Smoke Management in Subway Stations Due to Train Arson Fire Scenario

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ABSTRACT

Arson fire scenarios represent rapid fire growth conditions attributed to the use of an accelerant which can be approximated with a super-fast heat release rate growth rate. It is a challenging fire scenario which cannot be ignored when designing an underground subway rail station. Many transit and rail agencies design requirements include the design for an arson fire resulting in technical challenges to meet NFPA 130 evacuation requirements.

An active smoke management system makes use of mechanical equipment to extract the smoke out of the station via exhaust stack configured safely at grade. A non-mechanical system makes use of smoke baffles or downstands to guide the smoke flow away from egress pathways and towards the desired locations.

We have considered a train arson fire scenario where the fire had been initiated prior or after the train arrival at the station and quantitatively analysed the tenability at the station platform using a hybrid SES – CFD model. The hybrid SES – CFD model takes advantage of the individual features of both the Subway Environment Simulation program (SES) and the Computational Fluid Dynamics (CFD) program and is capable of presenting more details related to the mixture stream flow, heat transfer as well as tenability at any locations of the subway station.

Four different parameters, including the location of the fire origin, availability of fire detection provisions, stair enclosure arrangements and the smoke extraction capacity, have been analysed to investigate their impacts on tenability of a typical subway station. It is concluded that, with properly arranged smoke baffles, both the detection-communication provisions and the smoke extraction capacity play a significant role to maintain a tenable condition for the station. For a train fire already developed prior to the train arrival at the station, a key recommendation is to make use of a reliable on-board fire detection and communication system which can start the exhaust fans as early as possible to maintain the tenability of the station.

For a typical underground subway station, properly arranged smoke-proof baffles or downstands combined with a mechanical smoke control system would contribute to an optimized solution. For a fire developed before the train arriving at the station, it is recommended that enclosed stairs with smoke-proof downstands positioned with an optimum clearance height, working together with an on-board fire detection-communication system and a properly sized over-track extraction system can achieve the tenability in subway stations for the arson fire scenario.

This paper analyses the effectiveness of selected fire smoke management strategies, for an arson fire scenario in a typical underground railway station, to maximize the available safe egress time and to satisfy the NFPA 130 egress criteria.

KEYWORDS: Arson fire, subway station, fire life safety, ventilation, tunnel, SES, CFD, smoke management.

1. INTRODUCTION

Fire life safety is one of the major public safety problems for underground structure, especially for rail transit stations where mass transportation is involved. To maximize the tenability and minimize losses in an accidental fire in such public areas, consideration of fire safety normally started from the design stage. Complicating the situation would be a deliberate arson fire initiated in the train while in the tunnel or in the station.

It is well known that smoke development represents the most significant risk for loss of life when a fire incident develops. The best way to properly manage this emergency situation is to evacuate the occupants as quickly as possible by reducing the required safe egress time; and maintaining a tenable period as long as possible, and maximizing the available safe egress time and egress stairs.

Measures to reduce the required safe egress time includes providing early detection system to minimize detectiom time, sophisticated warning system such as live broadcast system to reduce the pre-movement time, and sufficient exits with a reduced travel distances to reduce the travel time.

When designing a system involing mass transit, more effort is being placed to engineer the system to maximize available safe egress time. This can be achieved by utilizing fire smoke management approach, such as smoke exhaust, smoke baffle and/or fire suppression, measures to guide the smoke flow toward a desired direction, and increase the egress time with the provision of effective fire detection and communication system, and an emergency management plan based on identified possible fire scenarios.

NFPA 130[1] dictates that the station shall be designed to permit evacuation from the most remote point on the platform to a point of safety in six minutes or less, and the station platform be cleared in four minutes or less. This paper analyses the effectiveness of smoke management strategies, considering an arson fire scenario in a typical underground subway station, to maximize available safe egress time and to satisfy the NFPA egress criteria.

2. DESIGN FIRE

Hazard analysis can help identify a credible fire scenario for a subway station. However, arson fire originated from inside the train is a major hazard and is unpredictable. Based on recent events, arson fire is being nominated as the design fire scenario in newer subway systems.

Table-1 is a review of design fire peak heat release rates (HRR) of train fires used in major rail and transit infrastructure projects. The design fire for smoke management ventilation system sizing is based on a fire size ranging from 7MW and 31.1MW, depending on the specifics of the project. It is noted that this table represent a combination of passenger rail and transit system projects.

Table-1: Design fire peak heat release rates used for rail infrastructure projects

Rail line	Location	Country	Peak heat release rate (MW)	Notes
North South Line (NSL)	Singapore	Singapore	24 MW	Chua 2003[2]
East West Line (EWL)	Singapore	Singapore	24 MW	Chua 2003[2]
North East Line	Singapore	Singapore	15 MW	Chua 2003[2]
Circle Line	Singapore	Singapore	10 MW	Chua 2003[2]
Airport Express Line(AEL)	Hong Kong	Hong Kong	10 MW	Chua 2003[2]
Chaloem Ratchamongkhon MRT Line	Bangkok	Thailand	7 MW	(Drake & Meeks, 2000)[3]
Athens Metro	Athens	Greece	10 MW	(Castro et al, 1997) [3]
St Paul's City Thames link	London	UK	16 MW	(Arup 2004) [3]
Mont Lebanon Tunnel light rail transit	Pittsburgh	USA	13.2 MW	(Kennedy & Patel 1998) [3]
New South link	Australia	Australia	10 MW	Chua 2003[2]
Shenzhen Metro	Shenzhen	China	14 MW	
New Lynn Rail	Auckland	New Zealand	15-30MW	
Washington DC WMATA system	Washington DC	USA	18 MW	(Hottinger & Barnett, 1991) [3]
Washington DC WMATA	Washington	USA	23.1 MW	(Kennedy,1998) [3]

system	DC			
Amtrak New York City Tunnels	New York	USA	31.1 MW	(Amtrak 2004) [3]
New York City Metro	New York	USA	8 MW	
Crenshaw rail and station	Los Angeles	USA	20 MW	
San Francisco Central Subway	San Francisco	USA	28 MW	
Copenhagen Metro	Copenhagen	Denmark	20 MW	(Mavromihales)[4]
Gotthard base rail tunnel	Switzerland	Switzerland	20 MW	(Fabbri 2004)[5]
English Channel Rail Tunnel	English Channel	UK, France	13 MW	
Warm Spring Station, CA	Fremont, CA	USA	14.9 MW	
Perth Rail Station	Perth	Australia	15 MW	

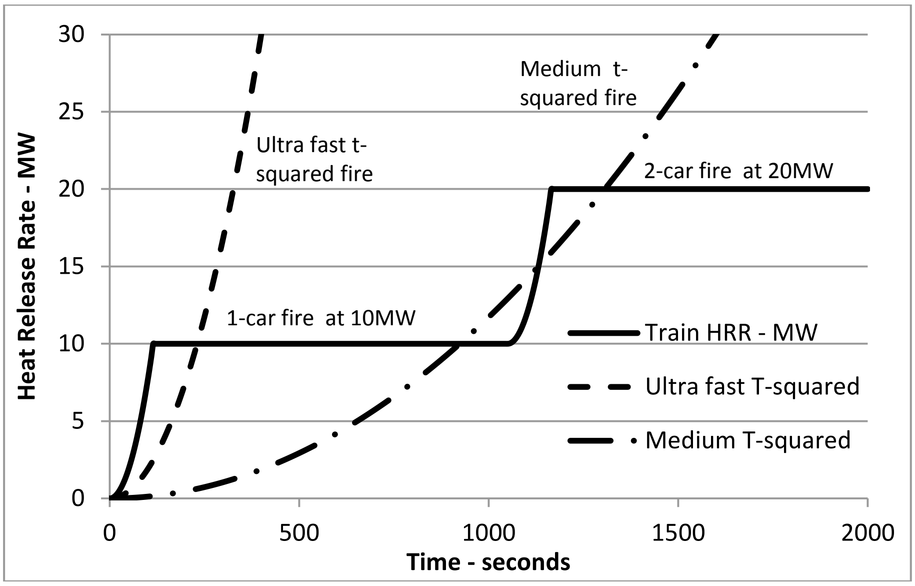

Figure 1: Nominated train fire HRR growth rate

In addition to fire peak HRR, fire growth rate is also a key parameter influencing the tenable time. Li [6] et al discussed the fire growth rate of train fires for the fire safety ventilation of stations. Based on train fire tests in Australia, Canada and Sweden, the fire growth rate for an arson fire can be faster than ultra-fast HRR growth rate that is defined in NFPA 130.

In this research, train fire scenario considers a peak heat release rate of 10 MW per train car, which is reached within 115 seconds for one car, which corresponds to a super-fast growth rate. The fire in a second train car is assumed to be initiated with a delay of 1050 sec after the initiation of the fire in the first car, giving a total heat release rate of 20MW maximum, as shown in Figure 1.

This paper focuses on arson fires with HRR of 10MW per car and at a faster than ultra-fast HRR growth rate as defined in NFPA 130.

3. SUBWAY ENVIRONMENT SIMULATION (SES) MODEL

As the station and the tunnel connections forms an integral system, airflow developed from the adjacent stations needs to be considered for the tenability analysis of an arson fire incident in a station.

Subway Environment Simulation Version 4.1[7] has been used for the airflow analysis. Key parameters for an example station and connecting tunnels for developing the SES model are given in Table-2, and the network node diagram and the resulting airflow are given in Figure 2.

It should be noted that no mechanical ventilation operates in the adjacent stations during the whole process of the fire incident at the subject station. The airflow in the connecting tunnel is developed by the negative pressure at the fire incident station with the operation of exhaust fans achieving an effective flow rate of 463 m^3/s.

Table-2: SES input parameters

Form No.	Description	
3	Tunnel cross section area	23 m^2
3	Length of the connecting tunnel	500 m
9A.5	Number of cars per train	3
9A.7	Total length of train	82 m
9A.8	Frontal Area of train	8 m^2
9B.1	Perimeter of train's frontal profile	12 m
9B.2	Skin friction coefficient	0.023
9B.4	Frontal train drag coefficient	0.65
9J.2	Roughness length for concrete surface	0.003 m
9J.3	Roughness length for tunnel services (cables, pipes, brackets)	0.009 m
9J.4	Roughness length for track bed	0.04 m
9J.5	Roughness length for other surface	0.009 m

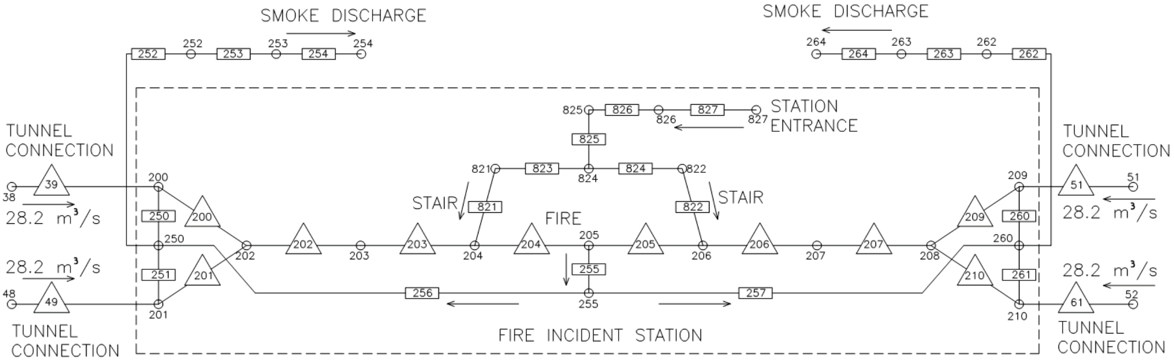

Figure 2: SES node network

Based on SES modelling, assuming fire located on one of the rail track beside the platform, the airflow developed at the connecting tunnels is approximately 28.2 m^3/s, which gives a total airflow supply of 112.8 m^3/s from all the four connecting tunnels. This will be the boundary conditions for the CFD modelling to analyse the tenability of the fire incident scenarios.

4. FIRE AND SMOKE MANAGEMENT SCENARIOS

Feasible solutions for smoke management include a fast response system to detect the fire as early as possible, start the mechanical ventilation sooner, and to guide the smoke flow towards the desired direction without unnecessary delays, i.e., timely extraction and discharge through the ventilation shaft outlet.

The following four different fire scenarios are considered: (1) fire started after train has arrived at the station, no smoke downstands utilised for stairs; (2) fire started after train has arrived at the station, and smoke downstands utilised for stairs; (3) train fire started prior to the train arrival at the station, train has an on-board fire detection system with communication to station, and train fire is fully developed to peak HRR upon arrival at the station (4) train fire started prior to the strain arrival at the station, train has no on-board fire detection system, and train fire is fully developed to peak HRR upon arrival at the station.

Effective over track exhaust (OTE) rate of 13 x 35.6 m^3/s achieved with three exhaust fans considering one fan out of service for all of the fire scenarios. Six OTE opening locations are uniformly distributed above the fire incident rail track, another two are on the concourse ceiling, and another five are above the platform on the fire incident rail track side. No OTE extraction dampers open for the non-fire rail track side, as illustrated in Figure 3.

Table-3 gives an overview of fire smoke management scenarios that have been analysed, to compare the variations of each design parameter, including the response time for smoke extraction system, layout of the extraction dampers and smoke baffles. CFD modelling has been performed with FDS[8] to study the tenability of the station for optimization of the mechanical system.

Table-3: Fire scenarios and smoke control provisions

Scenario ID #	Train fire scenario	Exhaust fan operation time	Fire growth rate	Smoke control provisions
Scenario #1	Fire started from the train after the train has arrived at the station	operate at 180 seconds	HRR to 10MW at 115 seconds	No Downstands
Scenario #2	Fire started from the train after the train has arrived at the station	operate at 180 seconds	HRR to 10MW at 115 seconds	Downstands for stairs
Scenario #3	Fire started from the train prior to the train arrival at the station, with onboard detection and communication to the station	operate at 0 seconds	HRR to 10MW at 10 seconds	Downstands for stairs
Scenario #4	Fire started from the train prior to the train arrival at the station, without onboard detection and communication	operate at 180 seconds	HRR to 10MW at 10 seconds	Downstands for stairs

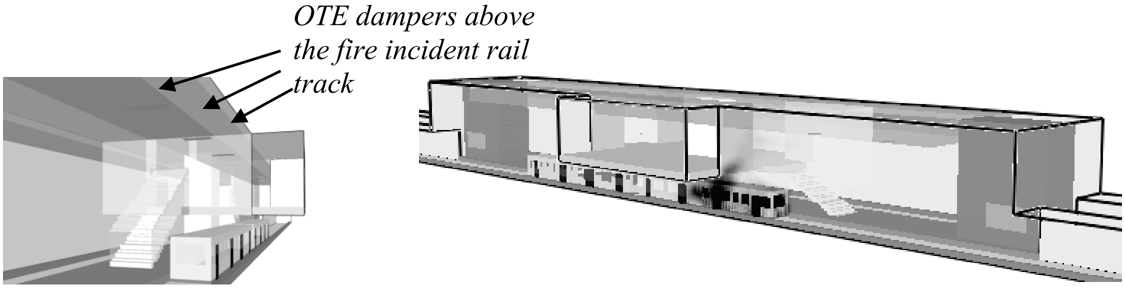

Figure 3: 3D Computer model for the fire smoke modelling of arson fire at a rail transit station

SES calculated air flow at the four tunnel connections to the station are 4 x 28.2 m^3/s for the full capacity extraction of 463m^3/s, the airflow at the tunnel connections are reduced at the same ratio accordingly before the exhaust rate reach its full capacity.

CFD analysis is based on the assumption considering one major fan out of service; the total achieved exhaust rate is 463 m^3/s. This analysis confirmed that this extraction capacity is sufficient for managing the nominated train fire in the station, if the smoke downstands are provided and the smoke management schedule including smoke management controls with on board fire detection is implemented for the train fire developed porior to the train arrival at the station.

5. TENABILITY CRITERIA

NFPA 130 and NFPA 502 recommended tenable criteria for fire emergency conditions are summarized in Table-4. The tenability analysis is based on NFPA 130 smoke visibility of 10 m at 2.5m above platform level since the untenable condition for visibility is usually reached prior to other criteria being reached.

Table-4: Tenability criteria recommended in NFPA 130 (2010)

Parameter	Acceptance threshold	Remarks
CO	Maximum 2000 ppm	For a few seconds

	1150 ppm	For the first 6 minutes of exposure
	450 ppm	For the first 15 minutes of exposure
	225 ppm	For the first 30 minutes of exposure
	50 ppm	For the remainder of the exposure
Temperature	80°C	For a maximum of 3.8 minutes exposure
	70°C	For a maximum of 6.0 minutes exposure
	60°C	For a maximum of 10.1 minutes exposure
	50°C	For a maximum of 18.8 minutes exposure
	40°C	For a maximum of 40.2 minutes exposure
Visibility	10 m	Measured at 2.5m above the floor
	30m	Measured at 2.5m above the floor, signage internally illuminated at 80 lx
Air velocity	Between 0.75 m/s and 11 m/s	For enclosed stations and trainways

6. ANALYSIS OF TENABILITY AND FIRE SAFETY PROVISIONS

To analyse the difference in fire scenarios considering different variants, such as smoke downstands, availability of on-board fire detection and communication system, the tenability acceptance criteria for the selected four scenarios have been summarized in Table-5. Because of the response delay of the initiation of the ventilation system, there is a temporary untenable period.

Table-5: Options of the smoke extraction configurations (considering ambient CO of 10 ppm)

Case ID	Visibility	Air Temperature	Airflow Velocity	Carbon monoxide(CO)	NFPA satisfy?
Scenario #1	< 10 m on concourse till 4 minutes, less than 10 m on platform till 9 minutes	40-50°C on platform for 4 minutes, 40-70°C on concourse for one minute	0.75 - 6 m/s for 90% of the region	120-250 ppm on up to 30% of platform area for one minute	No
Scenario #2	< 10 m over 50% of the concourse area for 0.5 minute, less than 10 m on platform for 4minutes	Concourse less than 40°C, up to 40 - 50°C on 50% platform area for no more than one minute	0.75 - 6 m/s for 90% of the region	platform: up to 450 ppm for 0.5 minute; up to 250 ppm for less than 2 minutes	Yes
Scenario #3	> 30 m on Platform and concourse	28-30 °C for concourse and platform	0.75 - 6 m/s for 90% of the region	10 – 20 ppm on platform and concourse	Yes
Scenario #4	< 10 m on concourse and platform till 7 minutes since train arrives the station	40-100°C on platform for 4 minutes, 40-60°C on concourse for one minute	0.75 - 6 m/s for 90% of the region	120-600 ppm for 4 minutes on platform	No

6.1 Influence of Smoke Downstands

CFD modelling is conducted to analyse the performance of smoke control provisions with smoke downstands enclosing the stairs that link the platform and the concourse. Scenario #1 assumes that smoke downstands for the stair entrance are not provided, and a train fire started after the train has arrived at the station. Smoke visibility is visualized for a vertical slice at the centre of the platform as shown in Figure 4.

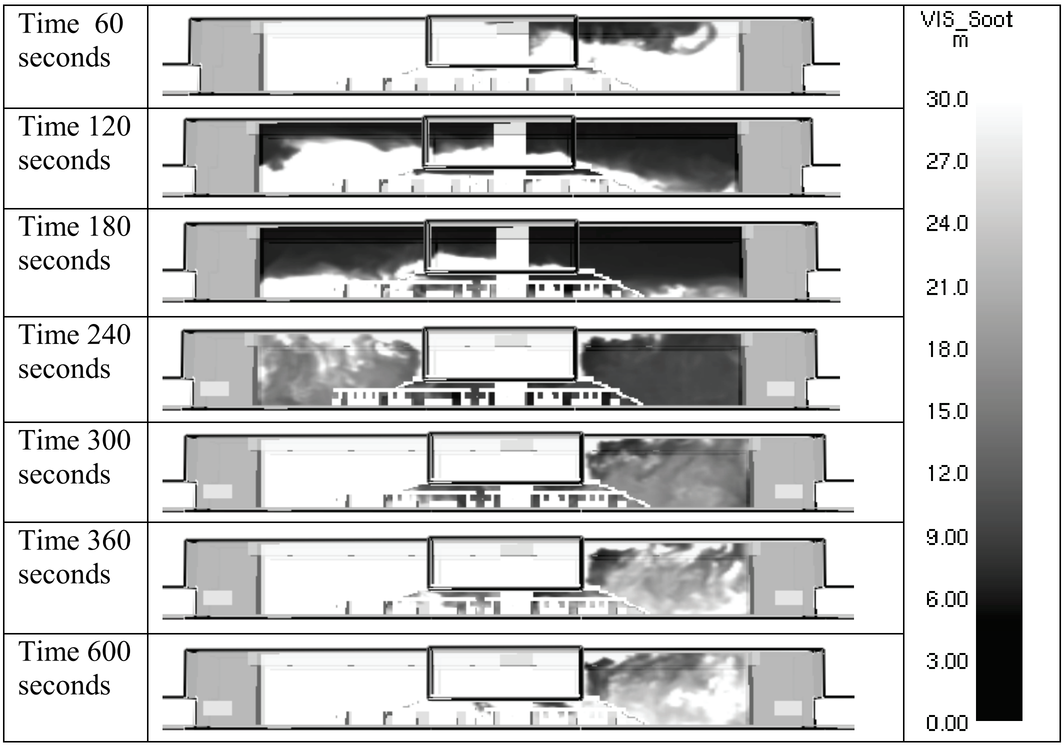

Figure 4: Smoke visibility along centre of platform for scenario #1

Because of the buoyancy effects, smoke developed from the train fire flows onto the concourse level within one minutes after the fire started. When the mechanical extraction system is turned on at 3 minutes, accumulation of smoke at the concourse level require an additional one minute of time from fans start in order for tenable conditions to be established in the concourse level. This resulted in an approximately 4 minute period that the concourse and the four exit stairs are untenable. This analysis has shown that the performance of the system cannot comply with NFPA 130 requirements because 4 minute tenable period cannot be provided for the concourse.

Scenario #2 also assumes a fire started from the train after the train has arrived at the station. However, the two stairs linking the platform and the concourse are enclosed with smoke downstands with a 2.7 m clearance height. Figure 5 shows the smoke visibility for scenario #2. The untenable period for the stairs and the concourse level is no more than 30 seconds before the station exhaust fans operate at full capacity. This is because the smoke can only flow onto the concourse when the smoke layer descends down to below 2.7m level. CO concentration, air temperature and airflow speed are all within the acceptance criteria as shown in Table-4 and Table-5.

This confirms that with the application of properly configured smoke downstands for the stairs, tenability on the concourse level can be significant improved to meet the NFPA 130 requirements.

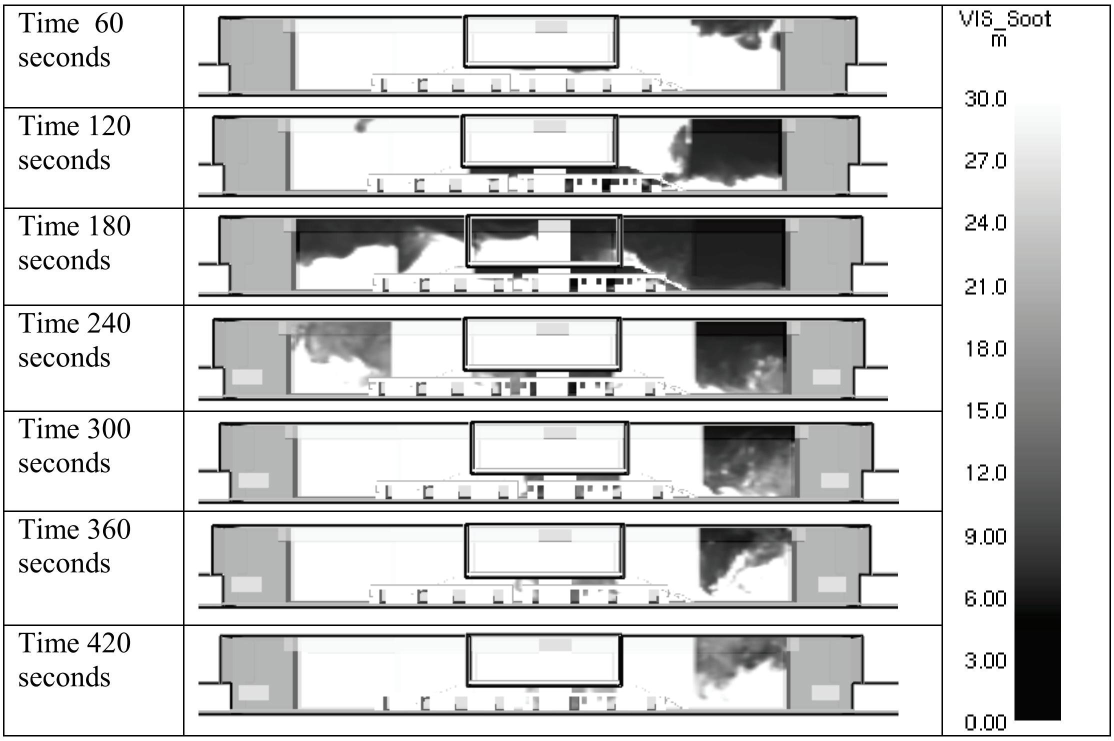

Figure 5: Smoke visibility along centre of platform for scenario #2

6.2 Influence of Train On-board Detection and Communication

Train arson fire can start any time and at any location, such as while the train is travelling in the tunnel. The emergency management strategy for an arson train fire while travelling in the tunnel is to make every effort to drive the train to the nearest station to manage the fire, including evacuation of passengers and smoke control, etc. Scenarios where train fire developed prior to train arrival at the station or with an extended delay of the response to operate the mechanical ventilation system are expected to have significant adverse impact on tenability at the station.

Comparison of scenario #3 and scenario #4 demonstrates station tenability considering the availability of train on board detection and communication system, considering fully developed train fire due to fire ignition prior to the train arrival at the station. Without the on board detection and communication with the station, response to operate the mechanical ventilation system can be delayed by up to 3 minutes.

When on-board train fire or smoke detection and communication system, the train fire can immediately be reported and communicated to the station, so that the station emergency can be implemented before the train arrival and the mechanical ventilation system can be initiated prior to the train arrival.

Figure 6: Smoke visibility along centre of platform for scenario #3

Figure 6 shows the smoke visibility upon the train arrival at the station for scenario #3, where on-board train detection and communication system is provided. There is no tenability issue for the station because prior activation of the emergency ventilation will enable the ventilation system to be at design capacity prior to arrival of train with fully developed fire at peak HRR. NFPA 130 requirements for smoke control are satisfied because unlimited tenable time can be provided with the mechanical system.

Scenario #4 is a sensitivity analysis scenario for the condition when no on-board fire detection or communication system is provided, and fire started in the train prior to the train arrival at the station and the peak fire heat release rate on one car has been developed. Assuming a three minute delay to operate the mechanical exhaust system, Figure 7 shows that smoke flows onto the concourse level because of the excessive delay of the system response; untenable time on the concourse level exceeds four minutes as shown in Table-5 and Figure 7. This analysis shows that NFPA 130 requirements cannot be satisfied if the response delay time is up to three minutes when considering station arrival of fully developed train fire at peak HRR due to fire ignition prior to the train arrival at the station.

7. CONCLUSION

Based on a hybrid methodology using SES and CFD, tenability at an underground station involving train arson fire has been analysed to optimize the performance considering the availability of train on-board detection system and smoke downstands for the stairs. It can be concluded that:

1. Smoke extraction is effective with the smoke extraction active above the track where the fire incident train is stopped, with the ventilation system capable of configuring a dedicated exhaust on the fire incident side of the platform at maximum plant capacity.
2. Smoke downstands used to enclose the stairs and the provision of exhaust dampers, when properly configured, enable the system to maintain tenable conditions for the platform and concourse level while accommodating one major exhaust fan out of service and a total achieved extraction rate of 463 m^3/s.
3. Stairs without enclosed smoke downstands can result in an untenable period of up to 4 minutes and 9 minutes for the concourse and platform, respectively.
4. If the design fire scenario considers an arson fire development on the train prior to arrival at station, it creates a condition where station fire safety systems are required to respond to initial fire conditions at peak HRR. System detection response time and ventilation equipment

start up time could introduce a 3 minute period of time where untenable conditions. The smoke will temporarily flow onto the concourse at 60 seconds, and the temporary untenable period for the platform can be as long as 7 minutes from the time the train (on fire) arrives at the station.

5. With train on-board fire detection and communication system, an arson fire started prior to the train arrival at the station can be communicated to the station, and the mechanical ventilation can be started and operating at design capacity prior to train (on fire) arrival at the station. Unlimited tenable time can be maintained for the station.
6. A combination of a properly configured over-track exhaust (OTE) with smoke downstands enclosing the stairs can help maintain tenable condition on the platform and the concourse to satisfy the NFPA 130 requirements.

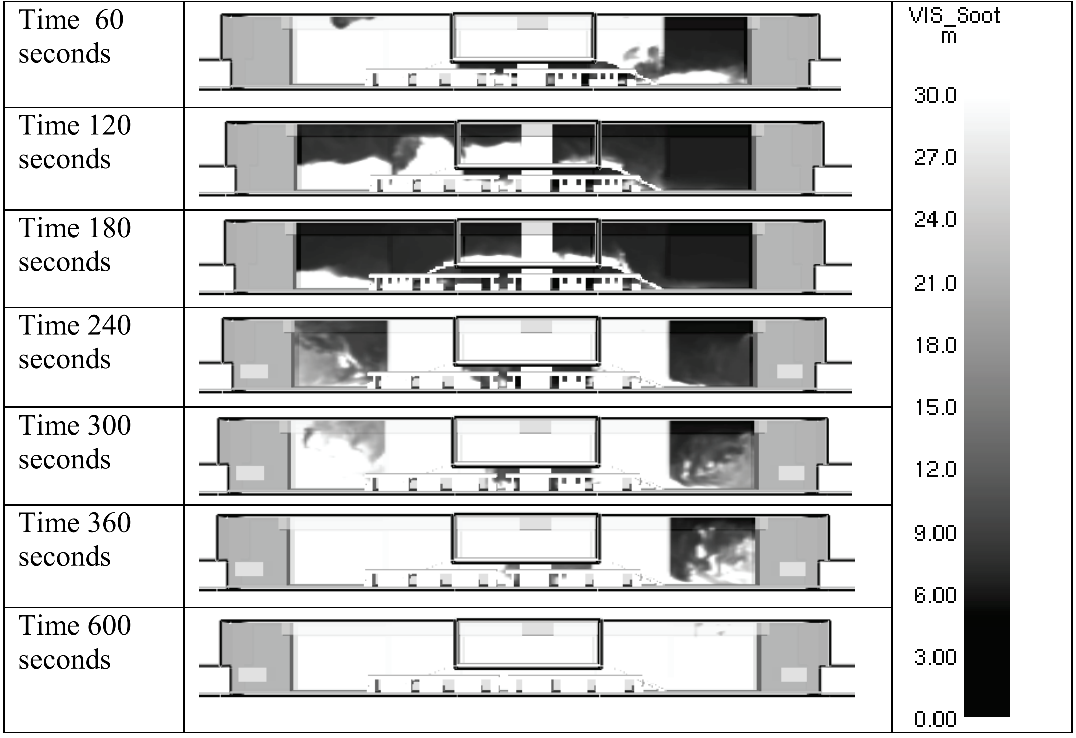

Figure 7: Smoke visibility along center of platform for scenario #4

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