Chapter 10

CURRENT ISSUES, ALTERNATIVE CONCEPTS, AND DESIGN CRITERIA FOR SUBWAY VENTILATION SYSTEMS

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ABSTRACT

With the growing urban population and the concern for traffic congestion and pollution (emissions control), public transportation is becoming more and more attractive to both city dwellers and managers. To gain access to the central area of the city, the subway remains the most viable alternative, despite its higher cost when compared to above ground or elevated transportation systems.

There are relatively few regulations and criteria for subway ventilation, particularly when compared with mine ventilation. The main document that provides guidance and general recommendations for subway ventilation and environmental control is the *Subway Environmental Design Handbook*, published in 1976 (2nd edition) by the U.S. Department of Transportation, Office of Research and Development. Many of the subway systems in existence today have been designed and built with ventilation features adequate for normal train operation, but their design does not consider stringent criteria for such emergency conditions as a train fire in a tunnel. The National Fire Protection Association's *Standard for Fixed Guideway Transit Systems* known as *NFPA 130* as well as the *ASHRAE Handbook - HVAC Applications* (1995) provide specific design and operation requirements for subway ventilation systems. Some of the existing, old subways are upgrading their ventilation systems to comply with the new regulations.

The ability of a particular ventilation system design to provide adequate ventilation during normal and emergency conditions can be evaluated using computer modeling and simulation techniques. A train fire will cause a sudden change in the tunnel ventilation pattern by adding an unsteady and fast-growing source of heat. The hot air and gasses created by a fire will tend to flow uphill, possibly against the normal flow, producing a "*backlayering effect*." To prevent this effect from happening, enough ventilation must be provided and the governing criterion to establish the required airflow is called "*Critical Velocity*."

Several software packages are available for special applications on tunnel and station ventilation as well as to model the spread of smoke and heat in case of a major tunnel fire, using Computational Fluid Dynamics.

This paper presents the current issues in subway ventilation, as shared by the public transit community around the world, together with modern alternative design concepts vis-à-vis the more stringent emerging Fire-Life Safety criteria. Examples of recent studies and ventilation systems design are provided.

INTRODUCTION

The population growth in general combined with current urban development around the world and the need to move people from their homes to their places of work, shopping centers or entertainment locations in large metropolitan areas, in particular, are the principal reasons for a continuous demand for more and more transit systems.

Whatever innovations will be brought to the design and construction of mass transit systems, one thing is sure: the systems need to move more people, more rapidly, and more safely. Systems will be above ground where possible, but the competition for space, together with the need to suppress noise pollution will cause some of the new traffic to be diverted generally underground (e.g., under cities, rivers, airports, etc.).

Urbanization brings a scarcity of available land for new transportation corridors. In addition, the price of land in large metropolitan areas, coupled with the interference of new corridors with the already congested street traffic and gridlock, makes the subway transit system a viable alternative.

New subway systems are currently under construction or on the drawing boards for many large or emerging metropolises - among them: Athens (Greece), Bangkok (Thailand), Cairo (Egypt), Copenhagen (Denmark), Sao Paolo (Brazil), Taipei (Taiwan), Tel Aviv (Israel).

Existing subway systems in other large (and still growing) metropolitan areas are becoming overcrowded, and the need for extending the network as well as for increasing the speed (and consequently the ridership) is always a top priority for operators. Almost all existing subways are currently extending their systems, e.g., Hong Kong, London, Moscow, New York, Paris, San Francisco's BART, Seoul, Tokyo, Toronto.

To illustrate the order of magnitude in public transit, see the statistical data for several subway systems around the world (from Jane's Urban Transport Systems, 1991) in Table 1 on the following page.

Moscow's "Metropoliten" carries nine million persons a day, followed by Tokyo Metro with eight million, Mexico City and Paris with five million each, New York City, Hong Kong and Seoul with only 3.5 million each while London is far behind with just 2.5 million passengers every day.

For suburban mass transportation, several high speed rail projects are under construction or on the drawing board all around the world. Most of them include long tunnels and challenging ventilation systems.

Under construction is a major subway-like project in London: the Heathrow Express (HEX), between Paddington Station in London's west end and Heathrow airport, scheduled to open in 1998. This express subway line will have 8 km of new railway tunnels and two major underground stations.

Another interesting project, not a subway but requiring major ventilation capability is the Channel Tunnel Rail Link, from the Channel portal in Kent to the St. Pancras Station in downtown

Table 1.

City	Metro Population (mlns)	Metro Riders (*) (mlns/yr)	Suburban Rail Riders (**) (mlns/yr)	Metro Length (km)
Mexico City	20.0	1,550	-	170
Sao Paolo	16.0	635	302	45
Seoul	13.5	1,007	422	117
New York	13.3	1,136	170	443
Tokyo	11.9	2,541	8,182	219
Paris	10.2	1,552	511	551
Moscow	9.9	2,741	1,365	223
Bombay	9.2	-	1,486	-
London	6.7	785	550	406
Hong Kong	5.5	1,066	-	117

* Metro includes subway, regional metros, light rail, and tramway

** Suburban rail includes conventional "heavy" and interurban commuter passenger rail

London. Out of a total length of 108 km, approximately 27 km will be in tunnels; the longest tunnel, in London, will have twin bores of 18 km in length. The link will allow high speed trains of up to 300 km/hr.

Special precautions must be taken to reduce the effect of a fire or of release of toxic substances in very long tunnels, such as the planned Gotthard (57 km) and Lotschberg (33 km) in the Swiss Alps [6], which have the following main parameters:

- Two parallel tubes, one for each direction, interconnected by closed cross-passages every 500 to 650 m and several open crossovers
- 41 m² and 46 m² clear tunnel cross-section, respectively
- No separate service tube will be provided
- Passenger trains, plus 240 goods or freight trains per day
- Continuous mechanical ventilation at reduced volume of 30-40 m³/s
- Amount of fresh air supplied to be sufficient for a train full of passengers (up to 200 m³/s)

In South Korea, the High Speed Rail Project from Seoul to Pusan (424 km, out of which approximately 80 km in tunnels), has two main underground tunnels and stations in the cities of Taejon and Taegu, 16.9 and 18.3 km long, respectively, requiring extensive ventilation. Three hundred trains per day are planned to travel at 300 km/hr at the beginning of the new millennium.

Several railway tunnels are under construction in Denmark. The Storebaelt Tunnel, a rail link between Korsør and the island of Sprogo consists of two separate bores, 8 km long, for high speed passenger and freight trains. The tunnels, with an internal diameter of 7.5 m, are connected by cross-passages located at approximately 250 m intervals.

Soon Denmark and Sweden will be connected by a combined tunnel and bridge link known as the Øresund Fixed Link. For these relatively short tunnels natural ventilation will be provided by openings of 25 m by 10 m, spaced evenly not more than 350-400 m apart [7].

ALTERNATIVE DESIGN CONCEPTS

Design Criteria

In order to evaluate the effectiveness of a ventilation system, there must be a basis or criteria to check for compliance. For normal conditions, the ventilation system should maintain acceptable environmental conditions for passengers and personnel as well as suitable operation of equipment and installations. In case of fire in a tunnel or in an underground station, the emergency ventilation system must be able to control the direction of movement of hot air and smoke form the fire to enable flexibility in establishing evacuation routes and points for fire department access.

Currently there are no international safety norms or standards applicable to subway ventilation systems. National standards are slowly emerging, yet there is no general consensus of their applicability. The most common practice is to have local procedures based on past experience and sometimes learn from the experiences of other agencies or operators.

Criteria for Emergency Conditions. Generally, emergency conditions result from a malfunction of the transit vehicle. The most serious emergency condition is a stopped train on fire in a tunnel, disrupting traffic and requiring passenger evacuation. The ventilation system must be capable of maintaining a safe evacuation path that is clear of smoke and hot gases. The critical velocity concept and computation has been developed based on observations during mine fires and on some small-scale modeling. Two empirical formulas have been established and have been used for years as a measure of the adequacy of airflow to prevent backlayering of smoke when ventilating a tunnel fire.

Basically, the emergency ventilation system must be of suitable capacity to support evacuation by providing safe escape routes to the surface. To be reliable, evacuation routes must remain free of fire products of combustion (smoke, heat) for the duration of the evacuation, regardless of the fire condition. The U.S. National Fire Protection Act (NFPA) 130 requires that the "*Emergency ventilation system shall produce airflow rates to provide a stream of non-contaminated air to passengers in a path of egress.*"

For tunnel fires, sufficient mechanical ventilation must be provided to move smoke in one direction as required to maintain acceptable conditions along a single evacuation route on one side of the fire. Acceptable conditions are defined as follows:

- The maximum temperature in the evacuation route shall be 60°C or less, ignoring radiant heating;
- The minimum air velocity in the evacuation path shall not be less than the critical velocity required to control the spread of smoke and hot gases from the fire into the evacuation path (and prevent the backlayering effect). Critical velocity is a site-specific value based on tunnel geometry, heat release rate, psychrometric conditions of ventilating air, and tunnel grade at the location of the fire;
- The maximum air velocity along the egress route should be less than 10 m/s.

For station fires the ventilation system should provide uncontaminated air along station entrances and non-pressurized emergency exits. Similar to tunnels, the maximum air temperature in the evacuation route should be less than 60°C.

Criteria for Emergency Fans. NFPA 130 requires that emergency fans be designed with redundant power supply from two power feeders from two separate sources (i.e., separate traction power substations or separate utility substations). In addition, fans should be fully reversible and satisfy the following conditions:

- Fans, their motors, and all related components exposed to the ventilation airflow must withstand a temperature of 250°C for a period of at least one hour
- Local fan motor controllers should be separated from ventilation airflow by a one-hour fire-resistance-rated separation
- Airflow induced by emergency fans should meet critical velocity criteria in either supply or exhaust
- Discharge and supply air openings to the fans should be at a sufficient distance apart or other measures should be taken to prevent recirculation of contaminated air
- Operation and fail-safe verification of fans should be provided at a central supervisory station, with indication provided for all modes of fan operation for each fan as well as from local control points
- Local controls should be provided at the fan location for complete fan operation

Criteria for Normal Operation. An operation is considered "normal" when trains are moving through the system according to schedule and when passengers are traveling smoothly through the station to and from transit vehicles. Since this is the predominant mode of operation, considerable effort is required and justified to assess the impacts of train movement on the station environment and to determine the requirements, if any, of a station Environmental Control System (ECS).

It would be preferable to maintain the following environmental conditions along station platforms and mezzanine area:

- Summer maximum dry bulb temperature not to exceed the ambient temperature by more than 5°C
- Humidity less than 60% in summer (no limitation in winter)

The following air velocity criteria apply to station platforms and entrances [3]:

- Average air velocity not to exceed 3 m/s
- Maximum air velocity not greater than 5 m/s

If analyses indicate that these criteria cannot be attained with the normal tunnel ventilation, recommendations are made for the station ECS.

Subway Tunnel Conditions. Maximum temperatures are defined by equipment manufacturers for operating limitations. Here are some examples:

- The vehicle air conditioning system can operate at its design capacity when the condenser air inlet temperature is less than or equal to 46°C
- Other system-wide and facilities equipment in the tunnel can operate at temperatures up to 46°C without a decrease in life expectancy and can operate for short periods at temperatures up to 52°C

Ventilation Design Concepts for New Subway Systems

The most effective ventilation system in tunnels would be a transverse system which would allow smoke removal close to the source, thus allowing the passengers to escape safely along the tunnel in both directions in case of a fire. Such a system, however, is very expensive since it involves the installation of extract ducting in the crown of the tunnel and, consequently, enlargement of the tunnel cross sectional area. The longitudinal system where the smoke is driven along the tunnel, away from fire and from passengers, thus enabling them to escape into the oncoming fresh air flow, is much less expensive [9].

Implementation of the ventilation system for new subways varies from country to country, and sometimes from city to city. In order to design a ventilation system capable of moving air in the most convenient direction to protect passengers and provide access for fire-fighters, the following concepts and design options are most common:

Station fans. In this concept, fan plants are attached to the station, most often at the end of the platform, or 10 to 20 m inside the tunnel. The shafts are designed to operate as blast/relief vents during normal operation (to alleviate the pressure of the incoming trains) and also as fan shafts (by closing the dampers on the relief section of the shaft). This system is popular in North America as well as for newer subways in Western Europe and Asia.

There are, however, systems where fan plants are located in the station and connect to the platform through ducts, often with air distribution along the entire platform. This concept is widely used in Russia and Eastern Europe.

Mid-tunnel fans. This concept applies mainly where the distance between stations is long, reducing the efficiency of station fans in case of an emergency in the middle of the tunnel. This system is common in Russian and Eastern European subways.

Combination of station and mid-tunnel fans. This system has significant advantages compared with the others, but its main disadvantage is the higher cost. However, for new subway systems or extensions to existing systems, the additional costs for the inclusion of such dedicated emergency ventilation systems can be justified.

Passive vents (with and without dampers). The oldest subways were designed and built with natural ventilation consisting of bays of vents connecting the tunnels and stations to the ambient at street level. Train movement causes the air to move in and out, producing the necessary air changes and controlling the heat. While suitable for normal operation of trains, this system provides no means of controlling the smoke and heat in case of a major fire in tunnels or in stations. Some newer systems have vents equipped with dampers (Chicago), designed to be closed when emergency fans are operated. This concept has certain advantages, but the operation may be unsure and the maintenance expensive.

In-line or jet fans. This concept is often used in vehicular tunnels, but local application is possible in rail tunnels as well. The jet fans act like booster fans to enhance the air velocity at the desired location. The main disadvantage is the requirement for additional space in the tunnel, and consequently larger cross sectional areas. Another disadvantage is the fact that the fans can be in the fire zone and exposed to high temperatures which may make them inoperable when needed most.

Portal doors. These are devices that can be of crucial importance and use in case of a fire close to the portal and when the required ventilation is downgrade, against the buoyancy of the hot air and smoke resulting from the fire. Interlocked with fan operation, the doors will allow the control of smoke and provide for a safe evacuation. Doors are made of collapsible metal sheet or another material that will not damage the train in case of an undesired activation.

Air barriers. This is a new concept to enhance the operation of emergency fans and restrict the air flow at pre-established locations. The devices act like air curtains in mines, except that they are deployed by a mechanism which interlocks with the emergency fans only in emergencies. During normal operation the un-deployed air barriers allow trains to pass without any restrictions or speed limitations. Still in the experimental stage, these devices have been successfully tested in the Washington subway.

Platform edge doors in stations is probably the most recent innovation in subway ventilation system design. A thin wall with doors along the entire platform isolates the tunnel from public areas. When the train arrives and stops, the platform edge doors open at the same time the train car doors open; before the train leaves the station, the doors close. The new subways in Hong Kong and Singapore are equipped with this system, which is gaining in popularity, particularly where the stations are designed with an ECS.

Other innovations in subway safety which have been tested in the Hong Kong subway consist of pedestrian cross-passages in tunnels, a hard wire telephone and radio communications system linked to the control center, video equipment installed at each station and monitored from the central control room, providing vital information on environmental conditions.

New subways under construction or on the drawing board provide for the installation of heat, smoke or gas sensors in the tunnels in order to detect a fire and its precise location and to transmit the information directly to the central control room. Some of these sensors will be monitored continuously (Los Angeles Metro).

Of particular interest is the design of the ventilation system for the recently built Channel Tunnel, connecting England to France, which started operation in 1994.

The Channel Tunnel, with a total length of 53 km, 38 km under sea, at an average depth of 40 m, consists of three tunnels: two running tunnels, 7.6 m in diameter, and a service tunnel, 4.8 m in diameter (in the middle), connected to the main tunnels every 375 m by cross-passages 3.3 m in diameter [8]. The running tunnels are also connected by 2 m diameter pressure relief ducts above the service tunnel, every 250 m. There are two undersea crossover chambers, each 163 m long, 21 m wide and 15 m high.

Two ventilation systems have been installed, one for normal operations, the other for emergencies, particularly those requiring the control of smoke [14]. The normal ventilation system supplies air to the running tunnels through air distribution units located above selected cross-passage doors, service tunnel and cross-passages by means of a ventilation plant located on each coast.

Each ventilation plant contains two variable pitch axial fans, each capable of supplying the required air flow. One fan at each end will be operational at any one time with the other on permanent standby, available for immediate use, should a fault occur with the duty fan.

For emergency and in order to control the smoke in a desired direction, two pairs of axial fans in parallel are located at coastal sites, near to each end of the tunnel. The air flow can be modified or reversed by varying the blade pitch, thus avoiding loss of control of air movement which would be caused by reversing the motor direction. Trains passing through the tunnels and their piston-effect produces both positive and negative air pressures; piston relief ducts have been constructed between the two running tunnels and specially equipped with valves and pressure restrictors remotely controlled.

Ventilation System Upgrade for Existing Subways

For an existing subway system the cost of upgrading the ventilation system to the level required by the current safety standards might be prohibitive due to disruption in service, acquisition of suitable land in built-up areas, congestion of the ground with utilities, etc. Alternative approaches to improving the existing ventilation system and the optimization of safety/evacuation procedures might be the only option in some cases. And yet the public perception of safety in general coupled with the competition caused by other transit systems make it necessary to look for feasible alternatives to upgrade the subway ventilation system for safe evacuation of passengers in case of fires underground.

Possible alternatives that are being considered by several transit agencies encompass one or more of the following alternatives:

- Larger fans at existing locations, which applies to systems with mechanical ventilation but of inadequate capacity
- Platform access doors, to be controlled in case of fire emergency
- Platform edge doors
- Jet fans in tunnels or stations
- Cross-passage fans
- Cross-passage blocking with doors
- Air barriers
- Portal closure (roll-up, train passable)

Several subway systems are currently upgrading their ventilation systems or studying available alternatives. Among them are London Underground, New York City Transit, Chicago Transit Authority, Boston's MBTA, Bucharest Metro, Buenos Aires's Metrovias.

CURRENT STATUS AND ISSUES IN TUNNEL VENTILATION

Subway Tunnel and Station Fires

Fires in rail tunnels may be caused by accidents, electrical faults, sabotage or vandalism. Priorities following a fire are rescuing people and saving lives, extinguishing the fire, preserving the structure, investigating the cause, and then undertaking modifications or implementing procedures to prevent a recurrence. The consequences of fires in tunnels are often serious, and there may be deaths and injuries. Burning fuel, oil, plastics, and some paints cause dense smoke and toxic fumes which hamper visibility and can produce death by asphyxiation. Temperatures may reach more than 1,000°C and may cause severe structural damages.

The infrequent but continued occurrence of serious transit fires has kept emergency response planning at a high priority for transit agencies. The emergency ventilation and evacuation procedures that are part of this planning are important because the smoke and other fire products have a tendency to move upwards out of the stations and contaminate normal passenger exit routes. The emergency ventilation system must be able to support evacuation by providing reliable evacuation routes out of the tunnel or station.

The most recent tunnel fire happened on November 18, 1996, when a fire started on a truck loaded on an 800 m long train freight carrying trucks only, 18 km into the westbound Channel Tunnel. The fire spread quickly to other trucks and a locomotive in the back of the train. The heat and smoke from the blaze were so intense that firefighters had to pull back every ten minutes. It took eight hours to put out the fire, with eight people injured by smoke inhalation and more than a dozen that required medical surveillance. The fire, labeled "the English Channel tunnel's worst accident" caused the closure of the Channel Tunnel for several days, the first major closure since it started operation.

A disastrous fire in the Baku subway, on 28 October 1995 caused the death of 289 passengers, with another 265 severely injured [19]. The fire was widely reported by news media all around the world (including on the Internet) and labeled by journalists as "the deadliest accident in the history of underground travel" (San Francisco Chronicle, October 30, 1995).

The fire at King's Cross Station of London Underground on 18 November 1987 resulted in the deaths of 31 people, including one fire-fighter officer. This fire accident has been the most studied and referenced transit fire, and its outcome is the application and acceptance of CFD modeling technique as the tool for the analysis of smoke control in case of a station fire.

The fire in the San Francisco Bay Area Rapid Transit (BART) transbay tube on 17 January 1979 led to the death of one fire-fighter and injury to 44 other fire-fighters. In the same year, a fire in the 2-km Nihonzaka Tunnel in Japan raged for 159 hours and destroyed 173 vehicles, causing the tunnel's closure for nine weeks.

Research and Development - Fire Tests

The public's increased awareness of safety issues together with an increasing density in train movements have forced subway operators to examine the options available in providing fresh air to passengers in stalled trains and providing safe egress routes in case of train fires in tunnels. Several research and development programs, including real fire tests have been conducted during the recent years in Europe, U. S. A., and Japan.

In the early 1990s, the Eureka 499 EUROTUN project included tunnel fire tests in an access tunnel to a copper mine in North Norway.

A series of tunnel fires was carried out in a gallery on the Health and Safety Laboratory test site at Buxton, U.K., using a range of fire sizes from 0.15 MW to over 4 MW and various fire dispositions.

STUVA and ARSENAL research centers in Germany and Austria, respectively, as well as Fire Research Station in U.K. have been actively involved in numerous studies related to tunnel ventilation and safety, mainly for railways.

In the United States, the Memorial Tunnel Fire Ventilation Test Program consisted of a series of full-scale fire tests conducted in an abandoned road tunnel, 853 m long, and having a 3.2% grade, situated in West Virginia. Various tunnel ventilation systems and configurations were operated from 1993 to 1995 to evaluate the smoke and temperature management capabilities of these systems. The tests generated a significant database for the design and operation of ventilation systems mainly for road tunnels, but with relevant information for vehicular tunnels as well. The tests goals and scope were formulated by the Technical Committee 5.9 of the American Society of Heating, Ventilating, and Air-Conditioning Engineers (ASHRAE).

The tunnel was equipped with instrumentation and recording equipment, including sensors measuring air velocity, temperature, CO, and CO_2. Smoke generation and movement and the resulting effect on visibility was assessed using seven remotely controlled. television cameras. Fires of 10, 20, 50, and 100 MW were generated, and systematic variations were made in airflow quantity, longitudinal air velocity near the fires, and fan response time for each ventilation system tested. A total of 98 fire tests were conducted, using various smoke management strategies and combinations of strategies, including extraction, transport, control direction of movement, and dilution to achieve the goals of offsetting buoyancy and external atmospheric conditions and to prevent backlayering.

An important conclusion of these tests was that the fan response time (the interval between the onset of a fire and ventilation system activation) should be minimized since hot smoke layers spread quickly, e.g., up to 490 to 580 m in the initial two minutes of a fire [5]. Complete test results will be available to those interested on two CD-ROMs, and an Internet WEB page is available.

Software for Tunnel Ventilation System Design

There are various computer programs available for tunnel ventilation in general, including some with special features for subway tunnels. Probably the most used software for this application is the ***Subway Environment Simulation*** computer program, which has been used for almost two decades to simulate tunnel fires and to predict the airflow to the incident train using one-dimensional flow simulation.

The SES model can be used to simulate air, heat, and moisture flow within a subway system. The simulation includes ambient conditions, train piston effects, fan operation, buoyancy effects, heat dissipation and exchange, etc. It is intended primarily for short-term simulations with results available second-by-second or as a summary for any selected time interval. A simple comparison between the SES predicted airflow and the required critical velocity at the fire location (based on the fire size, tunnel geometry, and grade) allows a rapid assessment of ventilation adequacy.

A fire condition as defined for this analysis is a fully engulfed, single car fire. This condition is generally simulated during winter ambient conditions when air densities and buoyancy forces may be greatest.

Fire conditions in tunnels are generally suitable for one-dimensional analysis with software such as the SES program. This method is inappropriate, however, when the incident train is stopped at a station platform or across secondary airways like cross-passages, vents or fan shaft connections. A three-dimensional software is required for fire simulation in such stations where the air flow is three-dimensional in nature and turbulent. Such software involves repetitive calculations of three-dimensional fluid dynamics and thermodynamic equations and is, therefore, called *Computational Fluid Dynamics*. This is a relatively new modeling technique which has been used and accepted by transit authorities in the aftermath of the King's Cross Station fire. Tests and computer simulations demonstrated that what caused that fire to spread with unexpected speed and following atypical paths was the "*flashover*" phenomenon. This happens when extreme heat concentrates at one location, causing the volatilization of significant amounts of materials that ignite suddenly due to either an introduction of oxygen or an auto-ignition.

The use of such numerical methods in tunnel ventilation design has become prevalent with the advent of faster micro-processors.

There are various software packages based on CFD techniques for simulating the movement, temperature, and composition of fire products and for analyzing the three-dimensional behavior of heat and airflow in a subway station during fire conditions. The simulation results provide air velocities, temperatures, pressures, and relative concentrations of products of combustion. Simulation results can be presented numerically and graphically as colored contours or vectors in any selected sections that cut through the station.

It is generally agreed that CFD models have been well verified, and that with careful application they can perform a valuable design function [17]. With the increased power and capability of simulation software and hardware, it is possible to develop models of increasing complexity, but information from simulations has to be reduced to a manageable and useable format (files that contain 50 to 100 Mbytes of data are not uncommon for a relatively small CFD application).

Smoke and temperature concentration contours can be presented in a sequence of time steps. Using computer animation, two-dimensional cross-sections can "compress" the information into an understandable form. It is possible to move the two-dimensional "slice" through the three-dimensional model and so to create a visualisation of the complete flow of smoke.

ARGOS, a computer program developed by the Danish Institute of Fire Technology, is used to calculate fire, smoke, and heat development as well as evacuation times for people in the tunnel [7]. The program simulates smoke and includes optical smoke density under certain conditions. The temperature in various smoke layers as well as heat radiation from the hot smoke layer as a function of time are predicted. The program is said to be capable of producing a more realistic portrayal of the smoke patterns in the tunnel (visualisation), and to give an indication of the reduction in visibility that follows the fire outbreak.

Visual assessments can be made of the safety of the proposed evacuation procedures by using the visualisation technique to view the smoke development, as predicted by a CFD model, from any angle and observation point, either moving or static, using the Silicon Graphics Explorer program.

Professional Associations and Organizations

ASHRAE's Technical Committee 5.9 Enclosed Vehicular Facilities consists of ventilation professionals from North America and some international corresponding members. The committee meets twice a year in formal meetings and is responsible for the specialized section of the society's handbook. Seminars, symposiums, and forums on tunnel ventilation are organized mostly during society's winter meetings.

The American Public Transit Association (APTA) has a subcommittee on tunnel ventilation, as part of the Structures committee. Annually, during the Rapid Transit Conference, the sub-committee organizes one or two seminars on tunnel ventilation, open for papers from around the world.

The NFPA 130 Technical Committee is in charge of the Fixed Guideway Standard 130, providing continuous review and update of this standard and making recommendations for inclusion of new safety norms.

Specialized international conferences on tunnel ventilation and other safety-related topics are organized at regular intervals by the British Hydromechanics Research Association (BHRA) and the International Technical Conferences (ITC) of the U.K. Occasional technical meetings are organized by the European research projects ARSENAL, STUVA, CETU (France), British Rail, and Fire Research Station.

CONCLUSIONS

Significant progress has been made in the design of subway ventilation systems during the last two decades. The need for more and safe mass transit systems and the public awareness for comfort and safety require attention from operators and designers alike, worldwide.

The CFD modeling technique is clearly advantageous as it provides the capability to predict what happens during a fire, showing the spread of smoke and heat in all dimensions, thus enabling development of meaningful evacuation and fire-fighting plans in large and complex subsurface structures. When considering the benefits and costs associated with this relatively new tool, both designers and operators should examine not only its applicability but also the benefits and advantages over other methods.

A thorough transient simulation of a fire in a transit tunnel or station requires much modeling and computational time. In addition to establishing a representative grid of control volumes, model development requires establishing time-dependent boundary conditions and fire effects. In dealing with tunnel and station fires, the required size of the physical model to incorporate all features of interest can be very large. Such a model would be comprised of hundreds of thousands of cells and would require an enormous amount of computation time, particularly if transient conditions are simulated. There are difficulties in measurement and experimental techniques for identifying accurate velocity components. Average velocities are obtainable, but directional components are difficult to determine. Therefore, experimental techniques for test studies to generate data for CFD problems need to be identified. The concept that test cases are always significantly simplified from real world situations is problematic.

The CFD modeling technique presents clear advantages over single-dimensional software, as it provides the capability to predict what happens during a fire, showing the spread of smoke and heat in all three dimensions, thus enabling the development of meaningful evacuation and fire-fighting plans in complex subsurface structures, such as stations.

Of the parameters that describe the state of the system, temperature, mass-fraction of smoke, and air velocity are the most revealing during a tunnel or station fire analysis. Graphical presentation of the results along cross-sections through the model, shown as color coded contours or vectors, provide a more comprehensible picture than does tabular output. For transient simulations, results obtained at frequent time steps during the propagation of a fire allow for animation and provide capabilities for video presentation.

Recent progress in presenting simulation results include virtual reality which provides a means of creating computer representations simulating the real world. A virtual reality user can "walk-through" the environment at will, pass through walls to see what lies behind or take a bird's-eye view of the complete field, such as in an evacuation situation.

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