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Fire Hazard Mitigation for the Øresund Link Immersed Tunnel

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Summary

The 3.8 km immersed tunnel for motorway and railway under the Drogden Channel, currently under construction and scheduled to open in the year 2000, is a significant component of the Øresund Link, connecting the Danish capital Copenhagen with the Swedish city Malmö. The toll-funded link will be owned and operated by Øresundskonsortet, a Swedish-Danish joint venture, which is also responsible for the construction of the 16 km coast-coast section of the link. The Drogden Tunnel accommodates two tubes for the dual track railway, two tubes for the four lane motorway, and a central installation and escape gallery. The latter is a major feature of the safety concept, by providing a safe and smoke-free escape route in case of accident or fire. The fire hazard mitigation includes fire insulation of the structure, and hydrants for fire fighting, but no automatic sprinkler system.

1. Introduction

The toll-funded motorway and railway link across Øresund will connect the city centers of Copenhagen in Denmark and Malmö in Sweden. The approximately 16 km coast-to-coast section comprises the following key components (see Fig. 1):

- An artificial Peninsula extending 430 m from the Danish coast at Kastrup
- An immersed Tunnel 3,510 m long under the Drogden navigation channel
- An artificial Island 4,055 m long south of Saltholm
- A western Aproach Bridge 3,014 m long between the Island and the High Bridge
- A cable-stayed High Bridge 1,092 m long over the Flintrännan navigation channel
- An eastern Approach Bridge 3,739 m long from the High Bridge to the Swedish coast at Lernacken
- A terminal area with toll station and Link Control Center located at Lernacken.

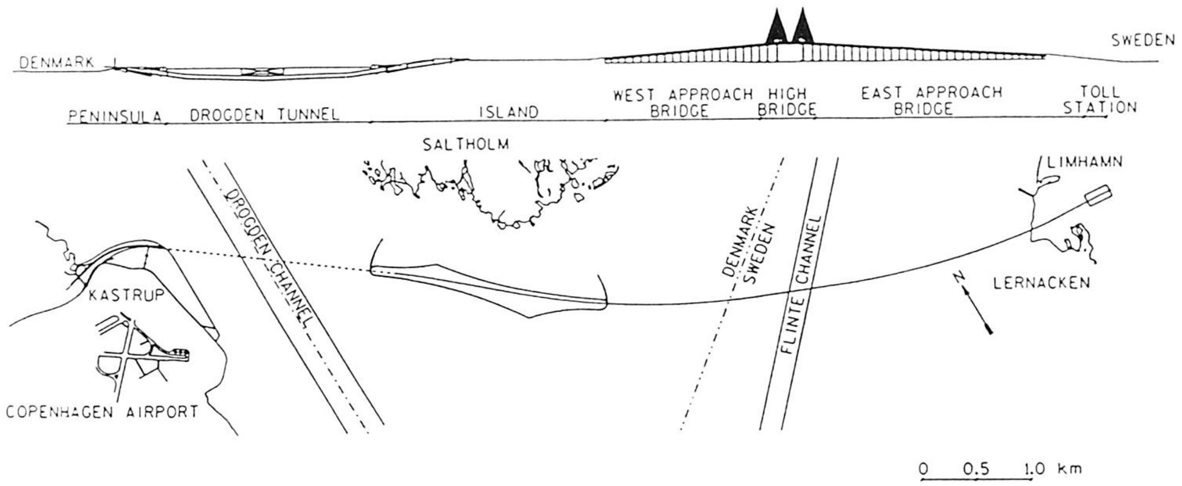

Fig. 1: Coast -to-coast section of the Øresund Link

The Drogden Tunnel is motivated by the proximity of the link to the Copenhagen airport at Kastrup, which precludes a high bridge over the busy navigation channel. The tunnel cross-section accommodates two tubes for the dual track railway, two tubes for the four lane motorway, and a central installation and escape gallery (see Fig. 2). The outer cross-sectional dimensions are 8.6 m by 38.8 m.

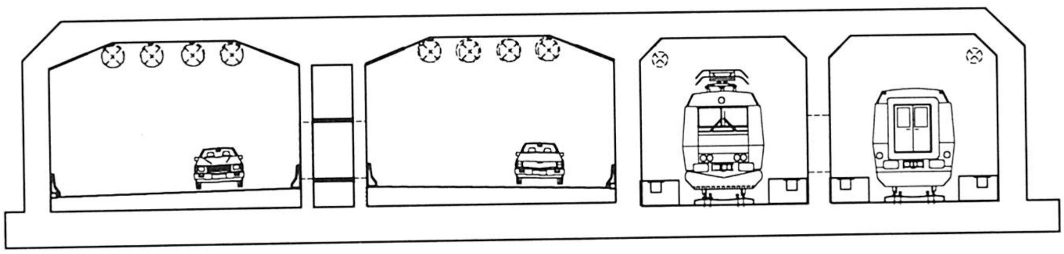

Fig 2: Cross-section of Tunnel

The approximately 3.8 km long tunnel consists of three main components (see Fig. 3):

- Ramp and portal building on the Peninsula
- Immersed Tunnel under the Drogden navigation channel
- Ramp and portal building on the Island

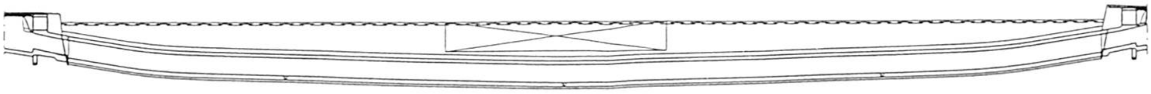

Fig. 3: Longitudinal Section of Tunnel

The portal structures accommodate underground service buildings with rooms allocated for tunnel installations, ie road lighting, ventilation, drainage, communications and energy supply.

The 3.5 km immersed part of the tunnel is constructed from 20 elements that are floated out and installed in the predredged trench. Each element is composed of 8 segments, which are match-cast and joined by injectable waterstops. During tow-out and immersion the integrity of the element is provided by temporary prestressing.

The first element was installed at the peninsula portal in early August 1997, and construction is proceeding on schedule (se Fig. 4). Thus six elements had been placed at year-end 1997, and the last element is due to be installed in December 1998.

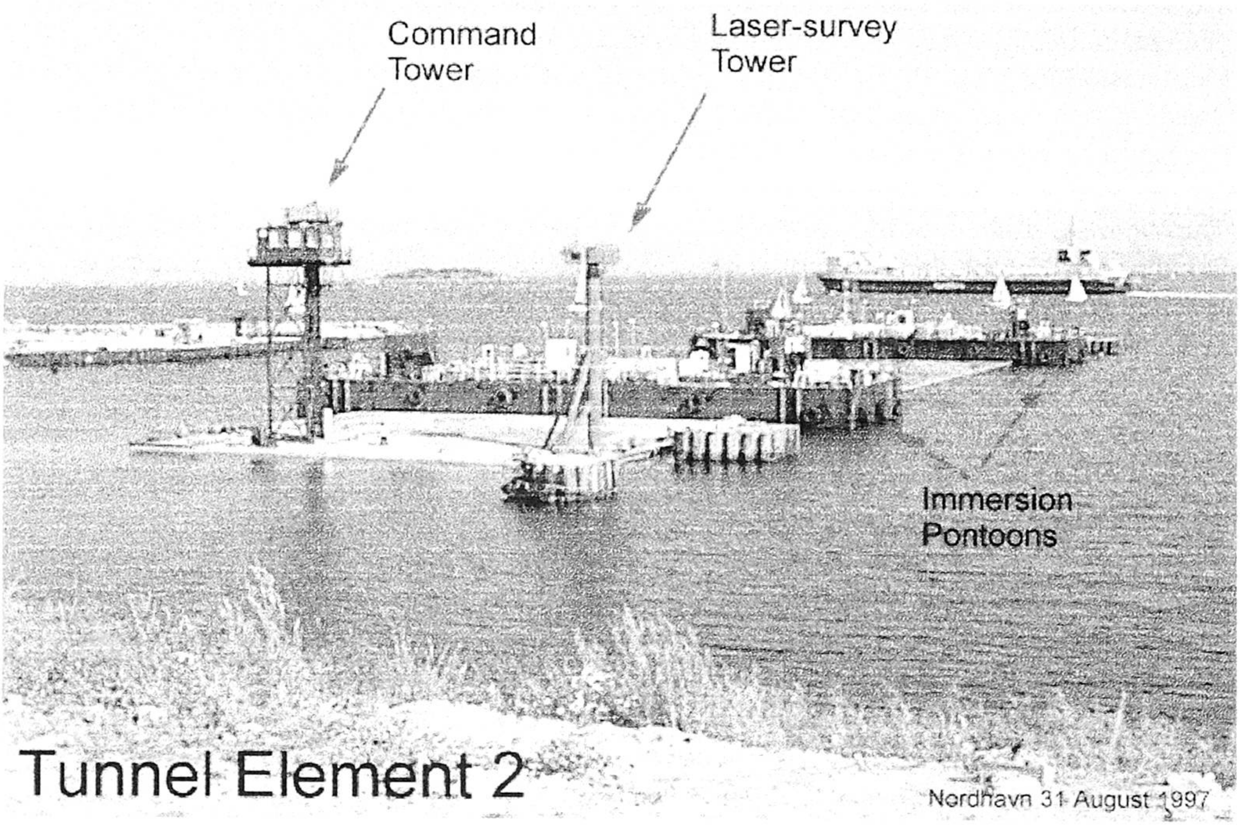

Fig. 4: Tunnel element moored at production facility north of Copenhagen, ready for towing to construction site for immersion

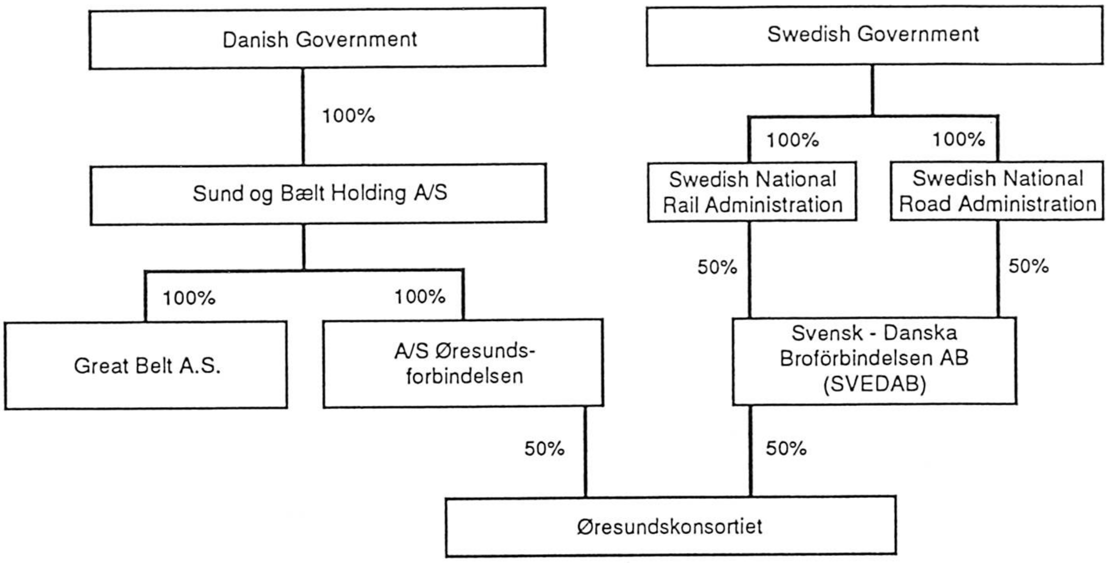

Fig 5: Øresund Link Ownership Organization Chart

The Øresund link shall be owned and operated by Øresundskonsortiet, a Swedish-Danish joint venture, indirectly owned by the two governments (see Fig 5.) The two partners - Øresundsforbindelsen and SVEDAB - are directly responsible for the Danish, respectively the Swedish, landworks, ie the traffic infrastructure connections to the city centres, whereas Øresundskonsortiet is in charge of the coast-to-coast section.

The major construction works are covered by three contracts tendered in 1994: Dredging & Reclamation, Tunnel, and Bridges. In July 1995 the USD 670 million Tunnel contract was awarded to the Øresund Tunnel Contractors, a joint venture between NCC Contractors (Sweden), Dumez GTM (France), John Laing (UK), Pihl & Søn (Denmark) and Boskalis Westminster (Netherlands).

The tunnel construction was tendered as a design-and-construct contract, implying that the contractor is responsible for the detailed design, based upon a conceptual design prepared by the Øresund Link Consultants (ØLC), acting as house consultant to the owner. ØLC is a joint venture between RAMBØLL (Denmark), Scandiaconsult (Sweden), Halcrow (UK) and Tunnel Engineering Consultants (Netherlands), in association with architects Dissing + Weitling (Denmark). Contracts for coast-to-coast installations, including the provision of control and communication systems and equipment, were tendered in 1997.

To ensure the owner's control of the environmental and aesthetic qualities of the Link the conceptual design is quite specific regarding geometry, dimensions, and major features. Furthermore, it is required that the design be performed in accordance with the Eurocodes, which is made possible by means of a Project Application Document, prepared by ØLC.

2. Safety Concept

2.1 Risk Analyses

It is the policy of the owner to ensure that the risk to users of the Øresund Link is reasonable and comparable to those associated with similar traffic installations in Denmark and Sweden. To examine various scenarios which could lead to fatalities or disruptions of the Link operational risk analyses have been carried out, including individual as well as societal risks. The individual risk is measured in eg the fatality risk per billion passages of the Link. The societal risk may be expressed in a risk profile (see Fig. 6). The frequency is plotted on the vertical axis, and on the horizontal a measure of the consequences (user fatalities, third party fatalities, days of disruption). The risk is traditionally calculated as the product of frequency and consequence, thus in a double logarithmic plot a constant risk level corresponds to a straight line with negative slope. Risks in the lower left hand corner are acceptable, whereas the upper right hand region is clearly unacceptable. In between is a region where the risk shall be As Low As Reasonably Possible. For designs in the ALARP region risk mitigation measures are introduced on a cost-benefit basis.

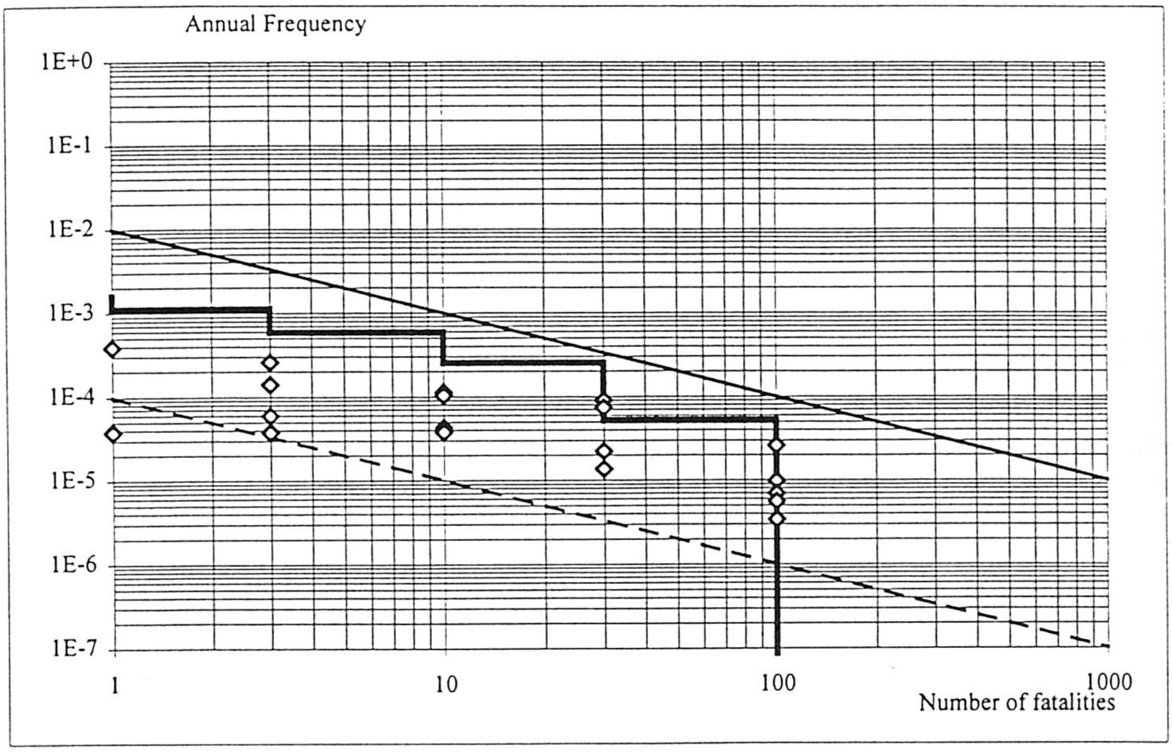

Fig. 6: Typical Risk Profile, showing the ALARP Region

For the Øresund Link a special study has been carried out concerning the transport of dangerous goods, and the operational risk analysis concluded that no restrictions need be imposed. Further risk reducing measures are, however, considered, such as the operational restraint of not allowing freight trains with dangerous goods in a tunnel tube simultaneously with passenger trains.

The following fire scenarios have been analysed:

Motorway

- Car
- Truck
- Heptane
- LPG

Railway

- Passenger train
- Freight train
- Heptane
- LPG

Thus scenarios with and without dangerous goods are included.

The evaluation of the structural consequences of fires take account of the fire insulation and the fire fighting, cf chapter 3 below. The human consequences are based upon the assumption that the ventilation system is operating to reduce the heat and the smoke.

In the motorway tubes the most severe scenario is a heptane fire with a catastrophic release of fuel. Depending on the time of day the number of fatalities is 3 - 30, and minor spalling could lead to the closure of one lane for a week.

For the railway tubes the consequences of fire could be more severe due to the larger concentration of people. Thus a pool fire with a large release of heptane could cause up to 300 fatalities, and close a track for 1 - 2 weeks. An LPG flash fire with a catastrophic release of fuel, which is highly unlikely, could lead to collapse of the tunnel.

2.2 Authorities' Requirements

In order to incorporate safety requirements in the design at an early stage Øresundskonsortiet in October 1993 instigated the formation of an advisory group, known as KKSURR (the Danish acronym for coast-coast safety, accident, rescue and clearance). KKSURR comprises representatives from road and railway authorities, as well as police, fire brigades, rescue organizations and municipalities from both countries, together with the owner and his consultants, thus involving all stakeholders in the operation of the road and railway link.

The work of the group is collated in the 'KKSURR Report', and the conclusions are incorporated into the 'Design Basis - Safety', which is part of the internal project Technical Design Basis (TDB). The requirements of the TDB are included in the relevant contract documents for the construction works.

For the tunnel the KKSURR report includes numerous recommendations regarding fire prevention and detection, but there are no requirements to fire insulation. This feature has been adopted by the owner in the tunnel design as regards fire hazard mitigation, which is summarized in the section below and detailed in the subsequent chapters.

2.3 Tunnel Design

A major feature of the safety concept is the central gallery between the motorway tubes, which serves as a safe and smoke-free escape route in case of emergency.

The outer walls, the roofs and the upper part of the internal walls of the four traffic tubes are protected with fireproof insulation material, and emergency installations containing fire-fighting equipment and telephones are placed at intervals of 88 m. At the same spacing safety doors are provided between the two railway tubes, between the railway and the motorway tube, and in the walls giving access to the escape gallery, which constitutes a safe exit for all tunnel users in case of emergency.

In case of a fire the ventilation system can be directed to control the smoke and the heat, facilitating the work of the fire brigades and rescue teams. It also serves to provide oxygen to avoid the accumulation of unburned gasses, which might impose an explosion risk. The ventilation will remain operational for at least an hour at a temperature of 250°C. Fire hydrants with connectors for both Danish and Swedish fire fighting systems are placed at the walls to the central gallery, next to the escape doors (see Fig. 7).

The tunnel is provided with a drainage system to remove water and any liquid spillage from the road and the railway. The 2% cross-fall of the carriageways leads liquids to drain pipes with inlets and water locks every 22 m. The tunnel tubes have separate pump sumps with spare pump capacity, fire detectors, and automatic foam extinguishing systems. The pump sumps are equipped with seals as well as oil and sediment separators.

The entire coast-to-coast link is supplied with high-voltage power, which can be fed from Danish as well as Swedish high-voltage grids. This ensures a high reliability of supply, and loss of high-voltage power would require at least two consecutive failures.

All essential power consumers are connected to Uninterupted Power Supply (UPS) units with battery back-up. The batteries of the UPS are automatically charged during periods of normal power supply, and the UPS systems take over immediately in case of public power supply failure.

The lighting system for the road tubes is designed to make the roadway and all objects on it sufficiently visible at the required distance.

The Øresund Link is provided with a supervisory control and data acquisition (SCADA) system to monitor the road traffic and control all installations. The SCADA communicates via an optical fibre system (a 'data highway'), and can be operated from control centres as well as locally.

3. Fire Protection and Materials

3.1 Fire Insulation

The main purpose of the fire insulation is to ensure the structural safety of the tunnel in case of fire. The functional requirements to the insulation is that it shall prevent spalling of concrete and deterioration of segment joints as well as immersion joints by offering protection during a two hour hydrocarbon fire.

The adopted material is Fendolite MII, applied by spraying to a thickness of 21 mm. Fendolite MII is a proprietary, cementitious material, the main ingredient being vermiculite 'aggregate' which provides resistance to thermal shock by allowing expansion to take place within the material, without inducing internal stresses. Application is by shotcreting technique, where water is added to the dry mix at the spraying nozzle. The fire insulation is applied to the tunnel roof and at the complete outer walls above the New Jersey barriers. The internal separation walls are only covered over approx.1m below the haunch of the bores (see Fig. 7).

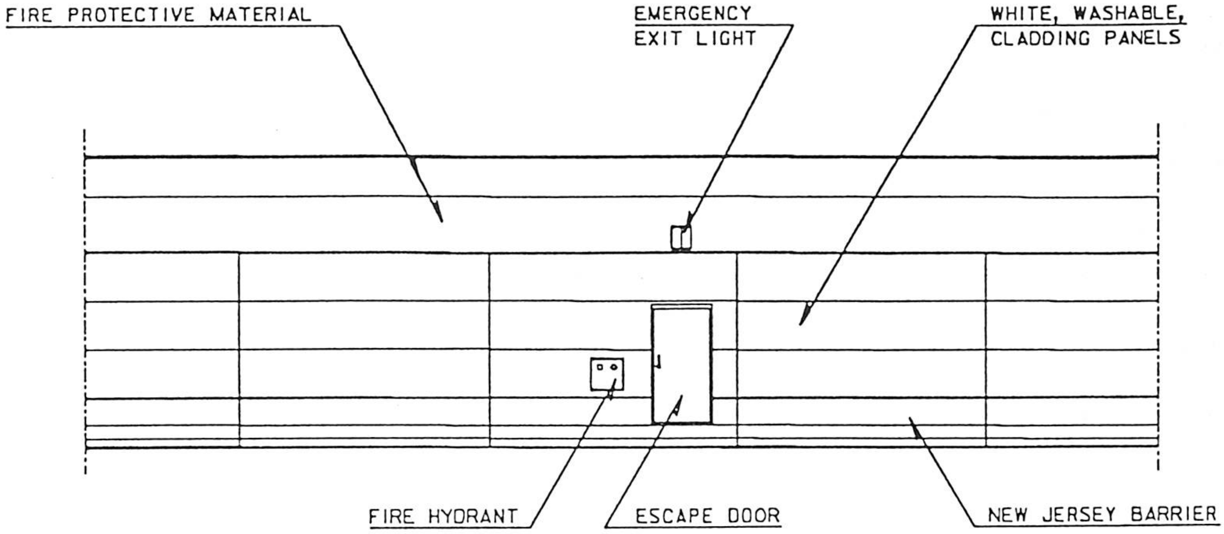

Fig. 7: Longitudinal section of roadway tunnel, showing the wall to the escape gallery

The fire insulation material has been used in tunnels in the Benelux and in Hong Kong, and the efficiency in preventing concrete spalling has been verified by laboratory testing. For the Øresund Link dedicated fire testing of segment and immersion joints is planned.

3.2 Fire Fighting

The need for a sprinkler system in the roadway and railway tubes has been discussed in the KKSURR group, and the recommendation was against deployment. The reason is that in case of fire sprinkling could force the smoke down, creating poor visibility and air quality, which would endanger evacuation and rescue actions. The main purpose of a sprinkler system would be protection of the structures, which is achieved by the fire insulation, cf the preceding section.

In the service gallery, however, a water spray system will be provided to protect the electrical system cabinets, cables and accessories. The water spray system consists of:

- A main plant in each portal building, including water storage facilities, pumps and control panel
- A main water pipe connected to both main plants, and running in the lower part of the central gallery
- Approximately 64 sections (at about 60 m spacing) connected to the main water pipe through a diverting valve, and feeding a dedicated section of spray nozzles.

The water storage capacity at each portal is sized to supply a maximum of one section for 10 min action at any time, resulting in capability of supplying two adjacent spray sections for 10 min.

Each main plant is equipped with a programmable unit located in the control panel, which ensures the local automatic control of the system. Information is transmitted via the overall SCADA system. An automatic fire detection system activates the water spray system, and sends general information to the SCADA.

For fire fighting in the traffic tunnels pressurised water is provided in fire hydrants located next to the emergency doors to the escape gallery (see Fig. 7). The main components of the fire hydrant system are:

- A fire main run in the central gallery, with branches every 88 m to the fire hydrant in each motorway tube
- A pumping plant and reservoir at each portal building.

The emergency panels, placed at 88 m distance in all four traffic tubes, are equipped with fire alarm push buttons and dry powder fire extinguishers.

The fire hydrants are placed in recesses, protected by a door, and fitted with couplings corresponding to Danish and Swedish fire fighting systems. Fire hose reels are located in each portal building. In addition the fire hydrant system is used to supply water to the water spray system reservoirs at the portals (cf above), and to the foam extinguishing systems at the mid-point pump sumps.

The water reservoir at the peninsula portal is supplied with municipal water from Copenhagen, whereas the island reservoir is supplied via the fire hydrant piping. The concrete reservoirs are placed in the immediate vicinity of the fire hydrant pumping stations to minimise connection piping. Each fire hydrant pumping station will be fitted with two main pumps, one being a stand-by. Under normal operation the main pump is designed to supply, on one half of the fire hydrant network, a 800 kPa maximum and 450 kPa minimum pressure at hydrant head, with two hydrants in operation (216 m^3/h).

A water treatment system is provided upstream of the peninsula reservoir for the addition of hypochlorite or similar to reduce scaling deposits in the pipes.

4. Safety Provisions for Users

4.1 Escape and Access Routes

To give the tunnel the same safety standard as a public building it is necessary to provide an escape route such that people can leave an accident area as soon as possible, and enter an environment which is physically separated from the accident, and from where they can safely leave the structure.

The Drogden Tunnel escape system is based on the escape gallery located between the motorway tubes. Access to the escape gallery is by emergency sliding doors placed every 88 m, and marked with emergency signs above the doors (see Fig. 7). For the railway tubes the escape routes are in the other tube, via the elevated foot paths. Consequently, emergency doors are located in the separation wall between the railway tubes. The doors are situated at the same chainages as for the motorway tubes, and emergency panels are placed adjacent to the doors.

The escape gallery is provided with an over-pressure system to prevent the entering of smoke. Internal signs give the direction of the way out. The gallery is split into two parts by the mid-point installations rooms, so the accessible portal is also the nearest.

When the evacuees reach the portal building they continue along the escape gallery out of the structure into the median strip between the New Jersey Barriers in the open air. Using the portal building itself as a way out is not feasible in a situation with many people under traumatic circumstances.

Depending on the severity of the accident in one of the tunnel tubes the complete tunnel may be closed. In that case rescue organisations like police, fire brigade, etc. are able to use the free motorway tube as an access route to the accident. Flashing emergency signs will give the position of the door to be used to cross the escape gallery and enter the accident area.

4.2 Lighting

The railway tubes are provided with a minimum lighting level which is sufficient for maintenance, and for finding the way out in case of accidents.

The purpose of the motorway lighting system is to give guidance to the driver regarding the alignment, and to show objects on the surface of his lane. The approach roads have a middle verge lighting system of low pressure sodium lamps. This lighting is the continuation of the lighting of the connecting roads.The tunnel structure is provided with a dedicated lighting system. The long tube will be extremely dark during day hours, and to prevent the so-called "black hole" effect the entrance lighting can be regulated in the right proportion related to the outside levels. Six different levels are available, and the switching will be done automatically, based on information from sensors under the daylight louver.

The tunnel structure is divided into 4 zones, the threshold zone, the transition zone, the interior zone and the exit zone. In each zone the lighting level will be adapted to the preceding zone. The threshold zone is provided with a daylight louver to gradually lower the level of the daylight so it can be continued by artificial light. Then in the transition zone the level will be reduced again until a level which is sufficient to recognise everything happening in the tube, and which also creates a relaxed driving situation. The interior zone lighting will continue at this level until the exit zone, where the level will be increased as preparation to the open air area.The level of the exit area is designed in such a way that in cases of two way traffic in one tube the zone is able to act as an entrance lighting system as well.

4.3 Ventilation

The design criteria for the ventilation are as stated below.

Wind velocity at the portals	12 m/s
Maximum air velocity created by fans at centre tunnel	10 m/s
Maximum NO_2 value	800 $\mu g/m^3$
Maximum CO value during free floating traffic	50 ppm
Maximum CO value during congested traffic	100 ppm
Maximum CO value during maintenance	35 ppm
Visibility during free floating traffic	0.005 m^{-1}
Visibility during congested traffic	0.007 m^{-1}
Visibility during maintenance	0.003 m^{-1}
Fire load	100 MW
Maximum temp. the fans shall withstand and transport air for at least one hour	250 °C
Maximum A-weighted sound pressure level of fans	95 dB(A)

Traffic characteristics

Traffic flow in each direction per annual average day	10,000 v/ad
Peak hour traffic flow in each direction	1,300 v/h
Congested traffic flow in each direction speed 20 km/h	2,000 v/h
Maximum peak traffic flow in each direction	65 v/min

Traffic composition during Peak Hour and Basic Traffic Emission

Traffic composition during peak hour		%	Basic traffic emission at 60 km/h		
			Ox	CO	Smoke
			g/(km, vehicle)	g/(km, vehicle)	$M^2/(h, vehicle)$
Cars		88.0	0.23	1.01	-
Heavy trucks, Diesel	< 7 tons	4.2	0.81	3.24	50
	7-18 tons	3.2	3.60	2.09	120
	> 18 tons	4.6	11.63	3.09	180

The ventilation of the motorway tubes has been designed to create a maximum air velocity of 10 m/s at the centre of the tubes. This velocity is necessary to blow out, under all circumstances, possible smoke in case of fire.

The ventilation system will also be used to keep the polluted air within acceptable limits. A detection system of CO and visibility sensors will be installed, which switches on the fans as needed to keep the pollution level acceptable.

The fans are fixed in niches in the ceiling in 3 sections in the tunnel, located at the entrance, the mid-point, and the exit of the tunnel. Each section consists of 5 rows of 4 fans each (see Fig. 2).

The ventilation system is completely reversible, providing the option of blowing in the most convenient direction in case of accidents. During normal conditions the air flow will be in the traffic direction.

The railway ventilation system is in principle the same, except that there is only 1 fan in each of the 5 rows (see Fig. 2).

4.4 Emergency Panels

Emergency panels are located in all four traffic tubes in the exterior walls of the motorway tubes and in the wall separating the railway tubes. The spacing is 88 m, the same as that of the emergency doors giving access to the escape gallery between the motorway tubes.

Each emergency panel contains a hand fire extinguisher, a telephone which is directly connected to the central operator, an alarm push button, two electrical socket outlets, and lighting connected to the UPS. The door of the panel can be opened and the alarm push button can be used as well as the telephone. In that way the Link operator will be informed immediately in case of accidents. Simply opening the door will give a signal to the operator by means of a built-in switch, alerting the operator to the fact that the door is open.