

Fire incidents during construction work of tunnels

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Abstract

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This report summarizes guidelines and solutions related to fire safety in underground facilities during the construction phase. Development of different fire scenarios in underground facilities under construction is presented. Based on different design fire scenarios, evacuation analysis was carried out. The situation of the fire services is discussed together proposals for solutions or improvements of their situation. Numerous tunnel sites under construction were visited and conclusions obtained from the visits are presented.

A test with a large scale tire of a front wheel loader was conducted in order to obtain input for the design fire of construction vehicle and model scale experiments to understand the fire physics before a breakthrough inside a tunnel with fresh air ventilation. Recommendations for constructors and authorities as well as for fire services are given. These recommendations are based on the work carried out during the project.

Key words: fire, tunnel, construction, evacuation, fire brigade

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Preface

This report describes a work that was carried out for the Swedish Civil Contingencies Agency (MSB) during period 2008 – 2010. The work was supported by a national advisory group consisting of numerous representatives from industry and authorities:

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Sammanfattning av projektet

Projektet som presenteras här har innefattat litteraturstudier, analyser av olyckor och regelverk, beräkningar, försök i liten och storskala samt insatsövningar tillsammans med räddningstjänsten. Flera arbetsplatser har besökts, exempelvis Norra Länken i Stockholm, en avloppstunnel mellan Partille och Lerum, Hallandsåstunneln i Skåne, Onkalo i Finland där framtidens lagringsstation för kärnkraftsbränsle byggs samt Citybanan i Stockholm.

Vi har identifierat flertalet områden som kan förbättras och utvecklas vidare. Den enskilt viktigaste punkten är om en brand inträffar i fasen före eller efter genomslaget eller genombrottet. Det påverkar både brandförlopp, utrymningsmöjligheter och möjligheterna att göra en räddningstjänst insats. Brandförloppet beror till en stor del på ventilationsförhållanden. Generellt kan man säga att är ventilationen låg minskar brandens intensitet och är den hög ökar intensiteten. Modellskaletförsöken som genomfördes inom projektet visar att om branden sker före genomslaget och den är för liten (några MW) orkar den inte alltid sätta igång den lufrörelse som krävs för att underhålla branden. Konsekvensen blir att branden minskar i intensitet och slutligen slocknar på grund av de inerta förbränningsprodukterna som återcirkulerar till branden.

Utrymningssituationen är avgörande för de som arbetar i tunnlar under byggnation. Det är viktigt att personer som vistas i tunneln är medvetna om objektets utrymningsstrategi och dess utrymningsmöjligheter. I tunnlar under byggnation gäller alltid i första hand självutrymning ut till det fria eller till säker flyktplats. För att hinna utrymma innan kritiska förhållanden uppstår krävs att alla som vistas i tunneln har nödvändig kunskap för att snabbt ta ett beslut om lämpligaste utrymningsväg. För att en effektiv utrymning vid brand ska kunna genomföras är tidig larmgivning och order om utrymning avgörande.

Med hänsyn till osäkerheten var personalen befinner sig i förhållande till brand, utrymningsväg/räddningskammare och stuff är bästa alternativet i de flesta fall att stänga av miljöventilationen. Högre lufthastighet kan visserligen i vissa fall förbättra sikten och den toxiska miljön om man tvingas utrymma i en rökfylld miljö, men samtidigt ökar risken eftersom detta kan innebära att brandens intensitet ökar. Med fördel kan stängningen av ventilationen samordnas med signal för utrymning, alternativt i samråd med räddningstjänsten.

De parametrar som har stor inverkan på utrymningen är brandförloppet och tunnelns tvärsnitt. Kritiskt avstånd till säker plats (flyktplats) är således framför allt beroende på storleken på tunneltvärsnittet. Det betyder till exempel att räddningskammarens eller räddningsvägens maximala avstånd från arbetsplatsen kan anpassas efter storleken på tunneltvärsnittet. Det innebär att ett mindre tvärsnitt kräver kortare avstånd, medan ett större tvärsnitt kan tillåta att avståndet ökas.

Tunnelbesök visa att personalen ska i första hand använda fordon vid transport i tunnelarna. Alla fordon ska ställas upp så att de är omedelbart tillgängliga för effektiv utrymning. Det är viktigt med tydliga instruktioner och ett enat handlings sätt vid nödlägen. En överenskommelse om vilket språk man skall använda vid ett nödläge är också viktigt.

Insatsplaneringen bör ske i samverkan mellan beställaren, entreprenören och räddningstjänsten. Någon namngiven person bör vara huvudansvarig för att ritningar och uppgifter alltid hålls aktuella. Vid tunnelbyggnationer kan många entreprenörer vara inblandade i samma eller parallella entreprenader. Löpande samverkan och samövning mellan entreprenörer är viktigt för att tydliggöra de enskilda entreprenörernas ansvar.

Samövning bör även ske med räddningstjänst, ambulans och polis. Insats- och utrymningsövningar kan med fördel samordnas. Scenariospel är ett bra verktyg för att öva ledningsfunktioner, såväl inom den egna organisationen som för räddningstjänsten. Övningar ska ske för att organisationen och enskilda ska få nödvändiga kunskaper att hantera den uppkomna situationen och för att brister ska upptäckas innan ett skarpt läge uppstår. Målet med en övning ska vara tydligt definierat och inte endast vara att övningen genomförs. Åtgärdslistor för upptäckta brister ska tidsättas och organisatoriska åtgärder följas upp.

När räddningsledaren tar beslut om hur räddningsinsatsen ska utformas är den viktigaste parametern huruvida personer fortfarande befinner sig inne i tunneln eller inte och vilka resurser som behövs för att försöka att undsätta dessa personer. Det är av yttersta vikt att personantalet är säkerställt, oberoende om ett manuellt eller automatiskt loggningssystem används. Räddningsledaren behöver också korrekta uppgifter på eventuella fordon som befinner sig i närheten av branden, i vilken mängd brandfarlig eller brännbara vätskor finns på fordonen och vilka övriga risker som finns nära brandplatsen eller i insatsvägen.

Projektet visar att räddningstjänsten kan inte göra en fullgod insats om tät toxiskt rök har hunnit spridas över ett längre avstånd mellan rökdykarinsatsens ”nollpunkt” och räddningsplatsen. Det måste påpekas att detta avstånd kan variera beroende på omständigheterna vid den aktuella insatsen. ”Nollpunkten” är den plats där rökdykning beräknas börja, och räddningsplatsen är den plats där personer som behöver hjälp befinner sig. Den baspunkt som etableras vid rökdykning i tunnel kan ligga utanför tunnelmynningen medan inträngning i tät rök i vissa fall kan ske först längre in i tunneln. En diskussion om ”nollpunkten” och dess definition bör föras vidare. Om tät rök har hunnit spridas mer än 200 m när räddningstjänsten börjar sin insats är möjligheterna att nå branden inom rimlig tid begränsade med de metoder, den utrustning och de föreskrifter som finns nationellt idag.

1 Introduction

In Europe and other parts of the world numerous tunnels and other underground constructions are built. The construction period is an important factor in getting the tunnel into operation. The stakeholders need to have the tunnel in operation without any delays in order to solve a given traffic problem or to obtain income for their investment. The necessity to adhere to the time schedule, both for the individual contractor and for the society at large, can cause difficult situations as well as incidents created by stress. The fire safety, the working environment and the measures at the site to ensure the fire and rescue services are able to perform a fire and rescue operation as efficiently as possible should it be needed, are important tasks for the building contractor.

Tunnel construction is usually carried out in two phases. The first phase often involves construction of an access tunnel, from which several working faces are started (before breakthrough). Each bore can therefore be constructed independently of the others, although they all stretch back to the access tunnel, see Figure 1. This means that many working faces share a common escape route, which also has to serve as the extraction route for smoke. At the same time, the access tunnel is also a transport route for the rock to be removed from the construction faces and for the materials to be delivered to them. The conditions at the construction site also vary over time during the construction period. The geometry and the length of the escape routes changes as do the number of people and the type of work performed at the site varies.

Traditionally, the focus has been on fire safety and fire development in fully operating tunnels. During constructions of tunnels the situation may differ essentially concerning 1) the physical and geometrical conditions 2) the fire load 3) the possibilities to evacuate and 4) perform a fire and rescue operation. The building equipment used for the construction and materials used are quite different from when the tunnel is in full operation, and many of the technical installations have not been taken into operation yet during the construction phase. Indeed, during the construction phase, the safety installations prior to the finished state are not installed or in function. Further, before the breakthrough, the tunnel can have a “dead end”, which can make both evacuation and fire and rescue operations very difficult. Many different organizations can be involved in the construction work and it is not uncommon that the workers have different nationalities. Both these conditions can, in case of an incident, influence the alarm chain and the quality of the information that reaches the emergency services.

People working in the site may also have difficulty hearing a fire alarm and moving to safety as the environment in the tunnel can be noisy and there may be few evacuation options as the evacuation routes may not be excavated yet or unavailable due to the position of the incident. The situation shown in Figure 1 is very representative for the situation that may occur in the case of a fire where workers can be trapped between the working area and the portal of the working tunnel.

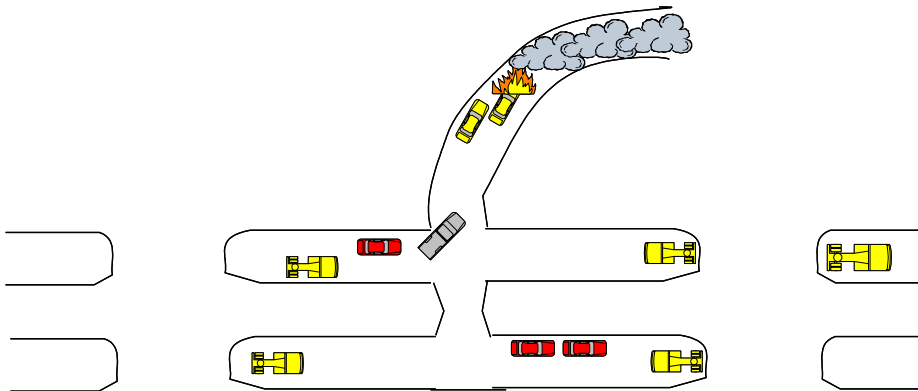


Figure 1 A typical situation during construction of tunnels prior to the breakthrough.

Very little research has been performed on the fire safety during the construction phase. There is a great need for further efforts as the safety is an important part of every project. Fire incidents during construction of tunnels can, and have occurred which can jeopardize or heavily delay the entire project.

Evacuation and ways of fighting fires, as well as selection of safety equipment, are normally based on the expected traffic situation in the completed tunnel. This means that such planning does not always consider the different risks that can arise during the various stages of construction. The dangers facing those who tackle fires can also be very different during the construction stage and when the tunnel is completed. The risk of a fire occurring can also be significantly higher during construction than during normal use.

The project group visited several tunnel construction sites in order to study working conditions, including the Northern Link road tunnel in Stockholm, a sewage tunnel between Partille and Lerum, the Hallandsås rail tunnel in Skåne, and Onkalo in Finland where a future repository for spent nuclear fuel is being constructed. One of the most important objectives of these visits was to look at the problems associated with emergency evacuation during the construction phase, to identify typical evacuation scenarios, and to analyse the safety of personnel during or in connection with evacuation. Description of these technical visits are given in the Appendix.

The aim of this project is therefore to quantify the risks and determine the consequences of fires during construction of different underground facilities. As the subject is very complex in its nature it affects the entire organization at the construction site. Systematic methods and organizations plans to handle this situation are badly needed. Guidelines in how to integrate the methods into the working schemes are therefore an important task. Recommendation on different organization plans for evacuation and rescue of workers in case of emergency is the ultimate goal.

The project has involved literature reviews, analysis of accidents and the regulatory framework, calculations and experiments in small and large scale operation and exercises along with the emergency services and site visits. In the following, a description of the main work is presented. Other reports that have been produced in the project include: large scale test with front wheel loader [1], models scale tests to study smoke spread in tunnels prior to the breakthrough [2], evacuation analysis [3] and fire and rescue operation activities [4].

2 Regulations and guidelines

In the following, a short summary of Swedish and international regulations related to safety in underground construction during work is given.

2.1 Swedish regulations

In Sweden numerous regulation documents are related to safety in underground construction at work. In addition to the general AFS regulation Workplace design (AFS 2009:2) two other regulations are relevant, AFS 2009:12 General Recommendations of the Swedish National Board of Occupational Safety and Health on Work in Confined Spaces (a confined space in AFS 1993:3 is defined as a temporary workplace), AFS 2007:07 Rök- och kemdykning – the Swedish Working Environment Regulation for BA-operations and AFS 2010:1 Rock work (Berg och Gruvarbeten). Another important document is the SveMin 2008 - Fire prevention in mines and rock workings (Brandskydd i gruv och berganläggningar). In the following a summary of Swedish guidelines and regulations are given.

2.1.1 AFS 2010:1 Rock work

In general, every contractor has to provide a safety and health work environment plan which describes how the work is supposed to be carried out and organised. In the AFS 2010:1 regulation document there are several sections/paragraphs which deal with fire safety. Later in the regulation comments/guidelines are given to each section. In the following some extracts from the regulation document are given and commented.

The vehicle engines shall be examined with regard to the risk of a fire. In the guidance section of the document it is pointed out that many vehicle fires are caused by electrical faults, e.g. as a consequence of damage to cable insulation.

Gasoline, ethanol or gas may not be used underground as a fuel for combustion engines where rock work is in progress. Emergency vehicles may, however, be fuelled with gasoline, ethanol or gas. This can be interpreted as the vehicles used in underground constructions should be diesel driven.

Every workplace shall be equipped to give alarm in the event of fire. Evacuation alarm can be given, for example, by means of light and acoustic signals, by radio communication or by telephone. This description sets the level of detection required.

An underground work area shall normally have at least two separate emergency exits. If this cannot be arranged, special measures shall be taken for safe rescue or evacuation. Mobile or stationary safe havens shall be provided where necessary. Exits shall be clearly marked. Special measures for safe relief or evacuation may, for example, include

- installation of rescue chambers or safe havens
- provision of equipment giving access to respiratory air,
- vehicles, electrical installations and material dumps shall be equipped with fixed automatic fire fighting devices,
- use of flame-resistant conductor materials.

Installation of rescue chambers or safe havens requires that the rescue chamber is not located too far from the working place. A suitable distance is said to be 200-300 m but the distance depends on factors such as gradient of the tunnel / location, distance to an escape route, distance to the tunnel portals, etc. Interesting to note, is the requirement on

fixed automatic fire fighting device. This is not explained in any details but the requirement is given. One problem is how to establish or define an automatic system. Usually these fires are difficult to detect, especially with heat detector cables. Further, it is explained that a rescue chamber can be either mobile or blasted out of the rock. Its size will depend on the number of persons who are to use it.

A chamber required to withstand direct fire should be made of incombustible material. In order for a rescue chamber to afford adequate safety,

- it must be adequately supplied with fresh air,
- the ventilation air tube and compressed air tube must have a shut-off device inside the rescue chamber,
- air emission from the rescue chamber must be adjustable so as to maintain a suitable gauge pressure,
- the temperature inside the chamber or safe haven have to be kept at an acceptable level in the event of fire,
- the rescue chamber or safe haven must have speech communication with surface level or with another manned control central unaffected by fire,
- no vehicles or flammable goods are allowed to be stored so close to the chamber or safe haven that it may jeopardize their rescue function.

A written action plan for measures to be taken in the event of an accident shall be written. Examples are given in the guidance part of the document. The plan shall be updated with reference to changes at the workplace. Evacuation from underground workings shall be exercised regularly and at least once annually. This is important information for the project presented here, as much efforts has been put into doing this type of exercises. This has been done in order to learn and improve the exercise concepts.

Details concerning the number of persons and their location underground shall be kept available, so that persons in distress can be located and rescue measures taken. This is important in case of accident as it may assist the fire and rescue teams to get an overview of the situation.

Underground workplaces shall have as low fire load as possible. Flammable products shall be handled and managed in a way so it will minimise the risk of fire or explosion. The term “fire load” refers to all objects or other factors which can help to enhance or spread a fire which has broken out. Material which emits health-endangering or explosive products when heated is unsuitable for use underground. Thus, actions should be taken to ensure that ventilation tubes in a shaft, next to fans and heating installations and openings (entrances, for example), are made of incombustible material. Activity involving a fire risk should if possible be located in an area with at least two access routes. Flammable objects should not be placed in such areas. The quantity of flammable material in stores should be limited. There is no information given on the maximum size of such store in AFS 2010:1.

The regulation point out that it is important that preventive maintenance is regularly carried out on all vehicles transported in the system. This should include inspection of fire fighting equipment. The risk of LPG (Liquefied Petroleum Gas) or other flammable gases escape is greatest when the gas flame is left unattended or when equipment is left with the valve still open after work is over. If LPG is used underground, the gas cylinder should be conveyed to the surface when work is over for a specific day.

In underground sites measures shall be taken to obtain effective fire fighting possible and the spread of combustion gases effectively prevented or controlled. Fire fighting

equipment, including hand held extinguishers, shall be provided on motorised vehicles and machinery.

The requirements given in the regulation document are very general and focus on important subjects. It is very much up to everyone to come up with detailed solutions. There are no direct functional requirements, such as the rescue chamber should be designed to resist a fire in certain number of hours. The more detailed formulations of the requirement are found in the guidelines from SveMin – GRAMKO committee - on fire prevention in mines and rock working.

2.1.2 SveMin 2008 –Fire prevention in mines and rock workings

The guidelines contains recommendations concerning preventive measures for reducing fire hazards aboard vehicles in mines. It states that short circuiting of a substandard electrical system is a common cause of such fires. Another almost equally common cause of fire is “hot surfaces”, in the sense of a flammable substance coming into contact with hot engine parts such as exhaust pipes and engine components.

When choosing fuel, lubricant oil and hydraulic oil for combustion engines, account should be taken of the chosen product’s flash point. Manual shut-off devices shall be terminated when the machine is left unattended. Release device to fixed-mounted fire extinguishing system shall be coordinated with emergency stop placement.

For remote machine shutdown of all power supplier, stop the engine and processing unit and discharge of fixed fire extinguishing system. Release device should be either automatic or semi automatic fire extinguishing system. Automatic and semi automatic fire extinguishing system shall release the extinguishing agent to act on the underground machinery / vehicles through:

- automatic release
- one release device inside the cab
- two release devices outside and on the back of the machine / vehicle and a release device in the vicinity of the machine / normal vehicle entrance / exit door
- machinery / vehicles equipped with lift basket shall have a emergency stop mounted in the lift basket
- emergency stop devices shall be coordinated with the placement of emergency stop for fixed fire extinguishing system

On remote machines, the above points shall be met as well as an emergency stop device accessible from the remote operator's control position.

If automatic release device is available, only a manual emergency stop device in the cab is needed. An indicator lamp shall be provided in the cab instrument panel showing the status of the automatic extinguishing system.

Requirement on fire resistance of tanks and fuel hoses is important. Fuel hoses and similar hoses to the tanks of flammable oils / fluids should be made of materials that meet or exceed requirements for fire resistance according to test standard ISO 7840. Continuous pressurized air tubes in the fire zone must be constructed of materials that at least meets the requirements for fire resistance according to test standard ISO 7840.

There are some requirements given concerning fuel shutoff. Underground machines must be equipped with electro-mechanical working shut-off device for fuel systems or valves.

Machine /vehicle shall be fitted with readily accessible hand fire extinguisher, and instructions for its use and inspections. For dry powder extinguishers, regulatory inspection instruction on the plate / decal shall be mounted in the cab and include information of relaxation of the powder. Hidden extinguishers (mounted in the cabinet, cab, etc.) must be marked with marker sign on the outside. A list of detailed information fire extinguishers is given as well:

- fire extinguishers containing powder or fluid must be pressurized and equipped with pressure sensor (gauge)
- minimum requirements of portable fire extinguishers with powder are Class 43A 233BC and minimum weight of 6 kg as given in EN 3
- For machines with high voltage insulation, a portable fire extinguisher of CO₂ should be used. Minimum requirements are Class 89B in accordance with EN 3
- In addition, an extinguisher with extinguishing fluid selected, minimum requirements are class 34A 233B in accordance with EN 3
- The number of portable fire extinguishers may vary depending on engine / vehicle type and use.

All machinery/vehicles underground shall undergo an annual fire safety inspection under the SweMin prepared checklist and guidance. Checks shall be performed by trained personnel.

When escape is concerned, the general rule is that in a plant should always have two independent escape routes. The alarm systems should be selected according to the special conditions at each location. Examples of alarm systems are given. It can be audible alarm, radio communication, flashing lights or new radio system with extreme long wave so-called "Through the earth".

Evacuation plans should be provided. It should contain appropriately located evacuation instructions featured as a schematic diagram showing evacuation routes. This should indicate how emergency services and other assisting organisations is alerted. The location of the manual alarm and emergency telephone as well as place for gathering of people must be shown.

Rescue and emergency plan must be provided. Review and revision of the plans should be made at least once a year.

The regulations and guidance presented above give a good overview of what is required for fire safety in underground constructions during work.

2.1.3 Project related guidance

For the North Link project in Stockholm (Norra Länken) a template for the plan is prepared by the Swedish Transport Administration (STA) which the contractors may follow. The minimum requirement is set by STA and must in any case be fulfilled. The template covers aspects as emergency preparations, training program, communication systems, passage control system, fire safety and evacuation requirements. The evacuation concept for the construction site is presented in the plan. The tunnel project is separated in several construction sites, each with a separate contractor.

The emergency preparations are stated in a Internet application which are common for the whole project. The Rescue Services are well informed about this and have access to the system in their Rescue Staff.

2.2 International Regulations

2.2.1 DACH document - Recommendations for a occupational health and safety concept on underground worksites

In Europe the regulations dealing with safety in underground construction working sites is found in the DACH document [5]. DACH stands for Germany (D), Austria (A) and Switzerland (SC). The document is intended to provide recommendations for clients, project designers and the contractors for the formulation of requirements and for the conceptual planning of an underground construction worksite health and safety concept. The following basic aims steered the formulation of the document:

- When preparing health and safety concepts for underground construction all characteristics of the construction project and its surroundings have to be taken into consideration.
- The project-specific health and safety concept has to be prepared in parallel with the phases of planning, tendering & awarding and construction.
- A project-based risk analysis has to be performed.
- Project-specific safety measures have to be specified on the basis of a risk analysis carried out in the framework of a safety analysis.
- Capabilities and responsibilities (of the client, contractor/ employer, emergency services, etc.) have to be clearly defined.
- With regard to the economic aspect of safety measures the first aim is to guarantee health and safety for the worksite personnel.
- A permanent process for updating and improving health and safety concepts has to be initiated.

The document does not deal in detail with questions regarding health and public safety, as they are subject to local rules and regulations which differ from one country to the next. This document is meant to be applicable to all manned underground worksites. The document is divided into chapters dealing with each part of the players i.e. client, contractor and authorities/fire services.

First it deals with the **client**, i.e. a company or public body which contracts or intends to contract with a company to work for payment. The important thing is that the client is responsible for the preparation of a planning concept which guarantees safe construction methods and procedures. The client has to ensure the preparation of safety principles and sees to the preparation of a worksite-related health and safety concept. There are several more obligations given but they are not presented here. It has to with implementation of the safety measures, defining measures and requirements which should be, the worksite rules including the access modalities and registration of persons entering the worksite, ensures the application of the “Worksite Directive“ and checks implementation of defined safety measures. The coordination of health and safety has to be granted during both the planning and the construction phase and includes the planning coordination as well as the work-site coordination.

The **Contractor** (a company which performs construction works) must define in the tender documents the essential principles of the worksite-related health and safety concept considering the conditions set by the client. The contractor must also form the same safety standard determined in the tender documents for the basis for special

proposals and additional offers. The contractor prepares the health and safety concept on the basis of the conditions set by the client and his own constructional concept and revises it consistently and is responsible for taking measures aimed at the prevention of events, such as fire. The contractor is responsible for the analysis of possible events and for the necessary machine-related technological requirements and has to inform every person involved in underground worksite activities about possible health hazards according to the risk analysis and has to educate these persons regarding to correct behaviour in case of the occurrence of an event. The contractor has to together with the client and the emergency services determines the type and extent of training exercises regarding evacuation, rescue and fire extinction. There are other important issues that the contractor has to deal with such as provide rescue guide, responsible for additional measures such as alert of staff, information about emergency, checks of safety devices, and implement and monitoring access limitation.

The **responsible authorities and emergency services** have to be involved in the entire preparation of the health and safety concept and especially in the preparation of alert and emergency operations plans. A primary issue of the guidelines is the preparation of the project-specific, individual health and safety concept. This entails the steps: risk analysis, safety analysis, document preparation of the health and safety concept as well as definitions for the practical implementation thereof. The aim of the health and safety concept is to consider the requirements of occupational health and safety in the three phases of planning, tendering & contracting and construction. On the basis of scenarios and specific safety targets it is demonstrated how the required safety of persons involved in underground worksites may be secured by means of appropriate safety measures.

Safety measures

Safety measures serve both to reduce the probability of the occurrence of an event and to deal with an event that has already occurred. In case of an event which has already occurred, their essential aim consists of reducing the damage extent. For the purpose of providing a basic structure, they are divided into the following categories of safety measures

- procedural/constructional,
- technical,
- organisational,
- person related.

In Table 1-6 examples are given how the method is described for each fire related area.

All fire protection-related safety measures have to be collected and described in detail in the fire protection plan. The fire protection measures include clearly defined regulations, regarding for example:

- the minimization of the storage of flammable building materials and the prevention of sources of ignition,
- the appropriate storage of fire loads and storage as far as possible from sources of ignition,
- the use of fire resistive hydraulic liquids,
- plan of ventilation in case of fire,
- the limitation of the “preparational sealing work” before building the concrete inner lining,
- fire protection-related requirements for sealing works,
- concrete after treatment,
- operation of mobile filling stations,

- “nostopping” signs in areas exposed to fire hazards,
- the instruction in fire prevention and extinction,
- the selection and instruction of persons working at machines and devices.

Before construction work starts an alert and emergency operation plan for the construction phase must be prepared taking into account the special characteristics of the worksite, the site-related conditions and the structures of the emergency services. The focus must be on the regulation and determination of measures to be taken within the time period between the occurrence/ recognition of an event and the start of emergency service operations. In case of complex construction projects or changes of the construction process the preparation and adaptation of the individual emergency service plans require the collaboration/support of the persons and entities involved in the project.

The preparation of the alert and emergency operation plan and the collaboration must be appropriately documented. The preparation is performed by the client in collaboration with the contractor, the health and safety coordinator, the designer, the emergency services and the competent authorities and associations. The alert and emergency operation plan for the construction phase is divided into a presentation of the processes and the related documents. In addition to the full version, a clearly structured abstract also has to be prepared for the emergency services and the worksite personnel. The alert and emergency operation plan regulates and/or describes – if necessary in relation to individual events – for example the following issues:

- alarm (alert plan, phone register),
- immediate measures at the worksite,
- evacuation pick up points/gathering points,
- special dangers at underground worksites,
- orientation system in underground worksites,
- control of emergency operations until the emergency services
- assume the control,
- tasks of the emergency services (short description of the interfaces for exchange of information),
- possible structure-related, material-related and personnel related measures to support the emergency services,
- collaboration and communication of the worksite personnel with the emergency services,
- access route for emergency services,
- emergency and supply rooms,
- water protection,
- documentation of emergency service operations,
- information of worksite personnel and emergency services about the alert and emergency operation plan (education and training, information board),
- collaboration with the media,
- the worksite (layout plans, abstracts, short instructions etc.).

In Table 1 examples of fire extinguishing measures are presented. It shows that fixed fire extinguishing device is required for stationary areas such as the TBM areas, work places, filling facilities and storage of fuel loads. It also requires for mobile areas of construction vehicles. It also mention portable fire extinguishers, education and water supply. A guidance according to ventilation is also given. In principal one should try to keep the smoke away from the working areas.

Table 1 Example of fire extinguishing measures and ventilation system.

Measure category	Measures	Explanatory notes
Fire extinguishing measures		Includes all measures which are required for the extinguishing of fires (at the moment of the ignition).
	Fixed fire extinguishing device	Automatic fire extinguishing facility (water spray, foam and possibly CO ₂) in areas of concentrated fire loads (e.g. in TBM areas, in work places, filling facilities, underground reserves of fire loads). Water curtains are required for example in case of machine-driven tunneling methods for smoke reducing purposes.
	Fire extinguishing device on mobile machines and devices	These fire extinguishing mechanisms serve to extinguish fires arising in the areas of engine, hydraulic or electrical components. It has to be noted that for example fires in engine compartments normally can not be fought by hand-held fire extinguishing devices, because of lacking accessibility.
	Fire extinguishing devices	There are various types of manual fire extinguishing devices available.
	Water extinguisher	Fixed or mobile fire extinguishing devices having greater capacities than manual fire extinguishing devices.
	Fire education	All people involved in underground worksite activities must be educated and instructed on: <ul style="list-style-type: none"> - fire detection, - fire effects, - fire spreading, - usage of existing fire extinguishing agents. The effects and usage limits of fire extinguishing agents have to be explained and must be practised by each person involved in worksite activities.
	Fire extinguishing water supply	The installation of a fire extinguishing water supply within the tunnel is meaningful if <ul style="list-style-type: none"> - the facility may be used by the present persons, - the fire extinguishing water reserve is enough, - there is sufficient pressure (upward tunnel boring), - there are sufficient flow pipes provided with locking valves and couplings, - fire extinguishing hoses are available in time. If these preconditions are not fulfilled, the fire extinguishing measure will not work.
	Choose of fire extinguishing agents	*** no note available ***
Fire ventilation system		The aim is to keep the escape and emergency routes as free from smoke as possible. The spreading of smoke plumes must be prevented.
	Ventilation control in case of fire	In order to be able to prevent the spreading of smoke plumes, it must be guaranteed that the ventilation system may be controlled from one or more suitable places.
	Suction of smoke plumes	The removal of smoke plumes may be performed for example by means of suction ducts (removal of plums and ducts due to blasting) or by means of equipment for fire gas removal purposes in traffic structures. When planning the sequence of construction works, the point normally is to decide whether to use existing worksite facilities or to use facilities designed for the operation of the tunnel under construction already in the construction phase.
	Keeping spaces free from smoke	In case of twin-tube tunnel structures with recirculating air ventilation systems, the ventilation in the fresh air tunnel has to be stopped in case of fire. In order to keep the exhaust tunnel (escape and emergency route) free from smoke, the ventilation system must provide the possibility to raise the pressure in this tunnel until slight positive-pressure is reached. This requires the installation of special ventilation systems.

In Table 2 examples on how to keep smoke free zones is given. The distances between fixed workplaces and smoke free areas must not exceed 500 m. This is an important rule in the entire concept given in these guidelines. There are numerous different situations and solution in order to obtain smoke free zones given in the table. Interesting to notice is that the second tube can be defined as a smoke free zone, but only if it is kept pressurized. Different types of rescue chambers are given.

Table 2 Example of smoke free zones and emergency air supply

Measure category	Measures	Explanatory notes
Smoke-free zones		Smoke free areas are required in order to improve the chance of survival in case of entrapment due to fire. Smoke free areas must be easily reachable. The distances between fixed workplaces and smoke free areas must not exceed 500 m.
	Emergency cabin	The emergency cabin functions as a smoke free zone if an escape into the open is not possible or is unsafe. Moreover, the emergency cabin gives protection in case of blasts and ought to be used as recreation room (in order to increase familiarity with it) Principally, the emergency cabin is not designed for purposes of protection against direct fire and heat.
	Emergency tent	In case of small mining diameters, there may be not sufficient space to install a fixed emergency cabin. If this is the case, emergency tents may be used which are made of fire-retardant materials, are un- or partly-compressed and may be put into operation (inflated) in case of fire.
	Rescue galleries	In traffic tunnels fitted with conduits under the carriageway feeding the trailer of a TBM, the rescue galleries shall be fitted with appropriated air pipes supplied with fresh air. A smoke-free area should be provided and is ideal as rescue and emergency exit. Measures shall be taken to have access to the rescue galleries especially on the rear part (e.g. provisional safe guarded exits)
	Second tube	In case of twin-tube tunnel structures with cross-passages, in twin-tube ventilation sections with recirculating air ventilation system the second tube may be turned into a smoke free zone.
	Decompression chamber	In case of shield tunneling the decompression chambers may serve as smoke free zones in case of a fire. They must be accessible rapidly and safely in case of fire
	Control cabin of the tunnel boring machine (TBM)	It is recommendable to design the control cabin of the tunnel-boring machine as smoke-free zone in case of fire. This aim may be achieved by connecting the control cabin with the compressed air supply.
Emergency air supply		Principally, all persons staying in the smoke-free zone must be supplied with air.
	Emergency air supply pipe	The emergency air supply to the emergency cabin is performed by an appropriately designed pipe leading from outside into the cabin. This pipe has to be run in such a way that it is protected in case of machine fires (under the floor or in the invert). It is recommended to use the normal compressed air supply of the tunnel mining facility.
	Compressed-air supply by compressed-air cylinders	Air supply to the emergency cabin by means of compressed air cylinders is sensible but is not suitable as main air supply. Alternatively to compressed air supply systems working from outside, self contained emergency cabins may be used.

All fire and rescue-related safety measures have to be brought together and described in details in the rescue plan. Fundamentally, the rescue measures regarding underground worksites are divided into self-rescue measures and rescue measures taken by another person. The importance of self-rescue rises with the length and the difficulty of the access which the emergency services have to pass before reaching the place of the incident. Time and energy for performing necessary self-rescue measures are determined by the expected maximum time period between the occurrence of the event and the arrival of the emergency services at the place of the incident. The maximum allowed number of visitors defined by the client has to be taken into account when determining safety facilities and capacity. The visitors have to be informed and instructed. There are certain rules to follow concerning how to instruct the visitors. They are obliged to wear the required personal protection equipments.

Table 3 Exampels of safety measures for fire and rescue

Measure category	Measures	Explanatory notes
Rescue planning		A successful rescue in case of an event, requires measures regarding both self rescue and rescue by other persons. Self-rescue is of crucial importance; it is complemented by the rescue by other persons.
	Fundamentals	The planning of the measures must start from the assumption that all consequences of a single event have to be taken into account. The occurrence of two isolated events at the same time cannot be excluded but is normally regarded as an acceptable risk.
	Agreement regarding rescue by other persons	Planning the rescue by other persons and the required measures in agreement with the competent and appropriate emergency services.
	Emergency planning	The emergency planning must take the actual situation into account as well as the technical and personnel-related capacities of the regional emergency services.
	Self-rescue planning	In case of an event, concerned people must be able to reach a safe area. This must be considered during both project planning and site preparation work.
	Visitors	Fundamentally, the possibility of visitors has to be taken into account when preparing the rescue protocol. The number of visitors allowed to enter the worksite must be limited, as they are not familiar with the situation and their reaction in case of an event is not predictable. The maximum number of persons allowed to stay at the worksite at the same time is determined by the number of existing safe areas.
	Management measures in case of floods	*** to be defined additionally by the users if necessary***
	Emergency training	Practical training in order to rapidly find all locations and all emergency supplies.
Rescue management plan		A successful rescue requires close collaboration between persons and entities involved in worksite activities and the emergency services. This must be considered when planning rescue management
	Rescue guides	Rescue guides are persons who are appropriately educated and can be contacted during the event. They must have the required language knowledge and act as the contact persons for the emergency services. Additionally, they have the required knowledge regarding the worksite area and the present worksite situation.
	Information of emergency services	The emergency services must regularly be informed about changes in the worksite conditions. Normally, this requires the supervisors of the emergency services to visit the worksite several times a year.
	Instruction of emergency services	Depending on the type of the rescue management, instructions covering the following activities are required <ul style="list-style-type: none"> - driving a locomotive, - operating shaft inspection devices and cranes (transport of rescue equipment), - using underground communication systems, - control of ventilation system.
	Meeting points for rescued people (in the open/under ground)	Meeting points which have to be marked, their location made known to the workforce by instruction and training.
	Worksite rescue team leader	The leader of the rescue team and his deputy must be determined and the appropriate instructions must be given.
	Training rooms	Appropriate rooms for training have to be provided.
Protective equipment		The protection equipment includes, among other things, protective clothing and protective respiratory devices
	Protective clothing	Rescue guides and persons entrusted with special fire extinguishing tasks must be equipped with appropriate protective clothing such as fire retardant suits and the appropriate protective shoes.
	Breathing apparatus	Normally, devices with duration of 4 hours are used. The respiratory protective devices commonly used by the fire brigade with duration of approx. 30 minutes are normally not suited for underground areas.
	Oxygen apparatus for self-rescue	The oxygen apparatus for self-rescue serves to allow to escape through a smoky area into smoke free areas such as emergency cabins or in the open. It is designed for single use only and may not be opened and activated before smoke is detected (the oxygen production cannot be interrupted). When planning the oxygen self-rescue equipment, third parties also have to be considered (e.g. visitors).

Concept of training includes the regular performance and documentation of training units. Before beginning with an exercise, all persons involved have to be informed as required about the presumed emergency situation and the aim of the exercise. The exercise has to be analysed after its conclusion and possible improvement options have to be put into practice. If it is the case or if necessary, previously determined safety measures have to be reviewed and revised.

Table 4 Example of fire and rescue training measures

Measure category	Measures	Explanatory notes
Rescue training		Self-rescue training and training involving the emergency services
	Internal rescue training	Training of giving alarm, correct behaviour in case of fire, self-rescue, use of escape ways, use of rescue cabins
	Rescue training involving emergency services	As few emergency services are experienced in rescue from tunnel constructions and underground worksites, they have to train in this type of rescue

Table 5 Example of fire protection measures

Fire protection measures	Measures aimed to prevent fires forms part of the worksite safety protocol and not of rescue protocol
	Fire fighting protocol
	Fire extinguishing devices

German part

In the part of the DACH document that's apply for Germany, a hazard categories are given for conventional tunnel driving methods and TBMs. In Table 6 the hazard categories are defined and cases which can be applied are given, see Figure 2 and Figure 3. Depending on the distance to escape routes, the hazard category is determined. Longer the distance, higher the category become.

Table 6 Hazard categories used for determination of different safety measures

Hazard category A (Lowest hazard category)	During tunneling the lengths of the escape routes leading to a safe area are shorter than 500 m. (Case 1 and 4)
Hazard category B	During tunneling the lengths of the escape routes leading to a safe area are longer than 500 m but shorter than 1.000 m. (Case 2 and 5)
Hazard category C (Highest hazard category)	During tunneling the lengths of the escape routes leading to a safe area are longer than 1.000 m. (Case 3)

In Table 6, there are some cases given as example. In Figure 2 and Figure 3 drawings from the guidelines [1] are given.

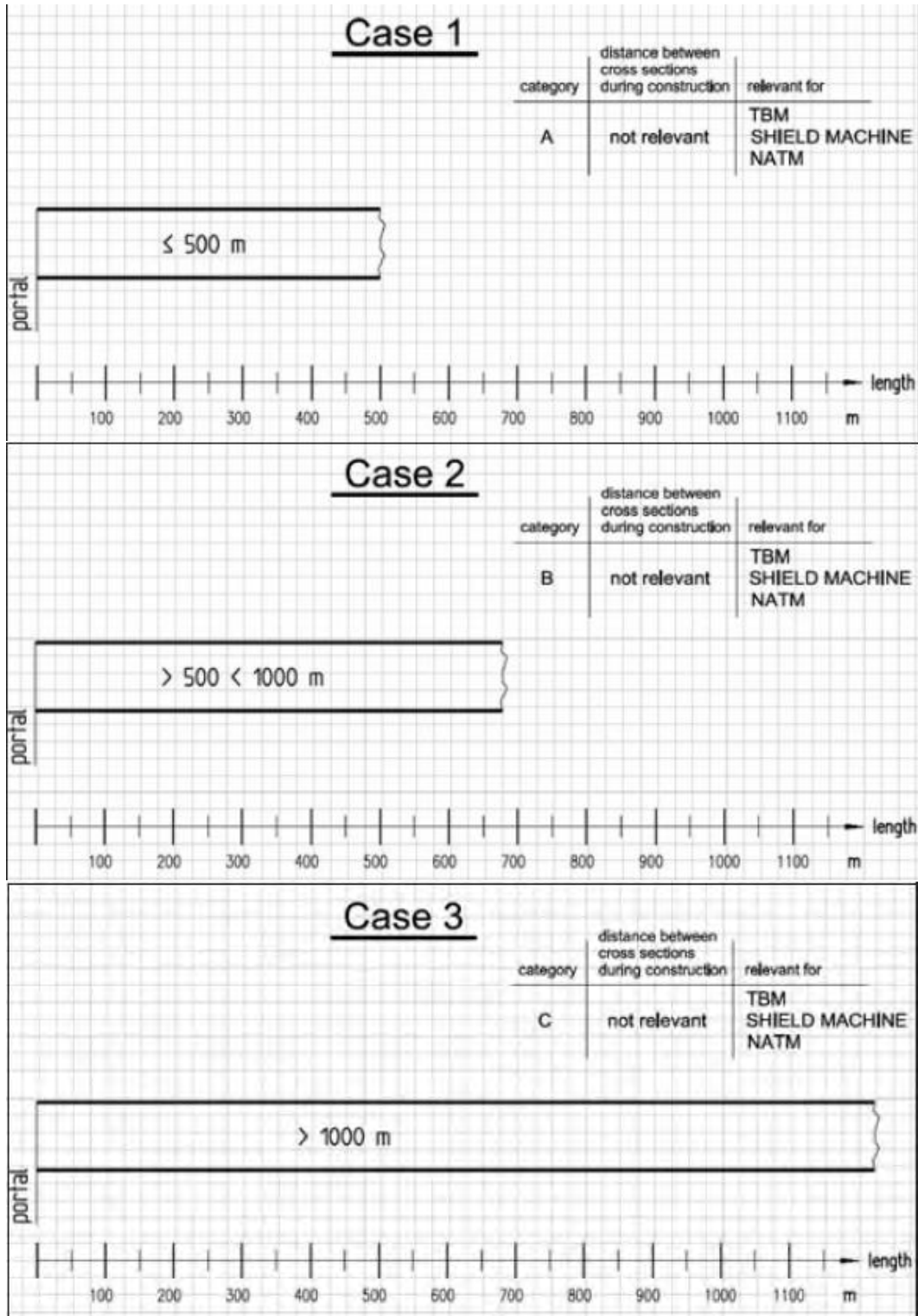


Figure 2 Distance to portal for Cases 1 ($<500\text{ m}$), 2 ($500 - 1000\text{ m}$) and 3 ($>1000\text{ m}$) from Table 6.

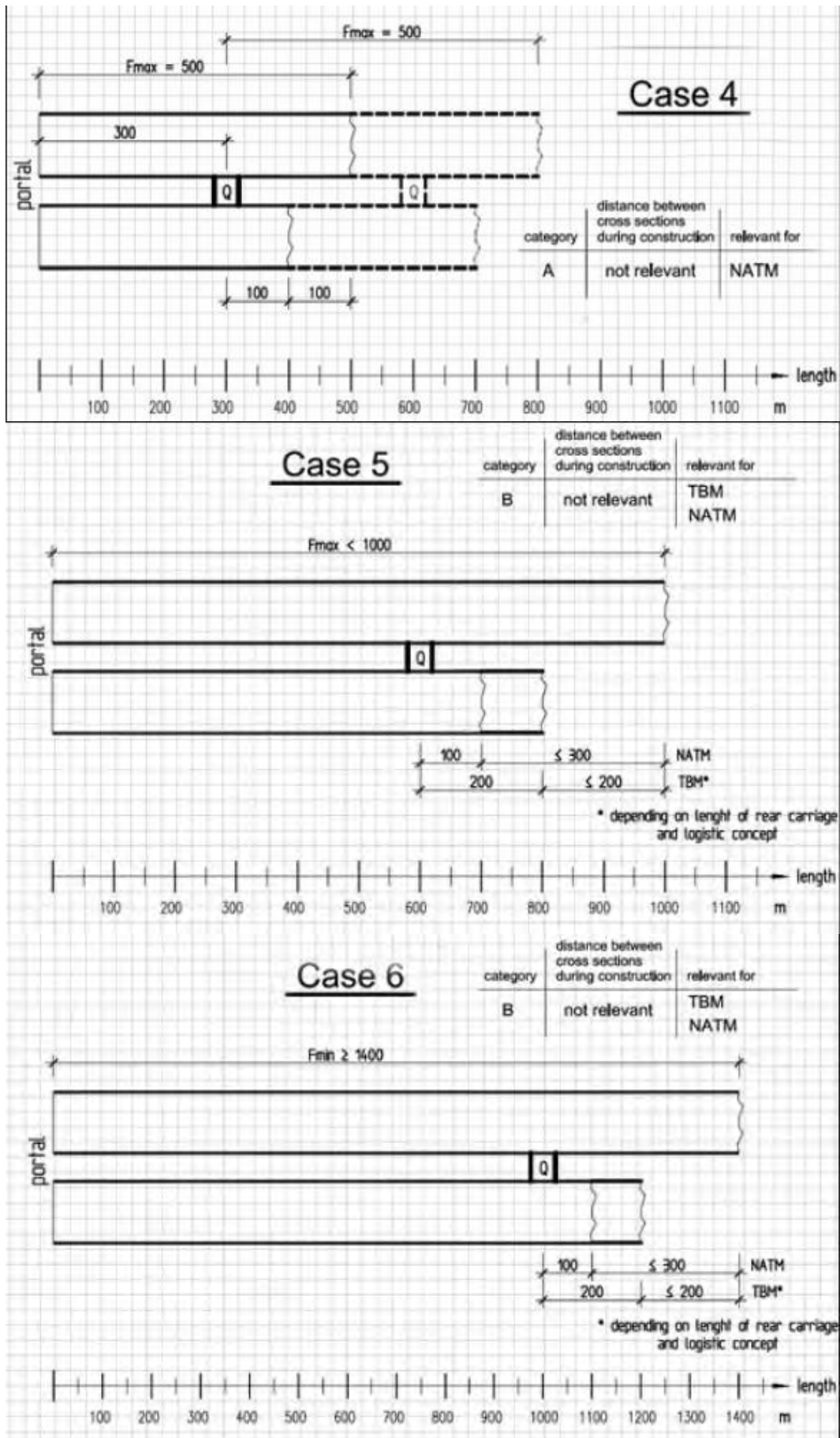


Figure 3 Cases 4, 5 and 6 from Table 6.

Protective cabins serve to protect persons against gases due to blasts and, in case of fire, against flue gases. Depending on the tunnel driving method, protective cabins must be located as near as possible at the heading face. The minimum requirements for **protective cabins** are:

- Design according to personnel and visitors to be protected in case of an event: The dimensions of the cabin must be designed considering the number of persons (personnel and visitors) to be protected in case of an event (at least 1.0 m²/person).
- By means of the compressed air supply system of the tunnel, the protective cabin must be provided with external positive pressure holding a positive pressure of ~ 0.001 bar or 100 Pascal. In case of a failure of the external positive pressure supply, air supply must be guaranteed for at least 4 hours by means of bottles. The estimation of the required amount of air must be based on an air consumption of 40 l/min per person considering the maximum number of persons permitted to stay in the cabin.
- The protective cabin must be provided with the following equipments:
 - Lighting with external power supply, in case of a blackout emergency handheld lamps (one lamp per person) and an emergency phone must be provided,
 - Additional oxygen self-rescuers according to the maximum permitted number of persons; the lasting time must be adapted to the lengths of the escape routes (approx. 40m/min),
 - Stretcher, first aid kit, toilet.
- The protective cabin must be clearly signed by colour (e.g. reflective paint). At the outside of the cabin, lightning lamps which are automatically activated in case of an event must be installed in order to facilitate the locating of the cabin. The routes leading to the protective cabin must be signed as escape routes.
- The doors must be provided with windows in order to enable the communication between outside and inside the cabin.
- Information boards indicating the correct behavior in case of an event must be fixed within the protective cabin.

The **emergency cabin** is designed to be reached if the oxygen self rescuer does not last for the time necessary to reach an area providing long-term safety.

- Emergency cabins should preferably be placed on the tunnel floor, fire loads must be stored in sufficient distances.
- The emergency cabin must be provided with compressed air supply from outside and with an energy supply (power/water) for climatization purposes. The associated components must be appropriately protected, for example, by running the cables and ducts under the floor (embedding in the concrete or in the floor).
- If the cables and ducts (compressed air, power, water) cannot be run under the floor, they must be designed in such a way that their resistance against fire is guaranteed (for example using thick-walled steel cables, appropriate heat resistant sealings).
- If the air and energy supply from outside is not possible, another sufficient air and energy supply lasting at least for 24 hours must be provided (e.g. 40 l of compressed air per minute and per person).
- The intrusion of heat into the emergency cabin must be prevented as far as possible (for example by sprinkle systems, isolation, cooling). The climatization system should be designed to hold temperatures of 30° C (for a time period of at least 8 hours with an outside temperature of 60° C).

Based on these guidelines one can design the protective chambers or the emergency chambers. The main parameters are number of workers, need of oxygen and climatization. The workers shall survive over 4 h fires or more.

The following safety facilities and/or measures are necessary in case of a fire during conventional tunneling methods for category A hazard:

- Providing appropriate fire extinguishers, fire extinguishing systems, etc at the main hazard points (especially at transformers in tunnels)
- Installing a fire extinguishing water supply (including a service water duct) with sufficient connections (at least hose c, maximum distance approx. 100 m, hose included) providing sufficient capacity and sufficient pressure when the system is out of operation.
- A protective cabin must be provided near the place where the tunnel is driven forward.

In addition to the safety facilities and measures listed for category A, the contracting company must provide for as follows (hazard category B):

- At dangerous points (transformer, hazardous materials store, filling station, blast materials store) automatic fire alarm systems (smoke detector, epichlorhydrin detector, heat detectors) with automatic release mechanism sending the alarm also to the office of the site manager must be installed.
- The length of the free-lying seals installed before starting the concrete works must not exceed 50m. If this length is not sufficient for reinforced inner linings because of the required sequence of construction works, the length may be extended to a maximum length of 150 m implementing the at same time appropriate additional fire protection measures. The plastic sealing sheets should be laid only after the tunnel is completely driven or after the implementation of other comparably efficient protective measures (e.g. plasticfree fire breaks, sprinkle curtains). If this is not possible, at least one location which can be reached within the lasting time of the oxygen self-rescuer must be provided between the seal area and the heading face.
- The installation of bituminous tunnel seals does not correspond to the technical state of the art anymore.

In addition to the safety facilities and measures listed for category A and B, the contracting company must provide for as follows (hazard category C):

- Near the point where the tunnel is driven forward an emergency cabin must be provided instead of a protective cabin.
- Installation of two separate communication systems (phone system/radio system)
- The cables of the communication system must resist fire and function for at least 30 minutes
- Providing locating aids for the rescue of persons staying underground
- Diesel-powered machines and transport machines which are regularly used at underground worksites must be provided with fixed fire extinguishing devices with manual or automatic release mechanisms.
- The necessity of a project-related tunnel fire brigade must be examined depending on the equipment and the education of the respective local fire brigades and emergency services considering also the conditions of the location.

Tunnel-boring machine drive of category A

- A communication system must be installed (e.g. emergency phone with automatic dial).
- If there is only a single person in the tunnel boring machine, there must be a handsfree phone connection with a person outside the tunnel.
- Transformers in the tunnel must be provided with fire extinguishing devices with automatic or manual release mechanisms.
- Fire blankets must be provided.
- Use of hardly inflammable hydraulic liquids.
- All supply aggregates and facilities must be provided with appropriate fire extinguishing equipments (e.g. fire extinguisher, foam, inert gas).
- All motorized transport and supply vehicles must be provided with hand held fire extinguishers (at least 2 x 10 kg).
- Existing service water ducts may be used for fire extinguishing water supply purposes; the required static pressure must be ensured.
- Flammable materials must not be stored for several days on the tunnel boring machine and at important rescue-relevant places.

The following measures must be considered in addition to those listed above for category A:

- Above the escape route, water curtains must be installed, at least at the end of the rear trailer. The water supply tubes must be thick walled.
- Two separate communication systems (e.g. phone system/radio system) must be installed in such a way that they are protected against fire.
- At the main hazard points appropriate fire extinguishing devices must be provided.
- An appropriate fire alarm system, e.g. with epichlorhydrin detection component, must be installed.
- A protective cabin, appropriately dimensioned to give protection to the maximum possible number of persons (personnel and visitors) present at the worksite, must be carried in the rear trailer.

The following measures must be considered in addition to those listed for hazard category A and B:

- Instead of the protective cabin an emergency cabin with appropriate dimensions to give protection to the maximum possible number of persons (personnel and visitors) present at the worksite must be carried in the rear trailer.
- An automatic fire alarm system (smoke detector, heat detector) with automatic release mechanism sending the alarm also to the office of the site manager, must be installed at the main hazard points (transformer, electric facility, hydraulic aggregates)
- Diesel-powered machines (engine, etc) must be provided with fixed fire extinguishing devices with manual or automatic release mechanism.
- If required, persons knowing the place and medically fit to wear a breathing apparatus who may help to improve the efficiency of emergency operations must be present at the worksite.
- Locating devices for the rescue of persons staying underground must be provided.
- The necessity of a project-related tunnel fire brigade must be examined depending on the equipment and the education of the respective local fire brigades and emergency services considering also the conditions of the location.

Interesting to notice in these guidelines are the specific quantified designs on the rescue of people. The protective chambers should take into account the number of personnel and visitors assuming at least 1.0 m²/person. This would require rather large chambers in case of large number of personnel. Also the overpressure of 100 Pa is rather high. The air supply of least 4 hours is in accordance to the Swedish SveMin regulations. Designing for the air consumption of 40 l/min per person is also interesting number. Additional oxygen self-rescuers according to the maximum permitted number of persons; the lasting time must be adapted to the lengths of the escape routes (approx. 40 m/min),

Other interesting specifications found in the guidelines is the requirement of the climatization system should be designed to hold temperatures of 30°C (for a time period of at least 8 hours with an outside temperature of 60°C). Also, the length of the free-lying seals installed before starting the concrete works must not exceed 50 m. If this length is not sufficient for reinforced inner linings because of the required sequence of construction works, the length may be extended to a maximum length of 150 m implementing the at same time appropriate additional fire protection measures. This is an interesting requirement considered for Swedish regulations.

2.2.2 Other related international documents

The COUNCIL DIRECTIVE 92/57/EEC of 24 June 1992 on the implementation of minimum safety and health requirements at temporary or mobile constructions sites (eighth individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC).

The COUNCIL DIRECTIVE 92/91/EEC of 3 November 1992 concerning the minimum requirements for improving the safety and health protection of workers in the mineral-extracting industries through drilling (eleventh individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC).

In the directive we find that one should implement protection from fire, explosions and health-endangering atmospheres. The employer shall take measures and precautions appropriate to the nature of the operation:

- to avoid, detect and combat the starting and spread of fires and explosions, and
- to prevent the occurrence of explosive and/or health-endangering atmospheres.

For escape and rescue facilities the employer shall provide and maintain appropriate means of escape and rescue in order to ensure that workers have adequate opportunities for leaving the workplaces promptly and safely in the event of danger.

Also, for communication, warning and alarm systems the employer shall take the requisite measures to provide the necessary warning and other communication systems to enable assistance, escape and rescue operations to be launched immediately if the need arises.

The EN 791 covers safety of drill rigs used in the construction, water well drilling and mining and quarrying industries above or below ground and includes percussive and/or rotary drilling methods.

There are regulations for testing of solid fire resistance solid products in machines for mines available. It is based on the ASAP 5001 document "Application Procedures for Acceptance of Flame-Resistant Solid Products Taken Into Mines" from the MSHA - Mine Safety and Health Administration, Approval & Certification Center in USA. This is related to the requirement in the Code of Federal Regulations (CFR), Title 30 which

contains mandatory regulations for flame resistant requirements of many products used in underground mines.

The purpose of the document is to establish a voluntary Mine Safety and Health Administration (MSHA) Standard Application Procedure (SAP) for the flame testing, evaluation and acceptance of solid products taken into underground mines. The following products may be accepted under this Application Procedure; air hose cover, belt skirt, belt wipers, chute liner, hydraulic hose cover, mine spray hose cover, pulley lagging (conveyor roller covers), rock dust hose cover, seat cushion material, water hose cover, (not as fire hose), impact bars, roof/Rib Grid Material and hydraulic hose protective sleeve. There are products also evaluated under these procedures and are required to be flame-resistant for example battery box insulation, cable reel insulation and packing material. Acceptable flame resistance of a product is determined by MSHA in accordance with one or more of the following flame test procedures:

- The “2G” test: ASTP5007 - MSHA’s Standard Flame Test Procedure for: Hose Conduit, Fire Suppression Hose Cover, Fire Hose Liner and Other Materials; Title 30, Code of Federal Regulations, Part 18, Section 18.65
- Standardized Small Scale Flammability Tests: ASTP5011 –Standardized Small Scale Flame Test Procedure for the Acceptance of Roof-Rib Grid Material; (Also see: 30 CFR, Part 7, Subpart B)

In instances where these flame test procedures may not be appropriate due to the physical characteristics or intended use of certain materials, another test may be specified by MSHA.

Same type of document is available to hydraulic fluids which should be tested in accordance to the ASAP 5003 “Application Procedure for Approval of Fire-Resistant Hydraulic Fluids According to the Code of Federal Regulations, Title 30, Part 35” from MSHA. There are numerous hydraulic fluid types identified; invert emulsion, water glycols & storage fluids, high water concentrate and synthetic (polyol ester, other).

There are three methods described to test the hydraulic fluid. The purpose of the first test, ignition-temperature test, is to determine the lowest autogenous-ignition temperature of a hydraulic fluid at atmospheric pressure when using the syringe-injection method. The purpose of the second test is to determine the flammability of a hydraulic fluid when it is sprayed over three different sources of ignition. The purpose of the third test is to determine the effect of evaporation on the reduction of fire resistance of a hydraulic fluid.

3 Fire accidents

Fortunately, not many fires have been reported for tunnel construction sites which have lead to serious human damage. Most cases only lead to property losses and construction delays but there have been cases claiming loss of lives and the potential for human losses is high especially for tunnel being refurbished and still being in operation like the tunnel fire in Tauern in Austria in 1999 [1].

This report covers, however, fire safety issues in construction sites under ground in general and those who are newly constructed or under substantial reconstruction. Three such tunnel fires are reported below.

3.1 Fire in the TBM under Store Baelt in Denmark

The fire occurred in the TBM in the railway tunnel approximately 2 km from the Zealand side the 11th of June 1994 [2,3]. The fire fuel was mainly hydraulic oil from the TMB power system which was distributed at high pressure as an oil spray. The cause of fire was unknown but the fire duration was about 11 hours. The fire started at approximately 7.30 in the morning and the fire department claimed to have the fire under control at approximately 19.30 the same day. Several attempts were made to fight the fire and also the tunnel workers did initial attempts to extinguish the fire but without success. In total approximately 2000 l of hydraulic oil was consumed in the fire.

The workers did manage to escape to the parallel tunnel through a crossing. The smoke was reported to be very thick and black i.e. the smoke seriously impaired the visibility for the persons escaping the fire. Several fire extinction systems were available; portable extinguishers, water hoses, a low density foam system and a “high density foam plug”. It is, however unclear what systems actually was used as it is stated in the report that “Those systems with a chance of success were attempted by trained personnel wearing breathing apparatus but were not able to extinguish the fire” [2]. All of the workers could escape safely and no one was seriously hurt.

3.2 Fire in the A86 ring road tunnel in Paris, France

A fire broke out the 5th of March in 2002 in the east section of the A86 route [4,5]. The tunnel is supposed to be used for light vehicles and the traffic is routed in two levels in the tunnel, one direction for each level, figure 1. The total tunnel diameter is 10,4 m and the clear height in the traffic area is 2,55 m. The fire started at 22.30 in a locomotive engine in the supply train approximately 550 m behind the TBM. The fire fuel was mainly the locomotive fuel and a conveyor belt. The smoke produced was very thick. Workers on the train tried to extinguish the fire but unsuccessfully. The 19 workers fled to the TBM and into the rescue chamber where they waited until the fire was extinguished. The fire-fighters had a first contact with the trapped workers at approx. 02.50 after a difficult movement, finally by foot, to the TBM. The local fire department had the fire under control at 06.00 the following day but the workers were rescued from the chamber well before that passing the fire location wearing BA-apparatus. The fire-fighting was conducted with great difficulties as all tunnel equipment broke down. There was no tunnel ventilation, the communication equipment did not work and the tunnel light did not work due to the fire. “High capacity ventilators/smoke extractors” [4] were used but it is unclear whether or not they were successful.



Figure 4 Tunnel section for A86 east link.

3.3 Fire in Södra Länken tunnel

Södra Länken is a road tunnel system south of Stockholm, Sweden. A fire started in the tunnel lining material on Thursday the 22 January 2004 [7]. The lining material consisted of polyurethane foam sheets. The lining material was located above the concrete ceiling to collect water from the rock above and to lead the water to a drainage system. The fire department was called to the tunnel due to reported smoke in the tunnel. The fire was quickly located to the ceiling and a foam extinguishment was performed after the reconnaissance. The damage extended approximately 400 m in the insulating material. There was a potential danger from the concrete ceiling slabs falling down on the fire and rescue teams. No person was hurt. The fire is believed to have been started in a heating cable used for preventing ice build-up in the polyurethane foam.

3.4 Zürich-Thalwil tunnel fire

In the morning the 5th of July 2000 at approximately 02.30 a fire started in a electrical power container at approximately 4,2 km from the access shaft at Brunau on the Zürich side of the fire [8]. The access shaft is 32 m deep and was later used for the fire fighters to reach the tunnel level. The shaft was equipped with a personal elevator and a crane which could be used to elevate large vehicles, up to 25 tons. The personnel that worked in the tunnel quickly noticed the fire as smoke came out of the electrical container and gathered in a mini van. They started to drive away from the fire and met a foreman who was alerted to the place because of an electrical problem alarm. He was convinced that there was a fire in the tunnel and joined the workers. At that time, i.e. at 03.15 in the morning, the fire department was alerted. All the workers, including the foreman, left the tunnel without any injuries.

3.5 Fire in the Björnböle tunnel at the Bothnia Line in Sweden

The Bothnia Line is the largest railway project in Sweden in modern time. The new single-track railway runs from north of Kramfors airport to Umeå in the north of Sweden. The total length of the new distance is 190 km of which 25 km are tunnels. The Björnböle tunnel is one of the longest with it's 5,2 km. The fire in the Björnböle tunnel occurred the 24th of March 2006, when 1300 meters of the tunnel had been driven. The fire started in

the drilling rig, which later was found totally burnt out. Just before the fire the workers heard a loud bang and then discovered the fire. There were two workers at the tunnel face at the time of the fire. The fire occurred close to a shift change at 7 o'clock in the morning and the workers had not yet started the planned work. The workers escaped by running approximately 400 meters to their car and could drive out safely from the tunnel. When they reached the car the smoke front was relatively close behind them. The workers described the fire development as fast. As no one was still left in the tunnel the fire and fire and rescue services decided not to try to extinguish the fire. The drilling rig stopped burning by itself after approximately four to five hours and the fire and fire and rescue services could reach the burnt drilling rig at lunch-time. The normal ventilation system was used during the fire to speed up the clearing of smoke from the tunnel.

3.6 Underground fire traps 3 miners at Missouri lead-zinc operation

A very interesting fire for the project discussed here, occurred recently in USA. It was reported in the Coal Tattto magazine that a truck fire broke out on January 21st 2010 at lead-zinc mine in USA. Three miners were trapped when their escape route became blocked by the 30-ton haulage vehicle. The blaze, which erupted around 10:30 prompted an immediate evacuation of the mine. When mining officials discovered that three of the 16 working underground remained unaccounted for and uncommunicative, they activated the company's two mine fire and rescue teams. Officials from the U.S. Department of Labor's Mine Safety and Health Administration (MSHA) arrived on the scene around noon, followed by a third fire and rescue team from St. Genevieve, Mo.-based Mississippi Lime Co.

While rescue activities were underway, the three miners travelled 730 m on their mining equipment to a designated refuge chamber – stocked with water and compressed air – where they waited safely inside. Meanwhile, six members of Doe Run's mine fire and rescue team entered the mine from the surface through a 176 m deep ventilation shaft. The team advanced approximately 426 m, and, around 15:50 (more than 5 hours later), located the miners in the refuge chamber. With the aid of a rescue escape hoist, the miners arrived at the surface between 16:00 and 17:00, and were transported by ambulance to Washington County Hospital in Potosi, Mo., for observation. They were treated and released that evening. The last of the mine fire and rescue team members reached the surface at 17:30.

3.7 Fire in bulldozer

MSHA report in 2002 that a miner was seriously burned when the equipment he was operating caught fire. The operator hit the manual fire suppression actuator, but did not pull the pin. Thus, it did not actuate. There was no fire extinguisher in the cab and the operator was burned when he tried to get out by the normal egress route. He finally managed to get out on the opposite side. The following suggestions may help avoid this situation:

- Training on fire suppression systems should be given to operators of trucks, bulldozers and other enclosed cab vehicles. A manual fire suppression actuator should be used as a training tool in this effort, if it is utilized. Special emphasis should be placed on activating the system in realistic conditions.
- All fire extinguishers and fire suppression systems including alarms, shutdowns and other associated equipment need to be thoroughly examined and periodically checked for proper operation by competent

personnel in accordance with the manufacturer's recommended schedule. Any defective equipment needs to be repaired, replaced, and the system retested for proper operation. The manufacturer should be asked for their recommended maintenance schedules.

- A small fire extinguisher commensurate with the level of hazard should be located in the cab of all vehicles to be readily accessible to the operator. The fire extinguisher should be a Type ABC.

Proper training and maintenance of fire suppression systems can reduce injuries and fatalities.

4 Fire scenarios

The knowledge about fire developments in construction vehicles is rather limited today. There have been carried out several tests on ordinary vehicles such as passenger cars, most of them under large scale hood calorimetry. The information from these tests is mainly heat release rates. The heat release rate is a measure of how fast the fire develop and give indication of the hazard of the vehicle. There has only been carried out one or two large scale tests with construction vehicles. This means the much of the work that needs to be carried out in this study relies on calculations or estimation of how the fire spread from ignition. The ignition process may vary, and the knowledge about the energy to ignite a machine is limited. Therefore, the fire spread from the initial fire source is of great importance.

Studies show that it is spray fires that hit hot surfaces that are most common [6]. The leakage from high pressure hydraulic hoses, can create a very fine spray resulting in an ignition of the leaked oil. When the oil ignites on the hot surface, the heat radiation from the flames, spread the fire to adjacent combustible solids. This in turn, creates even larger flame volumes resulting in higher heat release rates. The higher the heat release gets, the more dangerous situation is created. The personnel close to the burning vehicles starts to run and try to escape from the heat and smoke. As the fire get larger the faster the flames spread inside the machine. This means that fire will eventually spread to the tires, as can be seen in Figure 5. The tires are the most dangerous solids material found in the machine as the smoke production is very high and the heat radiation speed up the fire growth. The fire growth is the most important parameter when concerning the risk for personnel evacuating the tunnel. Under the vehicle one can find a pool fire, which contributes to the total heat release rate. The ventilation in the stuff (the area where work is carried out), which is usually about 0.5 m/s to 1.0 m/s in the cross-section, will influence the fire development. This in turn increase the risk that personnel may come to harm.



Figure 5 A burning articulated hauler.

The main problem is to estimate the above described process, as it is difficult to quantify. Hansen and Ingason [7] has developed a model to estimate the fire development in objects that starts to burn. It can be a vehicle with multiple objects of solid materials such as hoses, electrical cables, tires etc. The model was developed in order to estimate the heat release rate in vehicles where very little information is available. It can be enough

just to know limited information about a certain component in the vehicle. With this knowledge one can estimate how the fire grow by estimating when it spread to adjacent object. As the knowledge about the energy for each component is known, the final heat release rate curve, contains the energy balance. This in turn, gives a pretty good idea of when the maximum heat release rate will occur, and also the size of the maximum heat release rate. The advantage of such method is that one can add up from basic heat release rate information and predict quite well the final results. This methods needs to be validated further, but at the moment it was used for the project presented here. The results for construction vehicles are presented in chapter xx. Before we present those results we present a short overview of heat release rates from ordinary passengers cars and buses. This information is obtained from Ingason and Lönnemark [8].

4.1 Passenger cars

Numerous measurements of HRRs of passenger cars can be found in the literature. In Figure 6 and Figure 7 selected graphs of measured HRRs from single passenger cars are given [8]. Most of these data are extracted from graphs given in each reference. For comparison, the t-squared fast fire growth curve [9] is also presented. In the following, a short discussion of these tests is given.

Mangs and Keski-Rahkonen [10] presented HRRs from three full-scale laboratory tests using typical passenger cars (steel body) manufactured in the late 1970s (Car1, Car2, Car3). The experiments were performed indoors under a fire hood (using oxygen calorimetry). The cars were ignited either inside the passenger cabin (0.09 m² heptane tray under left front seat in test one) or beneath the engine with an open 0.09 m² heptane tray (~160 kW). Steinert [11] presented the HRR of a plastic passenger car from a test in the EUREKA 499 test series [12-13]. The car was a Renault Espace J11-II manufactured in 1988 and was ignited in a transistor in the console. This was to simulate a fire in the cable system. Steinert [14] also published HRRs of different types of passenger cars in a car-park, all with different types of car body (plastic and steel). A total of ten tests were performed where the aim was to measure the HRR and quantify the risk for fire spread in a car-park. The first three tests were carried out with single vehicles whereas the other six tests consisted of combinations of two and three passenger cars which were placed beside the ignited vehicle. In each case the cars were ignited by dripping flammable liquid on the front seat with the front window open.

Shipp and Spearpoint [15] presented the measured HRRs for two different types of private cars (Figure 6): a 1982 Austin Maestro and a 1986 Citroën BX. The Citroën BX test was ignited with a small petrol pool fire (5 kW) in the engine compartment, whereas the Austin Maestro was ignited in the seat with a small wood crib (10 kW). Lemaire [16] presented HRR measurements for two passenger cars performed with two different ventilation rates in the 2nd Benelux fire test series (Figure 7). The cars were Opel Kadetts, year 1990 with 25-30 litres of petrol in the fuel tank. The HRR was measured without ventilation and with a ventilation velocity of about 6 m/s, respectively. Lemair et al.[16] also performed a test with a Citroen Jumper (Figure 1) van which was carried out during a test with a deluge sprinkler system in the tunnel ceiling. The system was activated after about 13.6 minutes into the test. Ingason et al. [17] presented HRR measurements for a FIAT 127 (Figure 7) which was ignited in the engine compartment with an electrical device. The fire was extinguished by fire fighters 13 minutes into the test.

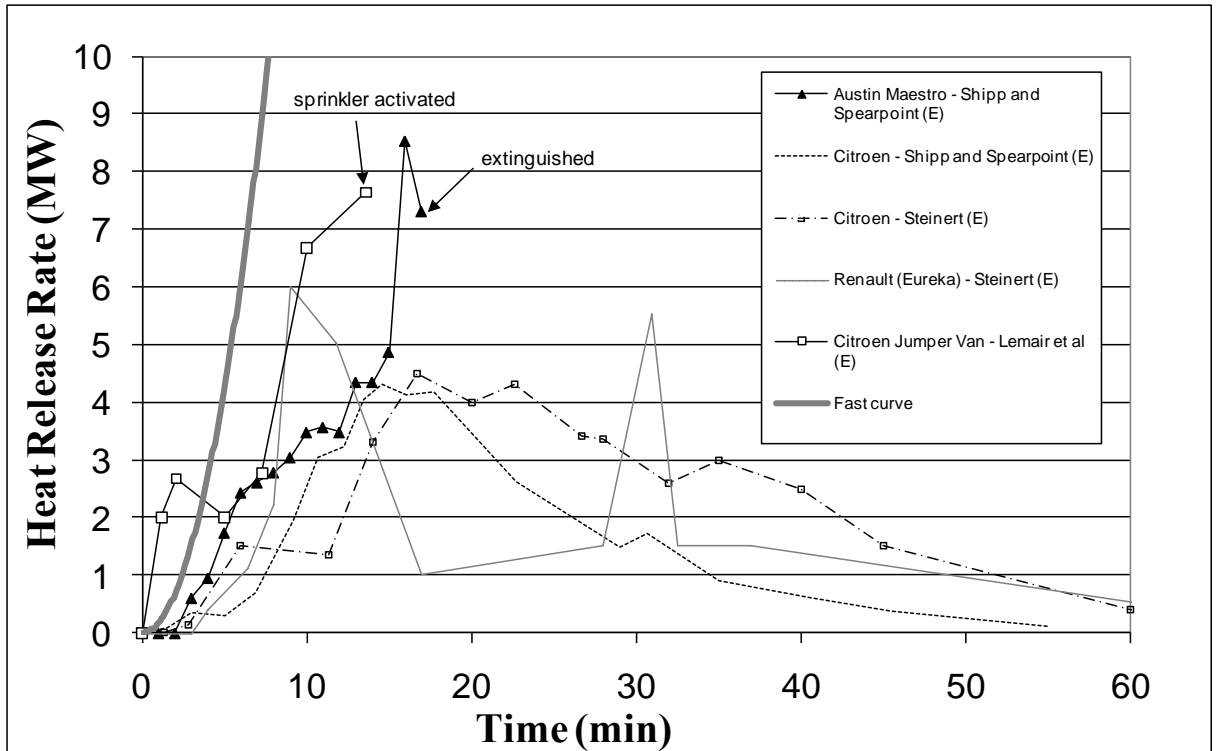


Figure 6 Experimentally determined HRRs for single passenger cars. Most of the data are extracted (E)¹ from graphs found in the literature. If measured data are given it is indicated with (M)² [8].

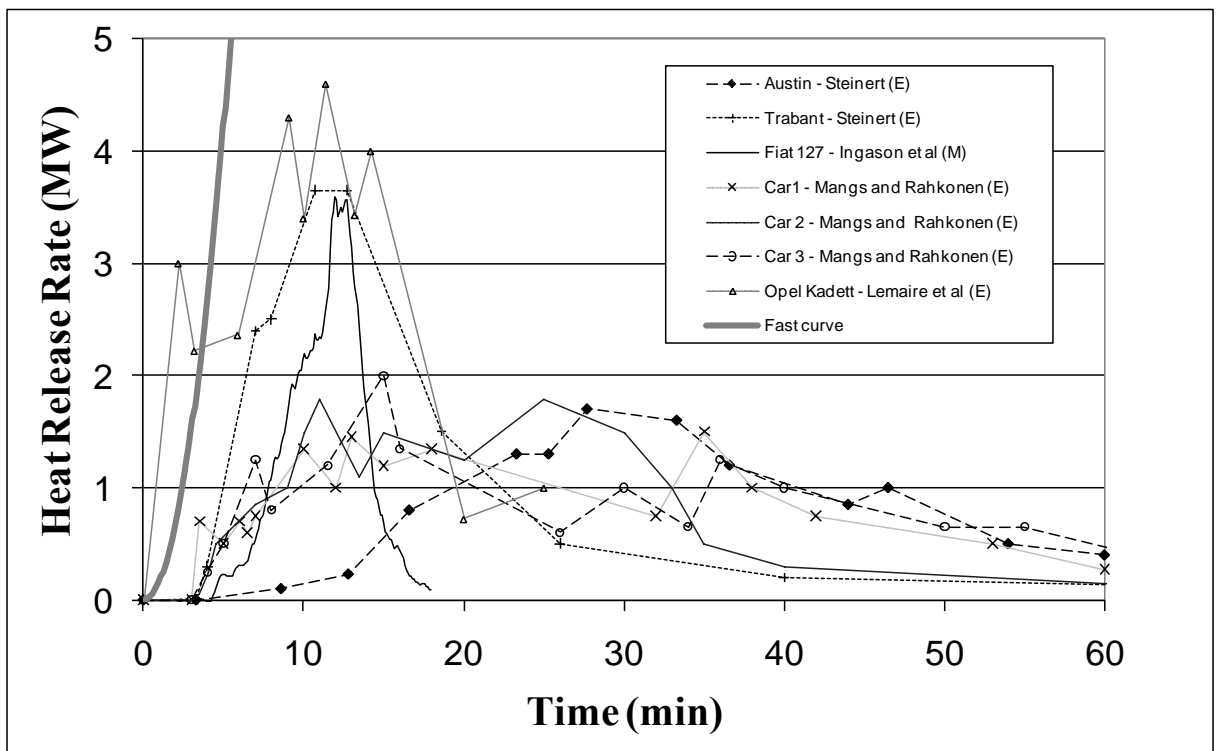


Figure 7 Experimentally determined HRRs for single passenger cars. Most of the data are extracted (E) from graphs found in the literature. If measured data are given it is indicated with (M) [8].

¹ Extracted means that the data has been manually obtained from printed graphs.

² Measured means values obtained as numerical values from a measuring file.

Joyeux [18] presented ten HRR measurements from passenger vehicle fires in a simulated car-park. Cars used in the tests included those from Mazda, Renault, BMW, Citroën BX and Peugeot, manufactured in the 80s and 90s. In the first seven tests, the first car was ignited with a small petrol tray under the left front seat. In the other tests, the first car was ignited by a petrol tray placed under the car at gear box level.

In the experimental tests, the HRRs for single passenger car (small and large) vary from 1.5 MW to about 9 MW, but the majority of the tests show HRR values less than 5 MW. When two cars are involved we find that the maximum HRR varies between 3.5 and 10 MW. There is a great variety in the time to reach peak-HRR, between 10 and 55 minutes.

Shipp et al. [19] presented a series of experiments with passenger cars in a car-park environment. The tests were carried out by the Building Research Establishment (BRE) in the UK. Both single cars and multiple cars (side by side or stacked) were burned. The objective was to examine the time to full fire development and the HRR of a fire starting in the passenger compartment or in the engine compartment of one of the vehicles. The risk for fire spread from car to car was also examined.

4.2 Buses

Ingason et al. [20] and Steinert [11] presented a measured HRR for a 25-35 year old 12 m long Volvo school bus with 40 seats (Eureka Bus, test 7). As can be seen in Figure 8, the maximum HRR was measured to be 29 MW by Ingason et al., and 34 MW by Steinert. The total calorific content was estimated to be 41 GJ by Ingason et al. and 44 GJ by Steinert, which is within acceptable level of accuracy. The estimated time to peak HRR was 8 minutes and 14 minutes, respectively. The reason for this discrepancy is related to the different methods used to calculate the HRR. Steinert's results for this test are based on convective flow whereas Ingason et al. used oxygen consumption calorimetry. The body of the bus was made of fibreglass. Therefore, the roof and walls of the bus were totally burned away (i.e., the fibreglass shell) down to the bottom edges of the windows. This explains why the fire was able to develop fully without any restriction of oxygen.

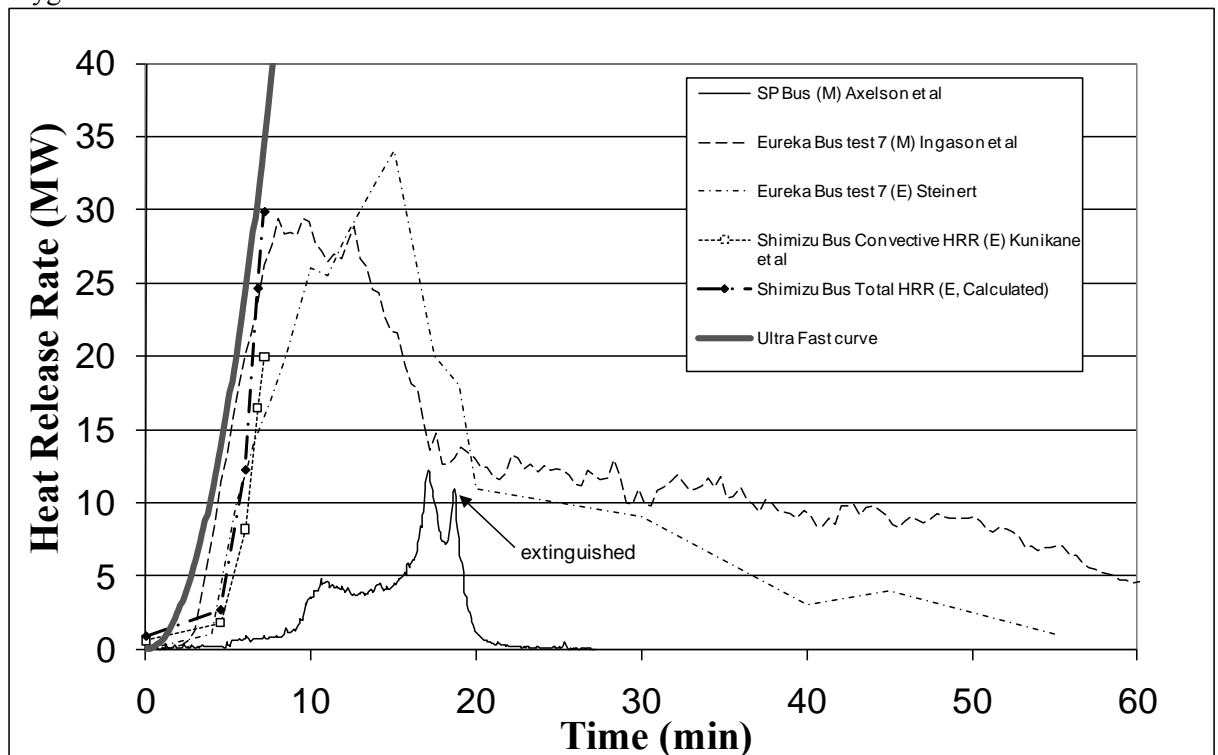


Figure 8 Heat release rates for buses [8].

In 2008 Axelson et al. [21] presented a large-scale experiment with a modern coach (Volvo) with 49 seats which was carried out in SP's fire hall. The test was carried out under a large hood calorimeter (10 MW). The measured HRR is shown in Figure 8. For comparison, the t-squared ultra-fast fire growth curve [9] is included. The initial fire development was relatively slow. One explanation for the slow fire development is that the fire was started with a 100 kW gas burner in the luggage compartment at the back of the bus, below the passenger compartment. The fire spread to the passenger compartment through the windows on the outside of the bus and fire growth increased significantly when three windows had broken, approximately 15 - 16 minutes from ignition. Three different peaks can be observed in the HRR curve given in Figure 8. The first peak occurs after about 11 minutes, when the fire broke out on the side of the luggage compartment. The fire then spread under the passenger compartment and into the passenger compartment through the windows, in the period between 15-17 minutes. As the fire grew in intensity, the situation became intolerable and the fire was extinguished manually approximately 18.5 minutes after ignition (the last peak of the curve). Due to leakage of the hood used to collect smoke and heat, the final peak was probably higher than the measured peak shown in Figure 8. It has been estimated that the HRR was approximately 14-15 MW when the fire was extinguished. At this stage approximately two thirds of the passenger compartment was involved in the fire. The authors of the report estimate that the maximum HRR could have been as much as 25 MW had the bus been allowed to continue to burn.

A bus test was carried out in the Shimizu Tunnel using a sprinkler system [22]. The HRR was not measured during the experiment but Kunikane et al. [22] estimated the convective peak HRR based on temperature measurements and mass flow rate. The peak convective HRR was found to be 16.5 MW when the sprinkler system activated. If the sprinkler system had not activated, Kunikane et al. estimated that the peak convective HRR would have been approximately 20 MW. If we assume that 67 % of the total HRR is convective we obtain a peak HRR of $20/0.67=30$ MW.

A bus fire occurred in the Ekeberg tunnel in Oslo, Norway in 1996 [23], which appears to have developed in a similar way to that in the Eureka 499 bus test [20]. This occurred despite the large differences in ages and types of buses. The bus had only been in use for three months. In the CFD simulation of the fire, the bus fire was estimated to have grown to 36 MW in under six minutes, continuing at a steady state of 36 MW for four minutes and then decaying to 1 MW over the following 12.5 minutes. The total calorific content was estimated to have been 28 GJ.

There are a number of sprinkler tests with buses available [24-25] but no HRR measurements have been carried out in these tests, although some temperature measurements have been performed, which can give an indication of the fire growth rate. An analysis of these temperature measurements appears to fit quite well with the HRR data given for the Eureka bus.

4.3 Construction vehicles

In the following a method to estimate the heat release rate in construction vehicles is given. The method is based on work that Hansen and Ingason [7] has developed. Prior to the estimation some fire tests were carried out in order to obtain some basic data to the model.

4.3.1 Method to calculate heat release rates

Ingason [26] proposed a method to estimate the HRR given as a single exponential function of time instead of several functions for different time intervals. The method

assumes uniform conditions – simplifying the input data. The design parameters are the peak HRR (\dot{Q}_{\max}), the total calorific value, E_{tot} and the retard index (n), which is an arbitrarily chosen parameter with no physical meaning. Based on these parameters, the time to the peak HRR (t_{\max}) and the fire duration (t_d) can be calculated. Other parameters used in the model include the amplitude coefficient (r) and the time width coefficient (k), which are calculated based on the input parameters the peak HRR and the total calorific value. The main challenge with the method is to relate the retard index n to some physically identifiable number.

When designing a HRR curve where several objects are included, the initial work will focus on the measured HRR curve of the initial object, applying curve fitting to obtain a suitable value of n . The appearance of the resulting HRR curve will be dictated by the linear increase of n in combination with the total calorific value (E_{tot}) and the peak HRR (\dot{Q}_{\max}) of each object. The total time interval can be used as an aid when estimating the difference in n .

The method uses the following equation when calculating the sum of all individual HRR [7]:

$$\dot{Q} = \sum_{s=1}^p \dot{Q}_{\max,s} \cdot n_s \cdot r_s \cdot (1 - e^{-k_s \cdot t})^{n_s-1} \cdot e^{-k_s \cdot t} \quad [\text{kW}] \quad (1)$$

Where:

- p is the total number of objects
- s is the pile number in a sequence of objects
- $\dot{Q}_{\max,s}$ is the maximum HRR [kW]
- t is time [s]
- n_s is a retard index
- r_s is an amplitude coefficient
- k_s is the time width coefficient

The amplitude coefficient and the time width coefficient are calculated for each type of object using the following equations:

$$r_s = \left(1 - \frac{1}{n_s}\right)^{1-n_s} \quad (2)$$

$$k_s = \frac{\dot{Q}_{\max,s}}{E_{tot,s}} \cdot r_s \quad (3)$$

$$t_{\max,s} = \frac{\ln(n_s)}{k_s} \quad (4)$$

Equations (1) – (4) can be used to estimate the total heat release rate if the heat release rate of each component such as tire, cables, hoses, pool fires etc. are known. As we have

found out that tire is an important parameter, and very little information is found in the literature on large tires, a test was performed to obtain data. This data was later used for estimation of four different construction vehicles.

4.3.2 Test with a front wheel loader tire

Ingason and Hammarström [1] presented fire test with a front wheel loader. The background was that the knowledge of the heat release rates from rubber tyres is limited. This information is very important when estimating the heat release rate from heavy construction vehicles such as drilling machines, front wheel loader (see Figure 9), articulated haulers etc. The tires constitute a large portion of the flammable material in such vehicles. Therefore, an understanding of the fire behavior of large rubber tires is important when designing for fire safety in underground constructions, especially in the mineral mining sector and during the construction phase of tunnels or other underground systems. Numerous large heavy construction vehicles can be used on-site at the same time which increases the risk that such a vehicles will be involved in a fire. A literature survey shows that very few fire research studies have been carried out worldwide on rubber tires and their heat release rates.



Figure 9 A front wheel loader with similar type of rubber tyres as used in the test.

The main objective of this test was to measure the heat release rate from a rubber tyre of a front wheel loader. In order to ignite the tyre, a relatively large ignition source is required. Therefore, a diesel pool with a steel pan diameter of 1.25 m was used as the ignition source. The size of that pool was reasonable in comparison to the width of the tyre (0.67 m). During construction of tunnels, the road surfaces are usually made of gravel (unpaved road surfaced with gravel) and therefore if there will be a leakage of any kind, the liquid will pour into the gravel. This may influence the size of the pool fire. In the literature, the heat release rate measured is usually based on pool fire tests with freely exposed liquid fuel (without the presence of other solid materials such as gravel).

The rubber tyre tested was of type Good Year with the identification 26.5R25 Tubeless. It also have the identification GP-4B AT, Unisteel, 193 B Type 65, Radial Construction, Made in Luxemburg, 0301 NJ 0520. The total diameter of the tire was 1.75 m and the total width (tread) was 0.67 m. The tread is the part of the tire which comes in contact with the road surface. The total external and exposed surface area of the rubber tyre is estimated to be about 8 m². The total weight, including the wheel rim, was 723 kg. After the test, the wheel rim, steel wires in the tyre and some left overs from the rubber were weighed. The total weight of steel products was 310 kg and of rubber was 35 kg. This means that the rubber in the tyre weighed 413 kg in total. Prior to the test, the air pressure was released in order to avoid an explosion of the tire. The wheel rim was welded to a

steel stand in order to stabilize the position of the tyre during the entire test. This means that the tyre could not collapse to the ground in case of sudden air release or opening up of the tyre which could occur in a real fire situation.

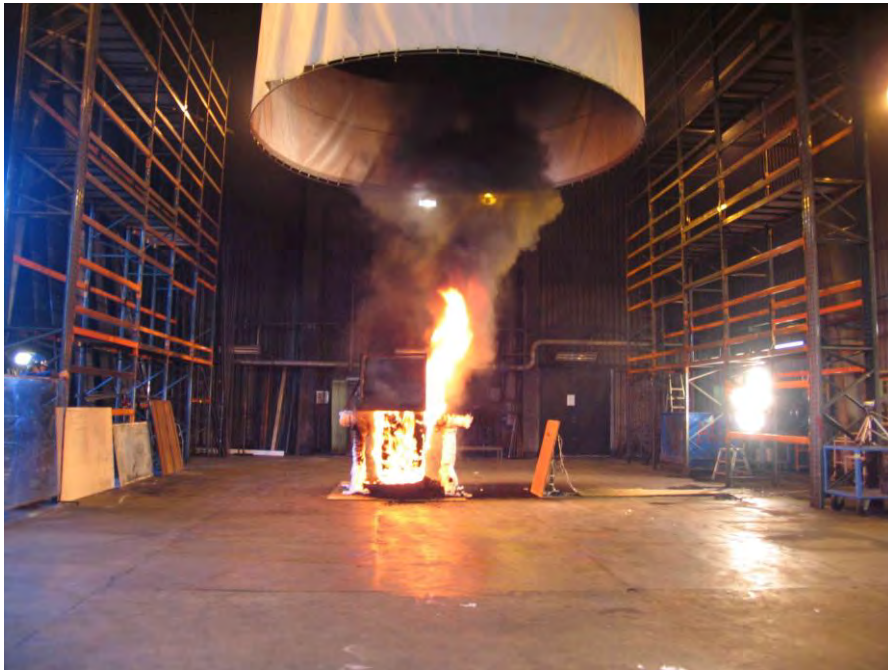


Figure 10 A photo taken 70 minutes from ignition. The heat release rate is about 2 MW [1].

The fire was initiated by pouring 1/2 litre of heptane into the pan mixed with gravel and diesel oil. The rubber tyre was mounted directly on the gravel surface, and therefore blocked a certain portion of the pan fuel surface. The radiation heat flux from the tyre and the heat release rate were measured during the test. An attempt to measure the smoke generation was made but due to technical difficulties no useful results could be obtained.

The heat release rate is presented in Figure 11. After ignition, the diesel fuel started to burn and flames very soon reached the top of the wheel house. After 2:56 minutes:seconds a first peak heat release rate of 2.3 MW was measured. The first heat release rate peak can only be explained as a combination of a burning rubber tyre (surface layer) and burning diesel. At this time mainly the sidewall (the side seeing the heat flux meter) and the lower parts of the tread were burning. Slightly later, or after 4:16 minutes:seconds the top of the tread was also burning. According to the free burn diesel/gravel pan test without the rubber tyre, the peak heat release rate was about 1.1 MW after 2:36 minutes:seconds from ignition. This would mean that about 1.2 MW was the contribution from burning rubber.

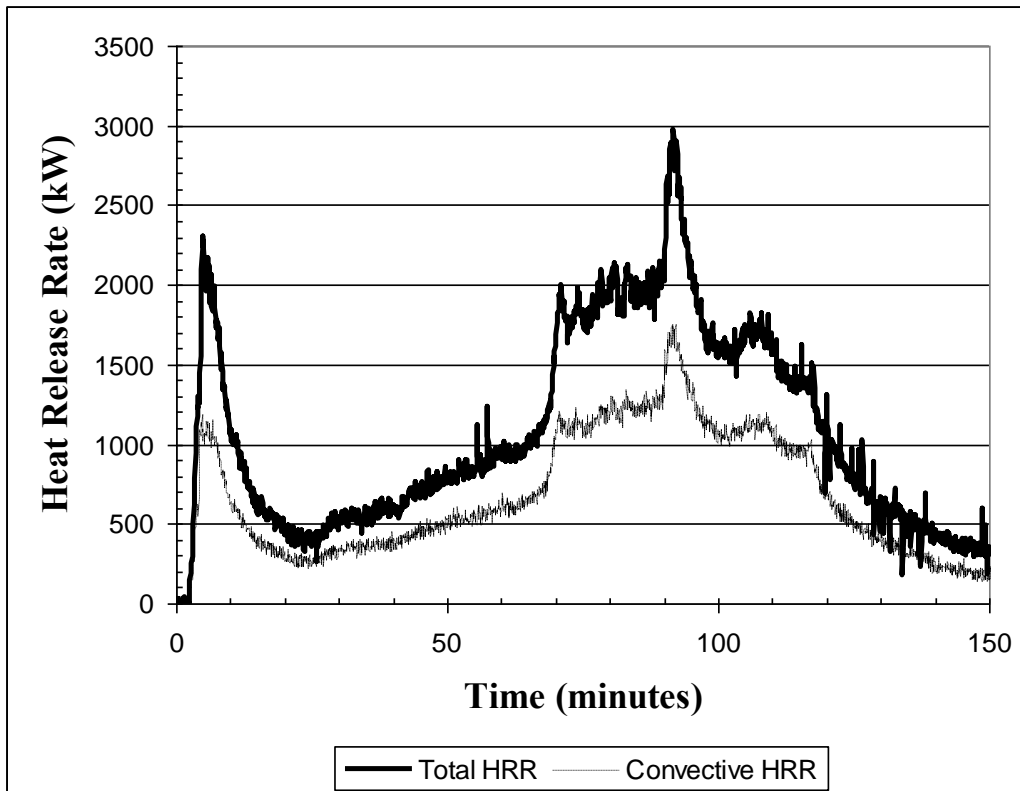


Figure 11 The measured heat release rate during the test with a front loader rubber .

The test with the tire was carried out by igniting a pan with gravel which was placed under the tire. After ignition the diesel fuel started to burn and flames very soon reached up to the top of the wheel house. A first peak heat release rate of 2.3 MW was measured after 2 minutes and 56 seconds. The first heat release rate peak can only be explained as a combination of a burning rubber tyre (surface layer) and burning diesel. At this time, mainly the sidewall (the side seeing the heat flux meter) and the lower parts of the tread were burning. A rough estimate of the burning area when the peak occur is 5.9 m^2 . If we subtract a contribution from the diesel fire of about 1.1 MW, we have approximately 1.3 MW from the tyre. This means that the heat release rate per exposed fuel surface at this time is 0.20 MW/m^2 . This is in line with the results obtained from other studies mentioned in the introduction. The fire intensity reduces again and the next abrupt increase occur after about 70 minutes, when both sides of the tyre are fully involved in the fire and certain amount of gases are coming from the inside of the tyre. The total exposed exterior fuel surface area of an intact tier is about 8 m^2 , meaning that the heat release rate per unit fuel surface area is about 0.25 MW/m^2 . This is slightly higher than that developed previously and can be explained by pyrolysis gases produced and leaking from inside of the tyre due to openings close to the rim. The third and last peak occur after about 90 minutes from ignition. The maximum heat release rate at this time was about 3 MW. It is very difficult to estimate the exposed burning area under these conditions.

The measurements were turned off 150 minutes into the test, before the tyre was totally burned out. At 150 minutes (2.5 h), the heat release rate was still about 0.3 MW. The total integrated heat content up to 2.5 h was 9.6 GJ. If we use a heat of combustion of 27 MJ/kg [27] and we know that the rubber weight was 413 kg, then the total heat content is somewhat higher, 11.2 GJ. This difference can be related to the fact that the measurements were turned off before all combustion had taken place and also due to uncertainty in the assumption of a heat of combustion value of 27 MJ/kg for this type of tyre. In conclusion we can say that after 2.5 h, about 86 % of the total energy was released.

4.3.3 Calculation of heat release rates for construction vehicles

The calculation of the parameters are based on several assumptions about the vehicle design. The method used depends on the information on the amount of combustible materials, the burning surface and type of materials that burn. The method used is based on a methodology developed by Hansen and Ingason [7] which sum basically up for each component of the vehicle and calculates the contribution to the overall fire growth. The end result is directly dependent on the reliability of the information used for each sub-component. In our case, we calculate the following subcomponents:

- number of tires
- Hoses
- Hydraulic & diesel oil
- Cab
- Electric cables
- No fixed extinguishing systems are assumed (conservative assumption)

Calculations was carried out for four different type of vehicles found at construction sites for tunnels. The results of the analysis of four different vehicles is shown in Figure 11. The vehicles analysed where:

- Truck
- Articulated hauler
- Boring drilling machine
- Front wheel loader

The conditions for each type of vehicle varies as well as assumptions of spread between each component in the vehicle. The principal procedure for the four different vehicles is as follows:

- A diesel oil leakage occurs and a small pool is formed on the roadway at the rear/front wheel which ignites (corresponding to the scenario used for the tire test) is assumed.
- The fire spread to the other rear/front wheel behind/infront of the cab. The tire is assumed to follow the curve shown in Figure 11.
- The fire spread to the electrical wiring / plastic parts and hoses in the vicinity and in the engine compartment within given minutes from ignition.
- Diesel and hydraulic oil leak may occur after a given time in minutes.
- The fire is assumed to spread to the driver cabin within given time in minutes.
- The fire spread simultaneously to both tires in rear/front and is assumed to follow curve shown in Figure 11. This is assumed to occur within given time from the fire start.
- The fire spread to the rest of combustible elements in the vehicle.

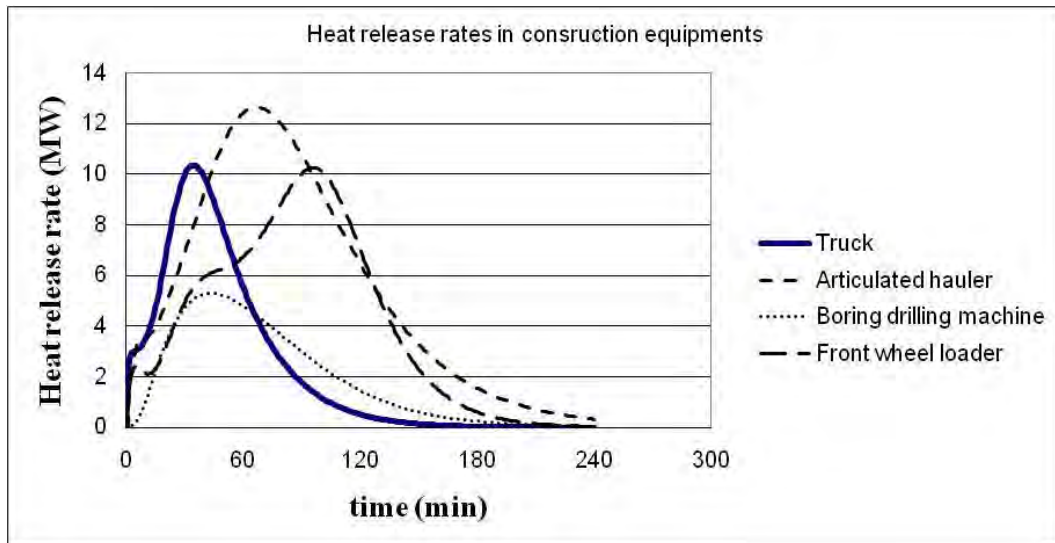


Figure 12 Estimated heat release rates for numerous construction vehicles.

These curves are only estimated and should be regarded as such. The maximum heat release rate is in the order of 5 – 12 MW. The fire growth rate in the beginning where oil leak is involved is much faster compared to the case where it is not. The boring drilling machine it was not assumed to have a leakage of oil.

4.3.4 Design fires

Selection of design fires for further analysis was one of the aims of this project. Based on the information given about passenger cars and buses as well as construction vehicles, one can make a selection of design fires.

In Table 7 a selection of different scenarios is given. This is based on the first discussion in the project group. Few of these scenarios were used in the evacuation analysis. The scenarios are divided into two parts, one before the breakthrough and one after the breakthrough. The results, and type of fire load varies. The number of scenarios given in Table 7 were found to be too extensive and ambitious and therefore the number was cut down to four for the evacuation analysis [3]. The final scenarios used for the evacuation and sensitivity analysis presented in next chapter. The sensitivity analysis was therefore performed using four different fire development curves:

- blast hole drilling rig (see Figure 12)
- two cars (see Figure 6, Figure 7 and Figure 13)
- articulated hauler (see Figure 12)
- bus (Figure 8 and Figure 14)

Table 7 The selected fire scenarios for evacuation and fire and rescue services design.

Nr	Fire Scenario	Position	Conditions	Notes
Scenario: Before breakthrough				
1	Drilling rig	Stuff		
2	Bus for visitors	Between stuff and working tunnel	Stand still	50 visitors/ultra fast
3	Bus for visitors	Between stuff and working tunnel	Stand still	50 visitors/fast
4	Bus for visitors	Between stuff and working tunnel	Visit	50 visitors/medium
5	truck/trailer	Between stuff and working tunnel	Stand still	Only truck that can burn
6	Articulated hauler	Stuff	Transport of gravel	
7	Articulated hauler	Between stuff and working tunnel	During driving	
8	Explosion transport	Stuff	Stand still	
Scenario: after breakthrough				
9	Bus for visitors	In the middle of the tunnel	Stand still	50 visitors/curve
10	Cable fire	In the middle of the tunnel	Installation of cables	
11	Storage with insulation	Quarter into the tunnel	Freely exposed	
12	Pickup	In the middle of the tunnel	Stand still	

For some of the fire development curves alternative heat release rate curves were used. This is done to determine if the development curves are close to result in a dramatic shift in the outcome. Figure 13 and Figure 14 show the heat release rate for the four fire scenarios compared to heat release curves for some traditional t_2 -fire curves. These curves were used for comparison in an extended sensitivity analysis where parameters affecting the shape of the four HRR-curves were varied. In the figures the so-called basic fire development curves are marked with a blue solid line. The alternative curves are marked with other point symbols.

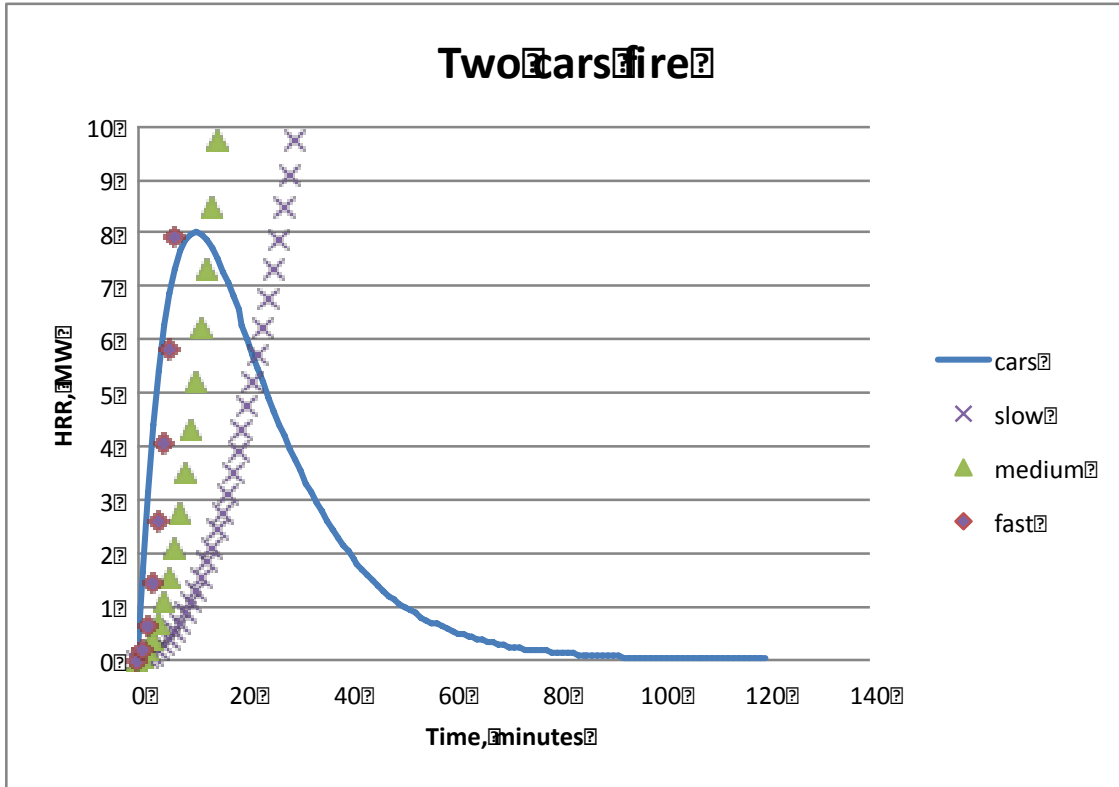


Figure 13 Heat release curve for two cars.

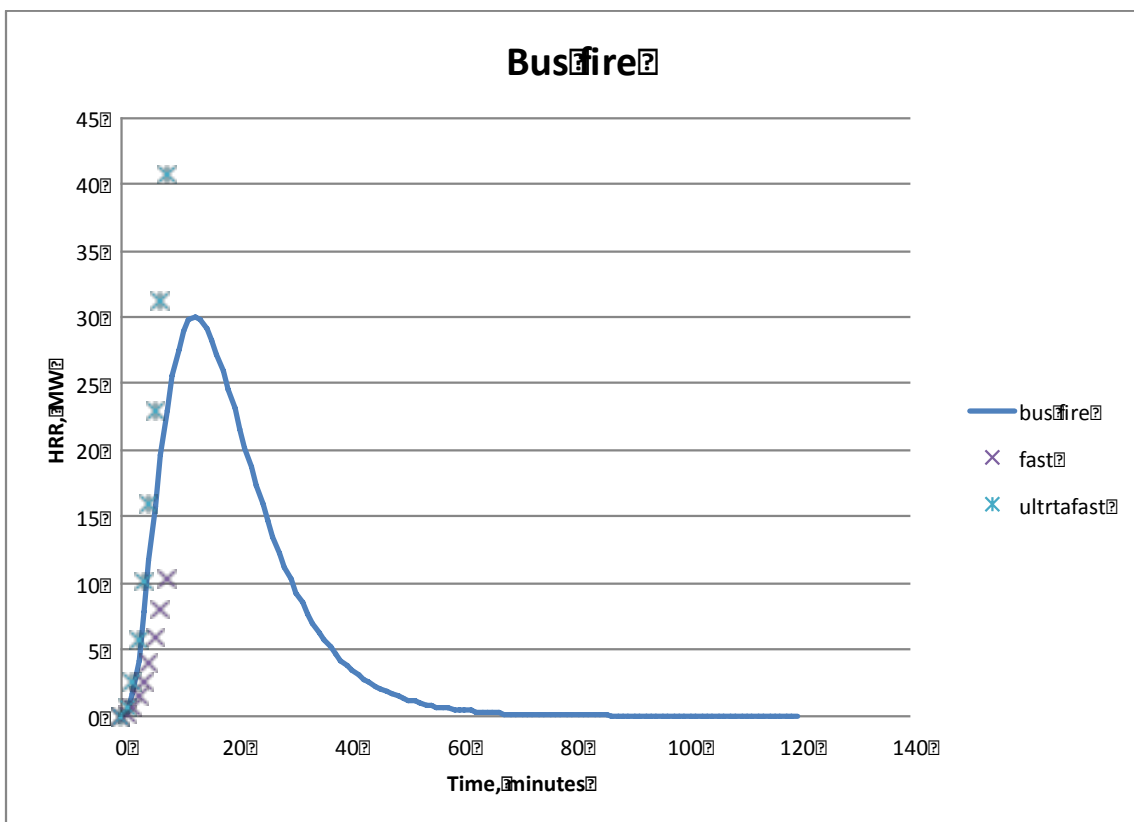


Figure 14 Heat release curve for a bus.

4.4 Influence of ventilation

As a part of the project, model scale tests were performed in order to better understand the effects of the comfort ventilation before the breakthrough. This work is presented in [2]. The report describes a series of model scale tests in scale 1:30 giving the situation before any breakthrough in a tunnel during construction, see Figure 15. This means that there is only one access tunnel, the rest will be a system of tunnels with no other connection to the surface than through the inlet tunnel. The tests were carried out in order to investigate the effects of smoke spread and ventilation in a tunnel during construction. The tunnel was tested during different ventilation conditions, lengths and slope. The tunnel consisted of an access part which simulated the access tunnel to the main tunnel. The access tunnel was sloped and the main tunnel was horizontal, directed in two equal distances from the access tunnel. The main tunnel had two dead ends, and a ventilation system that was provided through an air duct in the ceiling. The air duct outlet length and location was varied in the tests. A total of 36 tests were performed.



Figure 15 The model-scale tunnel system before the walls and windows were completed.

The main findings were the effects of the ventilation. If the fire occurs before the breakthrough and the fire is too small it will be difficult to obtain fresh air from the access entrance and the fire will decrease in intensity and finally extinguish due to vitiated products that are recirculated to the fire.

5 Evacuation

In Frantzich [3] a thorough analysis of the evacuation conditions for underground conditions are given. Here a summary of the analysis carried out by Frantzich is given.

A tunnel construction site may be seen as an example of a complex environment. It can therefore be assumed that in the case of a fire the evacuation from the different locations within the construction site can be more difficult than if the tunnel construction is finished. Evacuation conditions for people working at construction sites are very different from the conditions that can be expected in public buildings. Most importantly, the environments are sometimes very complex, i.e., difficult to evacuate due to both cognitive and physical obstacles. For example, a construction site is constantly changing, which means that the evacuation routes can be modified from one day to another and may not always be clearly marked. This type of constant modification can make way-finding problematic.

The environmental conditions may also impose other difficulties such as problems hearing an evacuation alarm because of background noise and problem moving to a place of safety due to narrow passages and obstacles in the path of travel. These types of factors make the environment complex with regards to fire evacuation, which can form extra hazards that have to be dealt with during operation in the complex space.

Factors that may increase the complexity are:

- Visual access - limited visual overview, dim lighting, darkness etc
- Sound level - noisy environment, wearing ear protection
- Familiarity - poor knowledge of the environment, changing environment
- Physical conditions - obstacles and narrow passages, rough floor surface, slippery, drops, remote locations
- Work that need to be terminated properly due to safety reasons - drilling, blasting, welding

Much of the preventive work safety relies on traditional procedures and not much work has been published focusing on the special problems facing workers during evacuation from these complex environments. However, a key factor for a successful evacuation from a construction site like a tunnel must acknowledge the importance of these procedural safety aspects. A typical problem that may occur in a tunnel construction site is the presence of several individually hired contractors, which may result in an unclear relationship of safety responsibility.

Still, the nature of the problems in the complex environments are similar to those in traditional assembly type buildings, i.e. there are problems getting aware of the fire threat, the cues related to fires have to be interpreted and a decision making process has to be initiated and finally there is a movement distance between the location of the people and a safe place. But, obviously there are differences, which are related to the increased complexity of the environment. It may be visual access, sound level, familiarity, physical conditions or work that need to be terminated properly due to safety reasons.

In order to increase the knowledge about evacuation from a complex environment like a tunnel construction site an initial attempt to analyse the conditions for evacuating has been performed. The objective for the analysis is to identify certain aspects related to tunnel evacuation which are typical for the construction phase. The work will also include development of a mathematical method which describe the evacuation situation for

workers exposed to a fire. This method will be used to analyse the safety for the workers for four different fire scenarios. Finally, conclusions will be presented on how to arrange a tunnel construction site in order to facilitate a safe evacuation. This is further elaborated in Frantzich [3].

5.1 Tunnel construction site evacuation

Evacuating from a tunnel construction site is very much depending on in which phase of the construction the tunnel has reached. There are basically two phases; before and after the breakthrough point. Before this point in time the tunnel has only one entrance and exit; i.e. it is basically a long tube into the mountain. After the breakthrough there is a possibility to access the tunnel from at least two ways also permitting evacuation in two directions.

During the first phase the conditions for evacuation is almost the same over time. The physical conditions do not change dramatically as the site has a rough environment when the rock is excavated or drilling is taking place. The most important change in the conditions is the continuous increase of distance to the exit from the most remote part of the tunnel. After the breakthrough the work goes into another stage and drilling, blasting etc. is not that frequent. The work becomes more similar to a traditional building site with installation work and a cleaner environment. The type of work personnel also change from traditional tunnel excavating staff to persons not so familiar with tunnels as they also perform work on other construction sites for example in buildings. The awareness for the problems associated with an underground construction can therefore be assumed to be different.

However, as the work comes into a stage with more than one evacuation option the possibility for a successful evacuation is increased. In the first phase the only available escape route is the excavated tunnel i.e. the way back through the tunnel to the outside. A possible issue to handle is then that the distance to the safe place, which mostly is assumed to be outside the tunnel, can be significant. In cases with extremely long distances to the tunnel entrance a refuge chamber can be used.

In the case the tunnel has a large cross section and there are long distances to the tunnel entrance the normal means for transportation is by car or a small train to reach different locations in the tunnel. Therefore there may be a possibility to use also the same car or train for evacuation in the case of a fire. It may though be a difference in accessibility comparing a car with a train as the train usually performs a number of tasks during a day and may not be available in case of a fire. Persons using a car often park the car close to the place of work will provide a better accessibility to the vehicle in case of an evacuation. It may, though, not be possible to evacuate using a vehicle if the fire is between the tunnel entrance and the location of the vehicle, it may then not be possible to pass the fire.

In order to increase the possibility for a safe evacuation most tunnel construction sites urge the workers to have direct access to a simple breathing apparatus, a mask with a small compressed air bottle or simply a filter mask. Using this equipment it can be assumed that movement distance through dense smoke can be extended.

Most tunnel construction sites are also equipped with other fire safety measures like a fire alarm, an evacuation alarm, means for communication, emergency lighting and way-guiding signs. The design of this equipment differs from site to site and no general recommendations are provided. In Sweden The Swedish Work Environment Authority issues regulations for work in underground sites, AFS 2010:1 (2010), mainly applicable for mines but can also be used for tunnel construction sites.

Another important aspect with tunnel construction sites is that they often are interesting places for others than the workers to visit. Groups of external visitors are sometimes allowed to visit the construction site to see how the society is developing. The visitors could be the general public or certain groups like decision makers or members of various organisations. These people may have different needs in the case of an evacuation and usually guides from the construction company accompany these visitors. But still, there might be an increased risk due to a larger number of persons with limited evacuation capability. Also, these groups may travel by buses, which may increase the fire load in the tunnel. In cases where visitors are allowed on the construction site this problem cannot be neglected.

Many of these general aspects on evacuation safety are relevant for both phases in the construction, however, more predominant in the first phase. Therefore, most of the attention in this report is on the initial phase. Many of the problems in the second phase is also similar to those in tunnels taken into use. Differences do exist depending on the degree of completeness of the tunnel work but basically evacuation is done in the same manner and with a similar strategy.

5.2 Physical environment

Generally, the environment in a tunnel during construction is rather rough. The environment is characterised by low illumination, wet surfaces, uneven and sometimes slippery ground, on-going construction work with partly finished constructions, noisy and mostly a constantly changing appearance of the environment. This is of course a result of the places being a construction site but it will at the same time make evacuation more difficult. To have a work environment that is appropriate for the workers to stay in most tunnels are equipped with a forced ventilation system that delivers fresh air to each work place where the tunnel progress in length. This results in an air draught towards the tunnel entrance, which also will govern the smoke flow during a fire. The fresh air is transported in a flexible textile tube beneath the ceiling.

Comparing the tunnel construction site with construction sites for traditional buildings reveal small differences apart from the tunnel being inside an enclosure. The most important factor with respect to evacuation is however the long distance from a working place in the most remote part of the tunnel to the tunnel entrance. This distance can in some cases be several kilometres. It is therefore important to have a pre designed plan for how to handle an evacuation and to have proper technical installations in the tunnel to make the evacuation safe given the conditions.

The environment is different depending on how the tunnel is excavated and two types of techniques can be identified; a tunnel being excavated using a blasting technique and a tunnel being excavated using a tunnel boring machine (TBM). There are also other types for example cut and cover tunnels but those do not pose the same problems for evacuation compared to the two first identified, mainly because of the length of the tunnel and the first two are enclosed.

Even if the tunnel is excavated with the use of a TBM some parts may still use the traditional blasting technique to do some constructions so both types may exist at the same construction site. The TBM itself is somewhat different as it is a huge mechanical construction often with several floors connected by stairs. But as the machine is a fixed construction, but slowly moving, it can be easy to prepare it for an evacuation situation for example providing it with an evacuation alarm and way guiding signs.

In some way all these factors affects the possibility to evacuate safely. Depending on the type of construction method, the size of the tunnel cross section and the possible fire hazards, they are differently important for different tunnels. But generally most of them have to be handled in order to have a fast response by the workers and others occupying the construction site. One thing that is not mentioned is that the tunnel gets filled with black smoke in the case of a fire, which will make the actual evacuation difficult. The smoke will follow the fresh air supply in the tunnel and the evacuation of smoke is depending on the forced ventilation being able to maintain the operation in the case of a fire.

5.3 Management aspects

Many of the problems related to evacuation safety can be handled with management procedures. In fact it is most important to have good procedures to be able to handle a fire situation and to be prepared for the occurrence of a fire. One of the major causes for management problems is the use of different constructing firms working at the same tunnel project and having them to cooperate in safety related issues. In many cases an infrastructure project like a tunnel is too large for a single construction firm to manage by itself so it is necessary to hire more than one.

Another management problem related to communication is the language problem. A tunnel construction is usually performed with people from different countries and with different backgrounds. People can in some cases not communicate in a common language and have to rely on key persons interpreting. This problem may occur both within a construction firm working isolated from others and when a break through has taken place and there is a physical connection to another contracted firm.

One interesting aspect that can be associated with management factors is the attitude among the workers with respect to safety issues. It can be assumed that the attitude can vary between individuals and between construction firms. There may also be differences with respect to the two main construction types, i.e. if the tunnel is excavated by traditional technique or by using a TBM. The relaxed attitude among some workers may be related to the time spent in the tunnel and to previous knowledge of tunnel work.

In order to increase the awareness about fire safety it is believed that evacuation drills are important. By participating in drills people get used to the idea about behaviour and conditions in the evacuation situation. But it is also believed that in order to benefit from the time and money spent by an evacuation drill it must be adequately planned and performed.

Knowledge about evacuation can also be provided to the workers as a traditional education where the objective is to inform about the safety arrangements. This is less effective but can be used as a complement to a physical evacuation drill.

A fire safety measure that is important during an evacuation is how to communicate with in the construction site and to the outside in the case of a fire. This aspect has to be clearly assessed before the work starts and has to be taught to the persons working in the tunnel.

As indicated in this chapter there are a number of management aspects that has to be addressed in order to have a safe tunnel construction site. The report [x] will explore some of these aspects and also evaluate safety in tunnels under construction.

5.4 Evacuation analysis

Before the analysis begins a number of important scenarios has to be identified and a model must be developed to handle these scenarios. The choice of scenarios for the analysis depends on

- whether or not a break through has occurred
- the tunnel shape i.e. the length and cross section area
- the fires typical for those tunnels and
- the capabilities of the persons present in the tunnel

All factors contribute to the outcome of an evacuation but not all of them are relevant in all tunnels. It is still necessary to consider them all together in terms of different possible scenarios in order to analyse the outcomes and to determine appropriate protection measures.

It was determined early that most of the attention should be on the construction phase before the break through. The results from these analyses can, however, with the developed model be used to predict also the consequences after the break through if the conditions downstream from the fire is the issue.

The tunnel configuration was identified as important for the safety of the workers and several cross section alternatives were investigated. A span of cross sections covering small wastewater tunnels to larger road tunnel alternatives was chosen, i.e. cross sections between 12 and 77 m². The tunnel length will also affect the outcome of the analysis and the tunnel length was chosen to be 1700 m in all scenarios. This length is chosen to represent a long tunnel but otherwise the length is arbitrarily chosen.

The choice of fire hazards is most likely the variable affecting the results more than any other. Therefore four different fire scenarios were chosen for the analysis ranging from a small fire exemplified with a drilling rig with a maximum heat release rate of 6 MW to a severe fire illustrated by a bus fire with a maximum heat release rate of 30 MW.

The last of the factors influencing the choice of scenarios is related to the persons working in the tunnel. It is assumed that most of the persons are aware of the conditions in the tunnel for example where the exits are located and how to move towards the safe location. Way finding is, therefore, assumed to be a small problem and the recognition and response time can be kept rather short. It is also assumed that the time to detect the fire is short and can be included in the recognition and response time. As the workers detect the fire by themselves none of the scenarios include any automatic fire alarm but the time to report the fire can be included in the recognition and response time i.e. the delay time before movement towards the tunnel exit. Conditions for fires more remote from the workers are also investigated reflecting a longer recognition and response time.

5.5 Results

The results are presented as five parameters related to various levels of unconsciousness. It is determined how far the workers can move until they have reached the chosen levels of unconsciousness and at what time this condition is reached. Figure B shows the evacuation situation for the 7 x 11 m² tunnel and 1 m/s air velocity for the case the fire occurs in two passenger cars. The lines show the distance the persons have moved (blue solid line) after the start of the fire and the location of the smoke front, also as a function of time (red - - - line)

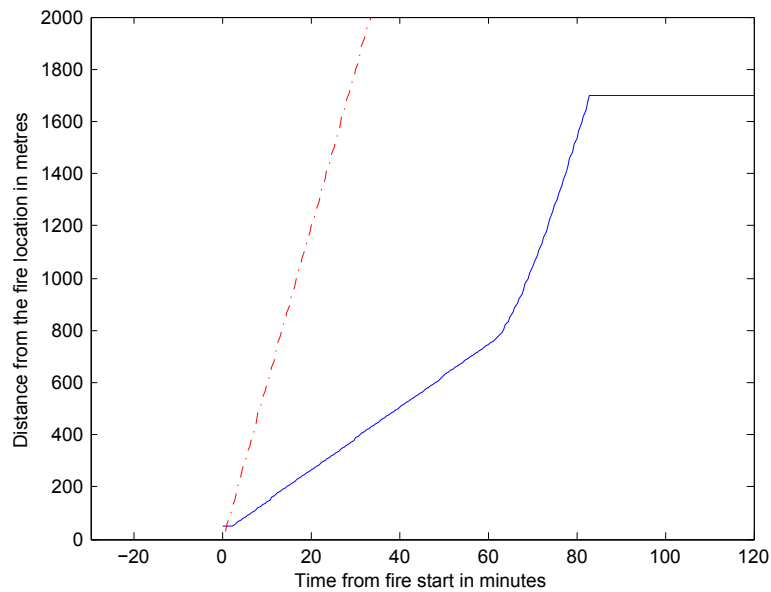


Figure 16 Location of persons (blue solid line) and smoke front (red hatched line) for evacuation in the 7 x 11 m² tunnel, 1 m/s air velocity and 2 minute recognition and response time. The fire occurs in two passenger cars.

5.6 Concluding remarks using evacuation model

Comparing the results from the different fire scenarios some patterns can be seen. The most obvious is that depending on when the evacuation starts the persons may either be trapped in the smoke and can then move a certain distance or on the other hand the persons can move ahead of the smoke front to reach a safe location. If, in the latter case, movement occurs in the smoke free environment it can be performed rather safely as the smoke front moves much slower than the normal walking speed. The time to reach the tunnel entrance is independent on the tunnel shape as only distance and movement velocity determines the time to reach safety.

But if movement occurs in smoke the fire development is one key factor that determines the duration the persons can stay in the tunnel without getting unconscious. The results is of course worse for the larger fire like for the passenger cars or the bus fire. It may be considered remarkable that a fire in only two passenger cars result in a severe situation for the workers. But this has to do with the rapid growth rate for the fire. The fire will grow to a rate of heat release rate which is dangerous already after just a few minutes.

It was also, beforehand, assumed that the air velocity in the tunnel would have an effect on the possibility to evacuate safely, or at least continue for a longer period of time. This showed to be true and a higher air velocity is better with respect to evacuation.

6 Fire and Rescue Operations during construction of tunnels

The fire and rescue services have limited possibilities to perform fire and rescue operations in tunnels due to long response routes, complex environments and sometimes lack of information. Operations in tunnels are in general a difficult task, where many times unknown parameters directly can influence the outcome of the fire and rescue operation. In tunnels, during construction, the environment can alter day by day, the escape and response routes can be very long – sometimes only give possibilities to escape in one direction. Many different organizations and entrepreneurs can be represented at the tunnel construction site. The complex situation raises high demands of knowledge and skills on the Incident Commander (IC) and sometimes the need of special equipment that can be used as tactical resources in case of a fire is essential for performing any result at all.

During the project tests, surveys, tunnel visits and interviews [4, 28] have been performed that have been the foundation for calculations and conclusions presented in this chapter.

6.1 Strategy and tactical approaches

A tunnel construction project can be divided into two main phases – before and after the break-through. This condition, together with the fire development, are the parameters that have the largest impact of the choice of tactical approach for the fire and rescue operation and furthermore on the outcome of the whole fire and rescue operation [4, 29]. In fire and rescue operations the rescue services can choose to work with either an offensive strategy (to fight the fire) or with a defensive strategy (to not fight the fire). These two strategies should not be combined at the same time but can alter from one to the other during the time span of a fire and rescue operation in a tunnel [30-31]. There are five different tactical approaches to handle a fire in a tunnel. These tactical approaches can be used one by one or in combination with each other. The tactical approaches are also depending of the chosen strategy of the fire and rescue operation and the available resources regarding personnel and rescue materiel [30-31]. The five approaches are;

1. Fight the fire from the inside of the tunnel, with the purpose to put out the fire and by this save people in danger.
2. Assist or rescue the people in danger from the inside of the tunnel and take them to a safe environment.
3. Control the airflow in the tunnel in order to take the smoke away from the people in danger or to support the fire fighting operation [31]
4. Fight the fire from a safe position to reduce the consequences of the fire.
5. Treat and take care of the people that without assistance rescued themselves to a safe environment.

The 8 fire scenarios that are chosen in this project have been analyzed regarding strategy and tactical approaches given two different preconditions;

1. Unlimited resources regarding personnel and no mobile fans
2. Unlimited resources regarding personnel and mobile fans (set of low flow/medium flow fans or large lorry mounted high flow fan [4, 31].
3. First fire and rescue unit of 5 fire fighters (which is the lowest number of fire fighters allowed for BA-operations according to Swedish national working environment regulations) [4, 32] and no mobile fans.

The results of the analysis regarding the tactical approach are presented in **Table 8** below;

Table 8 Strategy and tactical approach for TB scenarios

	Unlimited resources/ no fans	Unlimited resources/ available fans	First fire and rescue unit (5)/ no fans
Scenario A	5 and if fitted vehicle assistance is available number 2 or 4	5 and if fitted vehicle assistance is available number 2 or 4	5
Scenario B	Number 1 in combination with 2 and 5	Number 1 in combination with 2 and 5	5
Scenario C	Number 1 if the fire development is slow and/or if people are trapped in a dangerous situation, otherwise number 5	Number 1 if the fire development is slow and/or if people are trapped in a dangerous situation, otherwise number 5	5
Scenario D	Number 1 in combination with 2, 3 and 5	Number 1 in combination with 2, 3 and 5	5
Scenario E	Number 3 in combination with 1	5 and if fitted vehicle assistance is available number 2 or 4	5
Scenario F	Number 3 in combination with 4	5 and if fitted vehicle assistance is available number 2 or 4	5

6.2 The transportation speed of the fire and rescue operation

The fire and rescue services possibilities to assist or rescue persons in the tunnel are depending on their available resources regarding personnel and equipment but also on the transportation speed to the persons in need of assist or to the fire. Within the project tests have been performed to estimate the transportation speed. Swedish regulations demand safe water supply to the BA-operations when operating during fire conditions, wherefore the tests have been focused on what distances the fire and rescue services can cover in the actual environment.

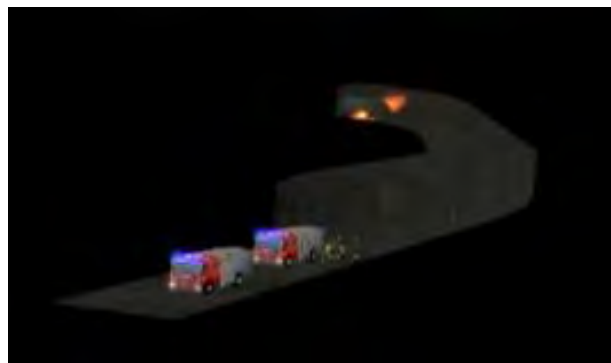


Figure 17 Test scenario in the Stockholm City Line [4]

Tests have been performed both with fully developed hose systems and single systems of 3*hose Ø63 mm plus 3*hose Ø42 mm plus fire nozzle including connection points in order to estimate the transportation speed. Each single sub-part of the test have later been estimated and used in the MatLab mathematical model. Each fire fighter is calculated to carry BA-systems with 2400 l of air of which, for safety reasons, 1600 l are available, with an air consumption of 62 l/min. In the calculations the restriction for the BA-operation has been the available time to reach the fire or persons in need, not the personnel. In real life of course the available resources are one of the most important factors. The total possible distance that can be covered with a primary fire and rescue force of 5 fire fighters have though been calculated separately [4].

The tests have also taken different fire and rescue material in consideration as a tactical resource and their impact of transportation speed and possible covered distance have been analyzed. The parameters that have the largest impact on the transportation speed are;

1. Visibility
2. Aid, resources (lightlines, thermal images etc.)
3. Methods for lay-out of the fire hose
4. Tunnel elevation
5. Ground conditions
6. Strain (empty/filled hoses, carried weight, transportation of injured etc.)
7. Individual physical capacity

The transportation speed in the tests varied between 0,05 to 1,5 m/s depending of the parameters above.

6.3 The Calculation of evacuation versus rescue operation

The main responsibility for the tunnel contractor is to ensure a safe working environment for its personnel. As the fire and rescue services has limited possibilities to assist persons out from the tunnel the contractor has to provide reliable options for evacuation. This can be escape routes out to open air or safe havens in form of fixed or mobile rescue chambers. Swedish working environment legislation demand sufficient evacuation [33] where handbooks [34] stipulate maximum walking distance to escape routes or rescue chambers to 150 meters. In order to estimate the real possibilities for fire and rescue service aided evacuation in tunnels under construction the evacuating persons possibilities to reach a rescue chamber and thereafter get assisted out from the tunnel by the fire and rescue services or to get rescued from the location inside the tunnel where they fell unconscious [3-4], where compared to the fire and rescue services capacity to reach the rescue chamber before the available breathing air runs out or the person inside the tunnel pass away.

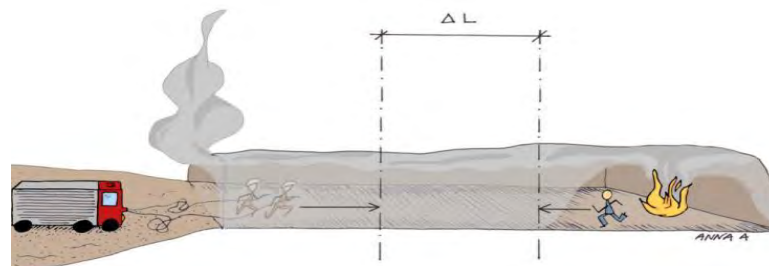


Figure 18 *Evacuation versus rescue*

6.4 Discussion about fire and rescue services

The results from the project clearly show that fire and rescue service aided evacuation in tunnels under construction not is an option in longer tunnels. In a majority of the chosen cases, especially before the break-through, the fire and rescue services do not reach the persons in the tunnel in time. In some cases even if the persons in the tunnel have evacuated to rescue chambers placed close to the tunnel face. The conclusions from the project can therefore be summarized [4];

1. Swedish regulations regarding BA-operations require safe water supply when working during fire conditions. The regulations are based on the conditions in compartment fires and not in tunnel environments. The risk in tunnels is mainly not a flash-over but to lose track and run out of breathingair. The regulations should therefore be given an overhaul regarding the need of safe water supply for all fire fighters, for example reconnaissance-teams. Alternative fire and rescue material, like thermal images and light lines, could provide the same level of safety for the fire fighters and allow faster response in to the tunnel. The regulations main aim is not the outcome of the fire and rescue operation, but to ensure the fire fighter's safety performing BA-operations. The regulations should though give more specific guidance to the IC regarding risk assessment in complex constructions [4, 32].
2. Recommendations regarding locations of rescue chambers and air supply should be overhauled.[4, 33]
3. Alternative systems for lay-out of fire hoses should be evaluated [4].
4. The use of thermal images at fire and rescue operations in tunnels can be very helpful, though can the low heat differences between the walls and the not yet finished roadway make it difficult to determine the path. In the early stages the tunnel often lack of installations, like for example lighting, which can be used as reference points. In cases when the smoke is relatively cold the thermal images can therefore be slightly less useful than in ready tunnels [4].
5. Systematic tests of the fire and rescue services transportation speed in different tunnel environments should be investigated. The use of alternative transportation, like different types of vehicles, should also be investigated [4].
6. Larger numbers of visitors in tunnels under construction is not to recommend, especially not before the break-through, as the fire and rescue services not will be able to assist them in case of fire and the rescue chambers in the tunnels are dimensioned for construction personnel and not visitors [3-4].
7. The interaction between the tunnel constructor, the fire and rescue services and other first responders are of great importance during the fire and rescue operation. The cooperation should start with a joint contingency planning, be exercised to discover shortages and restart with learning from the experiences gained from exercises, incidents and accidents [4, 29, 35].

A more detailed summary of findings and recommendations can be found in chapter 9.

7 Discussion

The project has involved literature survey, analysis of accidents and regulatory documents, calculations and experiments in small and large scale tests and exercises along with the emergency services. Several sites have been visited; the Northern Link in Stockholm, a sewage tunnel between Partille and Lerum in Sweden, Hallandsås train tunnel in southern Sweden, Onkalo site in Finland where the future storage center for nuclear fuel is being built, and City Line train tunnel in Stockholm. One of the main objectives of the visits was to identify the problems regarding the escape situation for workers during construction, identify typical evacuation scenarios, analyzing the personal safety with respect to evacuation and emergency services personnel situation. In the following a discussion about different focus areas is given.

Regulations

It is apparent that the regulations given today, cover very much of the problems that may arise during construction of underground facilities. The focus in each regulations and the level of details varies. The SveMin regulations gives the most detailed and comprehensive descriptions in Sweden. The DACH document is very comprehensive and detailed, maybe too much to be practical.

It is important to notice that the guidelines describes very much how to protect the workers and the construction machines. There are requirements on fixed and portable fire fighting systems, detection systems, rescue chambers, incident management, combustible materials etc. The part that is not covered very well is how to perform exercises, evacuation exercises and ventilation control in case of fire. There are no requirements on the performance of fixed fire fighting systems and detection systems. There are no guidelines in how to handle the ventilations system. Many of these question needs to be discussed and analyzed. The situation when there are vehicles that do not have fixed fire fighting systems, such as cars, buses for visitor etc needs to be looked into. The regulations usually do not consider the situation for the fire and rescue operation teams.

Ventilation

We have identified several areas where further improvements and development can be performed. The single most important point is if a fire occurs in the phase before or after breakthrough at the construction site. This has implications for the fire development, evacuation and the fire and rescue operation. The fire development depends to a large extent on the ventilation conditions. Low ventilation rate reduces the fire intensity and high ventilation rate increases the fire intensity. Ventilation before breakthrough consists of mechanical environmental ventilation and after breakthrough it is dominated by natural ventilation. Environmental ventilation transport fresh air through the ventilation pipes of plastic to the workplace where drill or blasting is carried out (dead end). The fresh air is in turn, transported back from the workplace to the tunnel portal. The model scale experiments conducted in the project show that if the fire occurs before the breakthrough and the fire is too small (a few MW) it will be difficult to obtain fresh air from the entrance. Therefore the fire is totally dependent on the oxygen delivered by the environmental ventilation system. If the environmental ventilation is shut off, the consequence will be that the fire decreases in intensity and finally extinguish because of the vitiated products that are recirculated to the fire.

The model scale tests show that the size of the working tunnel before the breakthrough (length, slope, cross section) plays a central role in how the fire will develop. After the breakthrough airflow is controlled by the tunnel length, slope and temperature differences between indoors and out. External wind can also affect the air flow inside the tunnels. Ventilation before breakthrough consists of mechanical environmental ventilation and

after breakthrough it is dominated by natural ventilation. Environmental ventilation transport fresh air through the ventilation pipes of plastic to the workplace where drill or blasting is carried out (dead end). The fresh air is in turn, transported back from the workplace to the tunnel portal. The model scale experiments show that if the fire occurs before the breakthrough and the fire is too small (a few MW) it will be difficult to obtain fresh air from the entrance. Therefore the fire is totally dependent on the oxygen delivered by the environmental ventilation system. If the environmental ventilation is shut off, the consequence will be that the fire decreases in intensity and finally extinguish because of the vitiated products that are recirculated to the fire.

A large fire might have the power to start a circulation of the air all the way from the opening, while a smaller fire will not. If the ventilation rate is low this could lead to that the fire self-extinguish. The ventilation creates a flow near the ceiling. This affects the flow pattern and together with the forces from the fire, a circulation “behind” the fire is created.

Burning vehicles

There is a lack of knowledge of fire development in work vehicles for construction of tunnels. There are almost no documented full-scale experiments conducted. Therefore, experiments were conducted with wheel loader tires. The intention was to identify how fast a tire burn and how much smoke is produced.

Experience shows that the most common cause of fire resulting from technical faults such as leakage of oils (hydraulic or motor oils) that hits the hot surface. This leads to a rapid initial fire development and depending on conditions and location of the damage fire can fire developed into a more serious incident. The tires are the dominating fire load in the construction machines and therefore it was important to carry out this test. The test show that a front wheel loader tire yield maximum heat release rate of 3 MW which is similar level as from a burning passenger car. If this value is converted to heat release per square meter fuel surface this corresponds to about 0.2 MW/m². This value match up well to earlier investigations with burning tiers. A fire in a front wheel loader tire becomes most intense after one and a half hour and the total duration is over 2.5 hours. The measured proportion of radiation from the total heat release rate of the front wheel loader tire was about 25%.

After the evacuation calculation it was concluded that an appropriate design fire during drilling and blasting phase (before breakthrough) should be a articulated hauler or two cars that burns. It was found that buses without sprinklers installed generated the most severe fire for the workers and therefore all busses must be equipped with sprinklers whether they are in the tunnel system before or after the breakthrough.

During construction of tunnels, there is often a need to mount plastic insulation under the spray concrete. This insulation is highly combustible and experiments carried out in Norway show that the tunnel can flash over if it is ignited before it is covered by spray concrete. If this material starts to burn on the vertical section and a fast initial flame spread is obtained, one should expect that the fire becomes impossible to fight. This means that the workers have to escape quickly to a safe place. As it is not possible to do so much if the fire get larger than few MWs, the focus should be on making portable fire fighting equipments easily accessible. A plastic insulation as mounted in many tunnels during construction can yield heat release rates up to 0.5 MW/m² [36]. If we assume an ordinary tunnel cross-section we can expect about 10 – 20 MW per meter of the tunnel. The only way to deal with this is by prevent the fire to grow at all and secondly make sure that there is easily accessible portable fire extinguisher equipment and safe places to run to.

The European DACH regulations [5] allow 50 m freely exposed plastic insulation in ceilings without any special fire safety measures. If this length is not sufficient for reinforced inner linings because of the required sequence of construction works, the length may be extended to a maximum length of 150 m implementing the at same time appropriate additional fire protection measures. The plastic insulation sheets should be laid only after the tunnel is completely driven or after the implementation of other comparably efficient protective measures (e.g. plastic fire breaks, sprinkle curtains). If this is not possible, at least one location which can be reached within the lasting time of the oxygen self-rescuer must be provided between the seal area and the heading face.

The tunnel visits show that the existence of the storage of combustible materials during construction varies between working sites. If we assume that the containment of flammable material should not generate a fire that is higher than 12 MW, which is comparable to a articulated hauler fire, and corresponds to a burning surface of 25 m². Assuming that solid plastic release about 0.5 MW/m² [36] we will obtain a total heat release rate of 12 MW.

Evacuation

Comparing the results from the evacuation analysis before the breakthrough for the different fire scenarios some patterns can be observed. When the evacuation starts the persons may either be trapped in the smoke and can then move a certain distance or on the other hand the persons can move ahead of the smoke front to reach a safe location. If, in the latter case, movement occurs in the smoke free environment it can be performed rather safely as the smoke front moves much slower than the normal walking speed. The time to reach the tunnel entrance is independent on the tunnel shape as only distance and movement velocity determines the time to reach safety.

The tunnel visits shows that it is important that workers in the tunnel are aware of the evacuation strategy applied in the construction project. In tunnels under construction it is first and foremost the workers or personnel at place that have to react to a threatening danger. This means that they have to evacuate before critical situations arise and quickly take a decision to find the most appropriate means of escape. In order to obtain an effective evacuation early alarm and orders to evacuate are necessary.

Given the uncertainty where the workers are located in relation to the fire origin, escape routes, rescue chambers and stuff, it is the best option in most cases to turn off the environment ventilation. Higher air flows may in some cases improve the visibility and the toxic environment, if workers are forced to evacuate in a smoke-filled environment, but this may lead to increased risk because the fire intensity may increase. There may be an advantage to shut down the ventilation coordinated by an alarm signal for escape, or in consultation with the emergency services. The communication and alarm system for evacuation should be available in each working team and be easy to use. In addition, fixed stations for alarm can be placed every 75 meters, preferably at the fire water supply.

The study show that parameters that have the greatest impact on the evacuation situation are the fire development and the tunnel cross section. The critical distance to the place of safety is therefore highly dependent on the size of the tunnel cross section. That means for example that the maximum distance to rescue chamber/escape route from the workplace can be adapted to the size of the tunnel cross section. This means that a smaller cross section requires a shorter distance, while a larger cross-section may allow the larger distance. The distances discussed in AFS2010: 1 are 200 - 300 m, while the Northern Link project in Stockholm it is 150 m. In the DACH document it is stated that this distance should not exceed 500 m but some risk classes the distance is allowed to be up to 1000 m. In summary, we can say that the distance needs to be determined in relation to the risk situation at each working place and also in relation to the tunnel cross-section.

The tunnel visits show that the workers should primarily use vehicles for transport in the tunnels. All vehicles must be situated so that they are immediately available for effective evacuation. It is important to have clear and simple instruction in case of emergency. An agreement on the language to be used in an emergency situation is important. We have found that various forms of contractor models may affect the evacuation situation. This can be factors such as attitudes, language skills and motivation regarding safety. In the case of many contractors in the same project the client is fully responsible for planning and coordinating the safety. The client, however, when all contractor forms are considered have the overall responsibility for the safety is fulfilled.

Fire and rescue services situation

The study show that the fire and rescue service and evacuation drills as well as scenario games are an important part of the safety concept. Fire and rescue service and the workers can sometimes be unable to get in contact, whether they are trying to get out or stay in the rescue chambers. This requires that one organize so that workers always can on their own reach a safe place within a given distance.

The parameters that have the greatest impact on the possibilities and the outcome of the rescue effort is the fire development and if the fire occurs in the phase before or after the breakthrough. It is important that the incident commander has access to accurate information during a fire and rescue operation. It is very helpful if a person with detailed knowledge of the workplace can serve as a contact person between emergency services and the rest of the organization. This person should have the power to take important decisions in a critical situation.

Action planning should be done in collaboration between client, contractor and fire and rescue services. Named person should be primarily responsible for drawings and data and a system to maintain updated information should be developed. During a tunnel construction, many contractors can be involved in similar or parallel contracts. Ongoing collaboration and drills between contractors is important to clarify the individual contractors' responsibility. Common drills should be exercised between the emergency services, ambulance personnel and police authority. Fire and rescue services and evacuation drills can easily be coordinated. Scenario games are found to be a great tool for practice management functions, both within the organization as the emergency services. Drills should be done for the organization and individuals to obtain necessary skills to handle the situation and deficiencies should be detected before an emergency situation occur. The goal of a drill should be clearly defined and not just to announce that a drill is to be executed. Action lists to detect shortcomings shall be organizational to give measures to be followed up.

The direction of the smoke determine in most cases how the fire and rescue operation will form their tactical direction. Ventilation is often used as a tactical resource during fire and rescue in a tunnel. For tunnels under construction, before the breakthrough, a limited opportunity to influence the direction of the smoke is possible.

There is a need to discuss which parts of the AFS 2007:07 Smoke and toxic gases diving, which are applicable to the complex environment in tunnels. AFS 2007:07 exist in order to regulate so that firefighters working environment become safe. However, AFS 2007:07 takes no account about the outcome of the fire and rescue operation. Some of the requirements of the AFS 2007:07 makes fire and rescue operations impossible in some environments and situations. Under the project tests have demonstrated that alternative equipments, such as lightline, in some cases provide better safety and improve the fire and rescue operation. The completed tests show a need to further explore alternative methods of emergency in the tunnels. The design of these experiments should be done in

parallel with the discussion of AFS 2007:07.

When the incident commander makes a decision on how the fire and rescue operation should be carried out, the most important parameter to consider is whether people are still inside the tunnel or not, and what resources are needed to try to rescue these people. It is essential that the number of persons is certain, whether a manual or automatic logging system is used. The incident commander also need accurate information about any vehicles in the vicinity of the fire, the amount of flammable or combustible liquids on the vehicles and the other risks that are near the fire place or along the rescue way. For example, the expertise needed to determine if any deterioration of tunnel construction in the event of fire is very useful. Vehicles and gas cylinders can advantageously also be "tagged" to automatically registered if such a system exists in the workplace.

The fire and rescue service can not undertake a serious assist in a dense toxic smoke that has had time to spread over a longer distance between the "zero point" and the rescue site. It must be noted that this distance can vary depending on the circumstances of the operation. "Zero point" is the place where the BA is to begin, and the rescue site is a place where people who need help are located. The base point that is established at BA in the tunnel can be placed outside the tunnel entrance while the penetration through the dense smoke in some cases can be first made further into the tunnel. A discussion of the "zero point" and its definition should be continued. If the dense smoke has had time to spread more than 200 m, when emergency services begin its operation, the possibility of reaching the fire within a reasonable time is limited by the methods, equipment and regulations that exist nationally today.

In order to perform effective fire and rescue operations in tunnels, especially in tunnels under construction, development of tools to facilitate the transport of equipment into the tunnel and the possible removal of the injured out of the tunnel is required. When the infrared camera is used in tunnels under construction, where the heat differences between for example floors and walls may be too small and may lack reference points in form of installations and lighting, the benefits from thermal imaging may be lower than in other tunnels.

8 Conclusions

The regulations given today, cover many of the problems that may arise during construction of underground facilities. The guidelines describes how to protect the workers and the construction machines. The part that is not covered very well is how to perform exercises, including evacuation exercises and ventilation control in case of fire. There are no requirements concerning the performance of fixed fire fighting systems and detection systems and there are no guidelines concerning how to handle the ventilation system. The regulations usually do not consider the situation for the fire and rescue operation teams during construction.

We identified several areas where further improvements and development are needed. The single most important point is whether a fire occurs in the phase before or after breakthrough at the construction site. If the fire occurs before breakthrough and the fire is small it will be difficult to obtain fresh air from the entrance and the fire will decrease in intensity and finally extinguish due to vitiated products that are recirculated to the fire.

The size of the working tunnel before the breakthrough (length, slope, cross section) plays a central role in how the fire will develop. After the breakthrough airflow is controlled by the tunnel length, slope and temperature differences between indoors and out. Further, external wind can also affect the air flow inside the tunnels.

There is a lack of knowledge of fire development in work vehicles for construction of tunnels. Partly, therefore, experiments were conducted with wheel loader tires. The test show that a front wheel loader tire yield maximum heat release rate of 3 MW which is similar level as from a burning passenger car.

It was found that an appropriate design fire during the drilling and blasting phase is an articulated hauler alternatively two cars that burn. It was found that buses without sprinklers installed generated the most severe fire and therefore they must be equipped with sprinklers independent of whether they are in the tunnel system before or after the breakthrough.

The European DACH regulations allow 50 m freely exposed plastic insulation in ceilings without any special fire safety measures. If this length is not sufficient for reinforced inner linings because of the required sequence of construction works, the length may be extended to a maximum length of 150 m provided appropriate additional fire protection measures are implemented at the same time.

The existence of the storage of combustible materials during construction varies between working sites. If we assume that the containment of flammable material should not generate a fire that is higher than 12 MW, which is comparable to a articulated hauler fire, and corresponds to a burning surface of 25 m² the same design fires can be used.

The tunnel visits shows that it is important that workers in the tunnel are aware of the evacuation strategy applied in the construction project. In tunnels under construction it is first and foremost the workers or personnel on site that have to react to a threatening situation.

Given the uncertainty concerning where the staff is located in relation to the fire location, escape routes, rescue chambers etc, it is the best option in most cases to turn off the environment ventilation.

The parameters that have the greatest impact on the evacuation situation are the fire development and the tunnel cross section. The critical distance to the place of safety is therefore highly dependent on the size of the tunnel cross section. The workers should primarily use vehicles for transport in the tunnels and vehicles must be situated so that they are immediately available for effective evacuation. It is important to have clear and simple instruction in case of emergency. An agreement on the language to be used in an emergency situation prior to the development of a situation is important.

The fire and rescue service and evacuation drills as well as scenario games are an important part of the safety concept. We found that different contractors may affect the escape the situation. This can be due to factors such as attitudes, language skills and motivation regarding safety.

It is important that the incident commander has access to accurate information during a fire and rescue operation. It is very helpful if a person with detailed knowledge of the workplace can serve as a contact person between emergency services and the rest of the organization. This person should have the power to make important decisions in a critical situation.

Action planning should be conducted as a collaboration between client, contractor and fire and rescue services. Common drills should be exercised between the emergency services, ambulance personnel and police authority.

The direction of the combustion gases determines, in most cases, how the fire and rescue services will form their tactical direction. Ventilation is often used as a tactical resource during fire and rescue in a tunnel. For tunnels under construction, before the breakthrough, a limited opportunity to influence the direction of the smoke is possible.

There is a need to discuss which parts of the AFS 2007:07 Smoke and toxic gases diving, which are applicable to the complex environment in tunnels. AFS: exist in order to regulate so that firefighters working environment become safe.

When the incident commander makes a decision on how the fire and rescue operation should be carried out, the most important parameter to consider is whether people are still inside the tunnel or not, and what resources are needed to try to rescue these people.

The fire and rescue service cannot undertake a serious assault in dense toxic smoke that has had time to spread over a longer distance between the "zero point" and the rescue site. If the dense smoke has had time to spread more than 200 m when emergency services begin its operation, the possibility of reaching the fire within a reasonable time is limited by the methods, equipment and regulations that exist nationally today.

In order to perform effective fire and rescue operations in tunnels, especially in tunnels under construction, the development of tools to facilitate the transport of equipment into the tunnel and the possible removal of the injured out of the tunnel is required.

9 Recommendations

List of recommendations based on the work carried out:

- Automatic fire fighting systems in cabs, and engine compartments in manned and remote construction machines should be mandatory. In most guidelines and regulations this is only recommended. Even the duration time of the system after activation should be specified.
- Automatic fire extinguishing systems in engine compartments of buses with visitors should be mandatory.
- A fire resistant hydraulic fluid should be mandatory in stationary construction vehicles working underground.
- The number of visitors should be adapted to available space in the rescue chambers.
- Workers will primarily use vehicles for transport in the tunnels. All vehicles must be situated so that they are immediately available for effective evacuation.
- Escape masks should be regarded as personal protective equipment.
- The main fire safety strategy is to turn off the environmental ventilation system at fire alarm if a rescue chamber or an escape route is available in the vicinity of the fire. Rescue chambers should be placed at a given distance from the workplace, depending on the size of the tunnel cross section.
- The communication and alarm system for evacuation should be available to each working team and be easy to use. In addition, fixed stations for alarm should be placed every 75 meters, preferably together with the fire water supply.
- A plan should be available for other types of fire and rescue missions, e.g. release of trapped persons and removal of falling rocks.
- A handbook for contractors, where basic knowledge and basic concepts that are valid for the whole fire safety of the systematic fire protection work, their performance of exercises, preparedness, response planning and crisis management are documented should be developed.
- Freely exposed plastic insulation up to 50 m freely in the roof requires no special fire safety measures, however, two 6 kg dry powder extinguishers should be available at the workplace. Between 50 m and 150 m, special fire protection measures should be incorporated (e.g. a guard and four 6 kg dry powder fire extinguishers placed at the workplace).
- Storage of combustible materials underground should not exceed the material that is used during one shift, and not exceed 25 m² of exposed surface (the surface that can burn). If the freely exposed surface storage area will be larger than 25 m², special fire safety measures should be introduced, for example, covering the stored combustible material with fireproof cloth or something similar.

These recommendations can be used by decision makers and regulation writers to improve fire safety in tunnels under construction.

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Appendix Tunnel visits

The project group visited several tunnel construction sites in order to study working conditions, including the Northern Link road tunnel in Stockholm, a sewage tunnel between Partille and Lerum, the Hallandsås rail tunnel in Skåne, and Onkalo in Finland where a future repository for spent nuclear fuel is being constructed. One of the most important objectives of these visits was to look at the problems associated with emergency evacuation during the construction phase, to identify typical evacuation scenarios, and to analyse the safety of personnel during or in connection with evacuation.

Norra Länken in Stockholm (2008-06-11)

General description

North part of road connections around Stockholm inner area. Total tunnel length is 9 km and net tunnel length is 4 km. The rest is ramps etc. Longest tunnel is 3 km. Finished in 2015. 90 emergency exits and 150 between them. 200 impulse fans. Internet site www.vv.se/norralanken. Total cost 12 000 MSEK split 75% Swedish Road Administration (VV) and 25% Stockholm city. In total 12 main contractors.



Figure A 1 The entrance of the Norra Länken (North Link) project in Stockholm.

General assumptions regarding evacuation and risk sources

Dark environment makes evacuation difficult. Tunnel site is equipped with external lights and all personnel is supposed to carry a torch. Unclear if all persons really has one. Lot of persons in the tunnel. In total 800 persons can be inside the tunnel at the same time but that is later in the construction phase, installation phase (year 2012). During the drilling phase only a few persons are at the same construction phase. Work is taking place at several construction sites at the same time and they will later join and form one site after the drilling of the tunnels are completed.

In order to know how many persons are at each site at the same time all persons will wear an identification tag which can be identified with a wireless system at the site entrances and inside the sites. Also equipment like gas bottles, flammable liquids etc are tagged.

Information from the ID tags is transmitted to the common rescue plan. The rescue plan is accessible via Internet and is supposed to show the current positions of all workers, equipment and work sites. The system with ID tags are taken into operation during autumn 2008.



Figure A 2 The fresh air ventilation ducts in Norra Länken.

At the site visited approximately ten persons were inside the tunnel. They were working with concrete spraying of the tunnel surface and tunnel blasting. Support persons like truck drives and supervisors were also in the tunnel. No visitors were at the site but it is likely that visitors can be at the site. They are always guided by a staff member from the road administration. Visitors do not get any special education before entering the tunnel construction site. Questions to be raised were how are the workers educated? and what is included? We do not know if they are aware of any fire related risks. The workers are trained by their employer.

Escape route

During the construction phase two "sub-phases" exist, before and after two sites are connected. In the beginning the only escape route is the entrance to the construction phase. No alternative escape routes exist. In some tunnel constructions rescue chambers are used for the workers to use as a shelter in case of fire. The chambers are located at places near the work place and more than one chamber can be used for large construction sites. In Norra Länken no rescue chambers are used. Instead all workers carry a rescue set with a mask and oxygen supply. Check how that work!! Have to check whether or not this is used in practice.

After two construction sites have joined there is an alternative escape route available. The distance to a place of safety can, however, be significant as the persons at the site have to move all the way to the next tunnel entrance or site entrance (for the case work tunnels are used).

If an evacuation has to be performed the persons in the tunnel have to move to the entrance. The surface can be rough, slippery and not very well illuminated. The conditions may also vary both transverse the tunnel as in the tunnel direction.

The conditions for evacuation also depend on the phase of the construction as the conditions get better closer to the opening date for the tunnel. At the beginning of the drilling a work tunnel may be constructed. The work tunnel is a smaller tunnel which leads from the surface to the location in the ground where the main tunnels are supposed to be located. The work tunnel can later be used for maintenance of the finished tunnel. At the visited location at Norra Länken the slope of the work tunnel was quite high. It can, therefore, be difficult for persons in the tunnel to quickly travel up the work tunnel to reach the safe place at the surface. Many workers have vehicles which they can use. If the tunnel site becomes smoke logged during evacuation there may be traffic hazards as people evacuate both by foot and by vehicles when the visibility is poor.



Figure A 3 Photos taken during the visit to the North Link.



Figure A 4 Photos showing some of the working vehicles used in the North Link.

Technical equipment for evacuation

Currently no general evacuation alarm is installed in the tunnel. There will be a sound and light (blue flashing light) evacuation alarm later in the construction. The evacuation alarm is activated by alarm buttons at the rescue stations, see below and from a PC at the contractor office. An automatic fire alarm (detection system and for calling the fire brigade) is installed in areas with high fire risk. In those cases the fire alarm also activates the evacuation alarm. The evacuation alarm is also transmitted to each mobile phone. A CCTV system shall be installed with a video monitor facility at the road administration and at each of the contractors' offices (separated for each contractor work area).

All emergency communications is made by mobile phones which will work in the tunnel. Not sure what type of phones that will be used and radio communication is still an option (decision autumn 2008). All contractors have to use the same phone operator, Telia. The phone can be identified in terms of the work area from where the call is made. Language can be a problem but everyone working in the tunnel site can call (know a typical phrase) the emergency call centre, i.e. SOS Alarm 112. SOS Alarm 112 will take necessary steps

depending on the nature of the emergency call. The evacuation alarm is also transmitted to each mobile phone.

At every 150 m a rescue station will be located. The rescue stations contain for example an alarm button, a phone, fire extinguishers, portable oxygen masks and a first-aid kit. This is not currently the case.

Part from the phone evacuation alarm the workers are equipped with an oxygen mask which can be used for evacuating through smoke. Each worker shall have proper training on how to use the mask. Emergency lighting is installed which operates with the aid of batteries. The power last for several hours.

Wayguiding signs are mounted on the walls to show the closet way to a safe place. The signs are, however, hard to detect as they are small and not very well illuminated. If persons in the tunnel have access to a vehicle that is probably used for evacuating purposes.

No rescue chambers are used.

Evacuation drill

The responsibility to perform evacuation exercises is on each contractor. So far no drills have been performed. The road administration want to have joint evacuation exercises. According to the regulations in AFS 2003:2 exercises shall be performed on a yearly basis.

Real evacuation

No real evacuation has been necessary. No fires have been reported. Each contractor must report all work accidents and incidents that might have escalated to an accident.

Sewer tunnel in Råhult (near Gothenburg) 2008-08-28.

General description of the tunnel

The objective of the tunnel is to be used as a sewer tunnel. It will go from Lerum to Partille and will be 8 km when finished. The width of the tunnel is 2.8 m at the base and the height is 4 m at the highest point. The cross-section is larger than needed, but is the smallest possible to have room for the vehicles and equipment during the construction phase. The client asked for a tunnel with a cross-section of 7 m², but will get a tunnel with a cross-section of 12 m².

There is a 300 m working tunnel connecting the site above ground and the tunnel construction site. This working tunnel has a slope of 15 %. From the bottom of this working tunnel, the tunnel will be 4.5 km towards Lerum and 3.5 km towards Partille. Right now the tunnel is 900 m in one direction and 800 m in the other. The construction is made by drilling and blasting. The pace is between 300 m and 400 m per month. The tunnel must be finished by 31/1 2010. They started in April 2007. The entire tunnel is sprayed with concrete

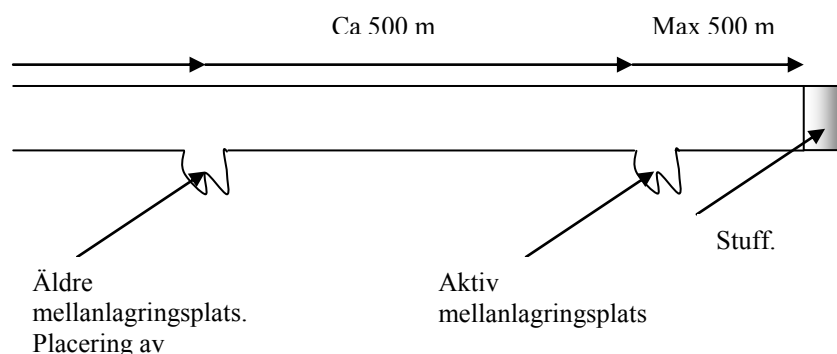


Figure A 5 Sketch over tunnel and stuff.

Personnel

The full crew is approximately 35 people. They are working three shifts, i.e. 1/3 is in the tunnel, 1/3 is above ground resting and 1/3 is at home. Approximately five people are working in each direction in the tunnel. The work is going on almost 24 hours every day. 20-22 people are employed by the company. The rest come from a Swedish staffing company. These people are mainly used for loading of the debris. There is a board at the entrance with key rings for all the workers (and visitors).

Vehicles

There is a binder containing information on all vehicles used in the tunnel. This will be made available for the research group. The machines has a water mistsystem by Fogmaker installed. This can be activated by a button if the engine is on fire. It does not help if the tires are on fire. All vehicles carrying explosives, wheel-loaders and drills have a system from Atlas-Copco.

The water mist system is checked by the supplier once a year.

The drilling machine is driven by diesel when it moves, but by electricity when it is drilling.

Vehicles in the tunnels are: jeep, tractor, truck with explosives, digging machine, engine for the train, wheel loader, drilling machine.

Work

The tunnel is made by drilling and blasting. The debris is transported by a wheel-mounted loader. This had to go in reverse all the way from the end of the tunnel to a blasted hole/niche in the tunnel wall where the loader can dump the debris. The debris is then loaded onto a train. These dumping/reloading niche were constructed each 500 m. In between these loading zones there was a smaller niche for a transformer.

Blasting was performed 4-6 ggr/dygn, each time 4 m (50 m³ material). 55 drilling holes. The explosives constituted of two substances, one matrix and one vinegaracid? With a special pump these are mixed in the drilling hole. These are stored above ground and transported on a truck to the stuff when needed. In the tunnel there is a small storage of dynamit (maximum 2000 kg or 4000 kg) and igniters (maximum 10000). These are stored in two containers. Only the head of blasting has the key.

Escape and rescue

The first zone/niche (for loading or transformer) not used for the construction, was used for a rescue chamber, i.e. the distance from the end of the tunnel (the drilling site) to the rescue chamber was between 500 m and 750 m, depending on the phase of the construction. The chambers were constructed from a pressure lock.

There was a risk for the rescue chambers to instead being used as storage or coffee room and the real purpose was forgotten. The chambers could hold 6 persons (8 people was too crowded). There was pressurized air that gave overpressure in the entire chamber. The host thought that the air lasted for four hours. The radio does not work inside the chamber. There is no wired tele communication. No heat insulation.

Most machines have escape masks. Visitors are given escape masks. There were antennas in the tunnel for the communication system. The same frequencies, as used by the BA-units of the rescue services, were used. In total 15 radios were used. Four are used by the office personnel; only key persons have a radio. The drill machine has a communication radio installed.

Communication can be a problem. Three different nationalities: Austrian, Polish and Swedish. In general English is used, but some of the people from Poland do not know English, some of the Austrian does not know English, and even some of the Swedes are not so good at English. There are interpreters for the Polish people, but the interpreter is at the site only during the days.

There is no alarm system, but the radio has an alarm button. If the button is pressed for 5 s the radio is routed to a cell phone number, to one of the three site bosses. The radios have only one channel so every one can hear the communication, but for the calls rerouted to the cell phone network.

The contact with the rescue service was considered to be important. It was the same level in Germany and Sweden. In USA there are differences (hard tubes so they can suck the air out of the tunnel). This does not work over 4 km.

They have talked about an evacuation drill, but not performed any yet. Personnel from a number of fire stations have been to the site, but not down in the tunnel since they have been in "alert mode".

The workers take courses for hot work.

Ventilation

Air flow into the tunnels is produced by two large fans outside the tunnel system. The air is guided into the tunnel by two tubes, 1100 mm in diameter. At the position where the service tunnel reaches the “real” tunnel, the air is guided in two directions into tubes 850 mm in diameter. Whenever the pressure becomes too low a booster fan is built into the system. The flow was approximately 9 m³/min towards Lerum and 6 m³/min towards Partille. The flow is measured 50 m from the stuff.

Water system

There is a pressurised water system in the tunnel (7 bar). The drill machine increases the pressure. There are junctions for the rescue services every 200-250 m.

Light

Fluorescent tubes are used for lighting, every 20 m. Every fifth of these are equipped with battery for emergency lighting. The last 200-300 m from the stuff is without lighting. It cannot be installed due to the explosions and it is easier for the loaders to see only with the light on the wheel loaders.

Visit to the Hallandsås tunnel 2008-08-29

General description of the tunnel

The tunnel will be 8.6 km long. It will increase the train capacity from 4 to 24 trains per hour.

Personnel

In the team there are people from Sweden, France, Poland, Australia and Austria. English is the language used. It is a working environmental problem that not everyone knows English, and therefore English education is sometimes included. When it comes to the group from Poland, the group leader must know English.

There is a movie in four languages that constitute part of the education. They work in a continuous 4-shift with 12 h shift. Two crew groups at the site working either 7-19 or 19-7 for six days. After that they are free for six days, when group 3 and 4 are working.

There are 40 people on each shift, 25 in the tunnel. Everyone has an education in hot work.

Communication

Most people has radios; all these people speak English. The pilot of the TBM is not allowed to leave his cabin. There is a telephone in the pilot cabin and in the rescue chambers. The radios have an alarm button.

Those who do not see each other, or who leave the TBM, have radios.

There is an evacuation alarm on the TBM. At the transformer station there is a telephone. In the tunnel where there is no TBM, there are flashing lights installed.

Vehicles

Most often only one train in the tunnel, for transportation of personnel and concrete segments.

Work

From the service tunnel, the TBM is now working towards the north and is 450 m into the tunnel (the TBM itself is 250 m long). The east tunnel (with the TBM) is now 5 km long. The service tunnel is 920 m and in 1997 they managed to come 10 m in each direction of the tune (the bore they are not drilling now). The west tunnel bore is 1.7 km long.

Hydraulic oil with a flash point of 310 °C is used in the tunnel.

There is a transport band (non-flammable rubber), from the TBM and all the way out of the tunnel.

There is a space between the concrete segments and the rock. This space is filled with shingle and spray concrete.

Safety measures

An aim of a certain number of incident reports per shift has been set. 80 % of all incidents/accidents are due to personal mistakes and clumsiness. There is a difference between the shifts how good they are at producing incident reports.

A number of different drills per shift are performed every year. These are known drills and it is informed over the radio that it is a drill.

They are not satisfied with the number of accidents. Work related injuries leading to sick leave have not decreased. It can be falling injuries, eye injuries, or injuries caused by crushing. Therefore they have visited road construction sites in Norway where they had

very few accidents. The aim is 20 injuries per million work hours, but right now the actual number is higher than that.

The investigation by the Hallandsås committee of the safety has been a motivation power. They say that they have a rather unique safety organisation with a number of people working full time with the safety.

Flight masks are placed in special cabinets. The workers have special shoes, safety cloths and helmet. Safety goggles are today placed at strategic places, but will be personal equipment. Tourists are not allowed into the tunnel construction site. Special groups may come and visit.

They use a tag system that automatically registers if someone is entering or leaving the tunnel. Temporary visitors are registered on a board. A maximum of total 40 people are allowed to be in the tunnel at the same time. Therefore groups have to contact the security guard before entering. The tag system does not work when entering through the service tunnel. The service tunnel is to be filled, and not used anymore, after the completion of the tunnels.

Drugs and alcohol are forbidden as is clothes with a hood. If a person has long hair a hair net is compulsory.

Fire load

On the TBM there are hydraulic oils, grease and gas bottles. 1-2 trains with diesel engines can be in the tunnel. Sometimes a diesel compressor is used. In addition to that there is a transformer, pumps and engines.



Figure A 6 The rear end of the TBM machine in the Hallandsås tunnel.

In the other tunnel bore where they do drilling and blasting, there are 4-5 vehicles and the drilling machine.

Only controlled diesel driven vehicles are allowed to enter the tunnel system. The vehicles shall always be parked with the front turned towards the exit. The keys should be left in the car. There should be as many flight masks as there are people.

Escape and rescue

The steering documents are the working environment regulation and the opinions of the rescue service. More than the minimum limit has been performed.

There have been fires and there are reports available. The fires have, however, not led to operations by the rescue service.



Figure A 7 The rescue train on the TBM drilling machine.

A drill is planned to October 2008. A secret scenario will be played. There are possibilities to visit as an observer.

There is one stationary and one mobile rescue chamber at the rear of the TBM. The mobile can be operated from the inside and can go on the rail out of the tunnel. The mobile chamber can hold 25 people and the stationary 15. The chamber on the TBM is dimensioned for 36 h. There are chemicals converting CO₂ into O₂. The mobile chamber is unique for this project. It also has a IR-camera at the front.

There are also rescue chambers at other places. They have masks connected to air tubes. There is also a telephone. There is one rescue chamber for 8 people at the bottom of the service tunnel. There is a powder extinguishment system installed in the hydraulic section of the TBM. There is a detection system, but manual activation. Totally approximately 200 kg powder is available for the system. There are water curtains at three positions, e.g. near the rescue chambers. Smoking is allowed, and it is rather much smoking, but only in specified zones. There is water available at each connecting tunnel and one in between. This mean a maximum distance of 250 m since it is maximum 500 m between the connecting tunnels. Since one bore is constructed at a time now, there are no connecting tunnels.

There are safety rounds once a week on the TBM and once a month in the rest of site. So far there has not been any incident that has demanded evacuation. In a case of emergency the pilot shall be alerted. The pilot then starts the alarm and contact the rescue services (112). The trains have hand held extinguishers.

Ventilation

The ventilation air is guided to the TBM through a tube with the diameter of 2,4 m. The air is there exiting the tube. A few meters after the exit of the tube there is a booster fan that through a pipe system distributes the air on the TBM. Ventilation flow?

Water system

Not known

Environment

They have there own water cleaning system. They are allowed to have a spill water of 100 L/s (as a 30 days average. This is a limitation; otherwise they would have 2 TBMs running.



Figure A 8 Photos taken during the visit to the Hallandsåstunnel.



Figure A 9 Photos taken during the visit to the Hallandsåstunnel.

Visit to the Onkalo Underground Rock Characterisation Facility in Finland (2008-11-06)

Objective of visit

To get familiar with the fire safety equipment and procedures at the tunnel construction site.

General description of the tunnel

The total length of tunnels will be 9 km. The underground research facility being built for rock characterisation for the final disposal of spent nuclear fuel is known as ONKALO. The lowest point will be 437 m below the ground (level -437 m). There will be a research center at the level -420 m.

The road tunnel is 5.5 m × 6.3 m with an incline of 10 %. The system today consists of a road tunnel and three shafts: fresh air, exhaust air, and for workers transport. The personnel shaft is not yet ready for transportation of people. Today the road tunnel is 3233 m.

Personnel

In the tunnel there are approximately 15 people working at a time. The total working force consists of approximately 40 people. There are three teams working in two shifts. Every shift is 12 hours. They work for two weeks and then free from work during one week. There is a manual board (with metal plates) above ground saying who and how many people are in the tunnel system.

Communication

The working language is Finnish. At least one in each working group must have a telephone that is working in the entire tunnel system. A leaking cable is used. The cable can endure some heat.

Vehicles

Only diesel engine vehicles are allowed. No inspection of the cars are made today. However, it has been discussed. The working vehicles have right of way over other vehicles. Vehicles should be parked with the front towards the exit of the tunnel. In total they have 15 large machines and five trucks.



Figure A 10 Photos taken during the visit to Onkolo.



Figure A 11 Photos showing some of the working vehicles in Onkolo.

Work

The progress of the work in the tunnel is 25 m per week. One blast (5 m) is performed each day.

Safety measures

All people in the tunnel should have a flight mask giving oxygen for 25 min. There are safety containers for 6 and 12 people respectively. Tubes with pressurized air are connected to the containers giving fresh air inside the containers for 16 hours. The containers are move as the tunnelling work proceeds. The longest distance to a safety container is 400 m. The distance between the containers is 500-500 m. A maximum of 7 visitors are allowed to be inside the tunnel system at the same time. The engine compartment of all the machines is sprinklered. This can be activated both automatically and manually. The system is controlled 1-2 times every year. There is also a hand held extinguisher in the driver's cabin.

Each shift there is a control of the machines. An inspection is performed every week and maintenance every other week. Explosives are stored above ground. Mostly the explosives are mixed in the holes, but for the contour ordinary explosives are used. Smoking is allowed.

Fire load

Mainly the vehicles (see above). Ventilation tube.

Escape and rescue

Evacuation drills are performed twice every year. Drills are performed together with the rescue services. There are several rescue services in the surroundings and they have good knowledge of the tunnel system. In case of a fire, overpressure is maintained in the fresh air shaft, which then can be used as an escape route by help of the lift installed there. The speed of this rescue lift is 8 m/min or 18 m/min. The rescue service know how to control the ventilation. The personnel are trained to do a first attempt of extinguishing a fire. The closest rescue service is less than 1 km away and has a force constituting of 1 chief and 5 other people.

The workers call 112 in case of a fire. The number goes to the nearest rescue service and they decide what to do. The people on the upside of the fire evacuate while those on the downside of the fire go to the nearest safety container. If there is smoke from tunnel opening the rescue service do not go in. If rescue of people is to be done, this is done through the fresh air shaft. There are plans on purchasing four sets of breathing apparatus for the rescue service.

Ventilation

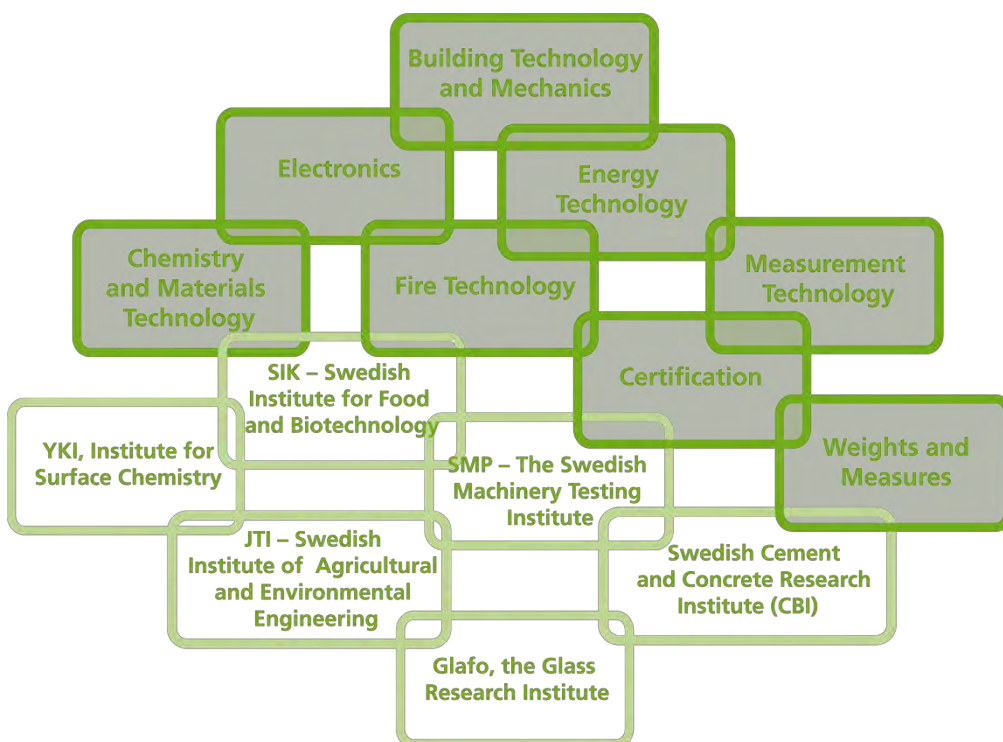
The ventilation air is guided to 70 m from the stuff through a plastic tube. The maximum air flow is 40 m³/min. Right now there are many holes in the ventilation tube and the air flow near the end of the tube is only 10 m³/min. The fan is taking air from the fresh air shaft and is today positioned at a level of -180 m, but will within a month be moved to a level of -290 m. There are plans to install extra fans along the tunnel to speed up the clearing of the smoke after each blast. Today it takes one hour to clear this smoke.

Water system

1 L of water per 100 m of tunnel is allowed during the work.

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