Case T1 - Heat release rate versus time

Temperature distributions at 33 s after fire initiation and for different views are presented in Figure 6, Figure 8 and Figure 10. Similarly, gas speed distributions at 33 s after fire initiation and for different views are presented in Figure 7, Figure 9 and Figure 11.

The figures clearly show the oxygen controlled nature of the Kerosene fire in the LLW building. As it can be seen, the air of the lower levels is sucked from other compartments and feeds the fire in compartment 6 (the compartment containing SS barrels). The combustion gases move towards the higher region of the building, increasing the temperature at the upper regions of the LLW building compartments. The high temperature regions in the fire compartment are, however, those closer to the floor. The combustion gas velocity distributions show a different behaviour, these are lower in other compartments and they increase as one moves towards the fire compartment. The combustion gas velocity increases fast in that compartment and reaches its maximum level in the upper regions and through the roof hole.

In conclusion, the high-temperature and high-speed combustion gas flowing out through the hole on the roof prohibits fresh air to flow in before ~180 s. The partial Oxygen recovery, after ~180 s will not be sufficient to sustain the Kerosene fire, due to the high concentration of CO_2, H_2O and Soot. The fire is finally suppressed at 807 s.

ILW Building Reference Scenario - Case T2

The CAD layout of the ILW building is shown in Figure 2. The barrels configuration and assumptions were discussed in the section “Fire Model for ILW Building”. As stated earlier, a direct exposure of the SS barrels to high temperature combustion gases can be realistically excluded. The summary of important, characteristic fire results is provided in Table 2.

Table 2: Case T2 - Summary of results

Mass of burned Kerosene [kg]	Fire duration [min:s]		Released Energy [MJ]		Temperature [°C]
	Simulation	Theoretical	Simulation	Theoretical	Max
438.6	30:00	15:01	17.06	18.86	946

Figure 12 and Figure 13 show the temperature distribution in the ILW building at 180 s and at Y = 4.4 m and Z = 4 m respectively. The fire dynamics of the ILW building exhibit very oscillatory behaviour. The fire evolution has a cycle of four phases, which duration depends highly on the dynamics of the fire:

1. Burning kerosene and generation of high temperature combustion gases.
2. Raising hot gas due to buoyancy effect and getting out of the roof hole.
3. Heat release and consequent air temperature reductions due to lack of fresh air feeding the fire.
4. Inflow of cold air and increase of oxygen level.

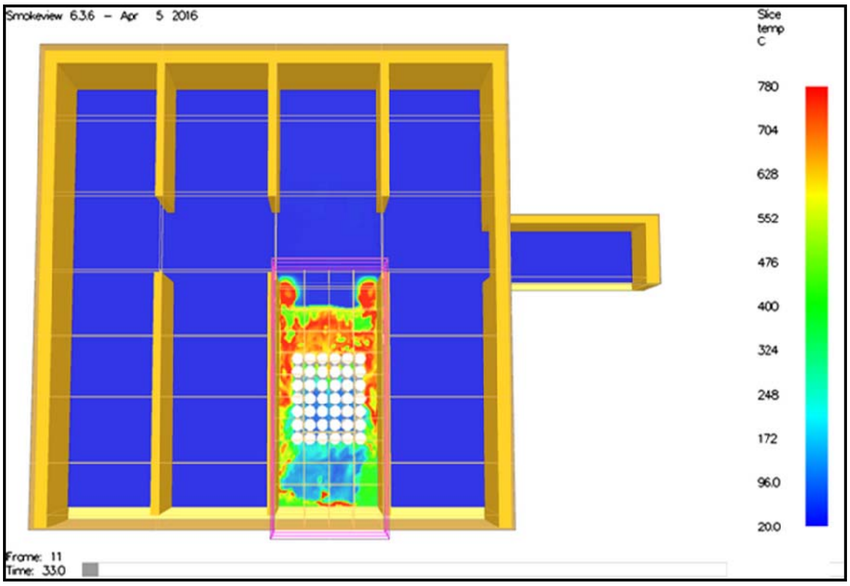

Figure 6: Case T1 – temperature distribution at Z = 0.2 m and at 33 s

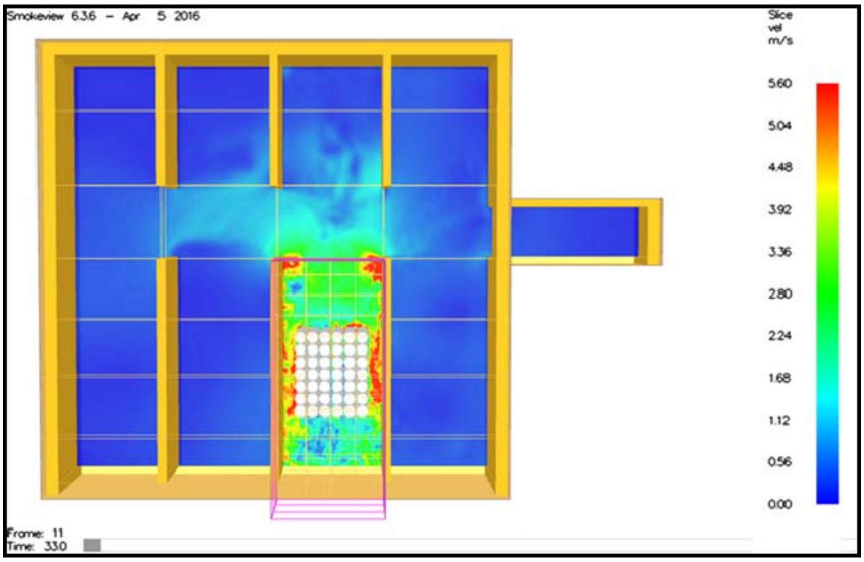

Figure 7: Case T1 – gas velocity distribution at Z = 0.2 m and at 33 s

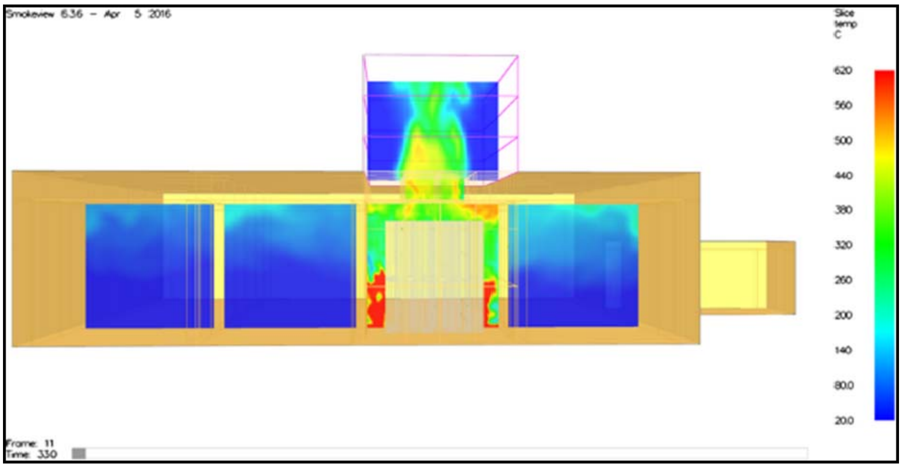

Figure 8: Case T1 – temperature distribution in the vertical XZ plane, at Y = 6.05 m at 33 s

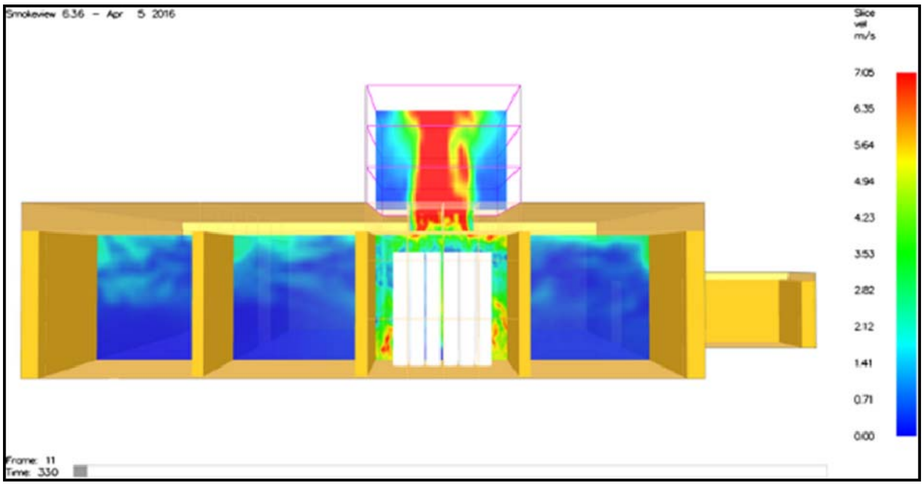

Figure 9: Case T1 – gas velocity distribution in the vertical XZ plane, at Y = 6.05 m at 33 s

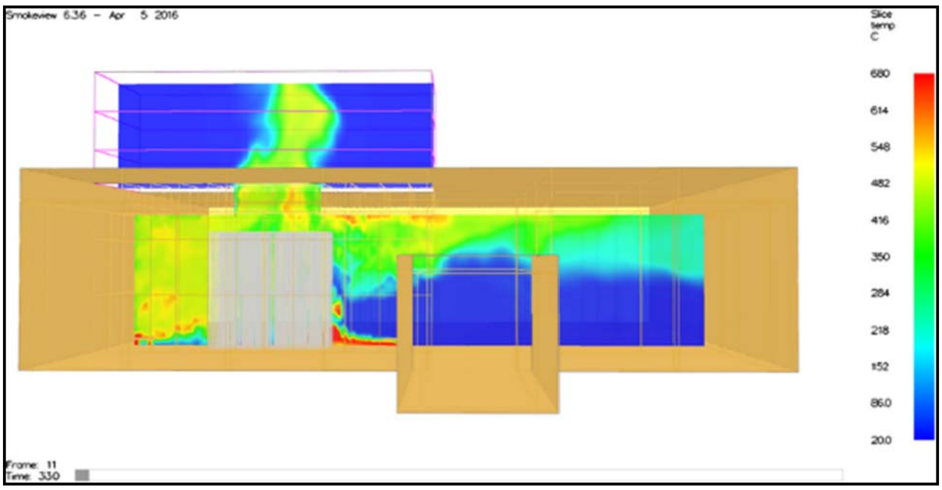

Figure 10: Case T1 – temperature distribution in the vertical YZ plane, at X = 14.3 m at 33 s

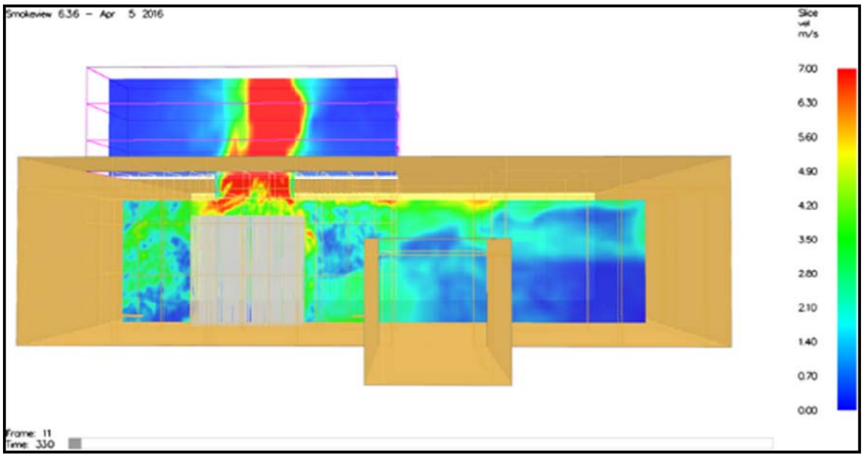

Figure 11: Case T1 – gas velocity distribution in the vertical YZ plane, at X = 14.3 m at 33 s

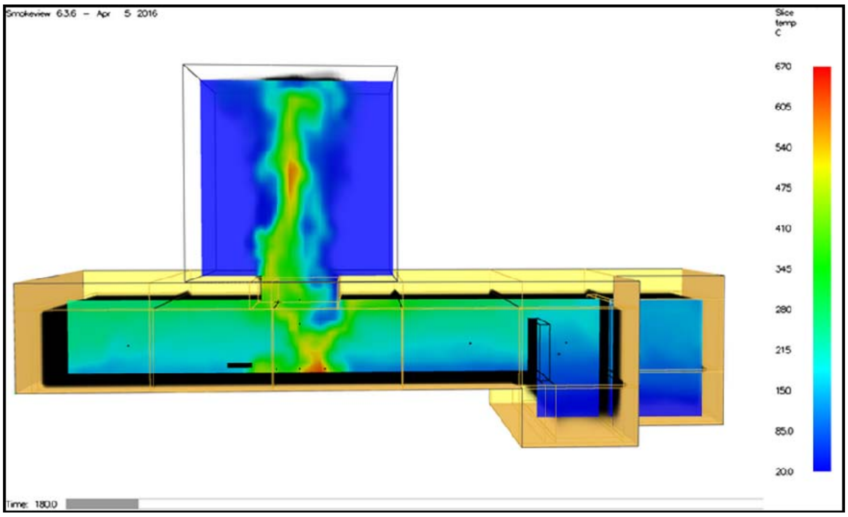

Figure 12: Case T2 temperature distribution at Y = 4.4 m, at 180 s

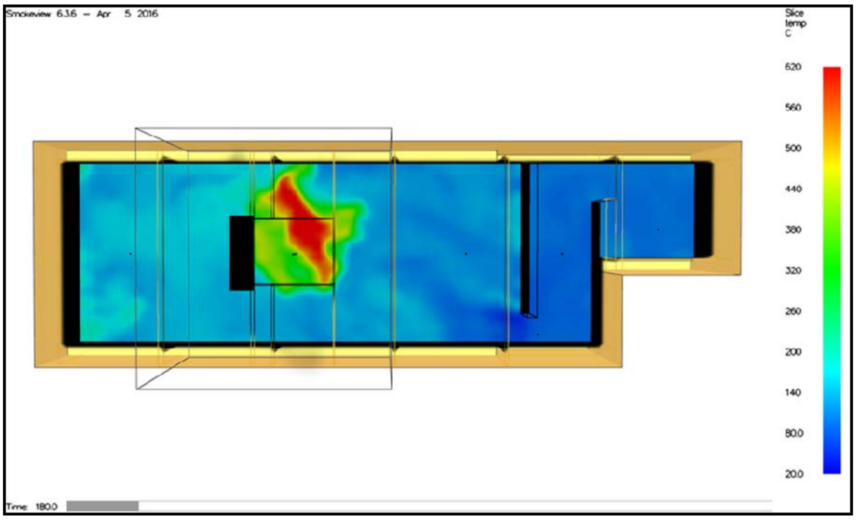

Figure 13: Case T2 - temperature distribution at Z = 4 m, at 180 s

CONCLUSIONS

Fire scenarios and parametric sensitivity cases have been defined for the LLW and ILW buildings, for which a set of realistic and to some extent conservative assumptions have been made. The results of the CFD fire analyses brought insights into the fire expansion and consequences as well as potential consequences on the waste barrels' integrity. Highlights of the analyses are:

- Fire dynamics depend on the stoichiometry of the reactions of combustible materials, volume fractions of Oxygen and the presence of combustion products (especially CO_2, H_2O, and soot), air ventilation, chimney effects, open and close physical boundaries (in particular the size of the hole created on the roof by the MAC), and of course on the amount of Kerosene fuel and the assumed kerosene pool depth.
- Fire simulations in the compartment of the LLW building, indicated fire extinction after some minutes. Moreover, the conditions (especially Oxygen and CO_2 concentrations) prevailing in the LLW building compartment after the Kerosene fire do not allow ignition of the bitumen.
- Fire duration has a rather weak dependency on the initial kerosene mass entering into the buildings; a lower initial fuel mass caused a higher portion of the kerosene to burn. Fire duration in the ILW building was longer than the firefighters' intervention time. In 30 minutes only half of the reference Kerosene mass was consumed, similar burned masses found for other cases with higher initial masses.
- Roof hole size instead is a parameter that strongly affects fuel consumption, high temperature reached and fire duration as it affects strongly the availability of oxygen in the buildings. Fires in both the LLW and the ILW buildings are oxygen controlled, therefore generally larger hole sizes would increase fire duration. In the LLW building, the combined effects of large hole and large kerosene mass led to a fire which had a shorter duration than the fire with the same hole size but lower kerosene initial mass.
- Fire dynamics showed strong oscillatory behavior, the waste barrels being impacted by high temperature peaks followed by low-temperature heating periods.
- The short duration of the high-temperature peaks and the average fire temperatures do no suggest damage to the barrels.
- Barrels in the compartment of the LLW building were exposed to high temperature peaks followed by low temperature periods where the temperatures were typically below the burning point of bitumen.
- In the event of fire in the ILW building, the direct exposure of the SS barrels located inside the wells (in the thick slab below the hall floor) to high-temperature combustion gases can be realistically excluded. Any small fire from kerosene leaking into the wells would be quickly suppressed by lack of oxygen.

The CFD simulations of fire suggest that the release of radioactive materials is not expected and in some cases can be totally excluded.

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