Case Study 1 – Underground car park

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1. Introduction

This paper presents the results of a case study of a fire safety design of an underground car park located under an office building. Although is not the intention of the authors of this report to fully comply with the national codes and national fire regulations, some of the approaches used in the design were addressed. One of the biggest challenges in large enclosed car parks is to provide sufficient level of safety for the occupants in which respect the smoke control strategy plays a major role. Thus the participants of this project strongly focused on the possible solutions to achieve an acceptable level of safety of the occupants based on a smoke exhaust ventilation system performance. In the course of the works a large number of cases and scenarios were checked however only limited number of results are presented herewith.

The subject underground car park comprises two levels. For the purpose of this analysis it is assumed that both levels are two separate fire compartments/zones "- 2" and "-1".

The study presents the results of the CFD computer simulations performed on a three dimensional model of the car park, taking into account its basic technical parameters such as geometry, the location of the natural and mechanical ventilation openings as well as the arrangement of the jet fans.

2. Building description

The subject building is a two storey enclosed underground car park located under an office building. Each storey is of approximately 13 000 sqm of net area. Each storey net height is 2.9 m from the floor to the ceiling. The ceiling structure is of a flat smooth surface. At each repeatable storey there are sixth protected staircases. In one area (only at level -2) are located car stackers. Three numbers of ramps are provided for communication purpose between levels. Design should include studies for two options where sprinklers are not a viable option and where sprinklers are provided.

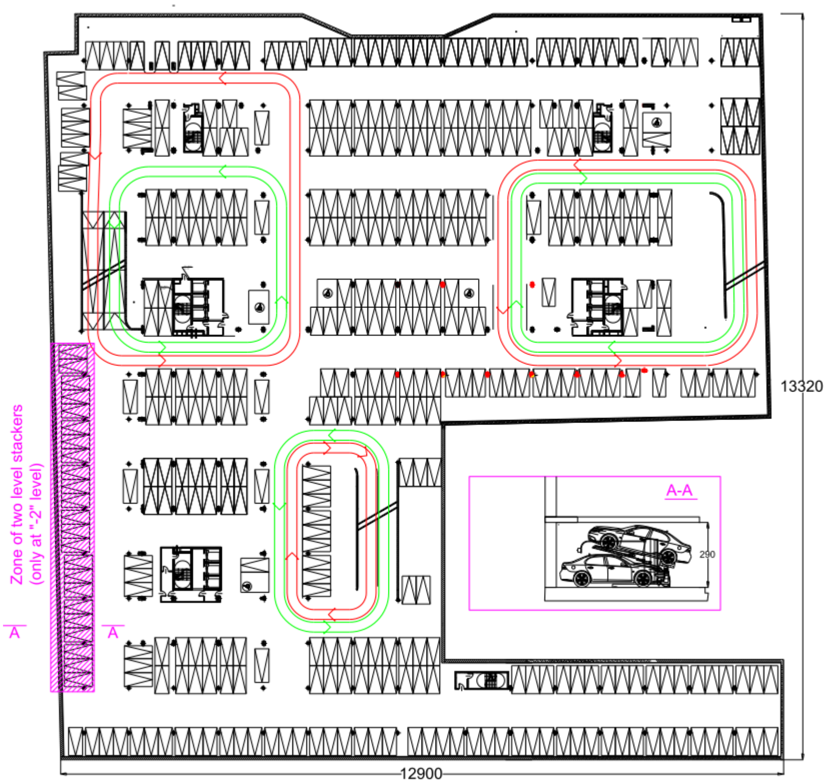


Figure 1. Layout of the subject car park.

3. National building regulations

3.1 Brief description

The polish Building Act came into effect from 7 July 1994. Since that amendments and revisions were provided up to February 2016. The Building Act regulates the issues related to environmental protection during construction and demolishing activities, specifies the types of works (including those which do not require a building permit) authorisation for use of the building procedures in the case of a construction disaster and describes the professional conduct of the persons involved in the design and construction and other activities including their obligations and penal liabilities.

In 2002 came into effect regulation of the Ministry of the Infrastructure which establishes the Technical Conditions, which must be met by the buildings and their location. The provisions described in the Regulation shall be applied to the design and the construction including fire safety requirements. As the legislation and design system is rather prescriptive, very limited possibility of use fire safety performance based design methodology is allowed in Poland in a simple and direct way. Every deviation from the prescribed requirements (including fire safety) is possible only by a special exemption procedure applied to the Ministry of the Infrastructure.

Most of the requirements which the subject building should meet are described in the Technical Conditions and are shortly described in the following section. However for the purpose of this paper it was not intended to fully comply with the local national regulations.

3.2 Fire safety requirements for an enclosed car park

The most important requirements which the subject enclosed car park should comply with are as follows:

1. Car parks are considered as a storage purpose group

a) Means of escape:

- The maximum travel distance (whether dead-end or alternative) should be not more than 40 m
- The maximum travel distances are allowed to be extended if additional fire safety measures are provided (i.e. smoke control system by 50%, fire suppression system by 50%, height of the storey more than 5m by 25%) - resulting in some cases with up to 90 m long even one direction travel distance
- All escape routes can be provided along the driveways (no separate and defined pathway is required)
- No escape is allowed across car park spaces
- The length of the travel distance should be measures in the middle of the escape route
- The minimum with of an escape route should be not less than 0.9 m, where 0.6 m required for every 100 persons
- The minimum door leaf clear width should be not less than 0,9 m (calculated as above)
- A protected staircase or another fire compartment is considered as a safe place where the travel distance is calculated
- All escape exits should be separated from each other with more than 5 m
- On every car park storey larger than 1 500 sqm at least two escape exits should be provided
- All exits should be fully accessible if fire compartment gates are provided (for horizontal and vertical fire compartmentation purpose)
- Adequate occupancy load factor is 30 sqm/person
- No special requirements are necessary for disabled escape purpose

b) Structural fire protection and compartmentation

- Maximum allowed compartment size up to 5 000 sqm (twice larger if fire suppression system provided)
- An underground enclosed car park should be fully compartmented from other car park levels if one of the storey area exceeds 1 500 sqm
- Fire resistance of the elements of structure depends on the classification of the building (based on the height: low, medium, high, high-rise), which is assumed as high classification:
    - Floor slab REI 120
    - Main structure R 120
    - Compartment separation REI 120
    - Compartment fire doors/gates EI 60
- The minimum clear height of the car park to the underside of structural elements should not be less than 2.2 m

c) Fire safety systems/measures

- Any car park with the total area of more than 1500 sqm should be provided with a smoke control system, which should meet the following requirements:

- Maintain tenability conditions for occupants that neither visibility or temperature at the escape routes will not restrict a safe evacuation for required safety escape time (RSET)
- Should have a reliable inlet of fresh replacement air source
- The main smoke extract fans should be of the temperature rating as follows:
  - F_{600} 60 if the predicted smoke temperature is more than 400 ^oC
  - F_{400} 120 if the predicted smoke temperature is less than 400 ^oC
  - Less if the predicted smoke temperature and safety of the fire brigade personnel allow for it (it is noted that no fire safety conditions for fire brigade personnel is defined by the authority)
- Other requirements are for duct smoke control system are also provided
- The minimum clear height under any part of service installations to be at least 2 m

- No sprinkler protection is required
- If sprinkler system is provided:
  - Twice larger fire compartment size is allowed (10 000 sqm)
  - Travel distances can be extended by 50%
- Staircases should be provided with ventilated protected lobbies (EI 30)
- No voice alarm system is required (for an office building purpose group)
- An automatic smoke and fire detection system should be provided
- Fire hose reels should be provided
- An emergency escape lighting and signage (not necessarily illuminated) should be provided

2. Commentary relating the smoke control requirements

There is no obligation to use extended travel distance limits when smoke control system is provided. In Polish building regulations there is no clear distinction between smoke control (for escape purpose) and smoke clearance. Thus in interpretation of Technical Conditions requirements by the designers some confusion often occurs. It is assumed, that if verification for smoke control use is performed (i.e. computer simulations) it needs to be clearly demonstrated that the system performance allows for such a flexibility. The regulations do not explicitly require that the analysis of the fire-fighting conditions needs to be carried out as a part of the overall analysis in an enclosed car parks. However, it is necessary to consider the safety of the fire brigade personnel and the performance of the smoke control system in safeguarding same when smoke fans with lower temperature ratings are proposed (see above). It also needs to be demonstrated by the designer, that the use of the smoke control system allows for extended evacuation time due to longer travel distances.

So above requirements for smoke control system use should be read as follow:

- The maximum travel distance (whether dead-end or alternative) for an unsprinklered car park is up to 40 m if smoke control system is not taken into account (even if provided), 60 m if smoke control system is allowed for.
- The maximum travel distance (whether dead-end or alternative) for sprinklered car park is up to 60 m (if smoke control system is not taken into account , 80 m if smoke control system is allowed for.

3.3 Examples of designs complying with Polish national requirements

For the subject car park to fully comply with the national fire safety regulations, the following requirements would need to be provided:

a) Unsprinklered car park:

- Maximum travel distance up to 40 m or 60 m if the smoke control system allows for extended TD by 50%

- Maximum fire compartment size up to 5 000 sqm (approximately four fire compartments at each level)
- Higher main extract fans capacities and temperature rating predicted

b) Sprinkler protected car park:

- Maximum travel distance up to 40 m or 80 m if the smoke control system and use of the fire suppression system allow for extended TD by sum of two 50% allowances
- Maximum fire compartment size up to 10 000 sqm (approximately two fire compartments at each level)
- Lower main extract fans capacities and temperature rating predicted

4. Fire safety measures and design approach

4.1 Assumptions and design approach

In this study it was assumed, that the subject car park will not fully comply with all the national fire safety and building regulation requirements. This was assumed because of the possibility of obtaining a derogation from the requirements of regulations in situation when performance based analised show the building with an adequate level of safety. As the major requirement which is not adopted in the design is the fire compartment size limitation. In the case study it was assumed that the fire safety limitations of the maximum compartment size or travel distance length can be dealt in an alternative way, as example by smoke control system performance on its own or combined with other systems as sprinkler or voice alarm system. Two different solutions for each scenario (unsprinklered and sprinklered) are provided. It is assumed that smoke barriers (whether static or active) are not considered as change to the building geometry. It was intended to consider for all scenarios similar parameters and fire safety measures for simpler comparison purpose. Type of the building (such as an office building) is also considered in the design approach in terms of fire safety management and maintenance level (higher than in comparison to residential). For the purpose of this study it was assumed that the design is performed for a lower level floor (-2) as the more demanded case (due to car park stackers and lack of use the entrance ramps as inlets points). For that reason it is assumed that the smoke control strategy will be adopted to the upper level (-1).

4.2 Fire safety measures

The following fire safety measures and systems are considered:

a) Unsprinklered car park:

- No fire compartmentation limit applies
- Passive fire protection measures will be provided (compartmentation subdivision taken into account)
- Passive or active smoke barriers will be provided (smoke curtains)
- Voice alarm system will be considered
- Two stage automatic fire and smoke detection system provided
- Way finding and active evacuation signage will be considered (for subdivision)
- Smoke control system for evacuation purpose will be applied (extended travel distances more than 40 m including dead ends)
- Fire management level of a higher standard
- Fire compartmentation between floor levels
- Escape doors within the gates when provided at the drive ways
- Fire brigade access point at the ground floor entrance hall

b) Sprinklered car park

- Sprinkler system parameters:
    - Fast response system to meet life safety requirements
    - RTI < 80
    - T= 68 ^{o}C
    - OH2 design group
- No fire compartmentation limit applies (larger compartment size)
- Passive or active smoke barriers will be provided (no compartmentation subdivision) - walls separating car park stacker platforms are provided (every three spaces)
- Voice alarm system will be considered
- Two stage automatic fire and smoke detection system provided
- Way finding and active evacuation signage will be considered (for subdivision)
- Smoke control system for evacuation purpose will be applied (extended travel distances more than 40 m including dead ends)
- Fire management level of a higher standard
- Fire compartmentation between floor levels
- Escape doors within the gates when provided at the drive ways
- Fire brigade access point at the ground floor entrance hall

5. Design acceptance criteria

5.1. Means of escape

It is assumed that acceptance criteria will be met when tenability criteria for safe escape of the occupants will be maintained for the time period longer than minimum required safe escape time (ASET > RSET).
The following design criteria were adopted for escape routes:
- Temperature at 1.8 m above FFL not exceeding 60 ^{o}C
- Minimum visibility of light-reflecting signs of not less than 10 m measured as 1.8 m above FFL
- fulfilment of the above criteria means that no toxicity limits are exceeded

5.2. Fire brigade safety criteria

In light of the national regulations, no fire brigade safety conditions needs to be checked unless the main exhaust ventilators temperature rating is lower than F_{400} (i.e. F_{300}).
However for the purpose of this study following design criteria were adopted:
- Temperature measured at 1.5 m above FFL not exceeding 100 ^{o}C with access of approximately 15 m to the bed of fire
- No visibility criteria is to be adopted

It is noted that some national fire safety codes impose to check visibility criteria for fire-fighters use such as British Standards or Singaporean National Fire Safety Requirements. However due to the course of this study it was realized that such requirements as 10 m visual contact to the bed of fire with the approach for downwind direction results in very high extract volume, increased number of jet fans provided and much complex fire matrix to limit active number of jet fans at one time to those close to the fire location.

5.3. Smoke control performance acceptance criteria

For the smoke control acceptance criteria all above mentioned criteria must be fulfilled. In addition it was assumed that at most 20% (approximately 2600 sqm) of the entire car park area can be outside of the visibility criteria (for evacuation purpose) when fully developed designed fire size is achieved (at minimum of 900 s of simulation time) respectively to the fire scenario considered. In the situation of the car park subdivision (fire compartments or smoke compartments) the most ideal situation is that smoke is limited to the smoke control zone where fire occurred.

6. Options and versions to be considered

For the purpose of the case study four different options of the proposed solutions are considered (two different scenarios unsprinklered vs sprinklered).

The analised scenarios are as follows:

CASE 1A. Unsprinklered. Each storey not divided into fire zones.
CASE 2A. Unsprinklered. Each storey additionally divided into fire zones.

CASE 1B. Sprinklered. Each storey not divided into fire zones.
CASE 2B. Sprinklered. Each storey additionally divided into smoke compartments.

For all the scenarios it was assumed:

- Fire can start only at one car space and then spread to others
- Depending on the scenario different numbers of cars can be involved into a fire (unsprinklered, sprinklered, stackers)
- Both levels of the car park are separate fire compartments
- All the lanes were assumed to serve as evacuation routes. It was assumed that the escaping occupants will not travel across the car park spaces. The arrangement of the parking spaces and the evacuation routes is presented in figures 4-7
- It is assumed that the disabled car spaces are located near the emergency exits
- The analysed arrangement of the inlet and extract ventilation points, the natural air inlet points and the jet fans are shown in figures 4-7
- Analysis includes two major designs situations: without sprinkler protection and with full sprinkler protection for which two solutions of the smoke control system provided
- Similar architectural solutions are used for unsprinklered and sprinklered designs, however small deviations between them are permitted
- A ductless jet fan ventilation system is used
  A detailed description of the ventilation system is described in section 10

7. Detailed design analysis

7.1 Means of escape

a) Estimated peak occupancy

Location	**Area** (m^2)	**Usage**	**Occupant Load Factor** (m^2/Person)	**Estimated Peak Occupant Level** (Persons)
Basement Car park	13 200	Storage	30	**440**

b) Final exits number/capacity

Location	**Estimated Peak Occupant Level** (Persons)	**Number of final storey exits – in accordance to case study project**	**Required minimum single exit width** (m)	**Proposed minimum single exit size** (m)
Basement Car park	440	6	0.73	**0.9**

By the nation codes it is not necessary to discount one from the exits for the purpose of the minimum required exit capacity calculations and exits number. The proposed minimum number and clear width of exits is adequate.
Only staircases are included as the final exits (no adjacent fire compartments are taken into account).

c) Travel distances

Type	**Recommended Limits** (m)		**Maximum Proposed** (m)	
	Dead End	Alternative	Dead End	Alternative
Basic	40		**60**	**62**
Extended	(up to 80)			

As per information provided in section 3.2 travel distance limits can be extended by use of a sprinkler system and a smoke control system suitable for escape assistance (by 50% respectively).

d) Characteristic of the occupancy:

The requirements for an office building are generally less onerous (when compared to other types of premises such as places of assembly and recreation, etc.). The reason for that is the occupants of the building are more likely to be familiar with the building, its layout, exits location, etc. Therefore the occupants of the building can be described as awake and familiar (no sleeping risk involved).

7.2 Fire compartmentation and structural fire resistance

The Polish regulations require compartment walls and floors separating an underground car park from the reminder of the building as well as any structural elements supporting such elements located within the car park to achieve fire resistance of at least 2 hours. This is a relatively high level of fire resistance, particularly for car parks protected with a sprinkler system. For this reason in this study the issue of thermal loads and the fire resistance of structure was not further investigated. It was assumed that the fire rating required by the Polish regulation (i.e. 2 hours) is generally adequate for the fire risk posed by a car park fire. It is noted that the risk of structural damage resulting from a large car park fire is greatly reduced by provision of sprinkler protection.

In the cases, when car park was divided into the fire or smoke zones, the boundaries are as fallows:

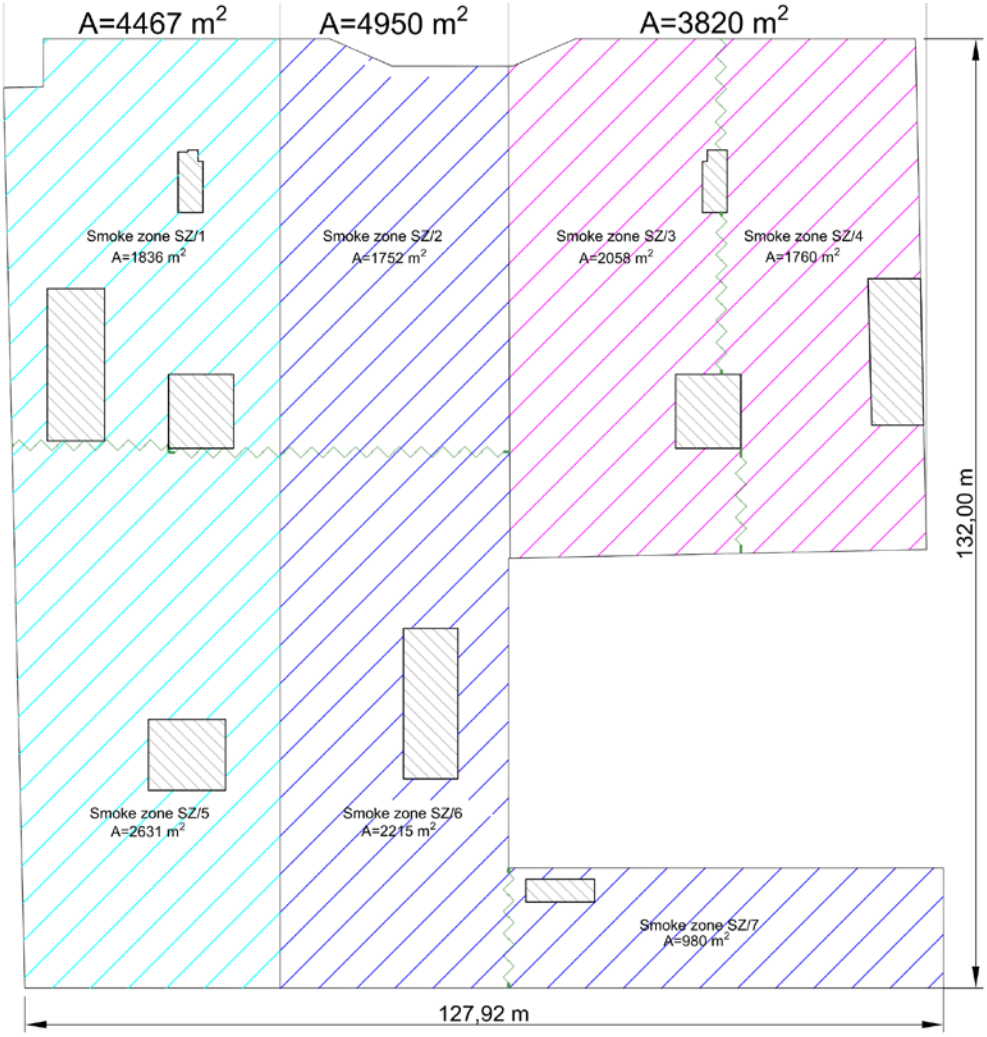


Figure 2. Schematic layout of the car park subdivision into fire and/or smoke control zones

8. Design fire sizes and its grow rate

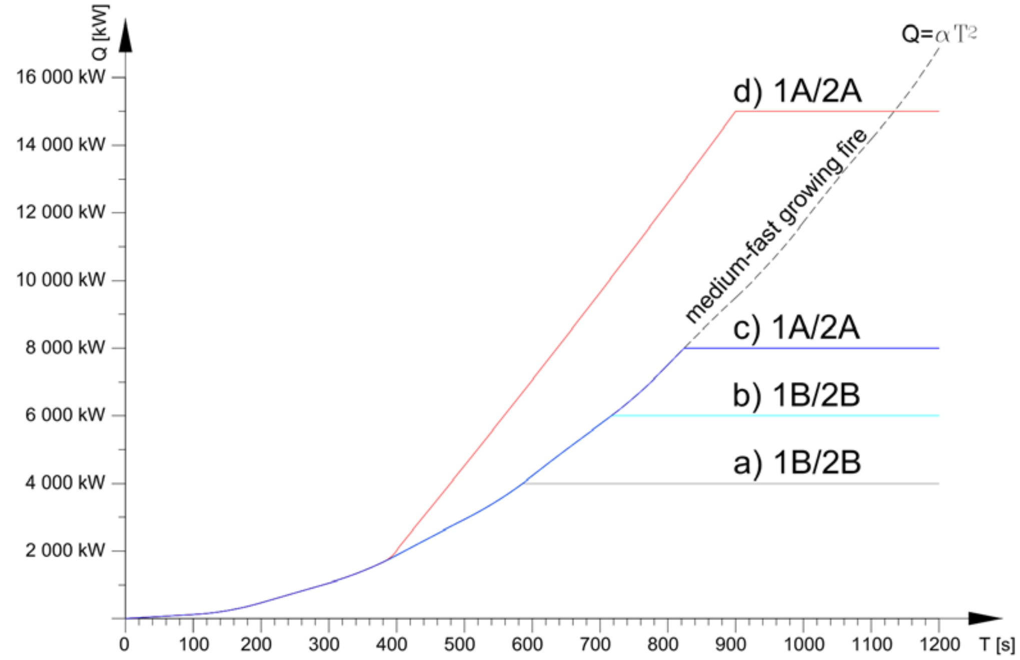
For the purpose of this case study design fire size recommended in British Standards [2,3] were adopted. Although many studies based on experimental data are published and available, however it was decided to use more conservative approach based on medium-fast growing fire curve.

In the subject building the most demanding fire scenario occurs where the car park stacker platforms are designed. In this case the largest fire size and the highest heat output are expected when no sprinkler protection is provided. This scenario is also most demanding in terms of the thermal reaction of the structural elements of the building to the fire. For the most demanding fire scenario for smoke control system performance, a fire located within the central part of the car park is predicted.

The following design fire sizes are used for given fire scenarios:

a) Sprinklered fire of one burning car – 4MW (case 1B/2B)
b) Sprinklered fire of two car stacker platform – 6MW (case 1B/2B)
c) Unsprinklered fire of two burning cars– 8MW (case 1A/2A)
d) Unsprinklered fire of three/four burning cars in stacker platform– 12/15MW (case 1A/2A)

Proposed design fire curves for listed above fire scenarios are shown on the graph below.



Graph 1. Theoretical fire curves

9. Details of the CFD software

The simulations were performed by means of **Fire Dynamics Simulator** (FDS), a specialist software developed by the National Institute of Standards and Technology – U.S. Department of Commerce.

Three versions of the software have been used for the purpose of this analysis, including ver. 4.0.7; 5.5.3 and 6.3.2 of FDS, which required high computer power to be involved. The older versions were used mostly for preliminary design studies. For later stage of the works two versions (ver. 553 and 632) for sprinklered scenarios were used simultaneously and their results were directly compared. However for the purpose of this assignment only FDS 632 results are provided. Sprinkler heads based on the proposed sprinkler system parameters are physically modelled in both FDS 553 and 632 versions input files.

10. Overall smoke control strategy and CFD simulation assumptions

10.1 Smoke control strategy

- The analysis was performed based on typical geometry of one of two car park storeys;

- CASE 1A, 1B:

  Analysed car park involves the area of two fire zones (fire zone on storey “-1” and fire zone on story “-2”) and is separated from each other by ceilings, walls and the fire gates marked on figures 1, as “BP”, all with the required fire resistance class. Each fire zone of analysed car park was divided into seven smoke detection zones SZ: SZ1 ÷ SZ7. The division into smoke detection zones are shown in figure 1;
  In addition, for CASE 1B, full height smoke barriers between car spaces along smoke zone boundaries are provided with shallow smoke barriers above driving ways

- CASE 2A, 2B:

  Analysed car park involves the area of three fire zones on each story and is separated from the other zones by ceilings, walls and the fire gates marked on figures 2, as “BP”, all with the required fire resistance class by the fire regulations;

- Each fire zone of analysed car park was divided into smoke detection zones: fire zone SF1 into smoke detection zone SZ1 and smoke detection zone SZ5, fire zone FZ2 into smoke detection zone SZ2, smoke detection zone SZ6 and smoke detection zone SZ7, fire zone SP3 into smoke detection zone SZ3 and smoke detection zone SZ4. The division into fire zones and smoke detection zones are shown in figure 2;

- Clear height of the both car park storeys (from FFL to the ceiling) is 2.9 m;

- The smoke curtains with the bottom edge at height 2.2 m are placed below the ceiling slab (fig. 4-7);

- Locations of the evacuation exits from the analysed area of the car park (marked with symbol "E") are shown in figures 1, 2.

- Smoke extraction is provided through mechanical ventilation inlet and exhaust points "NW" („NW1", „NW2", „NW3", „NW4", „NW5", „NW6", „NW7"), which arrangement is shown in figures 1, 2. Individual points are switched depending on the scenario as described in point. 3.2

- Air supply is provided through mechanical ventilation inlet and exhaust points "NW" " („NW1", „NW2", „NW3", „NW4", „NW5", „NW6", „NW7") and four natural air inlets points "N" of the effective area (net area) 5 m^2 each, located at the floor level of the car park on each storey which arrangement is shown in figures 1, 2;

- Maximum air flow rate through the ventilation points (net cross-section) was assumed at: 10 m/s for exhaust points, 5 m/s for inlet points and 2.5 m/s for natural air inlet points;

- The analysed jet fans are unidirectional fans with capacity: low speed – 0.91 m^3/s, full speed – 1.79 m^3/s as well as reversible Jet fan with capacity: low speed – 0.82 m^3/s, full speed – 1.6 m^3/s and temperature rating 400^0C/2h;

- Locations as well as possible flow directions of the jet fans operation are shown in figures 4-7;

- Height of the bottom of the jet fans from the floor is no less than 2.1 m;

- During operation of the system in the smoke ventilation mode the fans operate on at full speed.

- It was assumed that the ventilation points shall be activated immediately after the fire has been detected by two smoke detectors (two stage alarm system) in the same smoke detection zone or one smoke detector and brake glass unit and reach their design efficiency not later than 140 seconds from the start of the fire (i.e. after about 60 seconds from the detection of the fire);

- It was assumed that the jet fans shall be activated after 300 seconds from the start of the fire (i.e. after about 220 seconds from the detection of the fire); in case of the fire which is located directly below the jet fan, it was assumed as non-operating since it may be damaged by the fire;

10.2 CFD simulation main parameters

- Ambient (initial) temperature was assumed in all the simulations at 20 ^oC, soot yield was 0.091 / 0.1, heat of combustion = 36904 kJ/kg.

- The computational domain was represented by the multiple meshes build up of rectilinear cells. Each mesh was subdivided into quasi-uniform cells. The mesh resolution does not exceed 0.30 m in all x, y, z directions.

- The model size was 1.9 mln cells

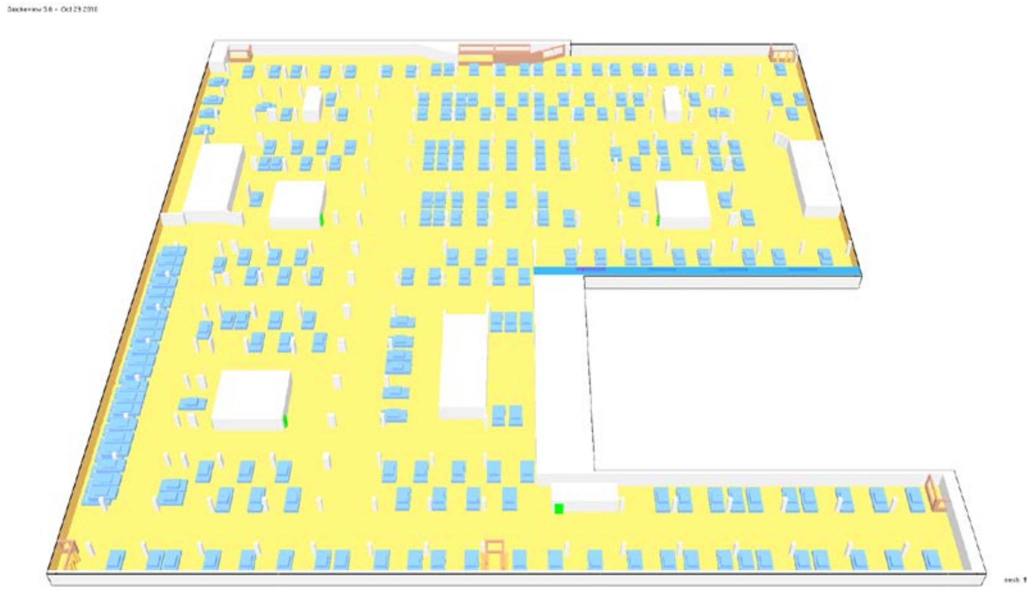


Figure 3. View of the CFD model of the car park

- The minimum run time is 900 s

10.3 Analysed simulation parameters

The analysis is aiming at determining the tenability conditions during fire within the time required for evacuation. To determine if the acceptance criteria of the simulations are met the temperature distribution and the visibility range at the height of 1.8 m above FFL are checked.

According to the literature data [9, 11] the threshold values of each analysed parameter are as follows:
- life hazard temperature – 60°C (taking into account possible differences between the temperature obtained from the simulation and the real temperature, the boundary temperature on the evacuation routes obtained from the simulation is assumed at the level of 52°C),
- visibility range – 10 m for structural elements, which is equal to 30 m visibility of illuminated signs

11. Detailed smoke control strategy for the scenarios considered

11.1 Smoke control strategy for CASE 1A

Figure 4. Diagram of the car park and the ventilation system – storey „-2" (repeatable storey). CASE 1A unsprinklered, without compartmention

In case of fire in the smoke detection zone where the fire was detected the fire gates between car park levels are closed. The following ventilation inlets - extracts points are switched on according to the table shown below:

Case 1A (without fire compartmentation, un-sprinklered fire)											
Smoke detection in zone:	Smoke exhaust in detection zone	Smoke exhaust in detection zone in case of penetration of smoke into the adjacent zone	Smoke exhaust in detection zone in case of penetration of smoke into the adjacent zone	Air supply from NW1	Air supply from NW2	Air supply from NW3	Air supply from NW4	Air supply from NW5	Air supply from NW6	Air supply from NW7	Natural ventilation flow from points N (allways open)
	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$
SZ/1	160 000	160000 (SZ/2)	-	-	40 000	-	43 000 43 000	43 000 43 000	43 000 43 000	-	31 000 31 000
SZ/2	160 000	160000 (SZ/1)	-	-	-	-	43 000 43 000	43 000 43 000	43 000 43 000	-	32 000 32 000
SZ/3	160 000	160000 (SZ/2)	160000 (SZ/4)	43 000 43 000 43 000	-	-	-	43 000 43 000 43 000	43 000 43 000 43 000	-	32 000 32 000 32 000
SZ/4	160 000	160000 (SZ/3)	-	64 000 64 000	-	-	-	-	64 000 64 000	-	32 000 32 000
SZ/5	160 000	160000 (SZ/6)	-	43 000 43 000	43 000 43 000	-	-	-	-	43 000 43 000	31 000 31 000
SZ/6	180 000	160000 (SZ/5)	-	43 000 43 000	43 000 43 000	-	-	-	-	43 000 43 000	31 000 31 000
SZ/7	140 000	-	-	-	-	-	-	-	128 000	-	12 000

The numbers of the jet fan fans in operation and the direction of their operation are shown in figure 4. Jet fans always act to extraction points.

11.2 Smoke control strategy for CASE 2A

Figure 5. Diagram of the car park and the ventilation system – storey „-2” (repeatable storey). CASE 2A – unsprinklered, with compartmention

In case of fire in the smoke detection zone in which the fire was detected the fire gates are closed. The following ventilation inlet - extract points are switched on according to the table shown below:

Case 2A (witht fire compartmentation, un-sprinklered fire)

Smoke detection in zone:	Smoke exhaust in detection zone	Smoke exhaust in detection zone in case of penetration of smoke into the adjacent zone	Air supply from NW1	Air supply from NW2	Air supply from NW3	Air supply from NW4	Air supply from NW5	Air supply from NW6	Air supply from NW7	Natural ventilation flow from points N	Natural ventilation flow from infiltration
	[m^3/h]	[m^3/h]	[m^3/h]	[m^3/h]	[m^3/h]	[m^3/h]	[m^3/h]	[m^3/h]	[m^3/h]	[m^3/h]	[m^3/h]
FIRE ZONE FZ1											
SZ/1	160 000	-	-	-	-	-	128 000	-	-	-	32 000
SZ/5	160 000	-	128 000	-	-	-	-	-	-	-	32 000
FIRE ZONE FZ2											
SZ/2	160 000	-	-	-	-	-	-	64 000	64 000	-	32 000
SZ/6	160 000	-	-	64 000	-	-	-	-	64 000	-	32 000
SZ/7	140 000	-	-	-	-	-	-	112 000	-	-	28 000
FIRE ZONE FZ3											
SZ/3	160 000	160 000	-	-	-	-	-	-	-	160 000/320 000	-
SZ/4	160 000	160 000	-	-	-	-	-	-	-	160 000/320 000	-

The number of active jet fans and their direction of operation depending on the fire location are shown in figure 5.

11.3 Smoke control strategy for CASE 1B - sprinklered

Figure 6. Diagram of the car park and the ventilation system – storey „-2” (repeatable storey). CASE 1B - sprinklered

At the fire and smoke detection system activation the following action will occur:

- Fire gates are closed separating fully both car park levels
- Openings between smoke control zones are maintained
- Active fire barriers are in operational mode (fully dropped)
- Smoke extract point at the activated smoke detection zone is activated
- Fresh air inlet points are open and fully operational

The details of the active extract and inlet points are listed table below:

Case 1B (without fire compartmentation, sprinklered fire)									
Smoke detection in zone:	**Smoke exhaust in detection zone**	**Air supply from NW1**	**Air supply from NW2**	**Air supply from NW3**	**Air supply from NW4**	**Air supply from NW5**	**Air supply from NW6**	**Air supply from NW7**	**Natural ventilation flow from points N (allways open)**
	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$
SZ/1	160 000	-	40 000	-	20 000	20 000	40 000	20 000	20 000
SZ/2	180 000	40 000	-	-	40 000	40 000	-	20 000	40 000
SZ/3	180 000	40 000	-	-	20 000	20 000	40 000	20 000	40 000
SZ/4	160 000	20 000	20 000	20 000	-	-	40 000	20 000	40 000
SZ/5	160 000	20 000	40 000	-	20 000	-	40 000	20 000	20 000
SZ/6	180 000	40 000	20 000	-	40 000	40 000	-	20 000	20 000
SZ/7	140 000	-	20 000	-	-	20 000	80 000	-	20 000

The number of active jet fans and their direction of operation depending on the fire location are shown in figure 6.

A partial separation in shape of walls or active fully drop down curtains acting as a full height smoke barriers, is used to maintain smoke propagation within the smoke control zone where fire occurred. Although smoke barriers of limited height are proposed above drive ways it is noted that due to the relatively small extraction rate in range of 140-180 000 m^3/h resulting with low cross flow velocity at the drive ways some smoke leakage to the adjacent smoke control zones might occur. Also as a fast response sprinkler system is proposed, it is assumed that lower temperature rating jet fans and exhaust vents can be used.

11.4 Smoke control strategy for CASE 2B – sprinklered and fire/smoke compartmented

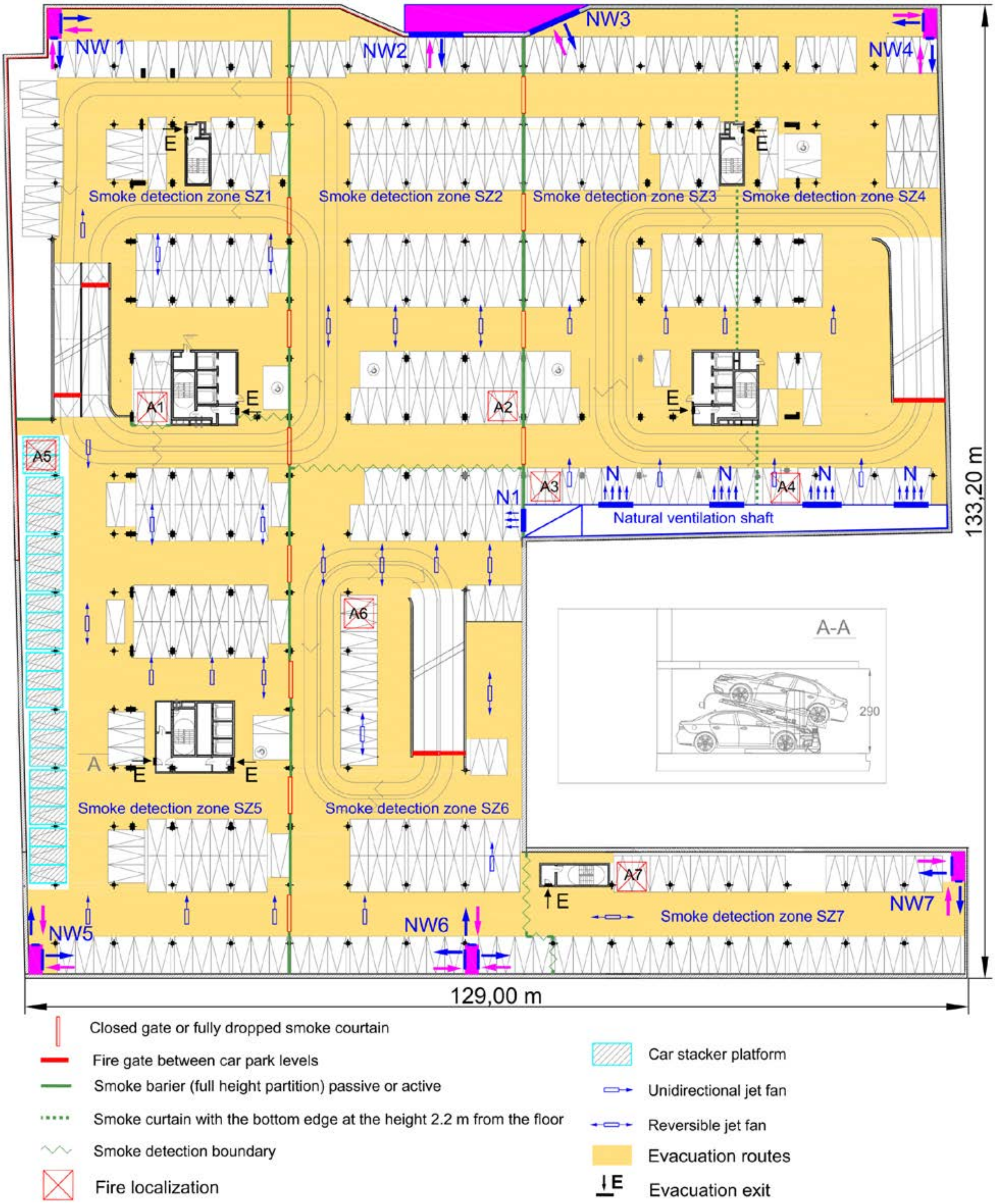


Figure 7. Diagram of the car park and the ventilation system – storey „-2” (repeatable storey). CASE 2B - sprinklered and fire or smoke compartmented

At the fire and smoke detection system activation the following action will take place:

- Fire gates are closed fully separating both car park levels
- All gates or fully drop down smoke curtains at the drive ways are closed creating a full smoke separation between smoke control zones
- Smoke extract point at the activated smoke detection zone is activated
- Fresh air inlet points are open and fully operational

The details of the active extract, inlet points are listed in table below:

Case 2B (witht fire compartmentation, sprinklered fire)											
Smoke detection in zone:	Smoke exhaust in detection zone	Air supply from NW1	Air supply from NW2	Air supply from NW3	Air supply from NW4	Air supply from NW5	Air supply from NW6	Air supply from NW7	Natural ventilation flow from points N	Natural ventilation flow from point N1	Natural ventilation flow from infiltration
	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$	$[m^3/h]$
SZ/1	90 000	-	-	-	-	80 000	-	-	-	-	10 000
SZ/5	90 000	80 000	-	-	-	-	-	-	-	-	10 000
SZ/2	90 000	-	-	-	-	-	40 000	40 000	10 000	-	-
SZ/6	90 000	-	40 000	-	-	-	-	40 000	10 000	-	-
SZ/7	90 000	-	40 000	-	-	-	40 000	-	10 000	-	-
SZ/3	90 000	-	-	-	40 000	-	-	-	50 000	-	-
SZ/4	90 000	-	-	40 000	-	-	-	-	50 000	-	-

The numbers of the active jet fans their direction of operation are shown in figure 7. Full smoke separation (in a shape of full height smoke barriers) are proposed to limit smoke propagation only to the smoke control zone where fire occurred. Due to the full separation between adjacent smoke control zones, much lower extract volume rate is proposed for smoke ventilation purpose. Also as a fast response sprinkler system is proposed, it is assumed that lower temperature rating jet fans and main exhaust vents can be used.

12. RSET calculations

The analysis of the assumed evacuation time is based on Published Document PD 7974 - 6: 2004 [1].
When determining the evacuation times, the existing fire protection system was considered, particularly:

- full protection of the building by means of a fire alarm system,
- building equipped with a voice alarm system,
- building equipped with fire hose reels and fire extinguishers,
- building equipped with an alternative, independent power source,
- an emergency lighting and escape illuminated signage

The following categories were assumed taking into account the above:

1) occupant behaviour category – **A** (awake and familiar)

2) alarm system quality - **A2** - (automatic fire detection and activation of the indispensable devices in the endangered zone by means of alarm signals via the second degree, and the alarm for the second degree is considered an alarm signal from two smoke detectors in the same smoke detection zone)

3) influence of the building complexity on the evacuation time - **B1** – simple single storey areas – easy orientation (in this respect, only the evacuation from the car parks is considered),

4) building management level - **M2**- security personnel is not expected at the car park level

For the above categories (A, A2, B1 and M2), the pre-movement time for the first occupants (close to the fire) shall be $\Delta t_{pre(1st\ percentile)} = 1$ min
and for the last persons another time $\Delta t_{pre(99th\ percentile)} = 2$ min.

It is assumed, that in case of fire the evacuating occupants shall use the designated evacuation routes to the nearest evacuation exits in directions other than the location of the fire.

The longest travel distance in the car park is about 62 m.
The walking speed of people moving along the evacuation routes was assumed as1,2 m/s.
In the worst case, the travel time to the nearest evacuation exit is :

$$\Delta t_{trav}=62m\ x1,2m/s=74,4s=75s$$

Based on the initial analyses carried out for the assumed fire parameters it was assumed that the time needed to activate the fire alarm system in the analysed building shall not exceed 80 s from the start of the fire (smoke layer size under the ceiling after 80 s from the start of the fire exceeds 20 m in diameter, which guarantees that at least two smoke detectors installed 2 m from each other shall be activated).
It is assumed that the fire alarm will be activated immediately (Δt_a=0s) after the detection of a fire (Δt_{det}=80s).

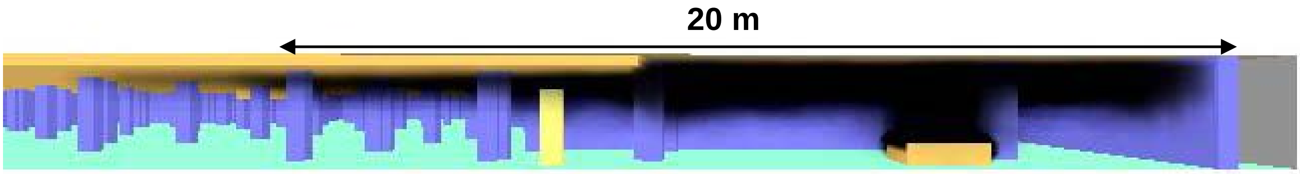


Figure 6. Expansion range of smoke after 80 seconds from the start of the fire according to CFD detailed analysis.

Accordingly, the Required Safe Escape Time (RSET) is:

- For „the first occupants" **from smoke zone covered by fire:**
  $\mathbf{RSET}_{1\%} = \Delta t_{det} + \Delta t_a + \Delta t_{pre,1\%} + \Delta t_{trav} = 215$ s (with safe margin **240 s**)

- For the last „99% occupants" **from all areas of the car park:**
  $\mathbf{RSET} = \Delta t_{det} + \Delta t_a + \Delta t_{pre,99\%} + \Delta t_{trav} = 335$ s

NOTE:

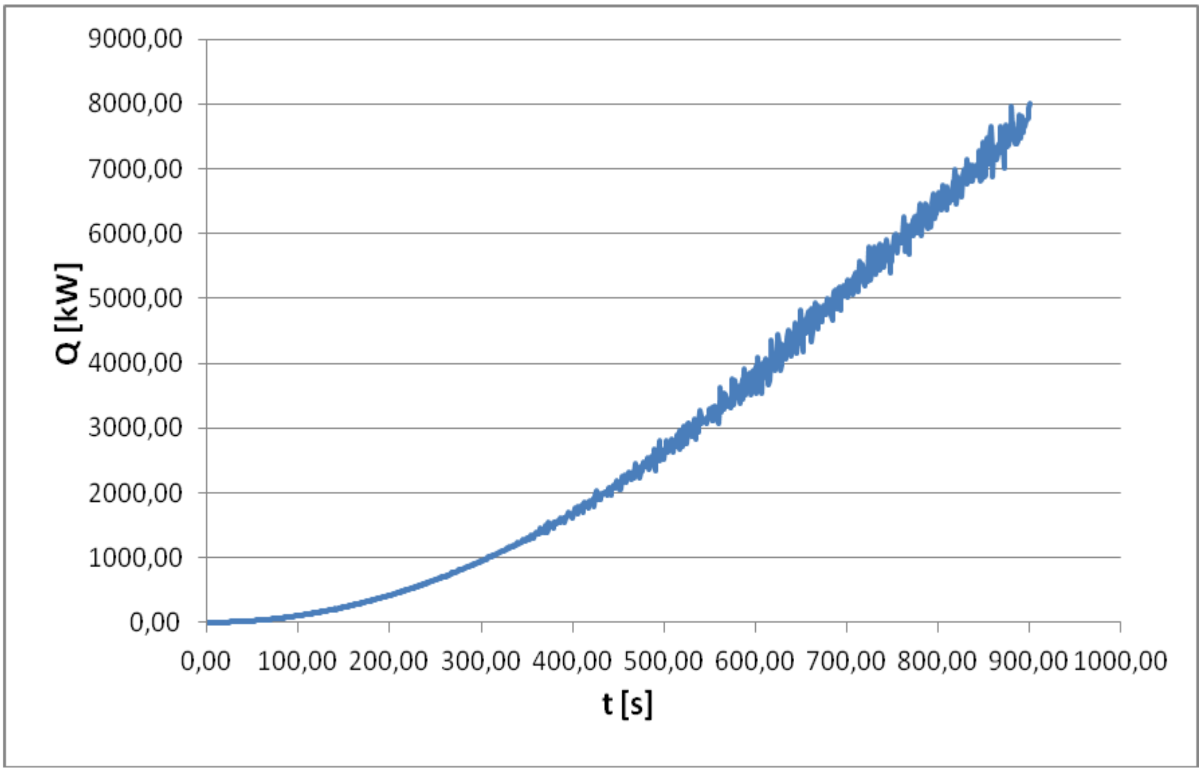
It is commonly know fact that the voice alarm system in open spaces where a good visual contact to the fire is provided plays a huge role in motivating the occupants to faster reaction. Based on those facts pre-movement time is proposed to be reduced by 35 s.

Therefore, RSET from all areas of the car park can be reduce **to 300 s.**

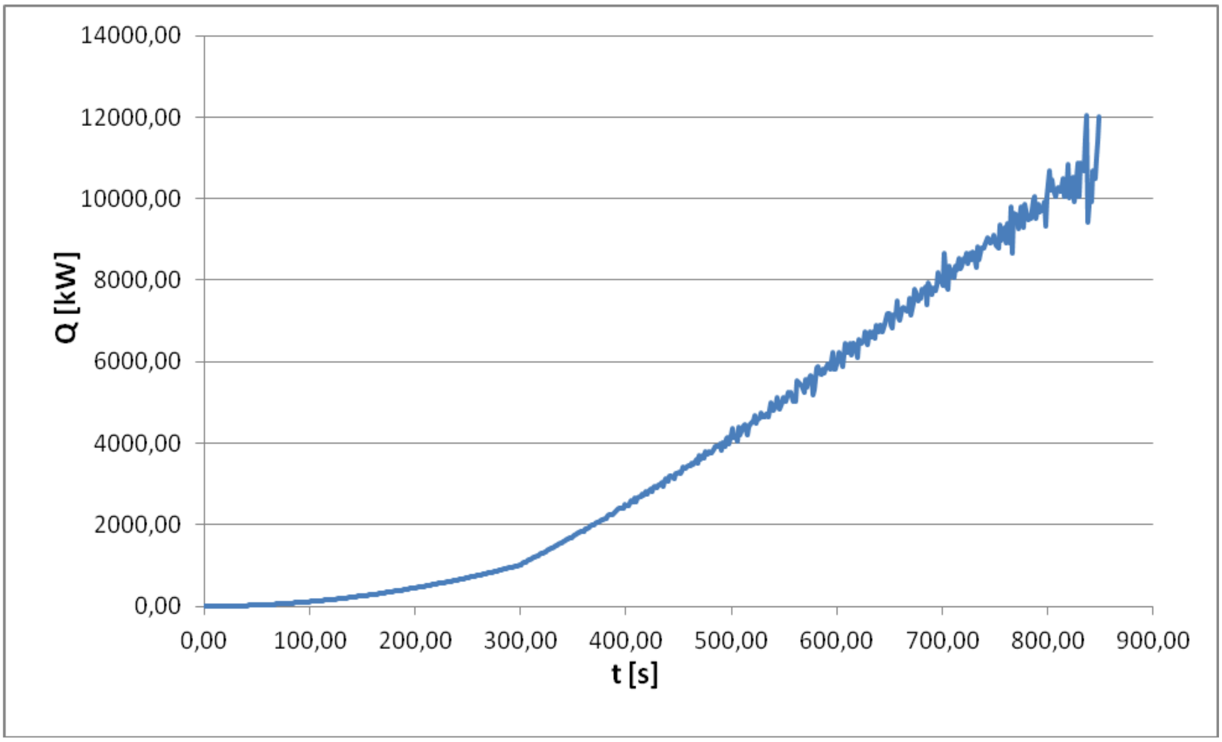
13. Simulations results

Results from three (A2, A3, A5) most demanding scenarios were selected from all seven analysed fire scenarios. The location of the fire in each fire scenario is marked on figure 4-7.

13.1 Unsprinklered fire curve

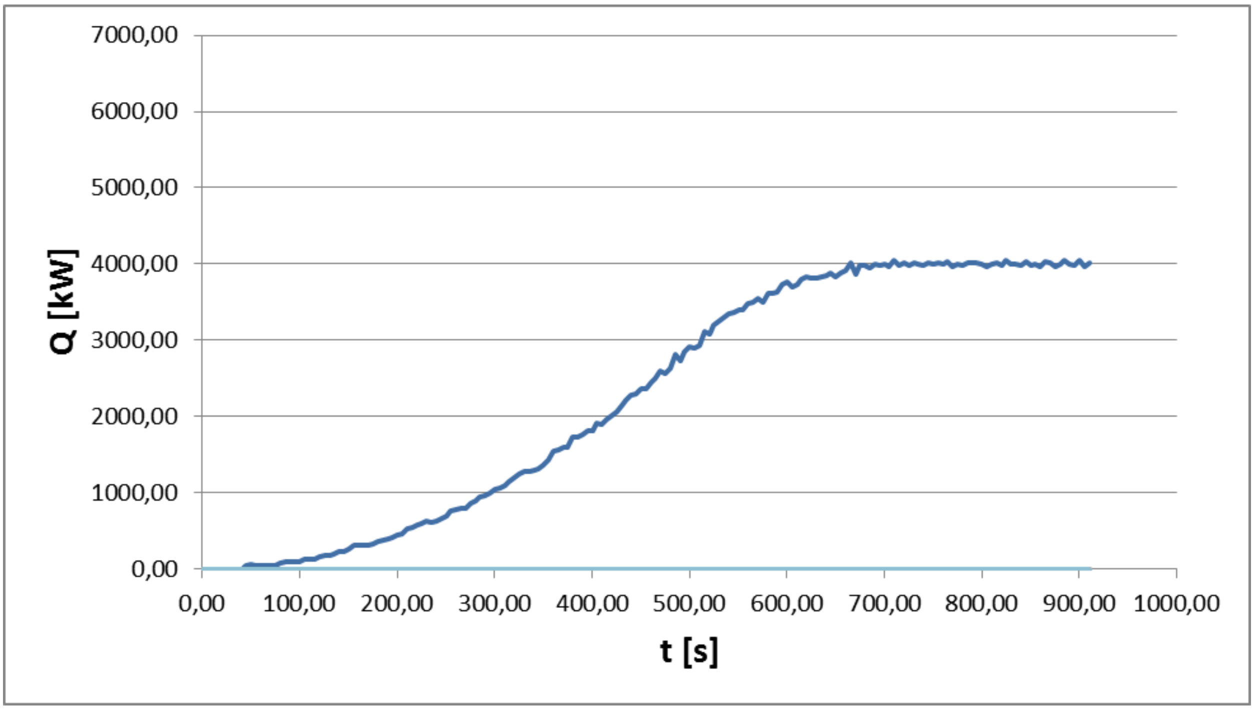


Graph 2. Fire growth rate for two burning cars – total HRR of 8 MW.

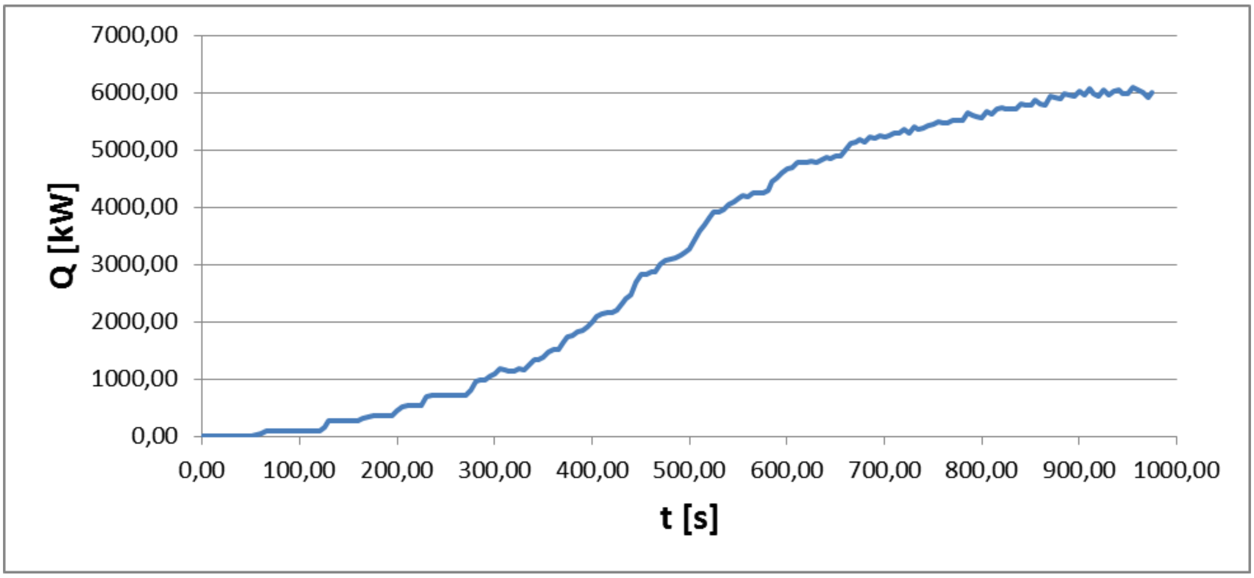


Graph 3. Fire growth rate for four burning cars – total HRR of 12 MW.

13.2 Sprinklered fire



Graph 4. Fire curve for one burning car with sprinkler protection – total HRR of 4 MW.

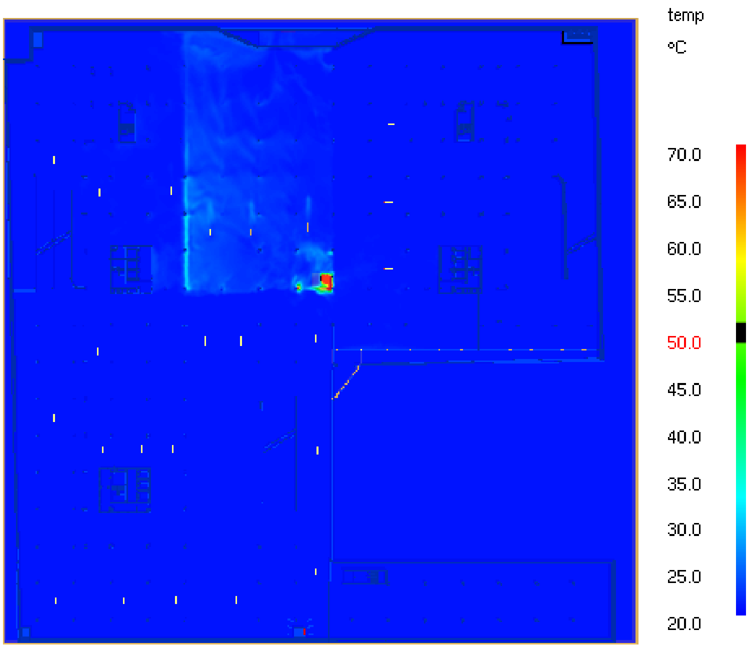
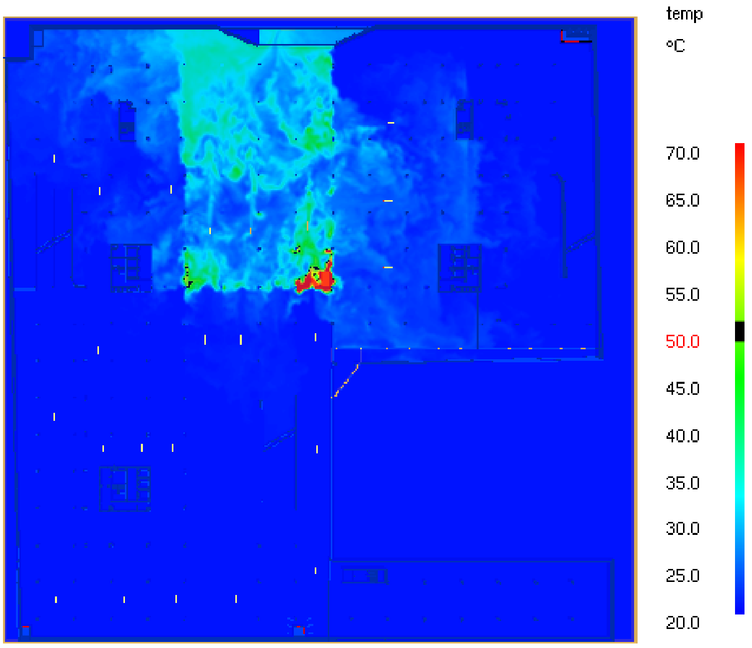


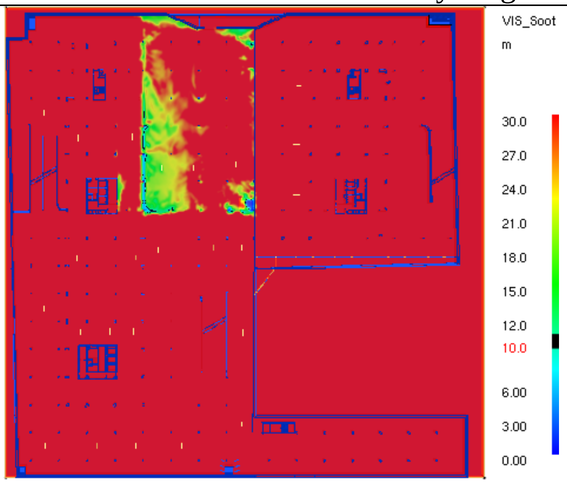
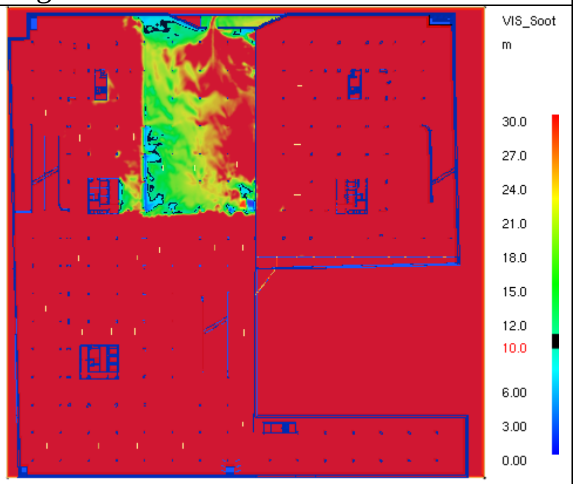
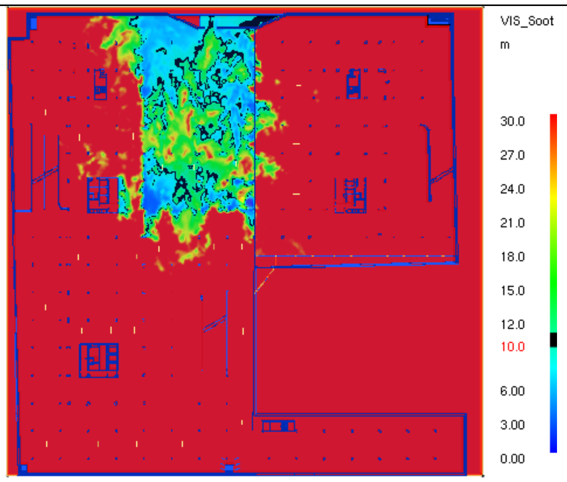
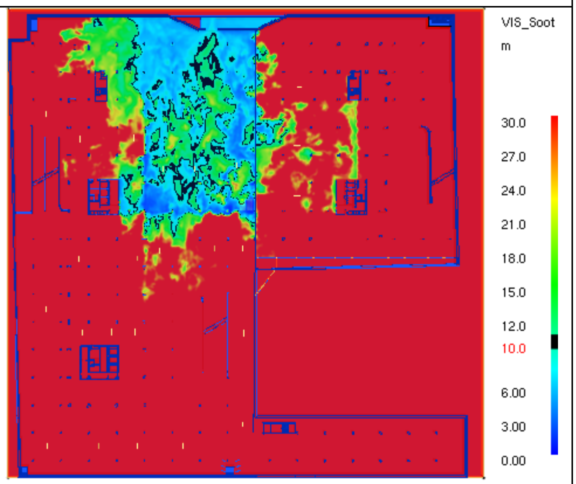
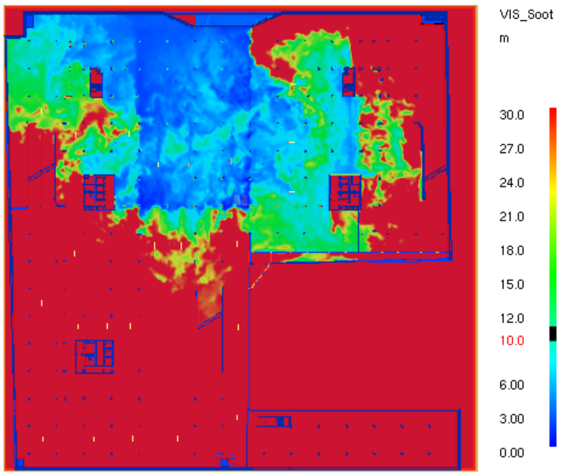
Graph 5. Fire curve for two car stacker with sprinklers protection – total HRR of 6 MW.

The simulation results are presented in following sections 12.3 – 12..

13.3 Results of the simulation A2 performed for the system operating in the fire ventilation mode. CASE 1A - Unsprinklered, without compartementation

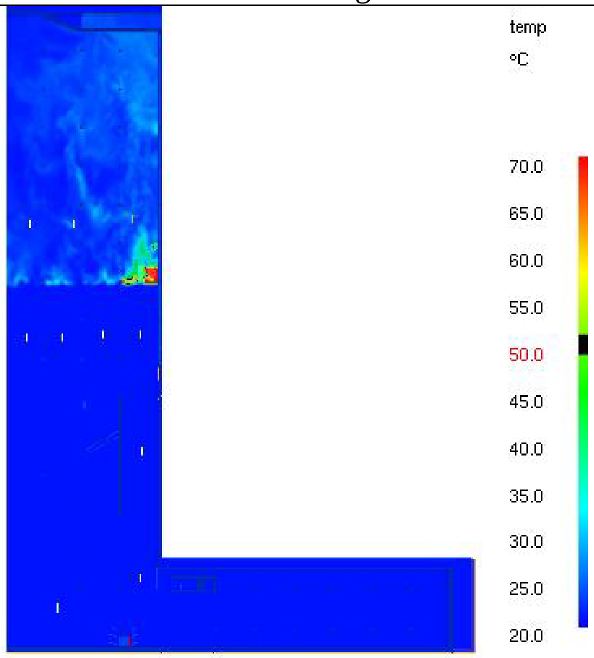
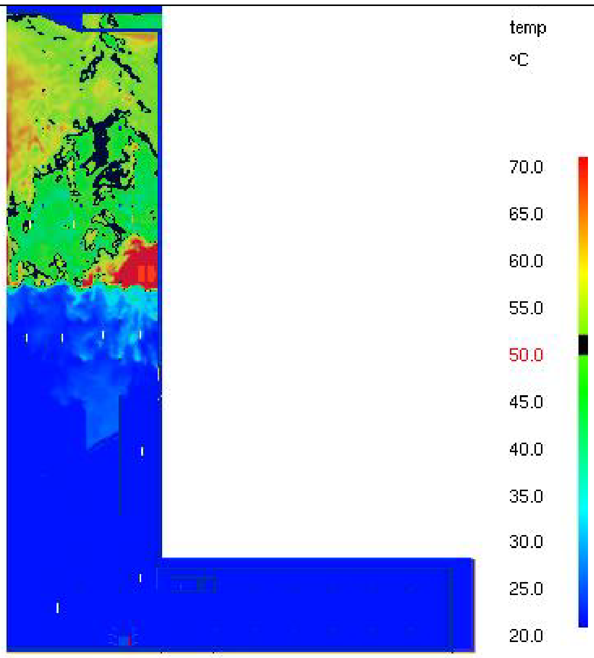
A detailed description of the fire ventilation system operation assumed in simulation A2 for fire located in the car park on storey „-2” was shown in point 3.2 and figure 1.

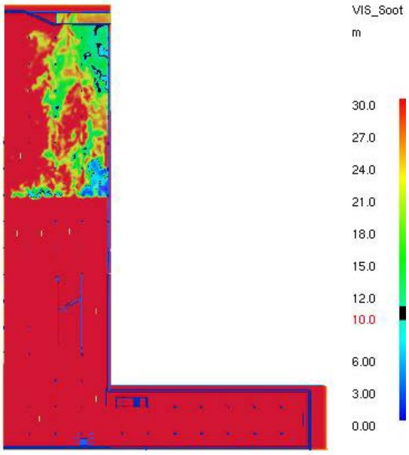
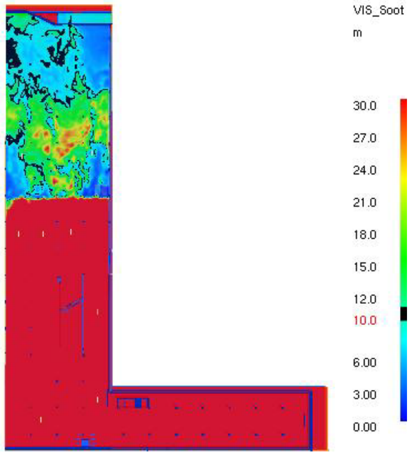
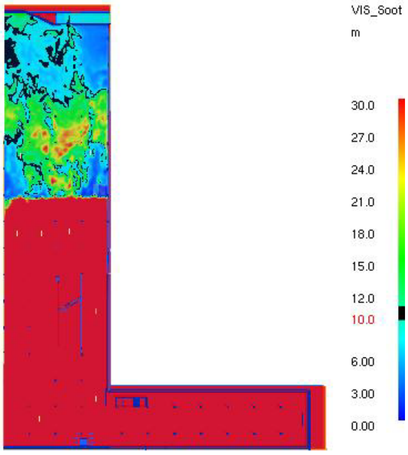
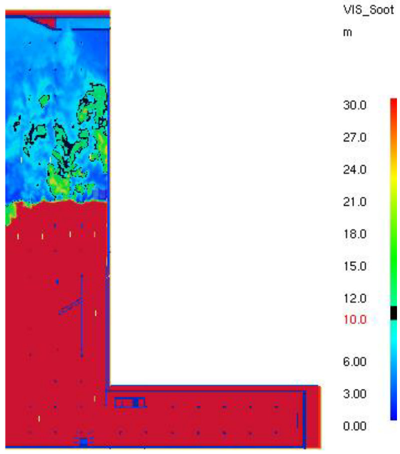
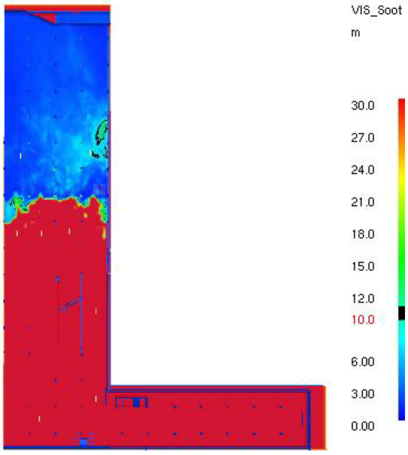
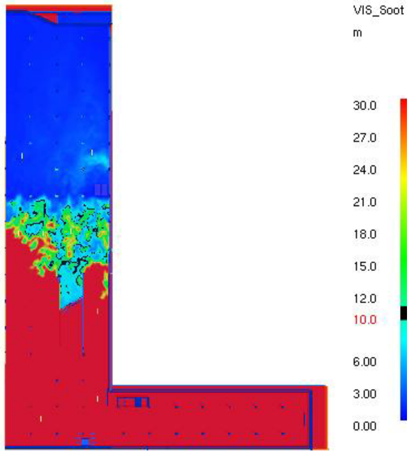
<table>
<tr><th colspan="2">A2 fire in the car park in smoke detection zone SZ2</th></tr>
<tr><th>Time</th><th>Temperature distribution at the height of 1,8 m</th></tr>
<tr><td>T=300 s</td><td>
</td></tr>
<tr><td>T=600s</td><td>
</td></tr>
</table>

A2 fire in the car park in smoke detection zone SZ2		
	Visibility range at the height of 1.8 m	
		
Time	**T=240s**	**T=300s**
		
Time	**T=360s**	**T=420s**
		
Time	**T=600s**	**T=900s**

13.4 Results of the simulation A2 performed for the system operating in the fire ventilation mode. CASE 2A - Unsprinklered, with compartmentation

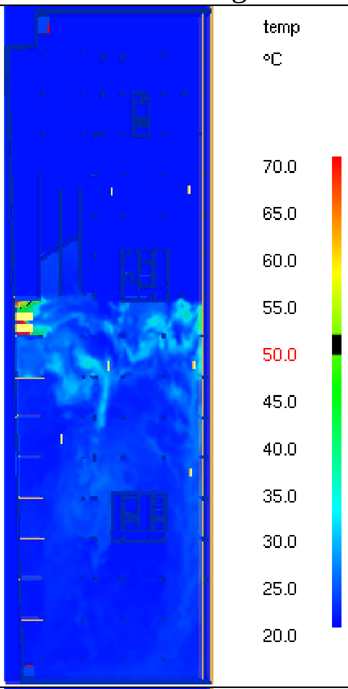
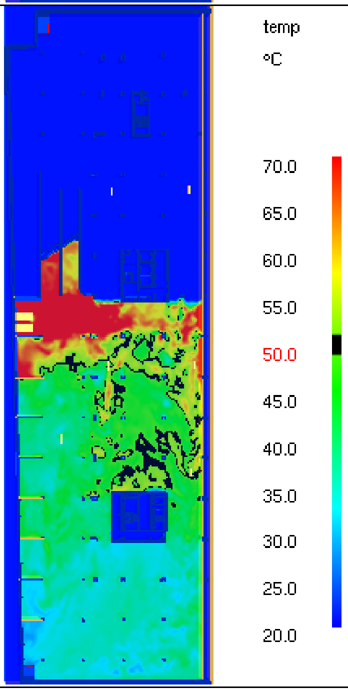
A detailed description of the fire ventilation system operation assumed in simulation A2 for fire located in the car park on storey „-2” was shown in point 3.2 and figure 2.

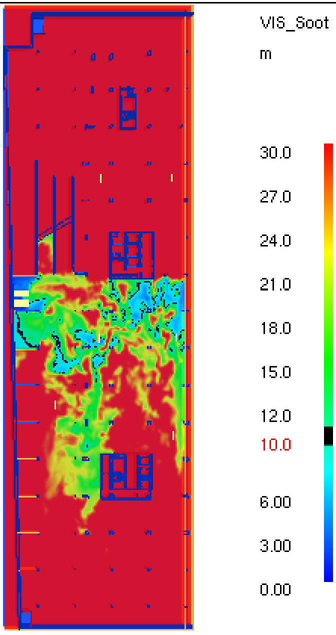
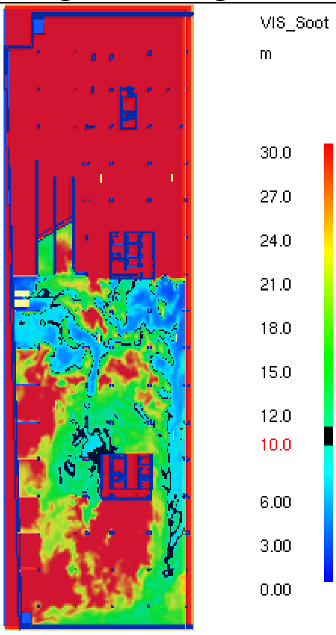
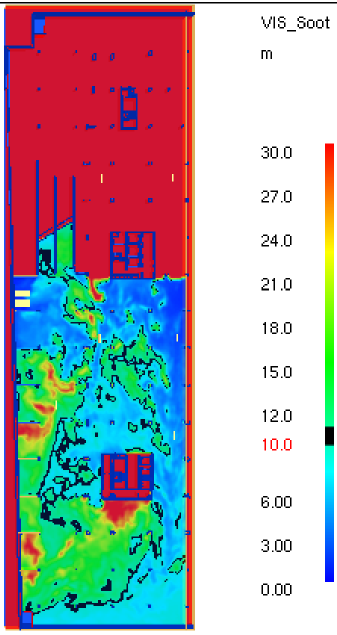
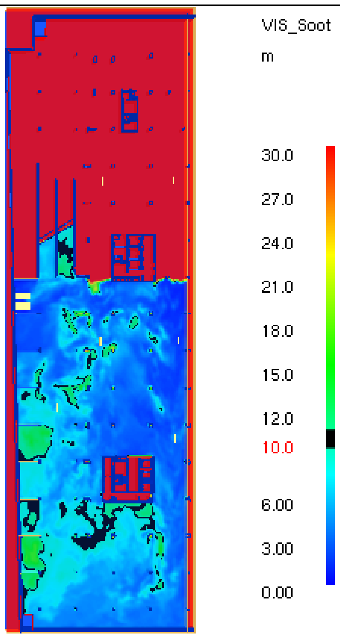
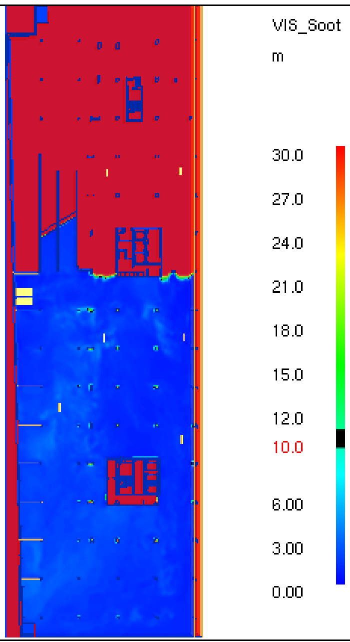
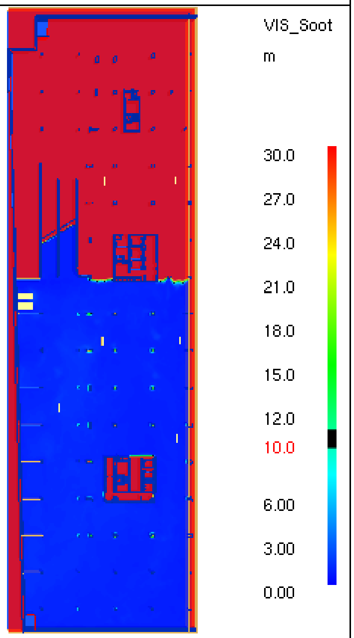
A2 fire in the car park in smoke detection zone SZ2	
Time	Temperature distribution at the height of 1.8 m
T=300s	
T=900s	

<table>
<tr><td colspan="3">A2 fire in the car park in smoke detection zone SZ2</td></tr>
<tr><td></td><td colspan="2">Visibility range at the height of 1.8 m</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=240s</td><td>T=300s</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=360s</td><td>T=420s</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=600s</td><td>T=900s</td></tr>
</table>

13.5 Results of the simulation A5 performed for the system operating in the fire ventilation mode - Unsprinklered, with compartmentation

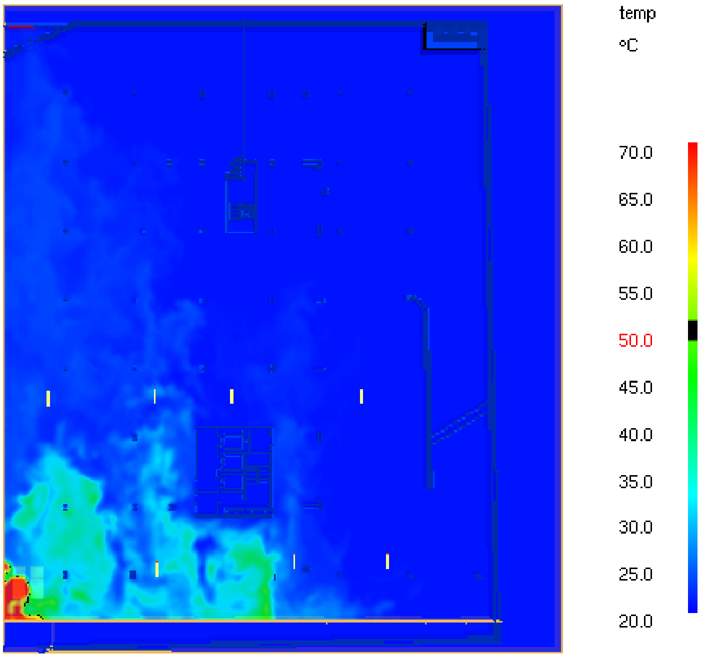
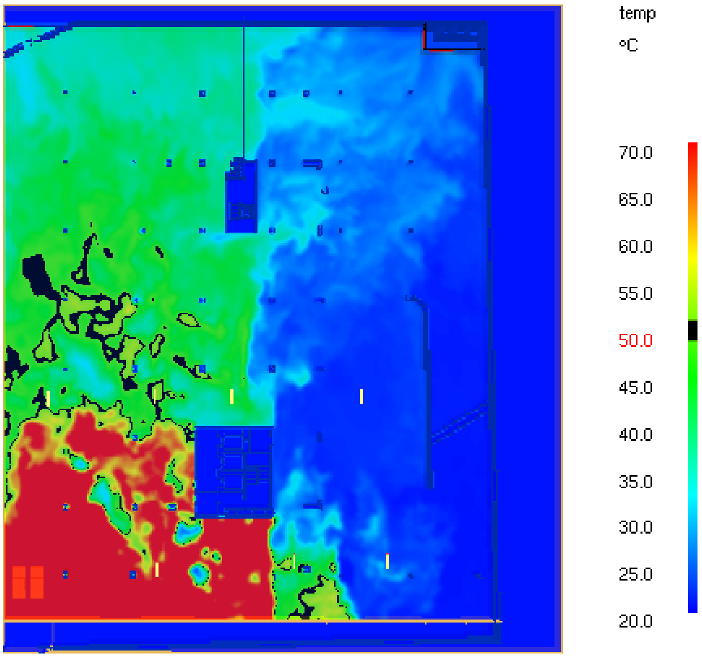
A detailed description of the fire ventilation system operation assumed in simulation A2 for fire located in the car park on storey „-2” was shown in point 3.2 and figure 2.

A5 fire in the car park in smoke detection zoneSZ5	
Time	Temperature distribution at the height of 1.8 m
T=300s	
T=900s	

<table>
<tr><td colspan="4">A5 fire in the car park in smoke detection zoneSZ5</td></tr>
<tr><td></td><td colspan="3">Visibility range at the height of 1.8 m</td></tr>
<tr><td></td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=240s</td><td>T=300s</td><td>T=360s</td></tr>
<tr><td></td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=420s</td><td>T=600s</td><td>T=900s</td></tr>
</table>

13.6 Results of the simulation A3 performed for the system operating in the fire ventilation mode. CASE 2A - Unsprinklered, with compartmentation

A detailed description of the fire ventilation system operation assumed in simulation A3 for fire located in the car park on storey „-2” was shown in point 3.2 and figure 2.

A3 fire in the car park in smoke detection zone SZ3	
Time	Temperature distribution at the height of 1.8 m
T=300s	
T=900s	

<table>
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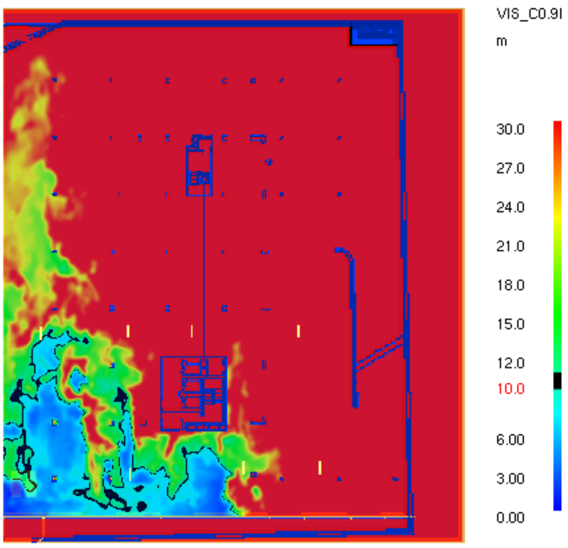
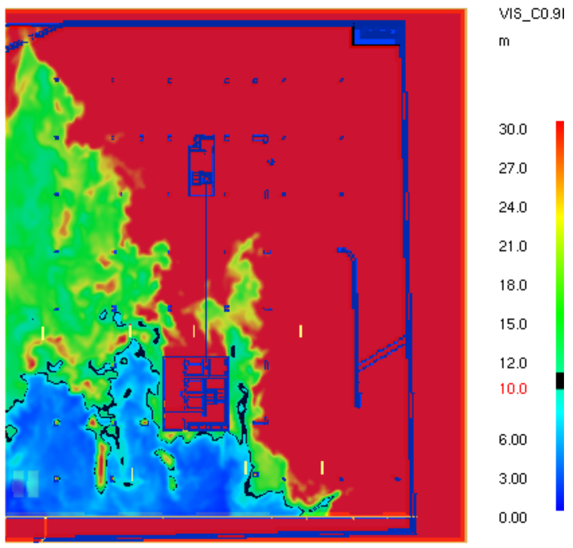
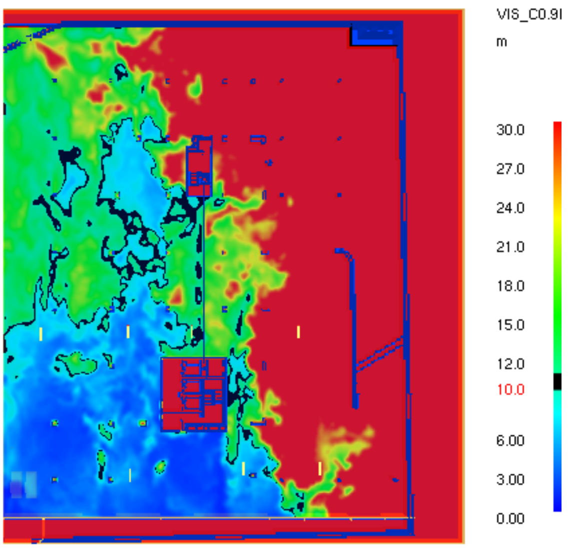
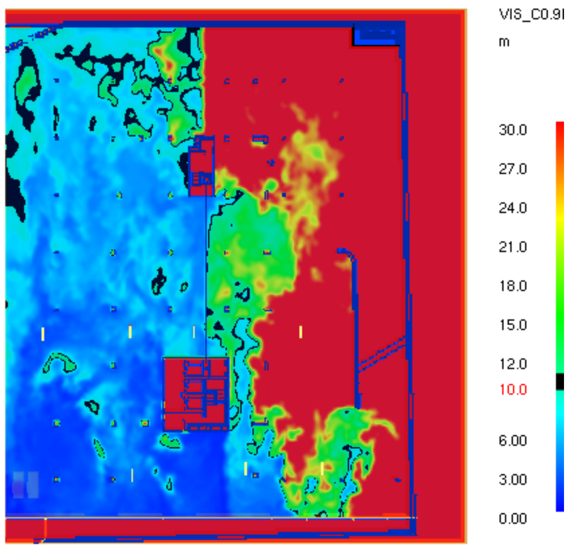
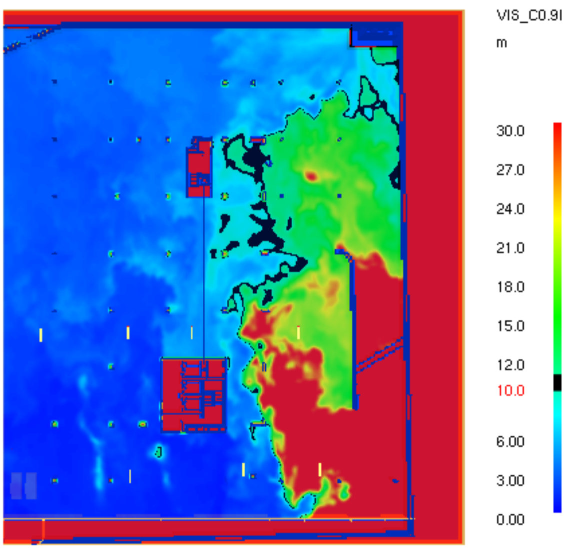
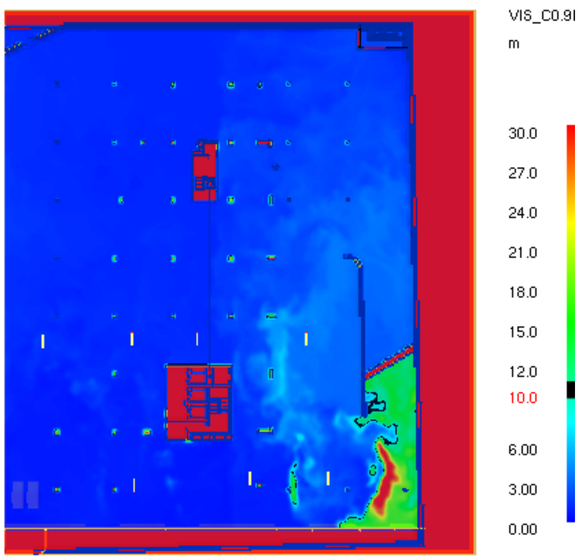
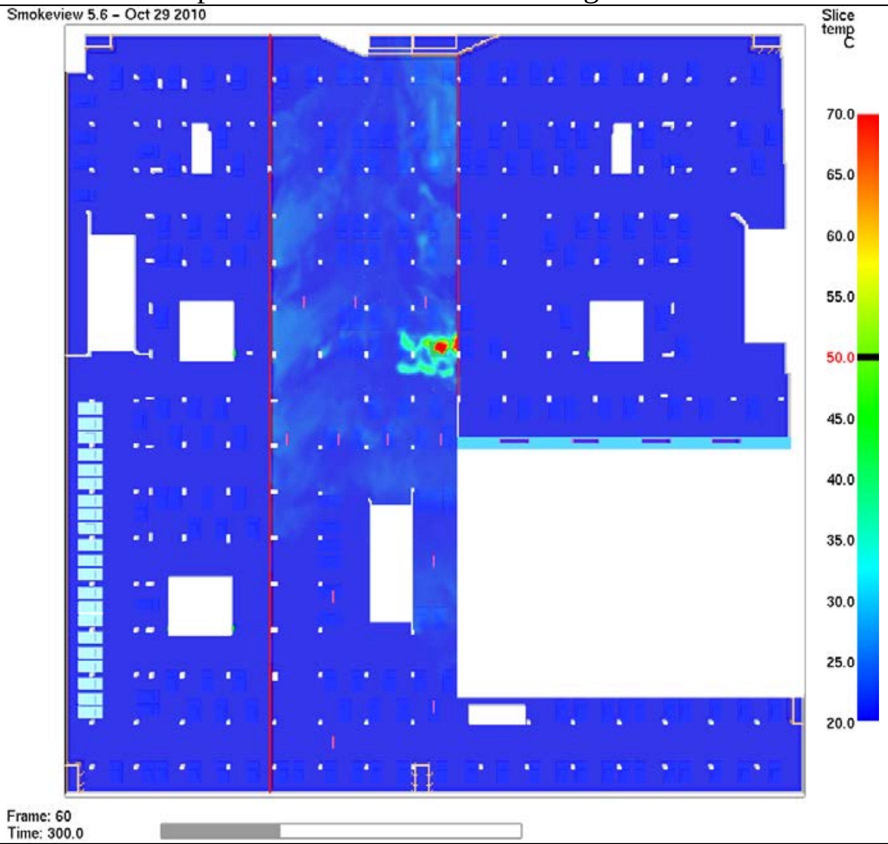
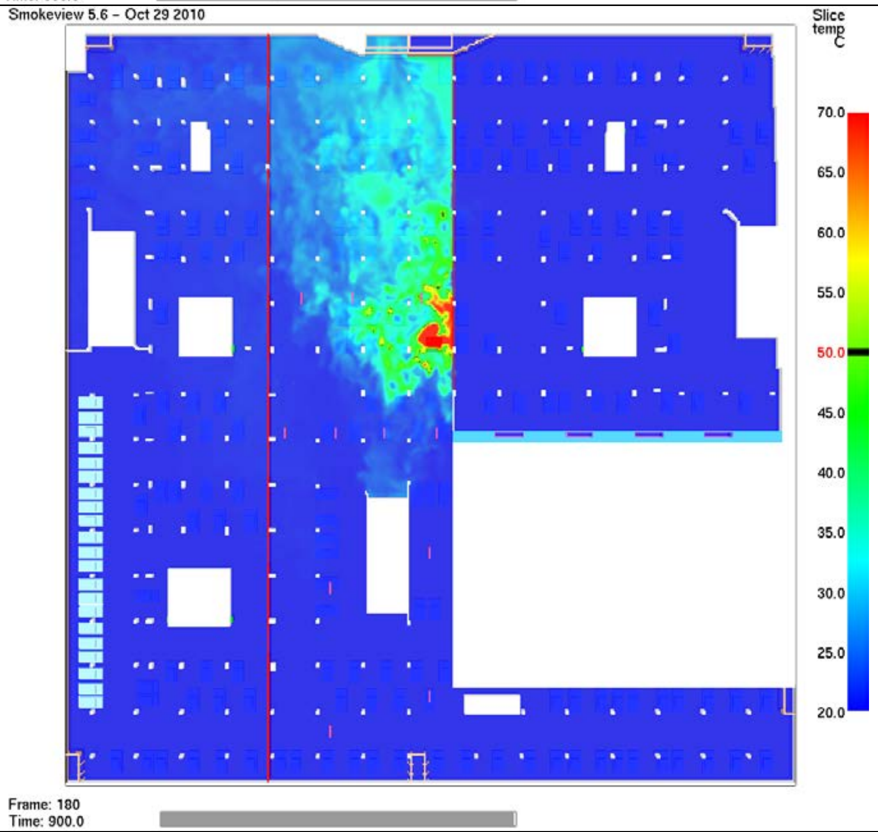
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=240s</td><td>T=300s</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=360s</td><td>T=420s</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=600s</td><td>T=900s</td></tr>
</table>

13.7 Results of the simulation A2 performed for the system operating in the fire ventilation mode. CASE 1B - Sprinklered

<table>
<tr><td colspan="2">A2 fire in the car park in smoke detection zone SZ2</td></tr>
<tr><td>Time</td><td>Temperature distribution at the height of 1.8 m</td></tr>
<tr><td>T=300s</td><td>
</td></tr>
<tr><td>T=900s</td><td>
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</table>

<table>
<tr><td colspan="3">Table 14. A2 fire in the car park in smoke detection zone SZ2</td></tr>
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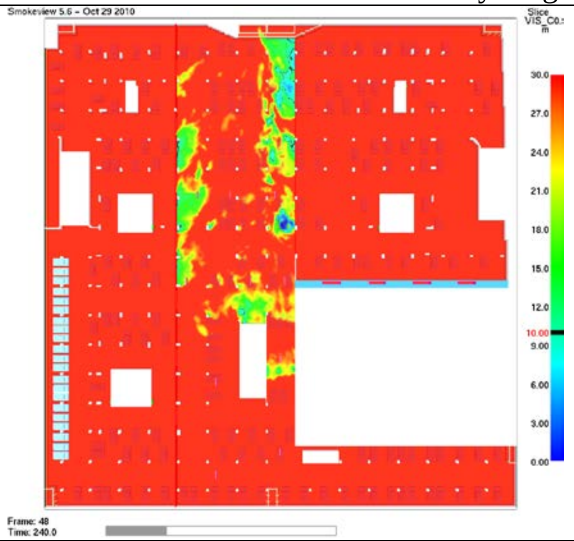
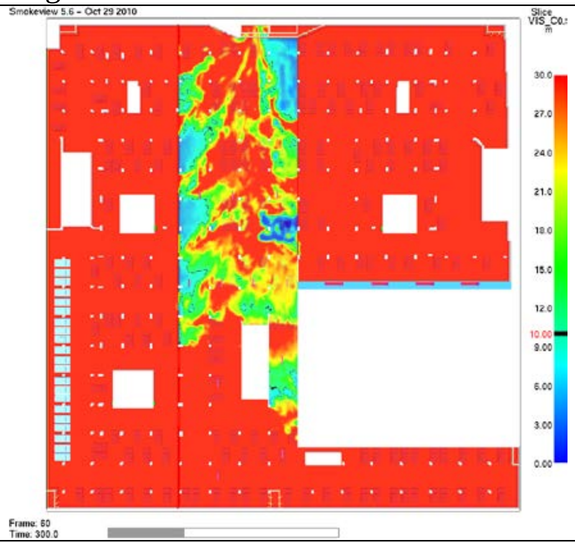
<tr><td></td><td>
</td><td>
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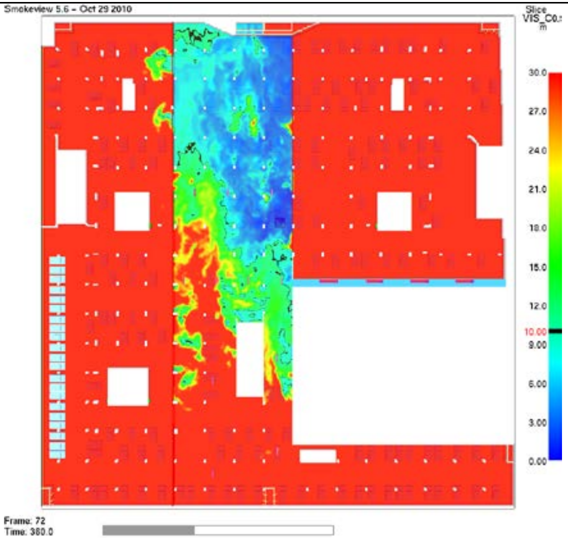
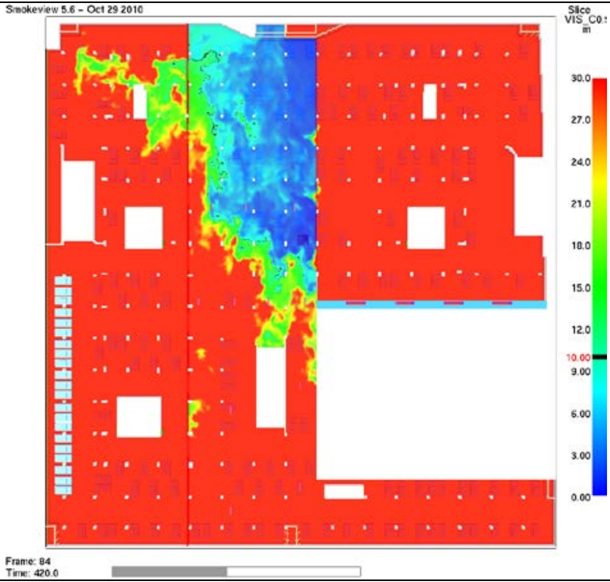
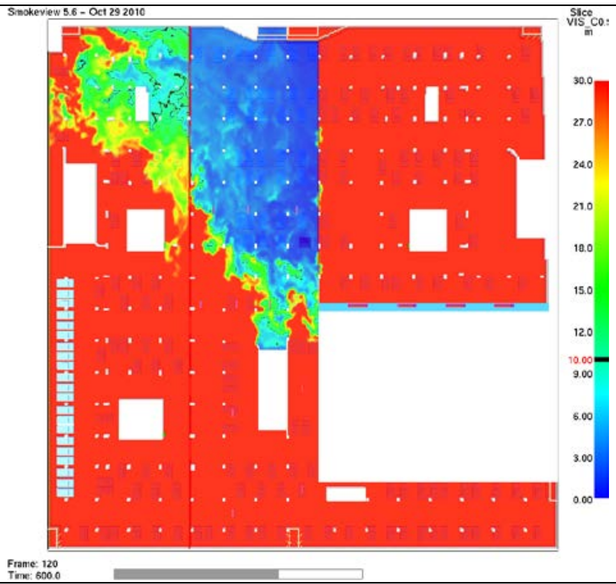
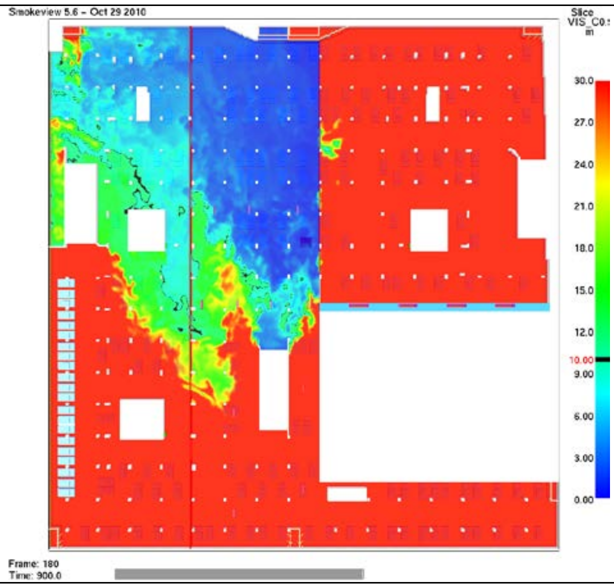
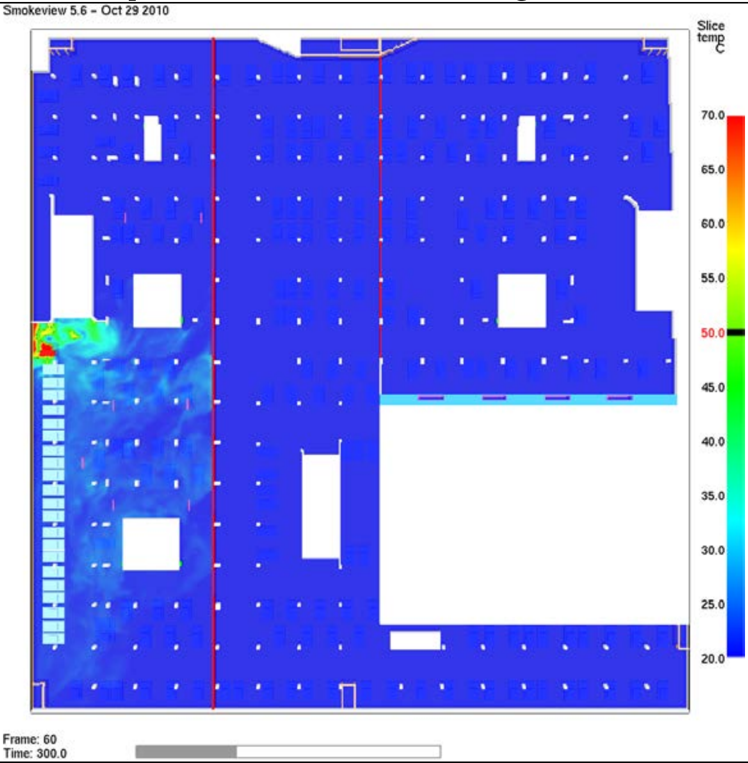
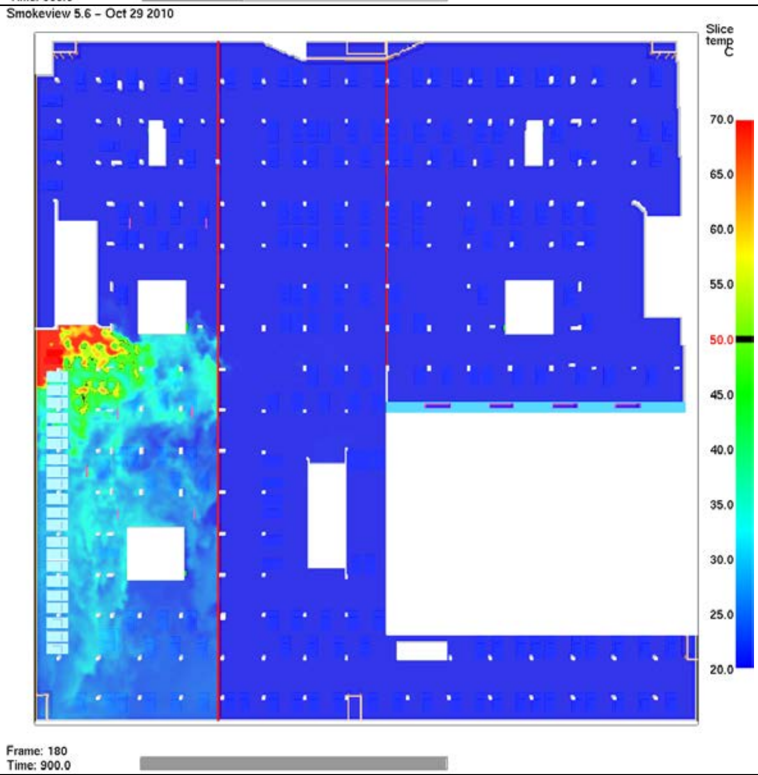
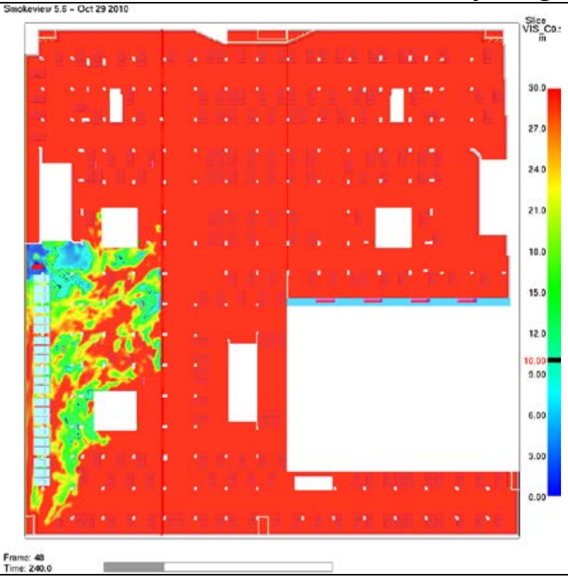
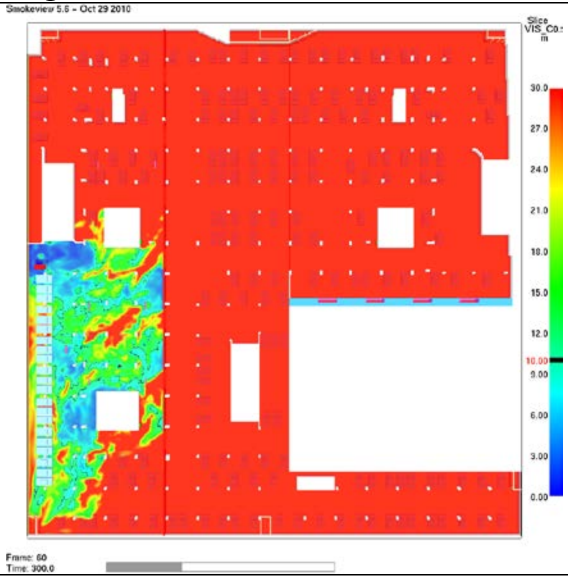
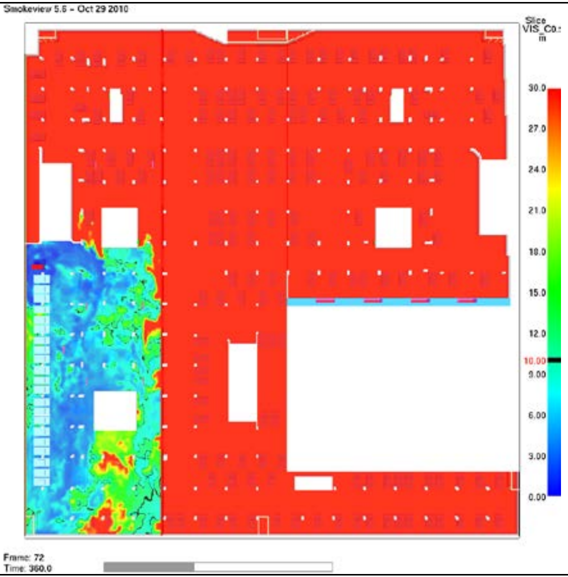
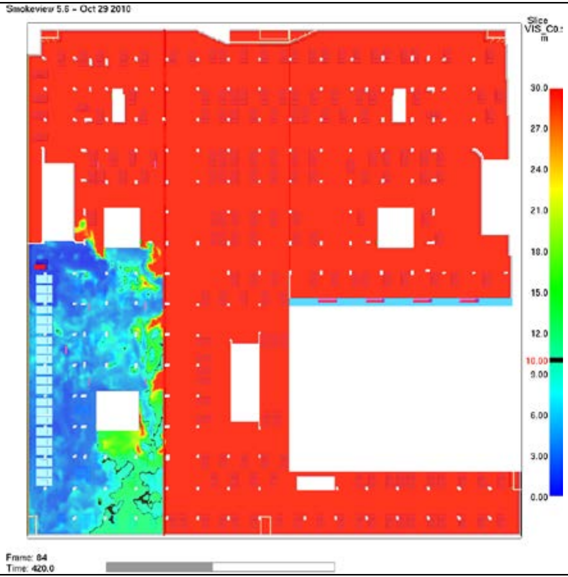
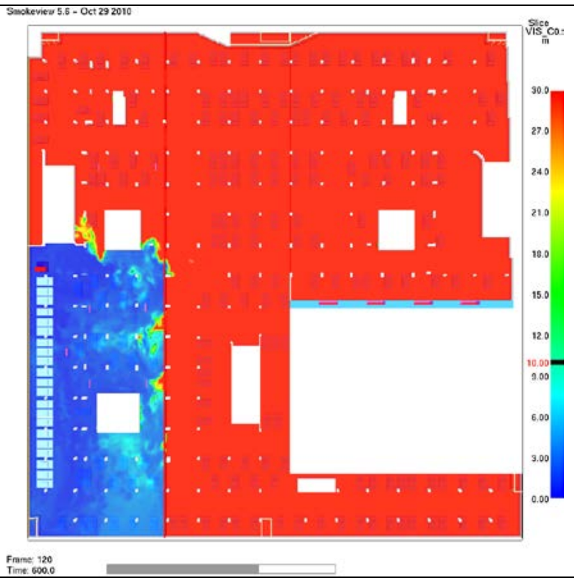
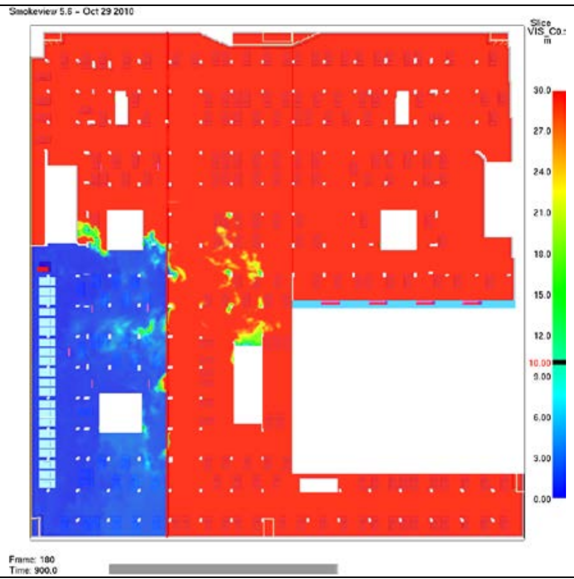
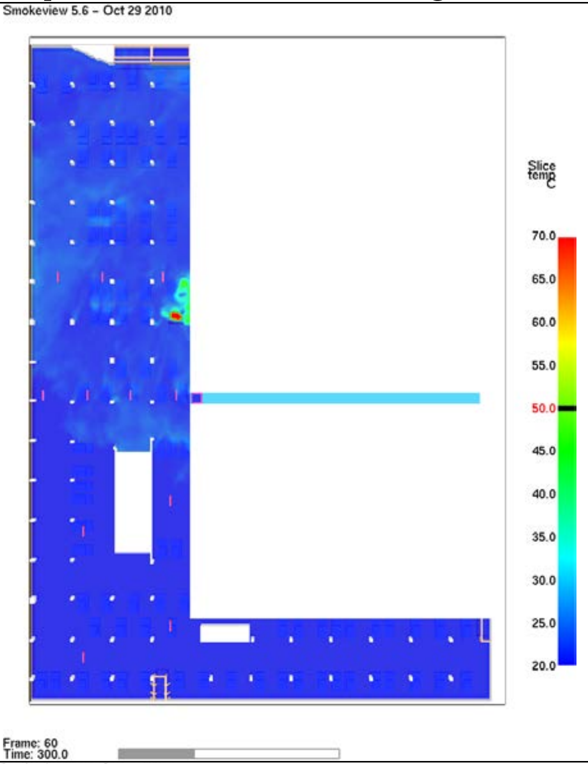
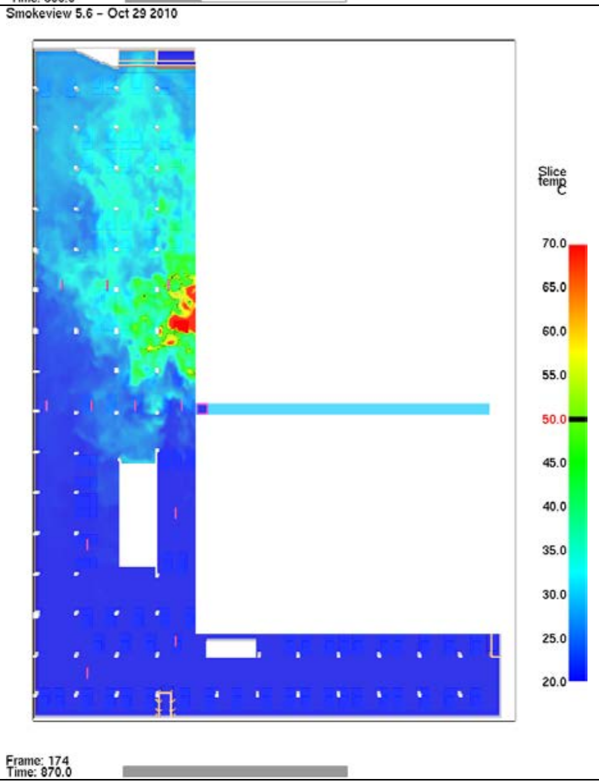
<tr><td>Time</td><td>T=240s</td><td>T=300s</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=360s</td><td>T=420s</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=600s</td><td>T=900s</td></tr>
</table>

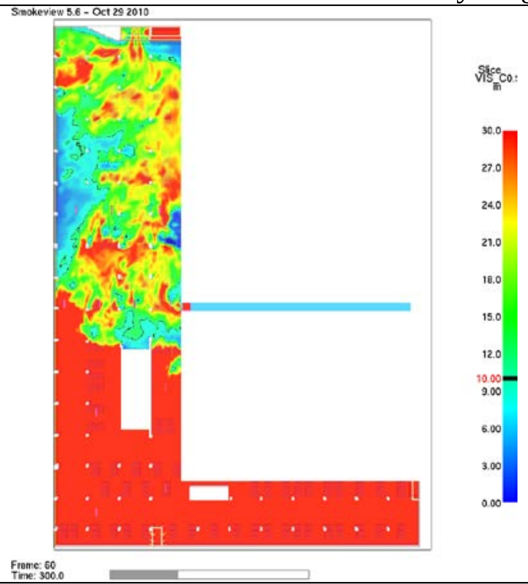
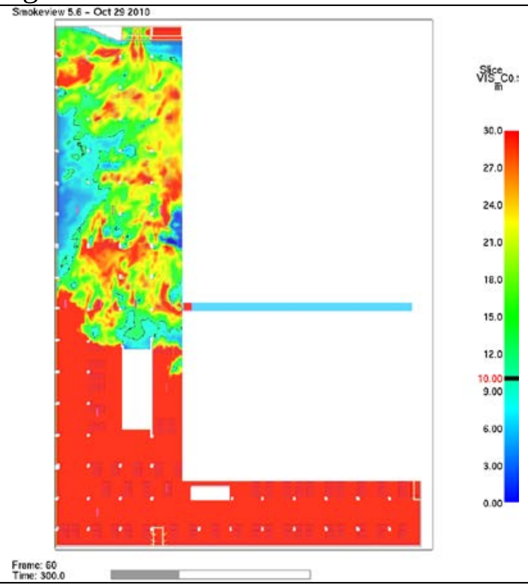
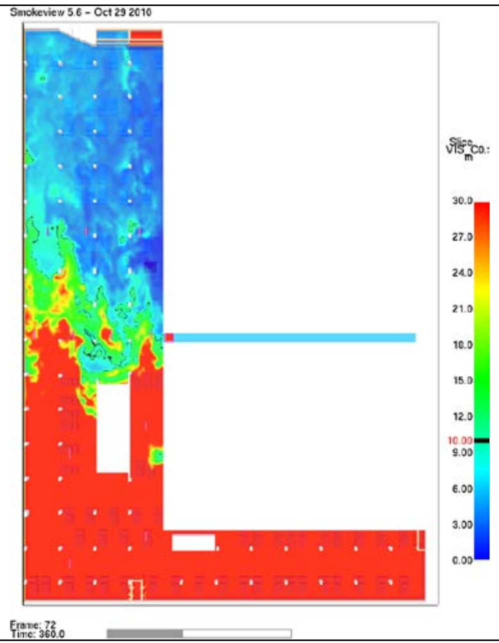
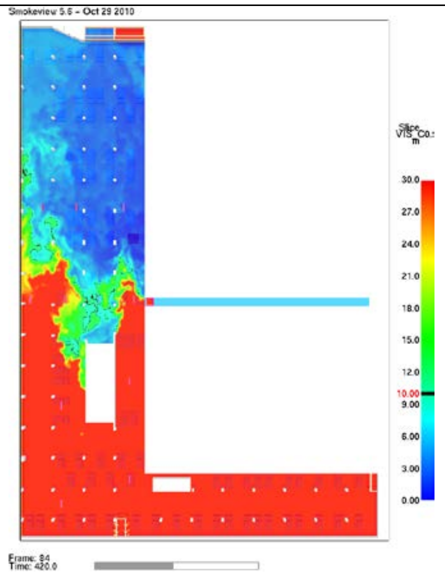
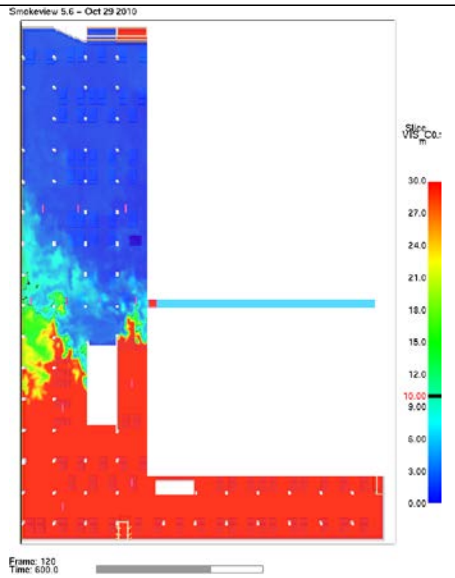
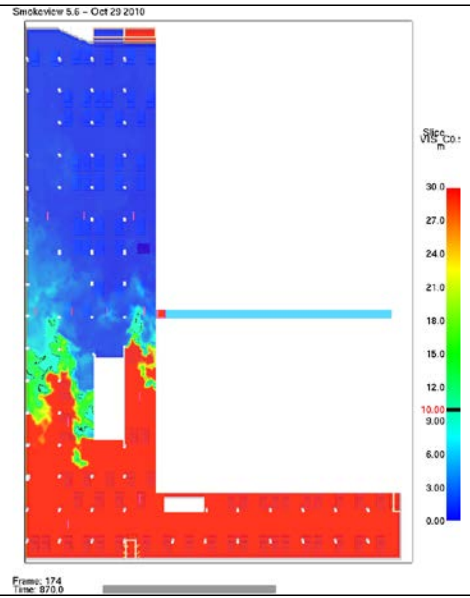
13.8 Results of the simulation A5 performed for the system operating in the fire ventilation mode. CASE 1B - Sprinklered

<table>
<tr><td colspan="2">A5 fire in the car park in smoke detection zone SZ5</td></tr>
<tr><td>Time</td><td>Temperature distribution at the height of 1.8 m</td></tr>
<tr><td>T=300s</td><td>
</td></tr>
<tr><td>T=900s</td><td>
</td></tr>
</table>

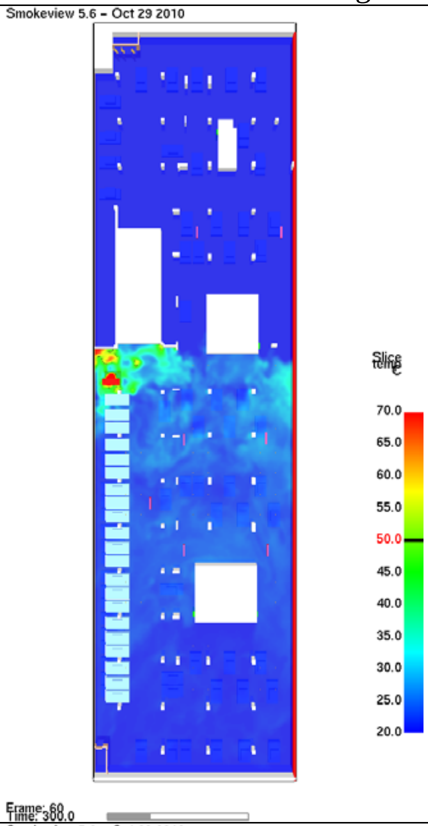
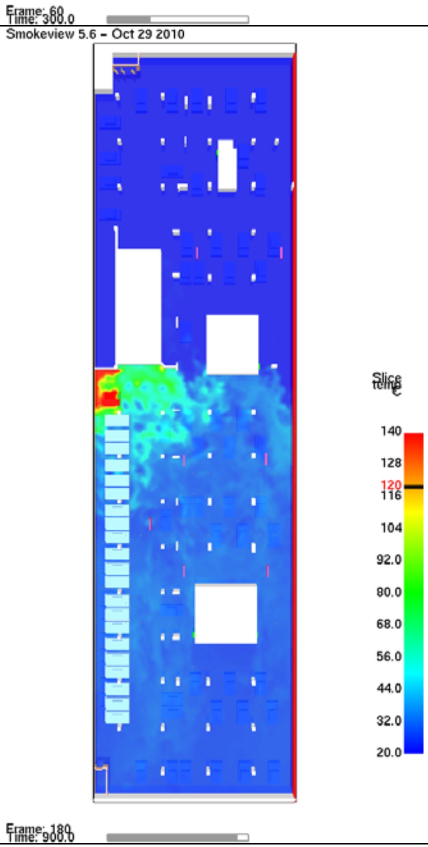
<table>
<tr><td colspan="3">A5 fire in the car park in smoke detection zone SZ5</td></tr>
<tr><td></td><td colspan="2">Visibility range at the height of 1.8 m</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=240s</td><td>T=300s</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=360s</td><td>T=420s</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=600s</td><td>T=900s</td></tr>
</table>

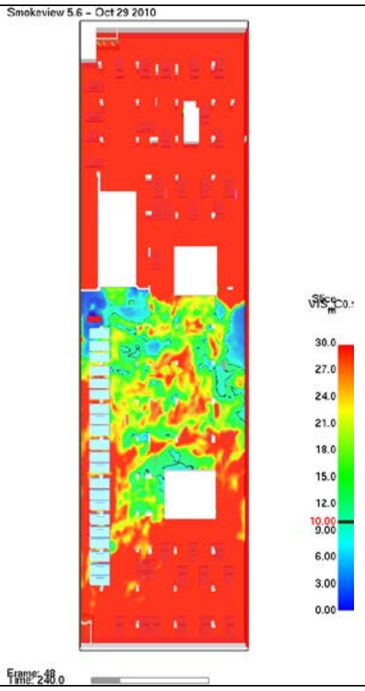
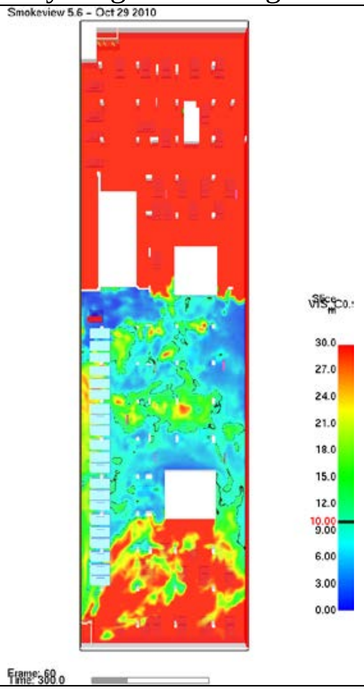
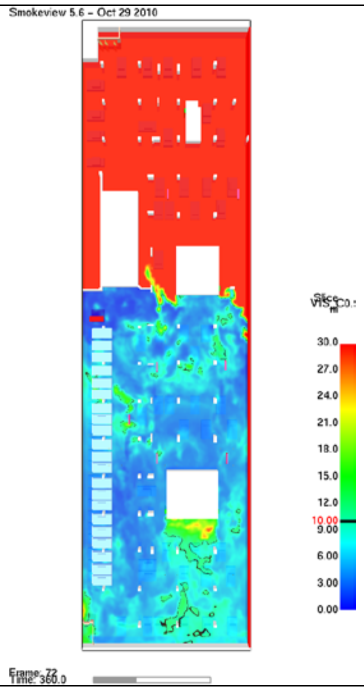
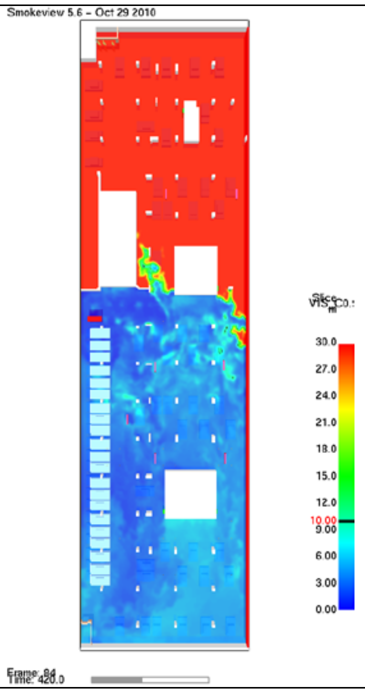
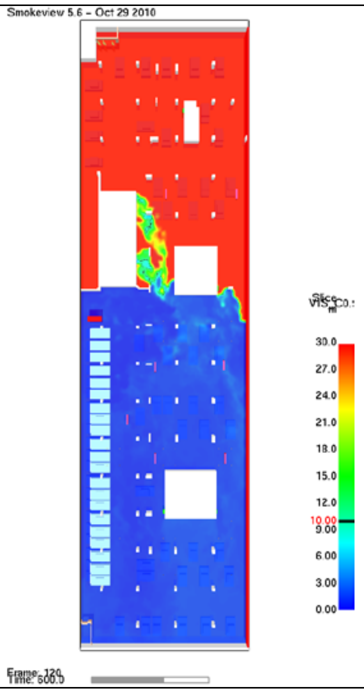
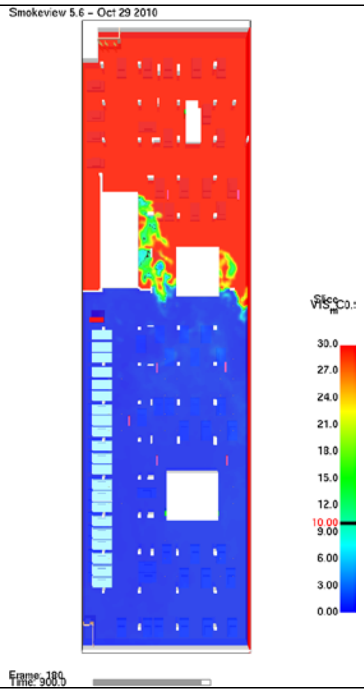
13.9 Results of the simulation A2 performed for the system operating in the fire ventilation mode. CASE 2B - Sprinklered

A2 fire in the car park in smoke detection zone SZ2	
Time	Temperature distribution at the height of 1.8 m
T=300s	
T=900s	

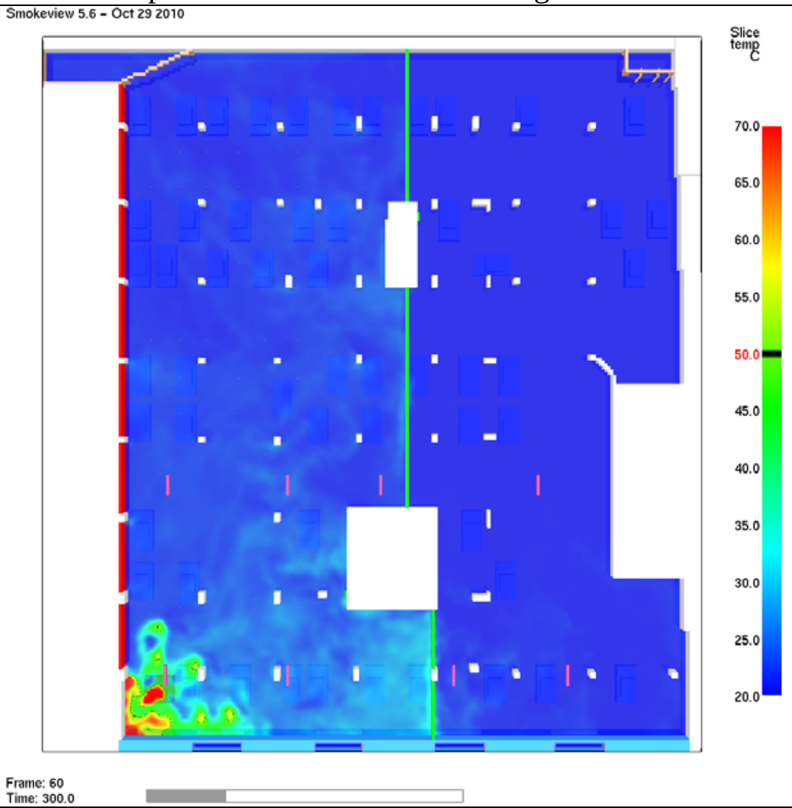
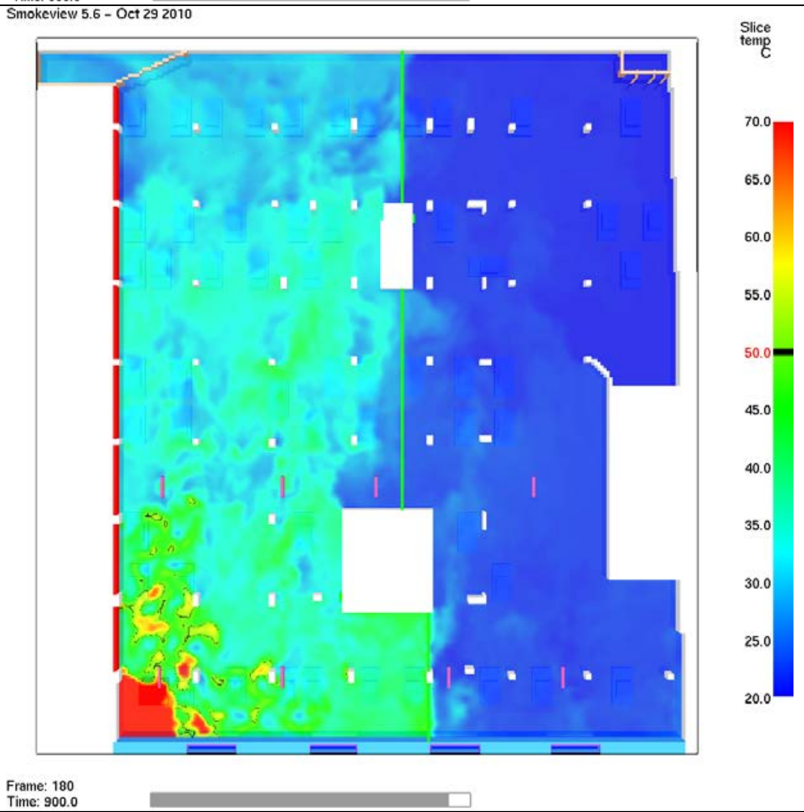
A2 fire in the car park in smoke detection zone SZ2		
	Visibility range at the height of 1.8 m	
		
Time	**T=240s**	**T=300s**
		
Time	**T=360s**	**T=420s**
		
Time	**T=600s**	**T=870s**

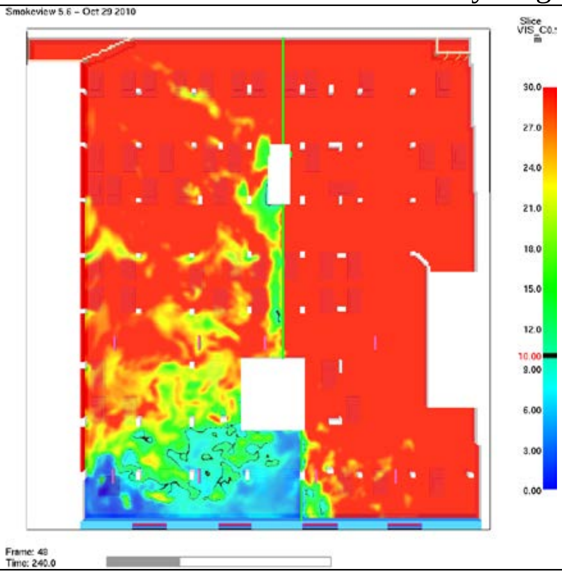
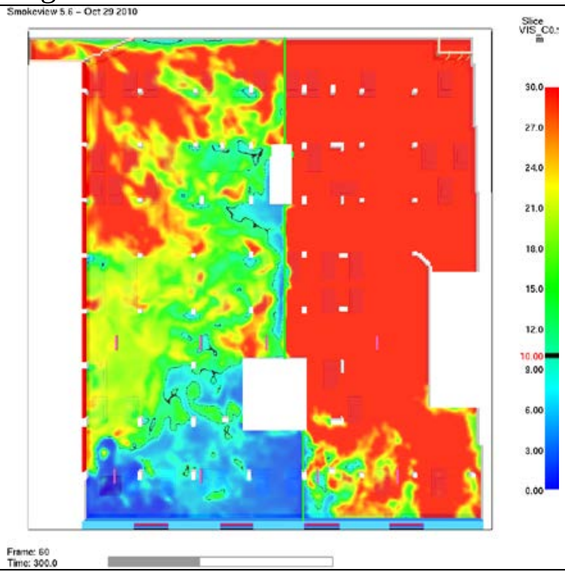
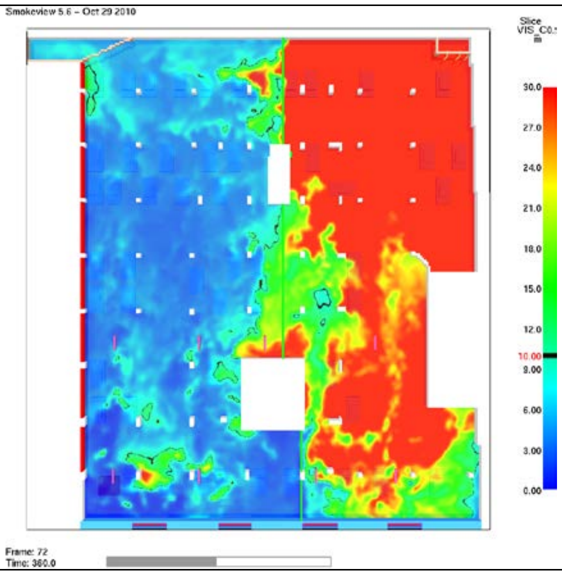
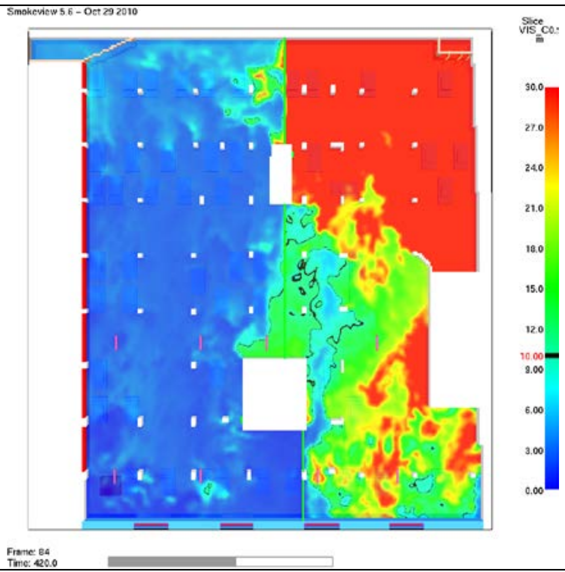
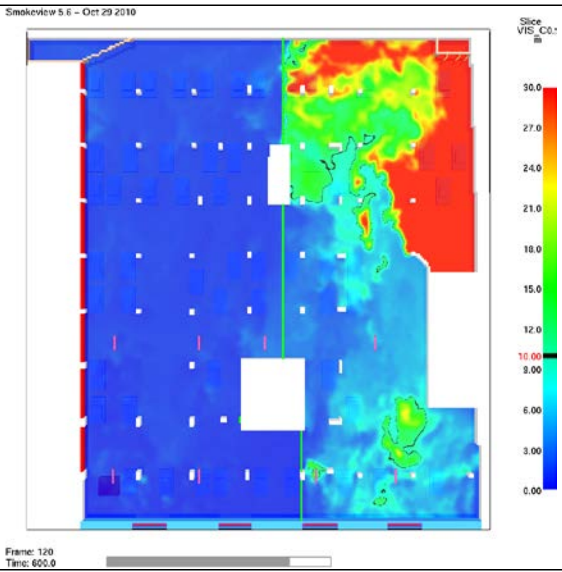
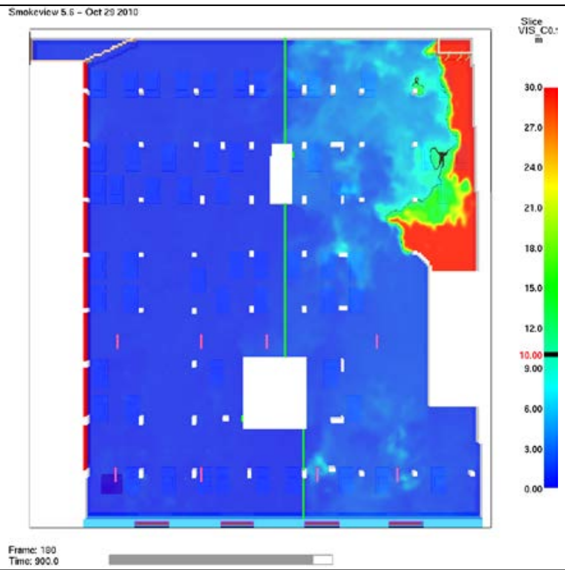
13.10 Results of the simulation A5 performed for the system operating in the fire ventilation mode. CASE 2B - Sprinklered

<table>
<tr><td colspan="2">A5 fire in the car park in smoke detection zone SZ5</td></tr>
<tr><td>Time</td><td>Temperature distribution at the height of 1.8 m</td></tr>
<tr><td>T=300s</td><td>
</td></tr>
<tr><td>T=900s</td><td>
</td></tr>
</table>

A5 fire in the car park in smoke detection zone SZ5			
	Visibility range at the height of 1.8 m		
			
Time	**T=240s**	**T=300s**	**T=360s**
			
Time	**T=420s**	**T=600s**	**T=900s**

13.11 Results of the simulation A3 performed for the system operating in the fire ventilation mode. CASE 2B - Sprinklered

A3 fire in the car park in smoke detection zone SZ3	
Time	Temperature distribution at the height of 1.8 m
T=300s	
T=900s	

<table>
<tr><td colspan="3">A3 fire in the car park in smoke detection zone SZ3</td></tr>
<tr><td></td><td colspan="2">Visibility range at the height of 1.8 m</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=240s</td><td>T=300s</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=360s</td><td>T=420s</td></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>Time</td><td>T=600s</td><td>T=900s</td></tr>
</table>

14. Conclusion and Summary

At the beginning of this exercise it was assumed that neither fire compartmentation nor smoke separation will be provided so that the fully open-space geometry of the car park is retained. However along the preliminary studies it was found that even very high smoke extract rates did not ensure good results (some spread to no more than 1/4 of the car park at the time of fully developed fire) regardless of whether sprinklered or unsprinklered case was considered.
It was assumed that the smoke spread should be limited as much as possible but at reasonable rates of extraction. A brief economic judgement of the proposed solutions was taken during the course on which basis the decision was made that the car park should be provided with a combination of passive and active fire protection measures.

The following conclusions can be drawn from the performed CFD computer simulations:

1. The analysis of the temperature and visibility distribution at the height of 1.8 m above FFL shown that in the analysed fire scenarios the threshold values of temperature 60 ^{o}C (50 ^{o}C from simulation) and visibility below 10 m on evacuation routes and near the evacuation exits are not exceeded within the required time for evacuation (RSET= 300s) in large extent.

2. For fully developed design fire in cases without sprinklers and compartmentation the smoke propagation exceeded the smoke control zone where fire occurs, so for the unsprinklered scenarios, it is advised that the car park area should be fire compartmented (internally subdivided).

3. Conditions for fire-fighters intervention in case of temperature range below threshold of 100 ^{o}C measured at 1.5 m at 900 s simulation time in all shown sprinklered cases and the unsprinklered cases with compartmentation allow for access within 10 m to the bed of fire

4. It is noted that the longest dead end travel distance is at the very low bottom right corner (60 m). Although it complies with the national fire requirements and regulations, it would be advised to reduce the travel distance by moving the staircase to the far end (cul de sac) or to reverse the staircase so that the travel distance is shortened or no dead end is present.

5. For sprinklered scenarios much lower smoke extract capacities are required. Also lower temperature rating for exhaust fans is possible.

6. For the unsprinklered scenario, provision of the walls separating the stacker platforms provided good result in terms of protection against uncontrolled fire growth and high temperature range at fully developed fire

7. In both cases (2A unsprinklered and 2B sprinklered) best results were achieved for rather high degree of separation dividing the car park into separated zones. Also much lower extraction volumes were sufficient in those cases. However it is noted that in this case a direct visual contact of the occupants present at the car park with the fire or exits will be limited. This can result with necessity of use an active evacuation signage system so that no occupants would evacuate through the smoke/fire zone where fire occurred. Nevertheless it brings a higher degree of safety, as in both cases, smoke propagation is limited mostly to the smoke control zone where the fire occurred.

The main purpose of the analysis is achieved by the provision of the results which meet the fire safety requirements for each case and design approach (unsprinklered vs sprinklered, fire compartmented vs not internally compartmented). A careful analysis including the cost and technical implications of all designs should be performed to determined which design approach is most beneficial. Depending on the sum of all elements and fire safety measures for each design, the cost can vary and thus impact the final choice of the design.

Large number of simulations has been performed in course of this exercise. In addition to the need for best results research a direct comparison of three different software versions were conducted. It is noted, that except the significantly extended calculation time, which is the biggest concern for its use, a FDS ver. 632 provided better results (less extensive smoke spread in comparison to ver. 553. (for exactly identical simulations, scenarios and parameters). In most cases the airflow and smoke propagation is represented in more natural and expected way in FDS ver. 632. This directly affected the results in terms of visibility and temperature. It brings to the conclusion, that for designs based on the older versions, an additional safety factor is included in the design, as the results were less optimistic. A more in-depth research would be beneficial, including comparison to real scale experiments i.e. based on the hot smoke tests, in order to verify those findings.

7. Literature

1. PD 7974 -6: 2004 The application of fire safety engineering principles to fire safety design of buildings. Part6: Human Factors: Life safety strategies – Occupant evacuation, behaviour and condition (SUB-system 6).
2. BS 7346-5: 2005 Components for smoke and heat control systems – functional recommendations and calculation methods for smoke and heat exhaust ventilation system, employing time-dependent design fires – Code of practice.
3. BS 7346-7: 2013 Components for smoke and heat control systems – functional recommendations and calculation methods for smoke and heat control systems for covered car parks.
4. Fire Dynamics Simulator Version 6 – Technical Reference Guide, NIST 2016.
5. Fire Dynamics Simulator Version 6 – Users Guide, NIST 2016.
6. Jansens M. “Heat release rate of motor vehicles” Fifth International Conference on Performance-Based Codes and Fire Safety Design Methods, Luxemburg October 2004.
7. Bukowski R. “The basis for egress provisions in U.S. building codes” NIST Building and Fire Research Laboratory, Gaithersburg, Maryland 20899 USA.
8. Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, Volume 7: Fire Dynamics Simulator, Final Report, May 2007, NUREG-1824.
9. Brzezińska D. “Projektowanie systemów wentylacji pożarowej, a nowelizacja przepisów techniczno-budowlanych” Ochrona Przeciwpożarowa 4/2009. („Designing fire ventilation systems, and the amendment of building regulations”)
10. VDI 6019-1 Engineering methods for the dimensioning of systems for the removal of smoke from buildings, Fire curves, verification of effectiveness.
11. Li Y, Spearpoint M J. Analysis of vehicle fire statistics in New Zealand parking buildings. Fire Technology, Vol. 43, No. 2, 2007, pp.93-106.