PHOENICS IN SAFETY ANALYSIS
OF OFFSHORE AND UNDERGROUND CONSTRUCTIONS

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Date: Phoenics User Conference, Melbourne, 3-5 may 2004

ABSTRACT

Phoenics has been used in safety analysis in Norway for more than 15 years. This is probably one of the largest and most important application areas for Phoenics today. The requirement for CFD aided safety analysis seems to be growing continuously. The brief review in this paper describes purposes, implementations and advantages of using Phoenics in safety analysis. The scope of work is confined to comprise fire safety only.

Offshore and underground constructions have many major elements of risk in common although they are very different objects. The concentration of people, fire load and technical outfit is often relatively large. They both represent considerable economic values and special values to the community.

Safety analysis usually represents subject studies that constitute parts of more comprehensive risk analysis on health, environment and safety. A brief review of various applications of Phoenics in this discipline for offshore constructions is presented in the first part of this paper. This review is based on experience gained from engineering projects carried out in Norway during the last 15 years. Safety analysis of underground constructions is then shown in more details in the second part of the paper. Verification by visualisation and measurements is finally presented in the last part of the paper.

It has been shown that the application of Phoenics in safety analysis is practically unlimited. The reliability of its performance has been confirmed by visualisations, measurements and empirical verifications in many of the safety studies that have been carried out. Phoenics has become a natural safety analysis tool for construction engineers today.

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CONTENTS

1. INTRODUCTION

1.1 Offshore constructions

The oil production in Norway started at the Ekofisk field in the North Sea in 1971. Since then numerous fixed and floating offshore platforms has been installed for production of oil and gas. The largest of them is the 472m high concrete platform Troll. Most of the new constructions today are subsea installations.

The consequence of an accident onboard an offshore platform could be disastrous, especially in the case of a large fire, explosion or collapse. The Piper Alpha catastrophe in England in 1988 took 167 lives. The economic loss of the Sleipner A disaster in Norway in 1991 was about $700 million. The crash when it sunk caused a seismic registration of 3.0 on the Richter scale, leaving nothing but a pile of debris on the bottom of the sea.

The Norwegian authorities did early on enforce a high level of safety for offshore constructions. CFD started to take over for wind tunnel measurements in obligatory safety analysis regarding offshore constructions about 15 years ago. Today CFD is prescribed for safety analysis of offshore constructions.

1.2 Underground constructions

The Norwegian landscape can be described by two words: fjords and mountains. About half the territory is elevated above the timberline. The length of the coastline equals about half the distance around the earth. Over the years thousands of tunnels have been constructed for public transportation. Notice, that many of the tunnels actually provide a safer way than older roads, even without any special safety arrangements.

Underground constructions have major elements of safety in common with offshore constructions. The dimension of the constructions, concentration of people, fire load and technical outfit is large. The constructions are furthermore exposed to natural wind forces, and the access for evacuation and rescue might be limited. The consequence of an accident could be disastrous, especially in case of a large fire, explosion or collapse. This has been confirmed by the historical disasters, such as the catastrophic fire in King's Cross underground station in London in 1987, which killed 31 people.

Although accidents and fire events are relatively frequent in the many Norwegian tunnels, no disaster has taken place as yet. There are historically less accidents inside the road tunnels than outside. Nobody has so far been killed by fire accidents in railway tunnels in Norway. The possibility is still there however. Risk analysis has therefore become regulatory for all car and train tunnels in Norway. Common safety requirements are being developed for the European Union today.

1.3 Safety Analysis

Safety analysis usually represents subject studies that are carried out to establish or verify the necessary basis for an overall safety risk analysis. The basic concept of the probabilistic risk assessment can be described in a relatively simple way.

Risk = Probability x Consequence

Initially in a study, all hazards or elements of risk are mapped and categorised. The probability of all significant occurrences, in processes of possible successive accidental events, is then considered. Probability is usually based on a combination of historic data, mean time before failure, human behaviour, and other relevant criteria. Notice, that a combination of many unfortunate events usually needs to occur to cause a disaster. A disaster usually has a relatively low probability and large consequence, which makes the risk less predictable.

The level of risk is further compared with predefined acceptance levels. When safety arrangements are necessary to make, cost effectiveness is compared for the feasible options. Economy in operation based on this principle is called risk management. It should be noticed that it is commonly preferred to lower the probability, rather than the consequence. This is simply due to Murphy's Law.
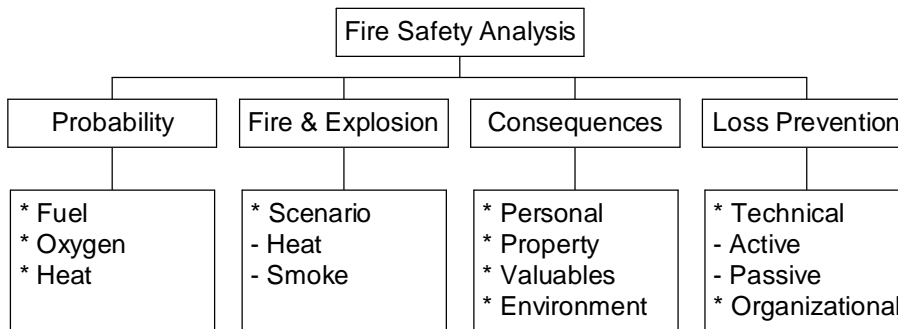
If anything can go wrong, it will.

1.4 Objective

Phoenics has been used in safety analysis in Norway for more than 15 years. Safety analysis is probably one of the largest and most important application areas for Phoenics today. The requirement for CFD aided safety analysis seems to be growing continuously. The brief review in this paper explains the purpose, implementation and advantage of using Phoenics in safety analysis. The scope of work is here confined to comprise fire safety analysis only.

2. OFFSHORE FIRE SAFETY

Phoenics has been used in many fire safety studies for various offshore installations in Norway. The examples in this paper have been selected to cover most parts of the risk analysis, as shown in the diagram below.

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                        Fire Safety Analysis

     Probability      Fire & Explosion    Consequences      Loss Prevention

   * Fuel            * Scenario          * Personal         * Technical
   * Oxygen          - Heat              * Property         - Active
   * Heat            - Smoke             * Valuables        - Passive
                                         * Environment      * Organizational
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2.1 PROBABILITY ANALYSIS

2.1.1 Heat Conditions

The scope of work comprises analysis of:

- Direct ignition (flames, sparks)
- Heat transport (conduction, convection, radiation)
- Physical state (gas velocity, pressure, humidity, mixture)
- Chemical state (exothermic reaction)

Phoenics is used to compute the conservation of heat. Of prime interest is usually the possibility of ignition and fire maintenance.
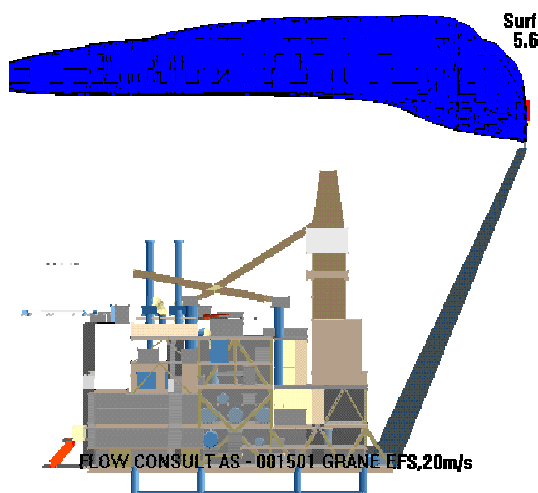

Figure 2.1.1
The offshore platform Grane, 2001.
Distribution of gas from non-ignited flare.
Sonic release at 433m/s (92kg/s).
Contour of 20% LEL (Lower Explosion Level).
Wind 20m/s from platform east.
Prediction of possible flame length.
Computation of heat radiation from flare.

2.1.2 Fuel Conditions

The scope of work comprises analysis of:

- Source (solid, dust, liquid, gas)
- Limitations (geometry, barriers)
- Dispersion (momentum, buoyancy)
- Physical state (diffusivity, homogeneity)
- Chemical state (pyrolysis, reaction)

Many factors make this type of analysis complex, and can therefore easily affect the confidence of the results. Typical examples are analysis of oil spills in complex constructions or on the sea. Furthermore, the flow rate and composition of natural gas is not steady in a production line. Warm light gas could become ice cold and heavy when released from a high pressure line into the atmosphere.
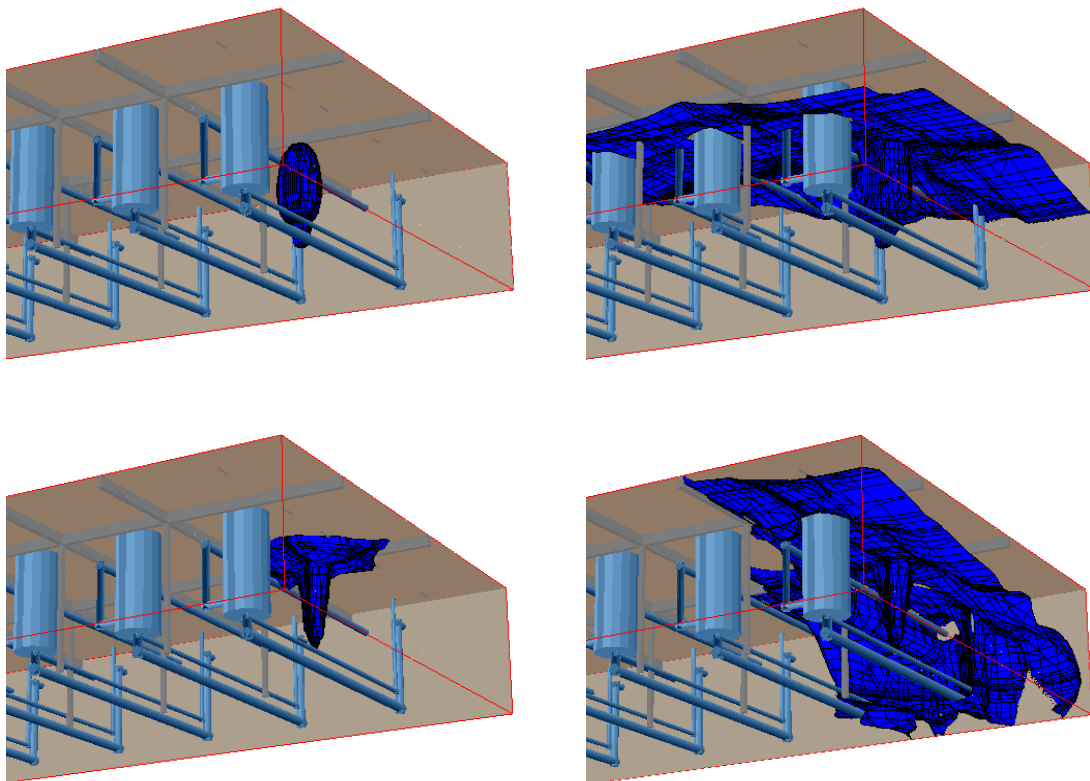

Figure 2.1.2
Dispersion of hydrogen gas 1 and 30 seconds after a flange leakage breaks out. Surface plot of LEL (4% volume concentration) from Phoenics. Upper plots show a diffuse leakage. Lower plots show a jet leakage, with increased ventilation in the area. The difference in dispersion of explosive gas is significant.

2.1.3 Oxygen Conditions

The scope of work comprises analysis of:

- Source (air, ventilation rate)
- Limitations (quantity, HEL - higher explosion limit)
- Mixing (turbulence, dilution, LEL - lower explosion limit)
- Physical state (homogeneity)
- Chemical state (reaction, kinetics)

Figure 2.1.3
Offshore platform Ekofisk 2/4J, in 1994. Concentration of explosive gas in a plane section of a typical module. The Phoenics results were used for various analysis. a) Identify gas dispersion area. b) Define hazard areas, with gas concentration between higher and lower explosion limits. c) Compute natural wind ventilation efficiency. d) Design of gas detection systems.
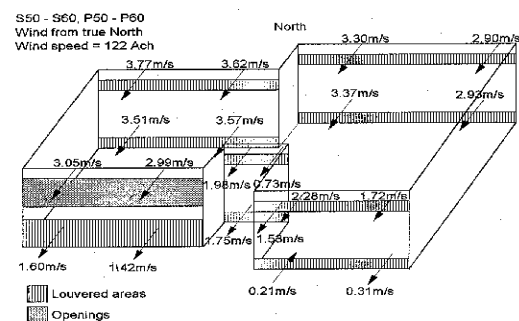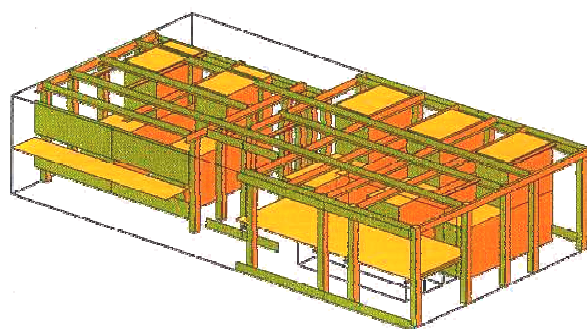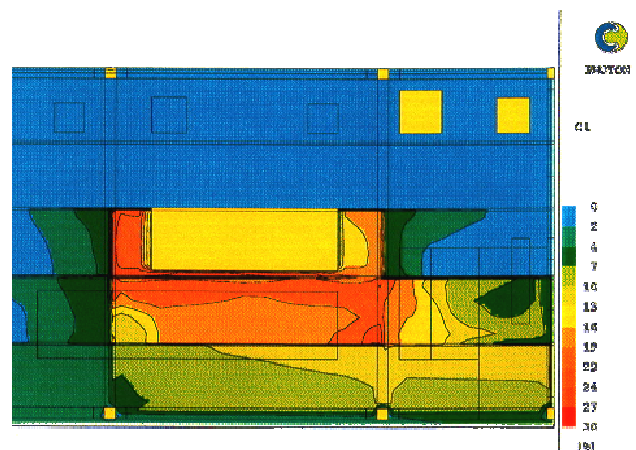

Figure 2.1.4
A typical Phoenics model of an offshore platform module, ten years ago. To obtain required working conditions, and an indirect safety arrangement, the modules were provided with claddings. Phoenics were initially used to find the local wind pressure field. Necessary openings, weather louvers, explosion relief panels were designed according to the Norwegian guidelines (NORSOK), requiring at least 12 Ach (air changes pr hour) 95% of the time. Wind statistics for all wind speeds and directions has to be taken into account. Today, the ventilation rates inside offshore modules are computed directly with Phoenics for all wind directions, together with the computation of the WCI (wind chill index).

2.2 FIRE ANALYSIS

The scope of work comprises analysis of:

- **Fuel**   Pyrolysis, evaporation, sublimation
- **Fluid dynamics**   Dispersion, buoyancy, turbulence
- **Thermodynamics**   Heat convection, conduction, radiation
- **Physics**   Actions, constructions, heat resistance
- **Chemistry**   Stoichiometry, exothermic reaction, post reactions

In order to perform realistic building fire simulations the resistance of all construction details, desiccation and humidity of all materials, joint cracks and other types of perforation of surfaces, has to be taken into account. Furthermore, the basis for the fire scenario is often relatively uncertain, such as the knowledge of how various fires occur and develop. Usually it is therefore chosen to perform simulations of several possible scenarios. The CFD models used for this in commercial projects are necessarily relatively simple and idealistic. The fire is usually simulated using an empirical source of heat and smoke, in cases where the fire is well ventilated.
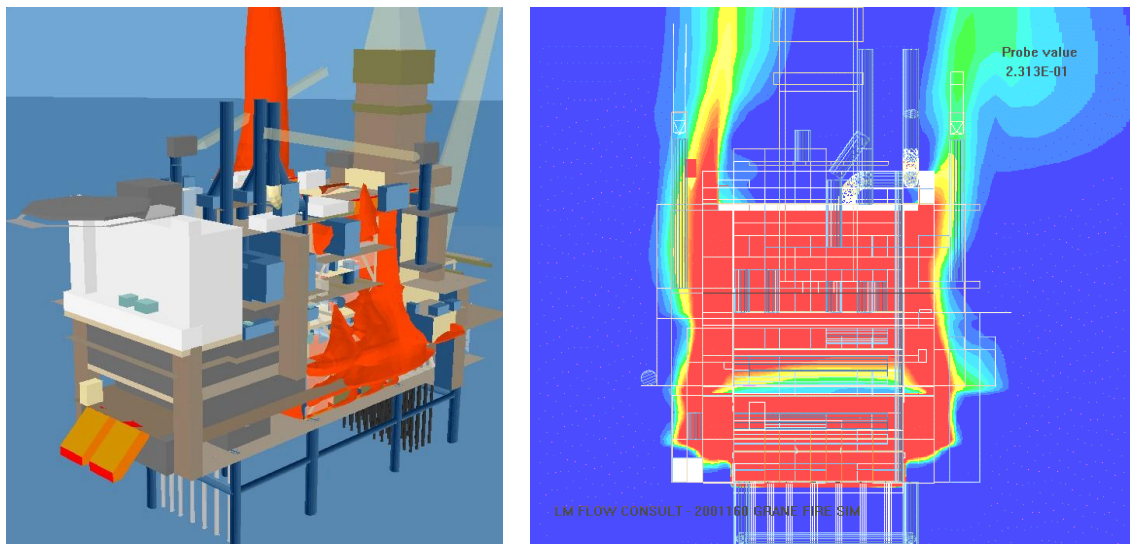

Figure 2.2.1
Phoenics simulation of a 400MW oil spill fire scenario onboard the Grane offshore platform, in 1m/s wind. The cross section shows the distribution and concentration of smoke from the fire located on the lower deck.

2.3 CONSEQUENCE ANALYSIS

The scope of work comprises analysis of:

- **Personal**   Death, injury
- **Property**   Insurance loss
- **Valuables**   Irreplaceable losses, cultural treasures
- **Environment**   Pollution, fundamental industry, community

Consequence analysis is probably the most common safety analysis implemented in deterministic risk analysis. In this type of risk analysis no significant loss is acceptable. In probabilistic risk analysis on the other hand, personal injury, specially the number of fatalities, is usually the most important issue.
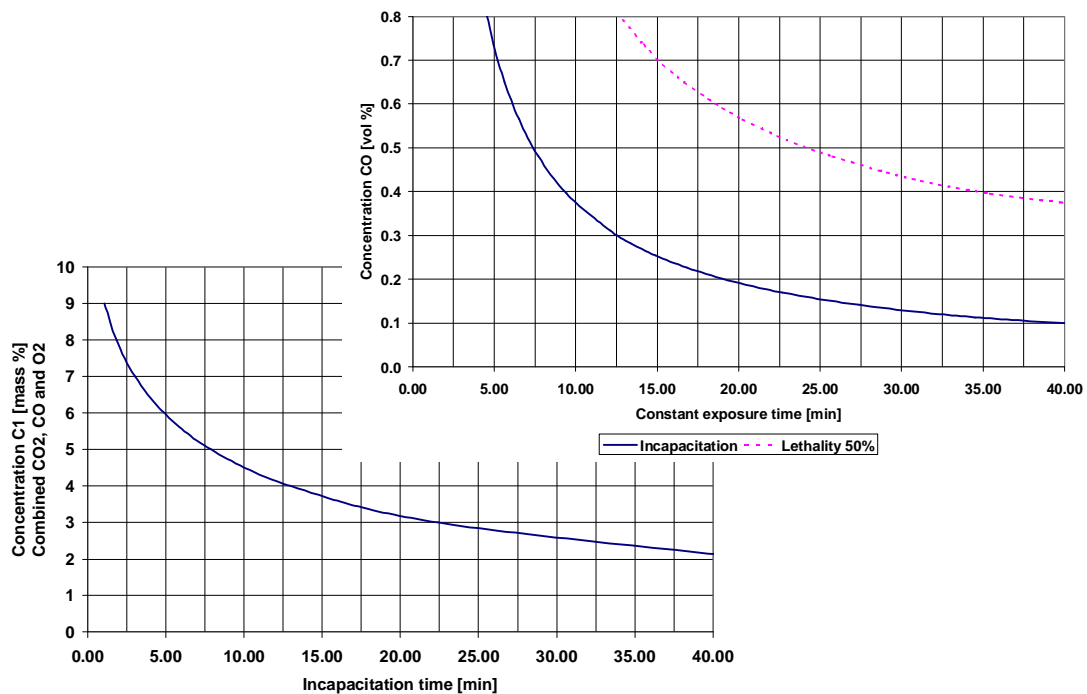

Figure 2.3.1

Incapacity and lethal dose of smoke components. Fire safety concepts are usually based on self evacuation. The arrangement requirements are specified in regulations and guidelines. In most fire situations, the lack of visibility due to the increasing concentration of soot and water vapour in the smoke is the first incident that makes people incapable of escaping. Loss of visibility is usually happening before incapacitation due to suffocation or smoke poisoning, and therefore often used as a major design criterion.

2.4 LOSS PREVENTION

The main elements in the loss prevention concept are:

- **Technical**   Passive and Active safety arrangements
- **Organisational**   Maintenance, inspection, education, exercise

Technical safety arrangements are usually sorted in two main groups. Passive arrangements are usually part of the construction, such as fire walls and smoke curtains. Active arrangements on the other hand are technical installations that need to be activated, or taken in use, such as smoke ventilation and sprinkler systems.

Figure 2.4.1
The offshore platform Grane, one main objective in the fire safety analysis with Phoenics was placement and protection of escape routes. The model shows the design of two protection walls on top of the weather deck, coloured red in the figure.
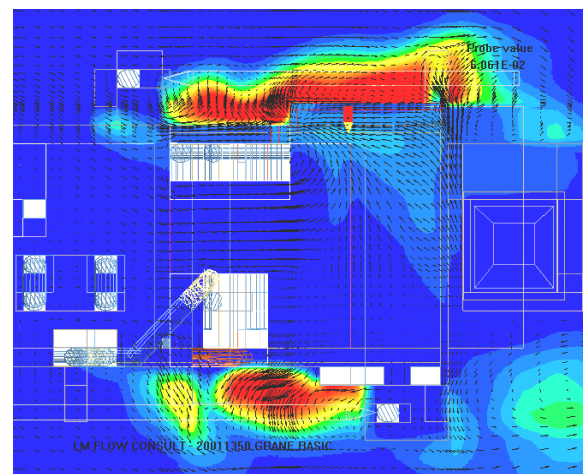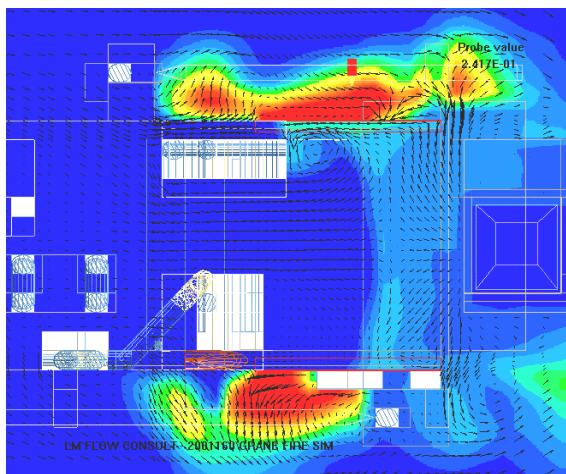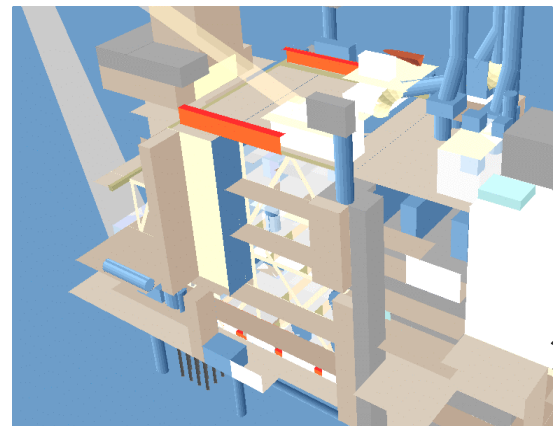

Figure 2.4.2
Phoenics simulations of an oil pool fire onboard Grane. The right figure shows in comparison with the left figure that smokeless access is provided from east to west, when protection walls are mounted on top of the weather deck.

3. UNDERGROUND FIRE SAFETY

Public underground constructions for motor vehicles and railway transportation may constitute a potential risk of catastrophic fires. This has been confirmed by the historical underground fire disasters in the past. The historical data show a relatively low probability of large disastrous fires. Even if the probability is low, the disastrous consequences of large fires in underground constructions nevertheless cause the risk level to be considerable.

3.1 UNDERGROUND STATIONS

Phoenics has been used in fire safety analysis of several underground train stations. The most resent study carried out was regarding Nydalen underground station on the new part of the metro in Oslo. The main objective in this study was to design a smoke exhaust system to ensure sufficient time for the passengers to escape in case of fire.
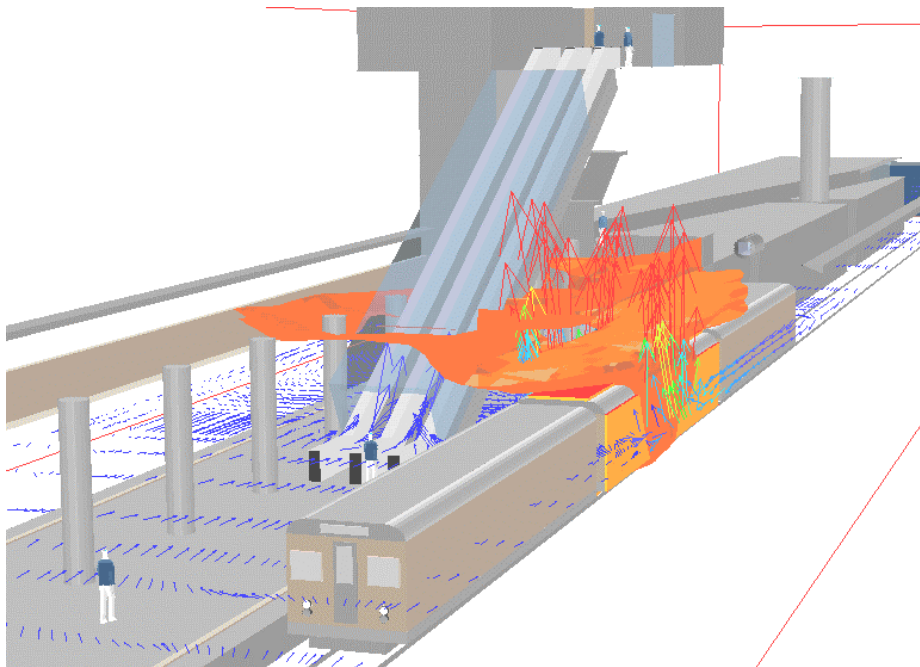

Figure 3.1.1
Phoenics simulation of a train fire in Nydalen subway station in Oslo. All trains are supposed to stop at the nearest station to evacuate the passengers in case of fire. The fire is spreading from the engine room underneath the carriage in this case.

3.1.1 Technical data

Tunnel length (1542+779):   2321 m
Platform length: 110 m
Station width: 20.4 m
Ceiling height above platform: 4.8 m

Two, 13m high, pressure relief shafts, one in each end of the station
3-6 train carriages, of length 17m, and heat value ca 46GJ (old carriage)
900 persons maximum at the same time (train and station)
3 escape routes: west entrance, east staircase and the escalator
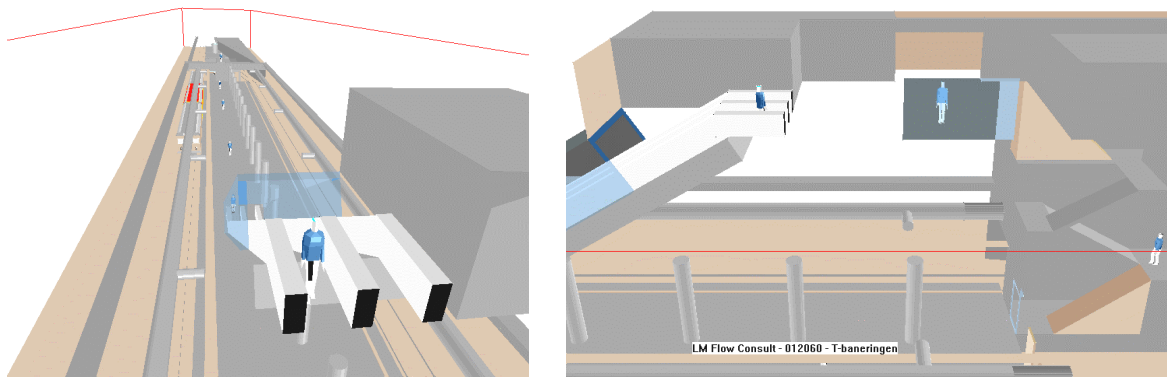7 minutes to evacuate the platform area (net computed)

Figure 3.1.2
Phoenics model. A view toward west from the top of the escalator is shown in the left figure. A large smoke exhaust duct with extending branches is mounted above each of the two tracks in the platform area. The right figure shows the main entrance at the top of the escalator and the eastern staircase.

The area covered in the CFD model was 310m in length, and the model had more than 250.000 cells. Momentum sources were provided at each end of the station to simulate various natural wind and buoyancy draughts in the tunnel. Smoke from a fire could flow freely into the tunnels, as well as into the escape routes. The time step in the transient simulations was 30 seconds in average. Several test runs were made to verify how sensitive the model was to mesh density and distribution, natural air draught, location and size of the fire (train) etc.

3.1.2 Fire simulation

Fire scenario:

The fire has been detected when the train is on the way to the station
The train has stopped at the station to evacuate the passengers
The pressure relief shafts have been closed (to provide fresh air in escape routes)
The smoke evacuation system has just started
The fire starts spreading out from the motor room underneath the carriage
Phoenics fire simulation starts

Fire dimension:

The fire is simulated for a single carriage only. It is simulated as an exponential or linear function from zero to maximum in 14 minutes. The maximum values are:

Heat release:	20	MW
Fuel consumption:	0.9	kg/s
Products:	6.6	kg/s
CO_2	1.2	kg/s
CO	0.025	kg/s

Fire analysis:

The results are expected to become increasingly more unreliable after about 10 minutes. Combustion of unburned fuel products in the smoke and accumulated radiant heat is then expected to cause flashover to the next carriages. An approximate comparison of the different threshold values of some of the critical components that could be hindering evacuation is given in table 3.1.1 below. The table reveals that the visibility usually is the most critical design criterion.

Critical component	Threshold value	Phoenics C1
CO_2	5% [A]	5.8
CO	0.2% [A]	7.1
O_2	15% [A]	4.0
CO_2, CO, O_2	combination [B]	5.3
HCN, HCl	150 ppm [B]	0.4
Visibility	3 m	0.15
Visibility	5 m	0.10
Visibility escape routes	10 m [A]	0.05

Table 3.1.1
Threshold values for some of the critical component for evacuation:
[A] Norwegian standard, [B] 7 minutes exposure (escaping the platform)

3.1.3 Phoenics results

Different designs of smoke exhaust systems were tested out in order to minimise the installation. The analysis with Phoenics included verification of:

- Fulfilment of all the conditions for evacuation (design)
- Smoke dispersion in the escape routes (design)
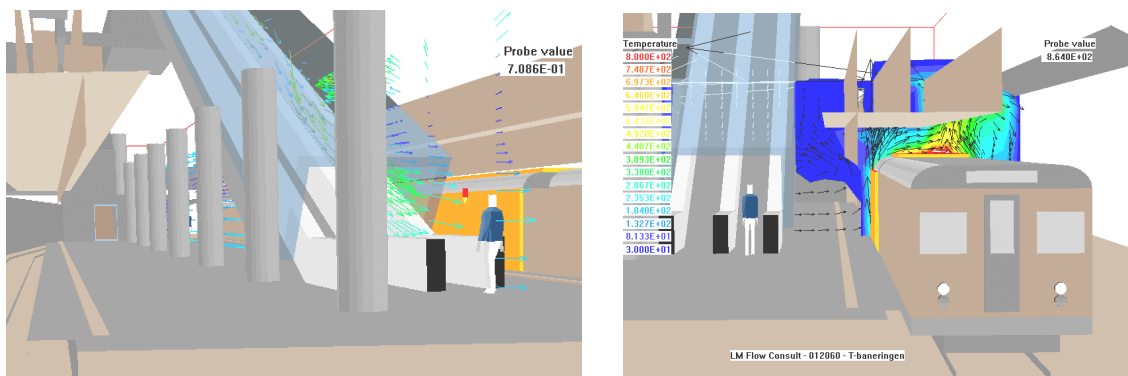- Natural supply of fresh air in the entrances (< 1m/s).

Figure 3.1.3
To the left, verification of the inlet air velocity down the escalator. Too high velocity could cause undesirable disturbance of the smoke layer. One of the less efficient design of the smoke exhaust system is shown in this case.
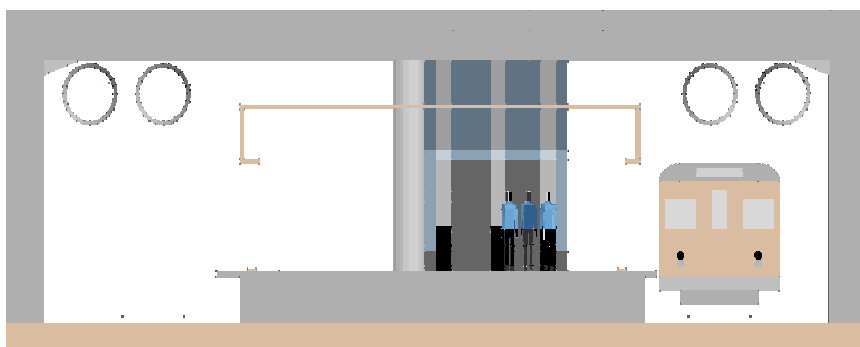

Figure 3.1.4
The final design of the smoke exhaust system. The system consists of four ducts above the tracks and a false ceiling above the platform. The ducts are extracting 75.000m^3/h smoke each, evenly distributed along the platform. The total fan installation is 345.000m^3/h, including a 15% safety margin. The compartment above the ceiling provides the necessary accumulation volume and assures open connection to all the ducts.

3.2 UNDERGROUND TUNNELS

Designs for smoke ventilation systems in tunnels are usually based on impulse fans or tunnel fans. In this type of safety analysis it is necessary to especially consider the following variables:

- Tunnel construction
- Fire dimension and development
- Natural wind and buoyancy driven air draught
- Conditions for evacuation and rescue
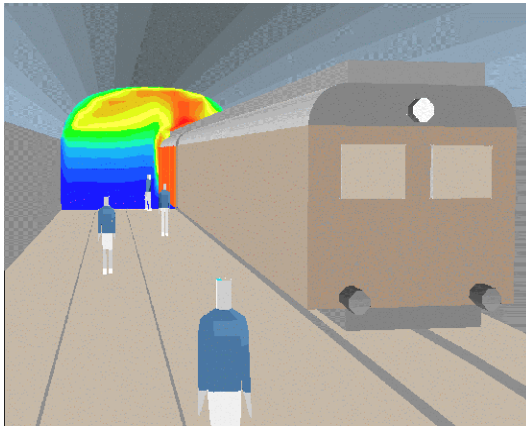- Tunnel fan efficiency and fragility

Figure 3.2.1
The figure shows evacuation of a train in a railway tunnel. The type of train is a BM69, of length 25m and 9 ton combustible materials (mainly plastic and wood). Evacuation times are long in tunnels, and the fire scenario therefore comprises more than one carriage. The maximum dimension of the fire, if a goods train is involved, is expected to be more than 200MW.
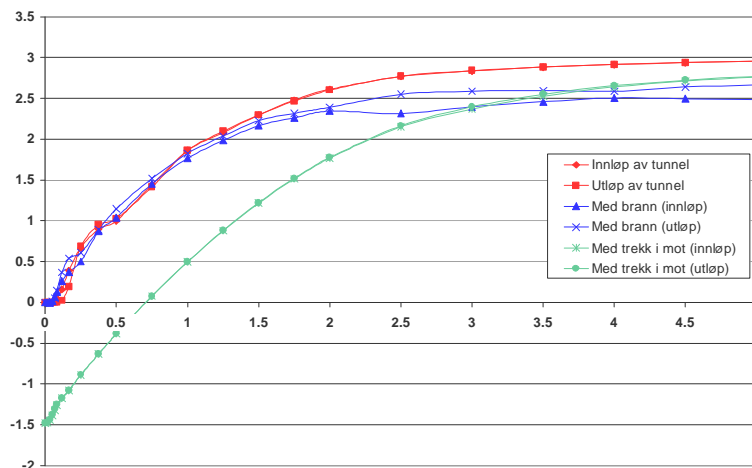

Figure 3.2.2
Computed tunnel fan initialisation time (minutes) to provide full ventilation (m/s). The hot smoke reduces the ventilation rate from 3m/s to about 2.5m/s. An initial opposite natural draught in the tunnel of -1.5m/s delay the ventilation less than 1 minute.
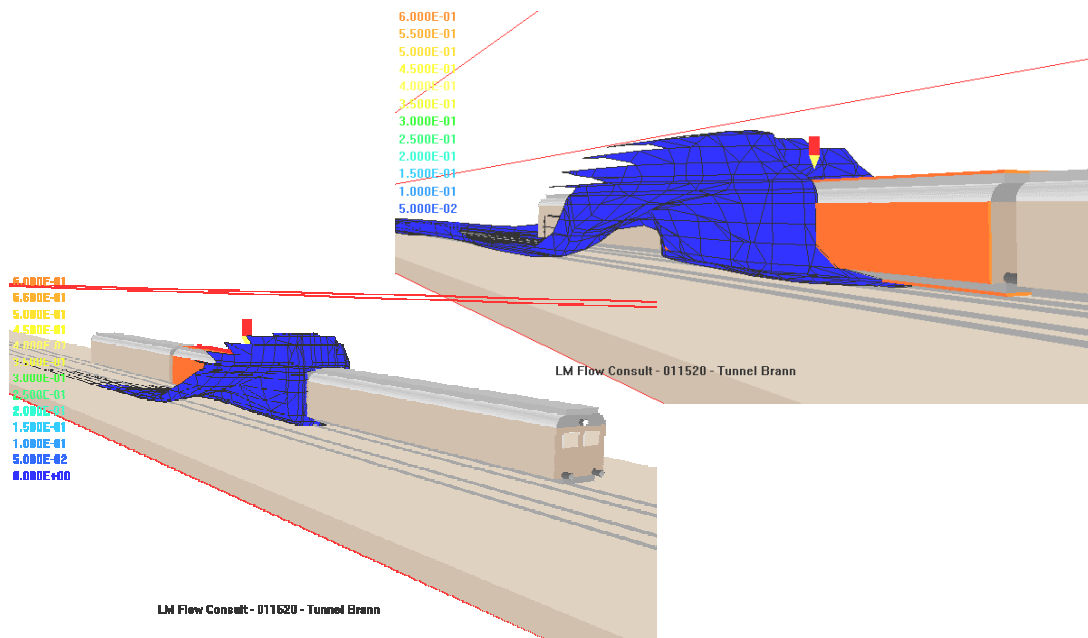
Figure 3.2.3
Phoenics results for a 20MW fire in a stationary train in a double track tunnel. The ventilation of 3m/s in the tunnel is towards the left. The figures show the surface plot of 3m visibility. The visibility is less than 3m to the left of the surface, due to the smoke from the fire. The upper and lower figures show the results respectively, 2min and 16min after the fire has started. The tunnel gradient was not causing any special effect in this case. A ventilation rate of 3m/s is usually sufficient, even for large tunnel fires. This is because the smoke momentum to overcome is essentially only dependent on (a constant) flame temperature and tunnel height.

4. VERIFICATION OF SAFETY ANALYSIS

The performance of safety arrangements should always be tested and verified by observations and measurements. Natural draught should for instance be measured in existing underground constructions, and verifications should also be made for new constructions. Velocity monitoring is always recommended to optimise the operation of smoke ventilation systems in underground tunnels.
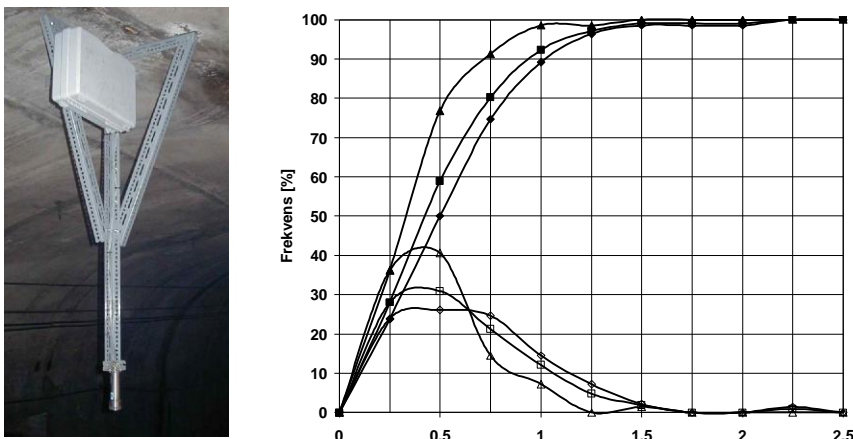

Figure 4.1.1
Measurements of natural air draught in a train tunnel, using ultrasonic directional anemometers. The measuring period included the coldest and hottest period of the year. The graphs show the frequency and accumulated frequency in percent, for the measured draught velocities (m/s).

Figure 4.1.2
A hot smoke visualisation test of a new smoke exhaust system in the new part of the National Theatre train station in Oslo. The pictures show a predicted undesirable transverse downward curved movement of smoke at the ceiling.

Figure 4.1.3
Full scale verification of a new smoke exhaust system at Lindeberg underground train station. Ventilation exhaust capacity was 240.000m^3/h. The measurements for the design verification consisted of velocities, temperatures, visibility and smoke gas components. Visualisation included use of infrared camera.

Figure 4.1.4
Evacuation exercise in the underground tunnel at Nydalen station. The event included smoke visualisation for testing of the new tunnel ventilation system.

It has been shown that possible applications of Phoenics in safety analysis are practically unlimited. The reliability of its performance has been confirmed by visualisations, measurements and empirical verifications in many of the safety studies carried out. Phoenics has become a natural safety analysis tool for construction engineers today.