INTRODUCTION

SFPE 11th Case Study had several case study options proposed and team Finland chose option 2 which was a case study for production and storage building. The task defined main objectives for study and also gave guidelines for building and purpose of use. The goal set by design team was to study different performance based fire engineering methods for production and storage facility. A separate all building covering performance-based strategy was not formed and team concentrated on various individual studies that involved activities inside the building.

Document archive

High bay storage area was used for document archive as described in assignment. In this type of spaces one key feature is to safeguard stored materials alongside normal fire and life safety objectives. Design team decided to install Oxygen Reduction System into archive to tackle all these aspects. The goal in archive was to study how performance-based methods could be applied to Oxygen Reduction System.

Car part storage

In car part storage design team studied two different problems. First, two different type of non-performance-based smoke extraction methods were analyzed with performance-based methods to find the pros and cons of the methods. Second problem was to study with performance-based methods would it be possible to store small amounts of flammable liquids with certain additional measures in storage with extinguishing system not compliant with flammable liquid storing. Another aspect was to study are performance-based methods suitable for this type of study.

Furniture production

In furniture production facility a study for load bearing steel structures was performed. One aspect of study was to determine whether separate fire protection is needed for steel structures or could steel structures be unprotected. Another aspect was to study sprinkler system’s influence to performance-based design

Other studies

Task that was not presented in the assignment was to study with radiative heat calculations how storage for flammable liquids can be placed to site. Also the safeguard of firefighters and environmental safety was studied. A site plan for operational firefighting was formed and extinguishing and waste water study was made.
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1 BUILDING DESCRIPTION

Building description was given in the assignment. Building is 180 m x 100 m and it is divided into three tenants with each having a footprint of 6 000 m$^2$. Floor to ceiling height was set to 9 m but after tenant demands a roof structure formed out of triangular steel structure was placed at 12 height from the floor. Layouts of the three different levels are shown in figures 1-3 below. In figure 1 is also shown the site plan with diesel storage and neighbouring building.

Figure 1. 1st level layout.
Figure 2. 2nd level layout.

Figure 3. 3rd level layout.
Fire technical specifications

Each tenant’s space is divided into own fire compartments which creates compartmentation by area into three larger fire compartments. Fire compartmentation between each tenants are firewalls so they limit possible fire to one tenants space only. Within each tenant separate types of uses have been separated with fire compartmentation but these are of normal structures.

The whole building is equipped with automated fire extinguishing system and with automated fire detection and alarm systems. However, it is noted that in archive area extinguishing system has been replaced with Oxygen Reduction system.

Evacuation safety is secured with 4 exit staircases and numerous exit doors at ground level.

Smoke extraction is discussed separately in following chapters.
2 DOCUMENT ARCHIVE

2.1 General description of the document archive

Document archive is located in the end of the building and is separated from car part storage with a firewall. Archive has a footprint of 6000 m$^2$, a one third of the whole building. The archive room itself occupies 5100 m$^2$ of the footprint and has three levels, having a total floor area of 15 300 m$^2$. Rest of the space is reserved for supporting functions each forming an own fire compartment; the 1$^{\text{st}}$ floor is occupied by docking, 2$^{\text{nd}}$ by office and 3$^{\text{rd}}$ by mechanical room all having the floor area of 900 m$^2$. Above all is an attic covering the whole archive (6000 m$^2$) but separated in five fire compartments, each of 1200 m$^2$.

In initial design all three levels of archive are connected with internal stairways and belong to same fire compartment. However, the analysis showed this configuration to be problematic in many ways and supported separating the floors from each other.

2.2 Fire and life safety principles in archive

Supporting functions meet the requirements of typical perspective codes; each function forms an own fire compartment, each space has at least two separate exits, fire compartment size is quite small and the structures can be made of fire-rated materials and have the sufficient fire resistance. All the spaces are also protected with sprinkler and fire detection system and smoke ventilation can be arranged with ordinary doors and windows. As in addition the activities performed in supporting spaces doesn’t cause any special threats to fire or life safety, are the areas of supporting functions excluded from further analysis.

Attic above the archive is divided in fire compartments having the size of 1200 m$^2$. However typical perspective codes would also require some lighter partition into smaller
compartments, which is not possible without compromising the sufficient ventilation of the present roof type. However, as the spaces next and below the attic are separated with fire-rated structures and will have efficient fire suppression or prevention systems, the risk following from large compartment size will be mostly connected to fires originating from the attic itself. As all the structures in the attic can be made of non-combustible materials and the number of ignition sources limited to very few, can risk posed by this scenario be deducted to very low. Based on this very rough risk analysis is the attic excluded from further analysis.

The archive room itself forms an interesting fire safety challenge as the archived documents are very vulnerable not only to fire, heat and combustion products but also to the most common extinguishing agent, water. This excludes sprinkler-based protection methods, as the fire can cause significant damage to documents even before the sprinkler system activates and water from sprinklers extends the damage even further. It is also assumed that archive is in active use and documents delivered, moved and investigated daily, which requires the storage area to be open space without walls and doors obstructing the traffic. In turn, this excludes gas- and aerosol-based suppression systems as the required volume of extinguishing agent would be enormous. Also the passive protection of document shelves would be highly impractical and reduce the storage capacity. Based on these challenges the chosen fire protection method was to prevent the fire from breaking out at all, which was achieved in two ways: by minimizing the number of ignition sources and equipping the archive room with oxygen reduction system. The former was done by placing all the HVAC equipment in the mechanical room and all other tasks but document storage to office floor. This means that no computers, copy machines, coffeemakers etc. are placed in archive room. This is also required due the reduced oxygen concentration; goal is to limit the working time in archive to minimum. The oxygen reduction system itself consist of compressors and nitrogen generators placed in mechanical room, and nitrogen-induction pipeline in archive room. In addition, control system with oxygen sensors is needed to maintain oxygen concentration in desired level. In addition to fire prevention, the reduced oxygen concentration also reduces aging of archived documents and is therefore a natural choice for archive.
Figure 5. System sketch of oxygen reduction system (Picture courtesy: Wagner Group)

2.3 Fire and life safety analysis in archive

As the oxygen reduction systems are designed case-by-case, it was decided to find out if the system could be designed using the widely-used fire simulation program, Fire Dynamics Simulator by NIST. It was recognized that this was far out from the typical range in where FSD is used and for which it is validated for. However, in imaginary case study building the possible uncertainty or errors in results wouldn’t be fatal and the process could give valuable information of FDS capabilities, so this approach was applied despite all the suspicion.

In oxygen reduction system design, it is crucial to measure how the air is moving and changing in protected space. This required the whole archive with adjoining spaces to be modelled as they interact with the archive room by leaks and openable doors. And as the air movement between spaces is driven by pressure differences, the model had to include realistic pressure distribution for all the spaces. Therefore, also HVAC systems, leaks and realistic environment conditions had to be modelled.

The analysis was started by modelling the whole archive (including archive room and adjoining spaces) and part of surrounding outdoor. The firewall between archive and car part storage was assumed to be air tight, and the rest of the building behind the wall was left out from the model. HVAC systems, shafts, openings and leaks were modelled in addition to building geometry and environmental condition both in- and outdoor set. Simulation was then run several times without any nitrogen generation, fire or activity in the building to achieve realistic pressure distribution. When this was obtained and proper parameters for HVAC and leaks found, some activity (like doors opening and closing) was added and model stability tested. Finally, when model was found to perform well enough, the nitrogen generation was modelled and its design started.
2.4 Simulation initial parameters - Document archive

2.4.1 Design scenarios
Following scenarios were investigated:

A – Building not occupied, all normal

All the HVAC systems and nitrogen generators are functioning normally. There is no activity nor people in building. The purpose of the scenario is to define required nitrogen flow to maintain desired oxygen concentration.

Table 1. Timeline of scenario A

<table>
<thead>
<tr>
<th>[s]</th>
<th>[hh:mm:ss]</th>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>Simulation begins</td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>1:06:40</td>
<td>Simulation ends</td>
<td></td>
</tr>
</tbody>
</table>

B – Building occupied, all normal

All the HVAC systems and nitrogen generators are functioning normally. Activity representing normal workday is taking place in the building, which means that doors are being opened and closed following pre-defined sequence. The purpose of the scenario is to define required nitrogen flow to maintain desired oxygen concentration.

Table 2. Timeline of scenario B

<table>
<thead>
<tr>
<th>[s]</th>
<th>[hh:mm:ss]</th>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>Simulation begins</td>
<td>Initialisation period of 400 seconds</td>
</tr>
<tr>
<td>400</td>
<td>0:06:40</td>
<td>Activity begins</td>
<td>Working day, peak hour</td>
</tr>
<tr>
<td>4000</td>
<td>1:06:40</td>
<td>Simulation ends</td>
<td></td>
</tr>
</tbody>
</table>

C – Building occupied, blackout

All the HVAC systems and nitrogen generators are functioning normally in the beginning, but then power is lost and systems shut down. Activity representing normal workday is taking place in the building in the beginning, but after power failure activity decreases and finally people leave the building. The purpose of the scenario is to find out how long the oxygen concentration will remain in acceptable level if the nitrogen generation fails for some reason. It is assumed, that in this case the ventilation in archive room will be stopped and archive evacuated.
Table 3. Timeline of scenario C

<table>
<thead>
<tr>
<th>[s]</th>
<th>[hh:mm:ss]</th>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0:00:00</td>
<td>Simulation begins</td>
<td>Initialisation period of 400 seconds</td>
</tr>
<tr>
<td>400</td>
<td>0:06:40</td>
<td>Blackout, activity begins</td>
<td>Nitrogen generators and mechanical ventilation turned off. Electric doors stay closed. Other working day activity begins.</td>
</tr>
<tr>
<td>460</td>
<td>0:07:40</td>
<td>Evacuation of archive</td>
<td>People move from archive to office and docking. Activity in office and docking continues.</td>
</tr>
<tr>
<td>1800</td>
<td>0:30:00</td>
<td>Evacuation of building</td>
<td>People start to leave the building</td>
</tr>
<tr>
<td>2700</td>
<td>0:45:00</td>
<td>Activity stops</td>
<td>Building unoccupied</td>
</tr>
<tr>
<td>4000</td>
<td>1:06:40</td>
<td>Simulation ends</td>
<td></td>
</tr>
</tbody>
</table>

D – Building occupied, fire

In the beginning all the HVAC systems and nitrogen generators are functioning normally and normal workday activity going on. After a while fire breaks out in the archive room next to the loading door leading to docking, where the local oxygen concentration is higher due the open loading door. When the fire is detected, ventilation in archive room shuts down, nitrogen generators starts running continuously and activity near the fire increases for the while until the archive room (and finally whole building) is being evacuated. The purpose of this scenario is to find out how quickly oxygen concentration can be reduced in an emergency, and also find out how quickly people have to leave archive room if this is done. One goal was also to study how FDS will model the fire in the environment with reduced oxygen concentration.

Table 4. Timeline of scenario D

<table>
<thead>
<tr>
<th>[s]</th>
<th>[hh:mm:ss]</th>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0:00:00</td>
<td>Simulation begins</td>
<td>Initialisation period of 400 seconds</td>
</tr>
<tr>
<td>400</td>
<td>0:06:40</td>
<td>Activity begins</td>
<td>Working day activity begins</td>
</tr>
<tr>
<td>430</td>
<td>0:07:10</td>
<td>Fire breaks out</td>
<td>Ignition near the Door 000-sisä-käyntiovi4</td>
</tr>
<tr>
<td>460</td>
<td>0:07:40</td>
<td>Fire alarm and evacuation of archive</td>
<td>Archive mechanical ventilation turned off and nitrogen generators on. Electric doors stay closed. People move from archive to office and docking. Activity in office and docking continues.</td>
</tr>
<tr>
<td>1800</td>
<td>0:30:00</td>
<td>Evacuation of building</td>
<td>People start to leave the building</td>
</tr>
<tr>
<td>2700</td>
<td>0:45:00</td>
<td>Activity stops</td>
<td>Building unoccupied</td>
</tr>
<tr>
<td>4000</td>
<td>1:06:40</td>
<td>Simulation ends</td>
<td></td>
</tr>
</tbody>
</table>

As the outside air temperature has a great effect to pressure distribution inside the building, the following options for outside air temperature were used:

1 – Summer

Outside air temperature 10 °C (representing Finnish summer)

2 – Winter

Outside air temperature -20 °C (representing Finnish winter)

First simulations were run both with winter and summer conditions and it was found out that in winter the higher pressure differences led to higher flow volumes through the leakages,
which increased the required nitrogen flow. Therefore, winter was considered as more challenging environment and rest of the simulations were run with winter conditions only. So finally the following scenarios were simulated:

- A2 – Building not occupied, all normal, winter
- B1 – Building occupied, all normal, summer
- B2 – Building occupied, all normal, winter
- C2 – Building occupied, blackout, winter
- D2 – Building occupied, fire, winter

2.4.2 Design fire

Fire was modelled in one scenario (D2) only, in which purpose was mainly to test how FDS will model fire in reduced oxygen concentration. Fire was placed in archive room near the loading door leading to docking and was set to ignite in same time when the door is open and oxygen concentration therefore higher than usually.

![Figure 6. Fire location in scenario D2](image)

The fire was modelled using simple pyrolysis model with pre-set heat release rate, e.g. a burner which ejects gaseous fuel with pre-defined rate. Fire reaction was chosen to describe polyurethane with properties from SFPE Handbook of Fire Protection Engineering (CO yield
of 0.042 and soot yield of 0.05) and released energy defined according to oxygen consumed (1.31E4 kJ/kg) with the radiative loss of 35%. For the suppression the default FDS fire suppression model with critical flame temperature of 1327.0 °C was used. Hear release rate was modelled to grow linearly from 0 to 1 MW in 160 seconds and to be constant from that on. However, as the oxygen concentration in archive room decreases during fire due nitrogen injection, also HRR begin to decrease at some point of the simulation.

2.4.3 **Used software and parameters**

Simulations were made by FDS version 6.3.2 The cell size was 40 x 40 x 40 cm in all computational domain.

The simulation time of one fire scenario was 4000 seconds, which includes the initialization time of 400 seconds in the beginning of simulation to stabilize pressure distribution. The final simulation run of scenario B1 crashed after 3230 seconds, but the results were find to be adequate and the case was not run again.

2.4.4 **Structures and leaks**

All the structures and surfaces were modelled with realistic material properties, as their temperature may have a significant impact on pressure distribution in building. In this case the temperature difference between in- and outdoor was as high as 40 °C, which means that heat transfer through structures can be quite intensive and thus cannot been ignored. Geometry of the structures was fitted to 40 x 40 x 40 cm computational mesh, but the realistic material thicknesses given in material properties.

Each closed room was defined as a pressure zone to allow FDS calculate stack effect correctly. Leaks between rooms were modelled in two ways. Bulk leakage through the walls (distributed evenly in whole wall surface) was modelled using a pressure zone leak approach of FDS and using typical air tightness values of each structure type. As the typical structures of building type in question (sandwich panels and concrete slabs) are quite tight, the pressure zone leakage was only a minor part of the total leakage. Major part were crack-type leakages related to doors and other openings in structures, which were modelled using local leakage approach of FDS by estimating a real leakage area in each door or opening.

2.4.5 **HVAC**

Ventilation system was modelled with simple supply and exhaust vents with pre-defined volume flow, as environmental conditions during each simulation were constant and therefore the ventilation system was assumed to find and maintain equilibrium. Ventilation rates were calculated according to Finnish HVAC codes except in the archive room, where the typical ventilation system would increase the required nitrogen generation capacity considerably and therefore only a minimum ventilation was used.
Table 5. Ventilation air flows.

<table>
<thead>
<tr>
<th>Room</th>
<th>Ventilation rate</th>
<th>Total area</th>
<th>Supply air flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Archive</td>
<td>0.25 l/h air change</td>
<td>5120 m²/floor</td>
<td>470 dm³/s/floor</td>
</tr>
<tr>
<td>Office</td>
<td>1.50 dm³/s/m²</td>
<td>820 m²</td>
<td>1230 dm³/s</td>
</tr>
<tr>
<td>Docking</td>
<td>7.00 dm³/s/m²</td>
<td>820 m²</td>
<td>5740 dm³/s</td>
</tr>
<tr>
<td>Mech. room</td>
<td>0.35 dm³/s/m²</td>
<td>820 m²</td>
<td>287 dm³/s</td>
</tr>
<tr>
<td>Attic</td>
<td>0.35 dm³/s/m²</td>
<td>1200 m²/compartment</td>
<td>420 dm³/s/comp.</td>
</tr>
<tr>
<td>Stairwell</td>
<td>0.5 l/h air change</td>
<td></td>
<td>40 dm³/s</td>
</tr>
<tr>
<td>Elevator shaft</td>
<td>4.0 dm³/s/person</td>
<td></td>
<td>132 dm³/s</td>
</tr>
</tbody>
</table>

In mechanical ventilation the exhaust air flow is usually slightly higher than supply to achieve negative pressure compared to outdoor. Also in rooms with contamination sources negative pressure compared to adjoining rooms is usually desirable. Therefore, in docking exhaust air flow was set to be 10% and in other rooms 2% higher than supply. In archive room supply and exhaust flows were the same, as negative pressure compared to adjoining spaces with higher oxygen concentration was not desirable.

2.4.6 Oxygen reduction system

The oxygen reduction system in archive room was modelled according to information of OxyReduct® fire prevention system provided by Mr Timo Savolainen from Are Oy, the cooperation partner of WAGNER Group GmbH. As the system is designed case-by-case, the information covered only general principles of the system and not the exact design. Therefore, the system was modelled following these general advices and the required nitrogen generation capacity estimated by hand calculations. The goal was that nitrogen generators should not be running more than 30% of time even if the ventilation is on and workday activities taking place in the archive room. Desirable oxygen level was set to 14 - 16 vol-%, which according to manufacturer is commonly used range in applications where people are required to work in protected space.

As the archive room has three levels with only small openings connecting them, each floor was equipped with an independent nitrogen injection system controlled by oxygen sensors located in that floor. In reality system would probably have only one nitrogen generator and nitrogen injected to one floor at a time, but to simplify control logic coding in FDS the injection of nitrogen was allowed to take place in all the levels simultaneously. Several oxygen sensors were placed in each floor to measure average oxygen concentration, and
Nitrogen injection programmed to begin when the average concentration exceeds 15.5 vol-% and to stop when the concentration of 14 vol-% is reached.

Injection of nitrogen was modelled with vents, which had the size equal to one cell (40 x 40 cm). In reality injection nozzles are much smaller, but due FDS limitations this way was the only reasonable one. It was also assumed that following error is small, as the amount and velocity of injected nitrogen per nozzle are small anyway. Nitrogen injection nozzles were placed near the floor and aimed horizontally to ensure proper mixing of nitrogen to air.

Several preliminary simulations were done to find the appropriate flow rate for nitrogen injection, and finally the rate of 1500 dm³/s/floor was chosen.
2.5 Simulation results - Document archive

2.5.1 Pressure distribution
In the following figures are presented air pressure measurements over time in archive. Measurements from shafts are excluded in results.

![Air pressure - scenario A2](image)

**Figure 8.** Air pressure measurements in scenario A2
In scenario A2 (building not occupied, all normal, winter) there is no activity in building and the variation in air pressure is caused solely by nitrogen injection. As the ventilation in the archive is modelled with simple supply an exhaust vents with fixed volume flow, ventilation will not react to pressure changes as it would normally do and the only way for overpressure to discharge is trough leaks. When the nitrogen generators start, the pressure rise in archive room may be over 30 Pa if the generators in all levels are running simultaneously (as they do a while in time 1840 s).

According to measurements if the nitrogen generators are not running, the two lower levels of the archive room have lower pressure than docking and office next to them, meaning that oxygen-rich and possible contaminated air will leak into archive. The leak from docking to archive was measured and was found to be around 500 dm$^3$/s when the generators are not running. Changing this by means of mechanical ventilation could be possible, but would lead to very high pressure differences over the structures in other parts of the building and cause many additional problems. Therefore, the recommendable action would be to close the openings between the archive room floors, which would cut the pressure differences generated by stack effect to one third of the current value.

**Figure 9.** Air flow from docking to archive in scenario A2

In scenario A2 (building not occupied, all normal, winter) there is no activity in building and the variation in air pressure is caused solely by nitrogen injection. As the ventilation in the archive is modelled with simple supply an exhaust vents with fixed volume flow, ventilation will not react to pressure changes as it would normally do and the only way for overpressure to discharge is trough leaks. When the nitrogen generators start, the pressure rise in archive room may be over 30 Pa if the generators in all levels are running simultaneously (as they do a while in time 1840 s).

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In scenario B1 (building occupied, all normal, summer) the activity in building (doors opening and closing) causes small variation in pressure distribution every now and then, but the nitrogen injection is still the dominating aspect. In this scenario in maximum two of third nitrogen generators are running simultaneously, leading to lower pressure rise as in scenario A2. Also the lower temperature difference between in- and outside lowers pressure differences.
Figure 11. Air pressure measurements in scenario B2

In scenario B2 (building occupied, all normal, winter) the pressure measurements are similar to scenario B1, but due to the higher temperature differences also the pressure differences are higher. As this also leads to higher flows through leakages and openings, it was assumed that winter is the most challenging environment what comes to oxygen reduction system and all the remaining simulations were done in winter conditions only.
Figure 12. Air pressure distribution in scenario B2 at time 3500 s.
In scenario C2 (building occupied, blackout, winter) HVAC systems shut down in 400 seconds from the beginning of the simulation and the nitrogen generators are not running at all. From the figure above it can be seen that the ventilation changes the pressure distribution only in office and mechanical room, in which the pressure rises gradually during the blackout. These spaces have quite tight structures and slightly higher exhaust volume than supply. Docking however, even having 10% more exhaust than supply, is not being depressurized by ventilation as the loading doors are quite leaky.
In scenario D2 (Building occupied, fire, winter) pressure in archive room rises strongly as the nitrogen generators in all the floors start when the fire is detected. Also the fire itself rises the pressure by generating hot gases, but this phenomenon deteriorates when the heat begins to transfer into surrounding surfaces. When heat release rate decreases due lack of oxygen, pressure drops even more.

2.5.2 Oxygen concentration in archive room

In the following figures are presented oxygen volume concentration measurements in archive room over simulation time in all scenarios. Scenario B2 is also introduced more in detail to demonstrate oxygen distribution over the space.

**Figure 14.** Air pressure measurements in scenario D2
In scenario A2 (building not occupied, all normal, winter) the doors leading to archive room are kept closed, so oxygen level rises gradually until reaching the value in which nitrogen generators are started. In each floor it takes around 2500 seconds oxygen concentration to rise from 14 to 15.5 vol-%. When generator starts, oxygen level drops back to 14 vol-% in around 850 seconds. (Both times measured in lowest floor where the required amount of nitrogen is highest). This means that nitrogen generator in lowest floor is running around 25% of time, a bit less than the original goal was.

Figure 15. Oxygen concentration measurements in scenario A2

Figure 16. Oxygen concentration measurements in scenario B1
In scenario B1 (building occupied, all normal, summer) opening doors cause peaks to oxygen concentration especially in lower floor, but otherwise measurements are quite close to scenario A2.

Figure 17. Oxygen concentration measurements in scenario B2

Scenario B2 (building occupied, all normal, winter) is similar to B1 except the outside air temperature. It can be seen that in winter the higher leak flows cause the oxygen level to rise faster than in summer, but the difference is smaller with respect to pressure difference between winter and summer. The reason is ventilation, which changes one fourth of archive air volume in an hour regardless of weather and accounts roughly for a half of total required nitrogen injection capacity.

Following figures demonstrates the oxygen level distribution in scenario B2. All the figures are from the lowest archive level +0.00.
Figure 18. Iso-surface of oxygen concentration of 15.5 vol-% in scenario B2. $T = 120$ s, ventilation is running but nitrogen injection is off.

As shown in figure above, the oxygen concentration begins to rise next to the doors leading to docking. Also the oxygen-rich air flow from ventilation supply vents is shown in the picture.
**Figure 19.** Oxygen concentration in scenario B2 2 meter above the floor on lowest level of the archive floor. T = 665 s and nitrogen injection is just about to begin.

In the figure above is shown a flow of oxygen-rich air from docking through the open loading door.
Figure 20. Oxygen concentration in scenario B2 2 meter above the floor on lowest level of the archive floor. $T = 1000$ s and nitrogen injection is going on.
Figure 21. Oxygen concentration in scenario B2 2 meter above the floor on lowest level of the archive floor. $T = 1500 \text{ s}$ and nitrogen injection is just about to end.
Figure 22. Oxygen concentration in scenario B2 2 meter above the floor on lowest level of the archive floor. T = 3500 s and nitrogen injection is off.
In scenario C2 (building occupied, blackout, winter) oxygen concentration rises steadily except in the beginning, where the archive evacuation causes doors to be opened. When the activity in archive ends, oxygen concentration rises around 1.8 percentage points per hour in lowest floor and around 1.2 percentage points per hour in other two floors. The higher rise in the lower floor is due the air leaking from docking to archive, as the highest pressure difference and also most doors are located in lower level.
In scenario C2 (Building occupied, fire, winter) nitrogen generators in all floors starts when the fire is detected (t = 460 s). The initial oxygen concentration is around 15 vol-%, and 14 vol-% reached within 9 minutes from the beginning of nitrogen injection. Respectively 13 vol-% is reached in 16 and 12 vol-% in 24 minutes.

2.5.3 **Fire behaviour in scenario D2**

In scenario D2 (building occupied, fire, winter) the fire broke out at time 430 s and ventilation was turned off and nitrogen injection on 30 seconds later. At the time of the ignition the loading door near the ignition source was open, providing oxygen-rich air for the fire. The door was however closed shortly afterwards and oxygen level gradually decreased due injection of nitrogen. It took however over 30 minutes until the fire begin to weaken, as in FDS fire reaction is not affected by the lack of oxygen until the oxygen concentration drops below 11 - 12 vol-%.

![Figure 25. Heat release rate of fire in scenario D2](image)

It was also noticed that in the end of the simulation HRR increases again. This is probably due external flaming, which happens when hot gases from fire break out from the archive room and find enough oxygen to ignite again.

As the fire burned over 30 minutes at HRR of 1 MW, the smoke from fire spread all over the archive room. As show in the picture below, 5 minutes after the ignition the smoke has spread to all three levels, as one of three openings connecting the floors locates right next to the fire. At same time smoke also begins to spread to docking, as the archive room has greater pressure due ongoing nitrogen injection.
In the end of the simulation smoke has filled not only the archive room, but also docking and attic. Even in office and mechanical room the amount of smoke is significant.
2.6 Analysis of the results - Document archive

FDS was found to be capable of estimating the pressure distribution in the building, when environmental conditions, HVAC-systems and leakages were modelled in addition to building geometry. However, it was not possible to estimate how accurate the results were as the building was imaginary and no real pressure data was available. It was also noticed that converting a measured leakage values (typically given as a leakage rate) to FDS input (defined as leakage area) is not very convenient and includes potentially a major source of error. Also modelling structures and their thermal properties in FDS requires a lot of simplification and may therefore reduce the accuracy of results.

The created building model was used to design the oxygen reduction system of archive room. With used parameters the nitrogen generation capacity of 1500 dm3/s/floor was found to be sufficient to maintain desired oxygen level (14 – 15.5 vol-%), generators running around 25% of time in most challenging conditions. If the archive room did not have to had ventilation, the required capacity would drop to 1000 dm3/s/floor. It was noticed that a great number of nitrogen injection nozzles are required to spread nitrogen evenly into the room, and still the oxygen level would vary quite a lot depending a location in the room.

It was found that if the nitrogen generators fail, by stopping the activity in the archive room and shutting down the ventilation, the rise of the oxygen concentration can be limited to approximately 1,8 percentage points per hour in lowest floor and approximately 1,2 percentage points per hour in other two floors (in most challenging environmental conditions). These values can be used to estimate, if for instance a backup power is needed for the nitrogen generators.

In one scenario it was also tested how a fire will behave in oxygen-reduced atmosphere. The initial oxygen level (15.5 vol-%) was much higher than the value in which FDS was found to begin limit burning, whereupon the fire burned over 30 minutes freely despite the continuous nitrogen injection. In real fire it depends totally on the burning material, if the fire will ignite at all and in which oxygen level it will be extinguished, so the result is just a demonstration of one possible scenario. However, it seems that at least with default values FDS gives quite conservative results what comes to suppressing fire by reducing oxygen level, as most materials should ignite and burn very poorly in simulated conditions. It was not tested was this related only to used critical flame temperature value or also to FDS extinguishing model.

More useful result from the fire scenario was that if the fire happens to break out, the designed oxygen reduction system is not capable of reduce the oxygen concentration quickly enough to put out the fire in reasonable time. A positive side of this is that the system will reduce the oxygen level so slowly, that there is a plenty of time to evacuate the archive until the oxygen level drops too low for humans.

During the simulations it was noticed that connecting archive floors with open stairways was not a good solution, as this increased the magnitude of stack effect and unwanted leakage
trought the structures. Also in a fire smoke can spread quickly to all floors increasing damage to archived documents. Based on the simulation it is suggested to separate archive floors from each another, which can be done by enclosing the stairwells between the floors.
3 CAR PART STORAGE

This report covers car part storage smoke ventilations studies. Purpose of this study is to compare two different smoke ventilation design method. In Finnish Building Code is defined minimum level of smoke ventilation. However, a choice of the used method is the discretion of the designer. That’s why it is interesting and helpful to compare different design methods and to find their pros and cons.

Method “E2” is based on the regulations and instructions given in Finnish Building Code (SRMK) part E2/2005. The aim of this design method in sprinklered building is to design smoke vents responding as 0,5% of floor area.

Method “RIL-3” is Finnish Association of Civil Engineers (RIL) publication of Smoke Ventilation in the Building – Design, achievement and maintenance. It is based on European standards and technical reports of smoke ventilation. It is alternative approach to design smoke ventilation.

Figure 28. Simulation domain. Car part storage in the middle.
3.1 The design for fire and smoke ventilation in car part storage

3.1.1 Design fire

The design fire was chosen according to RIL 232-2012 specification standard heat release rate. Design fire according RIL 232-20012 was defined taking into account:
- Type of building
- Area of the fire
- Level of fire protection (sprinklered)

Used fire growth rate is $t^2$ fast ($\alpha = 0.047$) up to 4 680 kW. Sprinkler system effect was not taken into account. The design fire was modelled as a forced heat release rate. Design fire consists of seven different burning surfaces. Size of the fire surfaces are 0.4 x 0.4 meters up to 1.2 x 1.2. The fire reaction was polypropylene, with soot yield of 5.0% (INSTA 950 5.2.1.3 + National Annex A Finland).

Figure 29. Car part storage heat release rate in smoke ventilation case E2.

Figure 30. Car part storage heat release rate in smoke ventilation case RIL-3.
3.1.2 **Design fire location**
This design was defined in corner of the compartment. The space is designed to work as premises for stocking car parts for repairing cars. The aim of the fire location is to see what are the differences of smoke spread in these two cases.

3.1.3 **Used software and parameters**
Simulations were made with FDS version 6.1.2 The cell size was 20 cm in the fire zone and 40 cm elsewhere inside the fire compartment.

The simulation time of one fire scenario was 20 minutes. It can be assumed that in this time the major differences in smoke spread is revealed

3.1.4 **Smoke ventilation**
Purpose of this study is to compare two different smoke ventilation design method. Compartment is divided into five different smoke ventilation sections. Each of them are 60m x 20m and those are separated by 5,2m high smoke barriers (note pitched roof).

**Method “E2”** is based on the regulations and instructions given in Finnish Building Code (SRMK) part E2/2005. The aim of this design method in sprinklered building is to design smoke vents responding as 0,5% of floor area. Area of the smoke vents in one smoke ventilation section is 0,5% x 1200 m² = 6 m² (the geometric surface area). Smoke ventilation was carried out by 0,8m x 1,6m vents/hatches.

**Method “RIL-3”** is based on European standards and technical reports of smoke ventilation. It is an alternative approach to design smoke ventilation. The aim of this design method is to design smoke vents in each smoke section responding the total smoke mass flow rate. Under these circumstances the smoke spread should be limited in to fire section.

Area of the smoke vents in one smoke ventilation section is 33 m² (the geometric surface area). Smoke vents was carried out by 1,2m x 1,2m vents/hatches. Smoke vents area was defined taking into account:

- Heat release rate
- Area of smoke section
- Height of smoke barriers
- Height of compartment

In both cases the smoke ventilation was defined to start automatically when in the roof placed smoke detectors respond. Cause of smoke ventilation start automatically was to compare the smoke layer spreading and effectiveness of smoke ventilation.

Smoke detectors were added to the roof near by design fire according to Finnish Fire Alarm Regulations. Smoke detectors were modeled using Pyrosim software smoke detector model Cleary Photoelectric P1, and value of obscuration threshold was 27,66 %/m. Smoke ventilation activates in case E2 at 99 seconds after ignition and in case RIL-3 at 115 seconds after ignition. Results of smoke detector values are shown in the following figures. The differences between smoke detector response times were not relevance of the results.
Difference between highest smoke detector values be due to that smoke ventilation in Case RIL-3 was much more effective.

**Figure 31.** Case E2 – smoke detector response (response value 27.66 %/m).

**Figure 32.** Case RIL-3 – smoke detector response (response value 27.66 %/m).
3.2 Results of smoke ventilation

The following section shows the comparison pictures from both cases.

3.2.1 Simulation results

In the following figures 33-50 are presented comparison of smoke layer spread during the simulations. Overlapping figures are from the same moment of time (100s – 1200s). Upper figure is from case E2 and lower from case RIL-3.

Figure 33. Case E2 - Smoke layer at 100s.

Figure 34. Case RIL-3 - Smoke layer at 100s.
Figure 35. Case E2 - Smoke layer at 150s.

Figure 36. Case RIL-3 - Smoke layer at 150s.
Figure 37. Case E2 - Smoke layer at 200s.

Figure 38. Case RIL-3 - Smoke layer at 200s.
Figure 39. Case E2 - Smoke layer at 300s.

Figure 40. Case RIL-3 - Smoke layer at 300s.
Figure 41. Case E2 - Smoke layer at 400s.

Figure 42. Case RIL-3 - Smoke layer at 400s.
Figure 43. Case E2 - Smoke layer at 500s.

Figure 44. Case RIL-3 - Smoke layer at 500s.
**Figure 45.** Case E2 - Smoke layer at 600s.

**Figure 46.** Case RIL-3 - Smoke layer at 600s.
Figure 47. Case E2 - Smoke layer at 1200s.

Figure 48. Case RIL-3 - Smoke layer at 1200s.
Figure 49. Case E2 – Cross section view of smoke layer at 1200s.

Figure 50. Case RIL-3 - Cross section view of smoke layer at 1200s.
3.2.2 Visibility results

In the following figures 51-60 are presented comparison of visibility section profiles during the simulations. Overlapping figures are from the same moment of time. Upper figure is from case E2 and lower from case RIL-3.

Figure 51 Case E2 – Visibility profile of design fire smoke section at 1200s (visibility scale 0-30m).

Figure 52 Case RIL-3 - Visibility profile of design fire smoke section at 1200s (visibility scale 0-30m).
Figure 53. Case E2 - Visibility profile of car part compartment at 1200s (visibility scale 0-30m).

Figure 54. Case RIL-3 - Visibility profile of car part compartment at 1200s (visibility scale 0-30m).
3.2.3 Temperature results
In the following figures 24-27 are presented comparison of temperature section profiles during the simulations. Overlapping figures are from the same moment of time. Upper figure is from case E2 and lower from case RIL-3.

**Figure 55.** Case E2 - Temperature profile of design fire smoke section at 1200s (temperature scale 20-80 °C).

**Figure 56.** Case RIL-3 - Temperature profile of design fire smoke section at 1200s (temperature scale 20-65 °C).
Figure 57. Case E2 - Temperature profile of design fire smoke section at 1200s (temperature scale 20-80 °C).

Figure 58. Case RIL-3 - Temperature profile of design fire smoke section at 1200s (temperature scale 20-65 °C).
3.2.4 Results of make up air flow

In the following figures 59-29 are presented comparison of make up air velocity section profiles during the simulations. Overlapping figures are from the same moment of time. Upper figure is from case E2 and lower from case RIL-3.

Figure 59. Case E2 – Make up air velocity at 1200s (velocity scale 0-5 m/s).

Figure 60. Case RIL-3 - Make up air velocity at 1200s (velocity scale 0-5 m/s).
3.3 Discussion

It can be determined from results presented in this study that smoke ventilation designed according to method RIL-3 is much more effective. Smoke remains in the ignited smoke compartment and the property loses are much lower. Actually this is the goal of this method, to prevent of property losses. Other practical point of view for method RIL-3 is that it is impractical because the number of smoke vents is really big. Large number of smoke vents degrade the heat insulation and set additional challenges of a roof surface design. Also this is the reason why this method is not commonly used.

Smoke ventilation with Method E2 limits the smoke spread at the beginning of the fire. Actually this is the minimum requirement of Finnish Building Code. After ignition smoke layer will spread the whole compartment, but does not compromise egress possibilities. Also the fire brigade actions can be performed in reasonable circumstances.

Finnish Building Code states as minimum requirement to provide smoke ventilation that is “sufficient enough”. Method RIL-3 is much more effective but it includes other problems. Therefore, method E2 is commonly used since it states the minimum level of smoke ventilation.
4 FLAMMABLE LIQUIDS POOL FIRE IN CAR PARK STORAGE

4.1 Design fire

This design fire existed in the fire compartment in the middle of building. The space is designed to work as premises for stocking car parts for repairing cars. Our hypothesis for this scenario was that a small amount, two stock pallets, of cleaning substances are needed to store in the premises. These substances are considered as burning liquids.

For this there is a two pallet space reserved for liquids. This storage spot has 60-minute fire walls on its sides, back and ceiling. Front is open. The goal was to study is this kind of storing possible without major complications in fire spread.

In the building, there are sprinklers and also shelf sprinkler system. Nevertheless, our analysis for radiation and its effect on spreading fire in this case is done without sprinkler-effect because water suppression in form of normal water sprinklers may not be the best way to cover the risks in storing flammable liquids. Sprinklers suppressing effect is taken into account when normal storage materials are burning and our assumption was that when the fire spreads from the pool fire to the upper storage level with normal materials, sprinklers will suppress the fire as normal.

Design fire consists three different burning surfaces. Most relevant design fire is an acetone pool fire. Size of the pool surface is 1,2 x 1,2 meters. Heat release rate of this fire is 2,8 MW. Cell size used in FDS simulations are from 10cm around the fire to 20cm on longer distance from the design fire.

Pool fire is ignited by a small forklift fire from its electric failure, with heat release rate of 1 MW. Forklift is mainly used to ignite the pool fire and is referred to a small vehicle fire. This pool fire causes an upper storage level fire which is separate design fire, which has a heat release rate of 1 MW.

Sprinkler effect was not taken into consideration otherwise, but assumption was made that sprinklers will extinguish the fire on the storage level 2 and fire will not spread any further. Our hypothesis is that small amounts of burning liquids could be stored as described. The biggest keypoint was to observe the radiation effect on the storage shelves opposite to this design fire and this way we could evaluate the risk of the fire spreading, or a risk on storage level structures.

The fire was modelled as a forced heat release rate. The fire reaction was polypropylene. We did not use pure acetone because it is probable that there is something else burning also e.g. packaging materials and car parts.
4.1.1 Fire Location

Fire location was defined into a corner of the fire compartment, on the first storage level which is floor level. Storage shelve lines are situated 3.8 meters from another, height of one level is 2m, and width of one pallet spot is 3m.

Scenario is that forklift ignites from an electric failure and therefore after 100s it ignites the acetone bottles which will form a pool fire on the 1,2 x 1,2 leakage area, limited by mandatory spill control metal borders.

Pool fire ignites the upper level pallets, which are normally burning storage materials, and after this sprinkler will control the fire so that it doesn’t spread any further.

This pool fire causes radiation to opposite storage levels, and this radiation was under analysis.
4.1.2 Used software and parameters
Simulations were made by FDS version 6.3.1. The cell size was 10 cm and 20 cm.

The simulation time of one fire scenario was 900 seconds. In this time, it can be assumed that the beginning of fire starting to fade. This can also be seen from the simulation results.

4.2 Heat radiation
The radiation towards the opposite storage line was not significant (blue line on the figure 63)
The radiation on the upper level will ignite the storage materials approximately after 8 minutes.

We assumed that the sprinklers will suppress this normal material- fire, and fire will not develop furthermore or escalate quickly.

![Graph](image)

**Figure 63.** Radiative heat flux

4.3 Conclusions
In this case study scenario and with these configurations seems that small amounts of acetone types of burning liquids would not form a big fire hazard when liquids are situated as in these simulations. Size of the pool fire is apparently so small that with these storage line distances and passive protection on four sides fire will not form such a big radiation towards opposite storage materials and upper level that the spread of fire would be eminent. Even though in this scenario we assumed that sprinklers would not have any effect on the pool fire and that is why sprinklers were not included in the simulations.

It seems that FDS could be used for his kind of very small scale pool fire and radiation simulations as a proper tool, when it is possible to model scenario without unknown variables.
Of course this case study should not be applied directly on larger scale without further analysis with different type of fire scenarios and implementations. There can be big variations with the materials, fire loads, design fire locations and heat release rates, passive fire protection and other materials. This is why this should be studied further before any direct conclusions on this matter can be made and each case should be studied further on case by case.
5 FURNITURE PRODUCTION - STEEL STRUCTURES

Load bearing capacity of steel structures was studied in furniture production area. A fire underneath of steel structure has a potential to compromise to load bearing capacity of steel structure and the goal for this study was to determine is additional actions needed for fire proofing or could steel structures of the roof be of normal unprotected steel. In this study sprinkler was modelled and another goal was to study its effects to results.

There are several areas in furniture production plant that were excluded from this study since the potential fire location is so close to ceiling structures and therefore it could be determined that in areas of direct flame contact it is possible to reach temperatures that can compromise the load bearing capacity of steel structures. These areas are for example raw materials storage, ready products storage, carpenter area and offices.

5.1 The Design Fire, Sprinkler and Smoke Ventilation in Furniture Production

Design fire was located underneath steel beam of roof structure as shown in picture 64. The location of fire was chosen with the assumption that distance to sprinkler nozzle would be longest and therefore fire would reach highest HRR at this location. If fire would be located next to wall or column sprinkler would activate faster due to smaller distance to sprinkler nozzle. Beam is located at 11,4 m height from floor level and fires are 1,0 m and 1,2 m high so minimum distance from burning surface to steel structure is 10,2 m.

Figure 64. Design fire location.

Heat Release Rate (HRR) of design fire was formed by combining HRR of 1,5m high wooden pallets fire and HRR of fair stand’s fire presented by Hietaniemi (2007, p.34, 53). The fair stand was chosen since the design fire is located at the furniture assembling area which has nearly ready kitchen cabinets located on the floor and it was determined that this setup is close to large
fair stand setup. Also the burning materials was assumed to be equivalent and since most of kitchen cabinets are of wood and fair stand probably had more versatile pallet of combustible materials this assumption can be considered to be on conservative side. Fires were modelled as "wood" reaction from Pyrosim’s library with soot yield of 1%. Initial fire was assumed to start from 1.5 m high wooden pallets fire and spread to surrounding kitchen cabinets at t=100s. Sprinkler activated at t=315s and it was assumed not to limit the fire growth. This assumption can also be considered to be on the conservative side.

HRR curve for wooden pellets is shown in figure 65 below. Maximum HRR for wooden pellets is 4.93 MW. Fire was modelled as a 1.2m x 1.0m area at 1.2 m height from the floor. Heat Release Rate per Unit Area (HRRPUA) was 4105 kW/m².

![Image](image_url)

**Figure 65.** HRR curve for 1.5m high wooden pellets fire.

HRR curve for fair stand is shown in figure 66 below. Maximum HRR for fair stand 13.9 MW. Fire was modelled as a 7 m² (2 x 3 m² + 1 m²) area at 1.0 m height from the floor. Heat Release Rate per Unit Area (HRRPUA) was 1990 kW/m².
Combination of these two design fires was formed and resulting HRR curve measured from one of the simulations and it is shown in figure 67 below. The maximum HRR of the combined fires is 18.9 MW.

Sprinkler is of OH3 class and have design flow of 5 l/m2/min. Sprinkler nozzles were modelled into the geometry and resulting flow per nozzle was 57.8 l/min so one nozzle had coverage are of 3.4 m x 3.4 m. Nozzles were modelled with activation temperature of 74 °C and with RTI of $100 \sqrt{m^2}$. 

**Figure 66.** HRR curve for fair stand fire.

**Figure 67.** Measured HRR.
Sprinkler was modelled with following main parameters:
- Jet stream offset 0,2m (default 0,05m)
- Velocity 7,5m/s (default 5 m/s)
- Latitude angles 23º and 72º (default 60º/75º)
- Median diameter 1121µm (default 500µm)
- Droplets per second 5000 (default 5000)

Studies from Sheppard (2002) and Bourque & Svirsky (2013) were used to select correct parameters for used sprinkler. In this case the selection was helped by the fact that flowrate and nozzle type could be selected by fire engineer rather than given by sprinkler designer or contractor. This way it was possible to select nozzle type that had all the needed parameters available.

Smoke extraction was designed according to Finnish Building Code part E2 as 0,5% extraction area per floor area resulting 17 m² of geometrical extraction area which was modelled as 9 pieces of 1,6 m x 1,2 m = 1,92 m² smoke extraction hatches. Hatches were placed on top of the roof ridge as shown in figure 68. There are also 2 hatches in raw materials storage. Smoke extraction system is automatic and it is activated after sprinkler's activation. Supply air was provided via 9 m² door.

![Figure 68. Smoke extraction hatches in furniture production.](image)

### 5.2 Simulations

Simulations were performed with Fire Dynamics Simulator (FDS) version 6.1.2 SVN 20564. Cell size in the fire plume and at the ceiling “triangle” of the fire was 20 cm and elsewhere 40 cm. Simulations were stopped after HRR was descending and it was clearly observed from the measurements that temperatures were also descending.

Steel structures were modelled as 0,1m thick steel surfaces and elsewhere surfaces were modelled as inert. Maximum temperature of steel structures was determined using maximum adiabatic surface temperature statistic box reaching from bottom of steel beam to top of the roof triangle. This is shown in figure 69 below. Statistic box was measured only above the fire since
temperature in other beams was assumed to be much lower. Gas temperature was also measured at fire plume with maximum gas temperature static boxes and with point detectors.

Figure 69. Maximum adiabatic surface temperature statistic box.

Four simulations were performed:
Base case simulation in which smoke extraction and sprinkler operated as designed (HK13)
Three sensitivity/robustness analysis:
Smoke extraction hatches were disabled to study is the system dependent on letting the heat escape via the hatches (HK14)
Sprinklers droplet size was changed from 1121 µm median diameter to default of 500 µm to study how modelling of the sprinkler droplet size “wrong” effects the results (HK15)
Whole sprinkler system was disabled from the model to study what is the effect of modelling the sprinkler to fire simulations (HK16)
5.3 Results and Discussion

Figure 70 shows the results of maximum adiabatic surface temperature box from four simulations.

![Figure 70. Maximum adiabatic surface temperature results from simulations.](image)

Maximum temperature of plume at 9 m - 10 m above fire is shown in figure 71 below. Temperature is measured as maximum gas temperature statistic box.

![Figure 71. Maximum adiabatic surface temperature results from simulations.](image)

Plume temperature was also evaluated with McCaffrey’s plume model which resulted 397 ºC at 9 m above the fire. For calculation fires were simplified as one 8.2 m² fire with HRR of 18.9 MW. Results corresponds quite well with simulation results at steady state with peak HRR. Temperatures from simulations are about 50 ºC lower but simplifying fires into one surface also
causes error between comparison since in simulations burning surfaces are spread to larger area hence resulting lower temperatures.

From results it can be determined that steel structures are not expose to temperatures that would compromise load bearing capacity of structure. Therefore, no additional measures to protect steel structures are needed at furniture production area. This conclusion is applicable only when fire load and height of combustible material is similar to described in this study.

Malfunction of smoke extraction system had the most effect to temperature of steel structures. Adiabatic surface temperature of structures rose about 150 °C but remained within acceptable level.

Changing the droplet size from 1121 µm to 500 µm did not cause significant changes to result. When HRR is descending after 700 seconds slightly higher gas temperatures can be observed in simulation with smaller droplet size at 9 m - 10 m above fire. This indicates that with smaller droplet size water was evaporated above 10 m level and sprinkler didn’t have that much cooling effect at lower parts of the plume. However, difference is insignificant and does not affect results of this study. Also, more studies should be available to draw more detailed conclusions on sprinkler and water behavior inside fire plume.

Leaving the sprinkler out of the model resulted in slightly lower temperatures between 500 s - 900 s. Difference is not significant and does not change the conclusion of this study but it was interesting to discover that leaving sprinkler system out of the model reduces temperature. The cause for this phenomena was not conclusively discovered but it was noticed that when sprinkler was modelled heat didn’t spread horizontally at the ceiling as well as in non-sprinklered model. This might lead to hotter plume and higher temperature results observed in this study since the heat is remained inside the plume longer due to sprinkler. Another noticeable aspect is that difference in results is about 15 °C and the computing time was in this case about 10 times longer which requires significantly more computing resources. Also considering the fact that sprinkler is not very well validated it would be acceptable that at least initial simulations are performed without sprinkler. If the results are, like in this case, clearly on the safe side additional modelling of the sprinkler might not bring additional value to results.
Finnish chemical legislation which is based on European Union’s “Seveso” directives states that risk of accident spreading from facility that is storing or using chemicals to neighbours and surrounding areas outside the facility must be assessed and if certain criterion is met some actions must be taken to mitigate the risk. Basic idea is that storage and using of chemicals can’t produce threats towards neighbours and their activities. One aspect of this risk assessment is to study radiative heat intensity from fire to neighbouring building. Finnish chemical authority TUKES has provided threshold values for different actions. These values are shown in picture 72 below. Threshold values are not same to all types of uses. For example, other industrial premises, dwellings and offices can endure radiative heat intensity of 8 kW/m$^2$ but more sensitive buildings such as hospitals, schools, hotels, etc. must be designed with threshold value of 1,5 kW/m$^2$ to ensure safe evacuation.

\[ \text{Figure 72. Radiative heat threshold values. (TUKES, 2013)} \]

In this case study it was assumed that neighbouring building is of sensitive type of use and that it has been built as close to lot border as possible allowed in Finnish Building Code which is 4 m. It was also decided that diesel fuel storage’s bund was located 12 m from lot boundary. This leads to total distance of 16 m from bund to neighbouring building. Dimensions are shown in figure 73 below. The goal of this study was to determine the height for radiation blocking wall height to ensure that radiative heat flux remains under 1,5 kW/m$^2$ at 2 m height from ground level at neighbouring wall. Fire scenario was a pool fire in the bund of fuel storage. Another goal was also to study what is the radiative heat intensity towards production facility located at the same lot at 20 m distance and to asses can metal-wool-metal sandwich panel as façade material endure radiative heat from pool fire at the fuel storage area.
Figure 73. Dimensions used in calculations.

Free area in the bund is 190 m$^2$. HRR was calculated using following formula:

$$Q = Af \times m'' \times \Delta Hc$$

where,

- $Af$ = Area of fire (m$^2$)
- $m''$ = Mass burning rate per unit area (kg/m$^2$s)
- $\Delta Hc$ = Heat of combustion (kJ/kg)

Resulting HRR was 390 MW. McCaffrey’s plume model was applied to calculate flame height and height of continuous flame and intermittent flame. Resulting continuous flame was 25 m wide and 13.7 m high with temperature of 845 °C. Intermittent flame was 25 m wide and 20.4 m high. For simplification, temperature in intermittent flame was averaged and resulting temperature was 492 °C.

Radiative heat intensity of these two surfaces was calculated with Stefan-Boltzmann -law:

$$E = \varepsilon \sigma T^4$$

where,

- $E$ = Radiant heat energy emitted from a unit area (W/m$^2$)
- $\varepsilon$ = Emissivity (0.9)
- $\sigma$ = Constant, $5.67 \times 10^{-8}$ (Wm$^{-2}$K$^{-4}$)
- $T$ = Flame temperature (K)

Visibility factors were taken from literature to estimate combined radiative heat intensity from both flames.
Resulting Radiative heat intensities were:

- Without radiative blocking wall maximum intensity is 23.7 kW/m² at 6.9 m height on neighbouring wall
- With 11.7 m high radiative blocking wall maximum intensity is 1.5 kW/m² at 2 m height on neighbouring wall
- With 11.7 m high radiative blocking wall maximum intensity is 7.5 kW/m² at 24 m height on neighbouring wall
- Maximum intensity is 17.7 kW/m² at 6.9 m height on production facility’s wall located on same lot

Radiative heat intensity was also calculated using method presented by McGrattan et al. (2000). Equation used for calculating height of luminous band is shown below:

$$ H = 6.4 \times 10^{-3} \times q_f'' $$

where,

- $H$ = height of luminous band (m)
- $q_f''$ = heat release rate per unit area (for fuel oil 1400 kW/m²)

Resulting height of luminous band is 9 m.

Maximum radiative heat intensity is calculated with equation below.

$$ q'' = F E_f $$

where,

- $q''$ = Thermal radiation flux (kW/m²)
- $F$ = View factor (in this case 0.140)
- $E_f$ = Emissive power of flame (for liquid fuels 100 kW/m²)

Resulting maximum radiative heat intensity of 14 kW/m² on production facility’s wall located on same lot.

The purpose of calculation was to ensure that used method described in this study is accurate enough and that other method to estimate radiative heat intensity gives similar results. The difference between calculated maximum intensities was 3.7 kW/m². When evaluating these two different methods it can be seen that they give roughly the same results. However, for both of these methods a several simplifications have been made and therefore they will always have some number of error when comparing to real fire. The fact that both of these methods which are independent of each other end up with roughly same magnitude in results give certainty to both methods and their results. It was also noted that there are various methods to tackle this type of problem. Some are more accurate and some are more robust so choosing the right method is essential in real life risk evaluations.

Radiative blocking wall with height of 11.7 m is proposed between fuel storage bund and neighbouring building. Calculations show that this wall reduces radiative heat intensity to 1.5
kW/m$^2$ to ensure safe evacuation. However, it could be speculated that if neighboring building has exits facing opposite direction then in a case of fire in fuel storage area it would be possible to use those exits. The main reason of having two exits independent from each other is to ensure safe egress if one exit is compromised. Fire spread risk from fuel storage fire to neighboring building is just under threshold value of 8 kW/m$^2$. However, this could also be speculated that usually sensitive building’s façade has to be made of building products that are will not ignite with 8 kW/m$^2$ radiative heat intensity. In some cases, it is possible to use for example wooden façade but even in these cases 8 kW/m$^2$ is quite conservative value. It would be better approach to do evaluation of threshold limit case by case rather than setting limits that are too conservative in most cases.

Production facility located on same lot is facing maximum radiative heat intensity of 17.7 kW/m$^2$. This intensity does not pose a threat of fire spread to building as long as all visible material on façade is non-combustible. Basic metal-wool-metal panel and other metal or concrete materials are acceptable. Windows should block radiative heat or they should be covered on the façade facing the fuel storage.
7 SUPPRESSION WATER NEED AND SUPPRESSION WASTE WATER CONTROL SYSTEM

The building is equipped with a full coverage automatic fire suppression system except the archive which is equipped with Oxygen Reduction System. The calculation of the water demand is made on assumption that the fire is on one fire compartment at a time. Sprinkler system is working also in one fire compartment at a time. Largest fire compartment is 6000 m$^2$.

The amount of water that is needed for the sprinkler system is 1080 l/min according the Finish national sprinkler standard. In 60 minutes, that is the estimated suppression time, 65 m$^3$ of water is needed. Water source is of type B secured which means common water supply network where the water is supplied from two different directions.

The following estimations and the equations are from a study made by A. Wieneke. The study is based on fires in industry buildings analysed by the Fire Department of the city of Hamburg and a literary report made by Schweitzer.

With the equation from Wieneke¨s study it can be estimated that it takes approximately 32 hours from rescue department to extinguish the fire in the premises. This equation does not take the sprinkler systems influence into account.

\[
t_s = C \cdot A^{q} = 25 \text{ min/m} \cdot (6000 \text{ m}^2)^{0.5} = 1936 \text{ min} = 32 \text{ h}
\]

\( t_s \)= time needed for extinguishing (h)
\( C_2 \)=proportionality factor (\( C_2 = 25 \text{ min/m}, \ A > 1600 \text{ m}^2 \))
\( A \)=area of the space on fire (m$^2$)
\( q= 0.5 \)

In those 32 hours´ fire department uses approximately 15 000 m$^3$ of water.

\[
V_{sw} = C \cdot A^{r} = 2.5 \text{ m}^3/\text{m}^2 \cdot 6000 \text{ m}^2 = 15 \text{ 000 m}^3
\]

\( V_{sw} \)= suppression water (m$^3$)
\( C \)= proportionality factor (\( C= 2.5 \text{ m}^3/\text{m}^2, \ A > 1600 \text{ m}^2 \))
\( A \)= area of the space on fire (m$^2$)
\( r=1,0 \)

The theoretical water supply for the rescue department´s needs is 7,75 m$^3$/min. The water is received from a pillar hydrant and from the fire departments own water tankers.

\[
V_{swf} = C_1 \cdot A^p = 0.1 \text{ m}^3/\text{min} \cdot \text{m/m}^2 \cdot (6000 \text{ m}^2)^{0.5} = 7.75 \text{ m}^3/\text{min}
\]

\( V_{swf} \)= suppression water flow (m$^3$/min)
\( C_1 \)= proportionality factor (\( C_1=0.1 \text{ m}^3/\text{min} \cdot \text{m/m}^2 \))
\( A \)= area of the space on fire (m$^2$)
\( p = 0.5 \)

The waste water from fire suppression work is estimated by Wieneke to be half of the water needed for fire suppression. The amount of the waste water from the rescue services suppression
action is 7 500 m³. In case of a working sprinkler system after 60 minutes the amount of the waste water is approximately 33 m³.

In conclusion it can be said from these calculations in this study that big fires, which the rescue service is not able to take into control in the early minutes of the accident, pose the threat for the environment. In these cases sprinkler system can be held as a mean to reduce the quantity of the suppression waste water because of it’s early reaction and because of that diminish the risk of environmental hazards.

The regional rescue departments and the Finnish chemical authority gives instructions for handling the waste waters in production facilities. In Finland collection of the suppression waste waters is only demanded in facilities that have large quantities of chemicals in their process or in the storages.

In our case for production and storage facility itself it is only recommended. Embankment are mandatory only around the large chemical containers on the yard. The size of the embankment is 110 % of the size of the container. Oil separation wells should be installed in the sewerage system. The system should also have a main drainage valve what closes the system so that the waste water is not able to run to the public sewerage system.
REFERENCES