DESIGN OF THE VENTILATION AND COOLING SYSTEM FOR THE INSTALLATION PHASE OF EQUIPMENT IN THE GOTTHARD BASE TUNNEL

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ABSTRACT

When finished, the 57 km long Gotthard Base Tunnel in Switzerland will be the world's longest railway tunnel. It will form a central part of the European high-performance rail network. At the moment, the excavation and lining of the tunnels is in progress. The next major step will be the installation of the mechanical and electrical equipment. The paper focuses on the design process of the ventilation and cooling system in the tunnel during the installation phase of the equipment. On underground construction sites, distinct climatic limits have to be fulfilled (pollution, temperature, etc.). Furthermore, safety requirements must be considered, e.g. protection of smoke-free rescue areas and smoke extraction. Finally the ventilation and cooling systems must not restrict the installation progress. Since the installation will last over several years and the installation sites extend to more than 10 km each, a sophisticated design of the ventilation and cooling of the tunnel is needed. Based on the predicted installation schedule, 19 ventilation and cooling phases are considered. The basic concept consists in the separation of the installation sites by air locks. This reduces the locally needed air flow as well as the propagation of smoke in case of a fire in the tunnel. Up to 4 tunnel sections for each phase must be ventilated and cooled. Numerical calculations for all the phases were conducted to find the venting and cooling power required. Accordingly, the ventilation and cooling system was designed (distribution and sizing of axial fans, air coolers etc.). The ventilation design requires 24 axial fans, 6 air locks and 16 air barriers. The cooling system includes 30 local air coolers, 130 km of cooling pipes, 12 circulation pumps, 1 pressure exchange system and 3 cooling towers. In conclusion, the design requires to consider various aspects like different, highly transient heat sources and sinks, emissions and the various interfaces, for example to the construction phase. The flexible venting and cooling system allows coping with possible deviations of the assumptions made during the design phase.

***Keywords**: Gotthard Base Tunnel, ventilation, cooling, installation*

INTRODUCTION

With the New Alpine Rail Link Project (NEAT) Switzerland is creating a rail link for future high-speed travel through the Alps. A main part of the new transalpine rail route is the world‘s longest tunnel – the 57 km Gotthard Base Tunnel. This pioneering achievement of the 21st century will bring major improvements to travel and transportation systems in the heart of Europe (cf. Figure 1).

The new Gotthard railway will bring much shorter journey times. Rail travel will be a genuine alternative to road and air. In addition the freight train capacity along the Gotthard route will be increased and can compete with road traffic.

At the present the excavation and lining of the Gotthard Base Tunnel is in progress. The tunnel system consists of 2 single track tubes, 4 crossovers, 178 cross-passages, 2 shafts, several technical rooms and 3 side-adits (cf. Figure 2).

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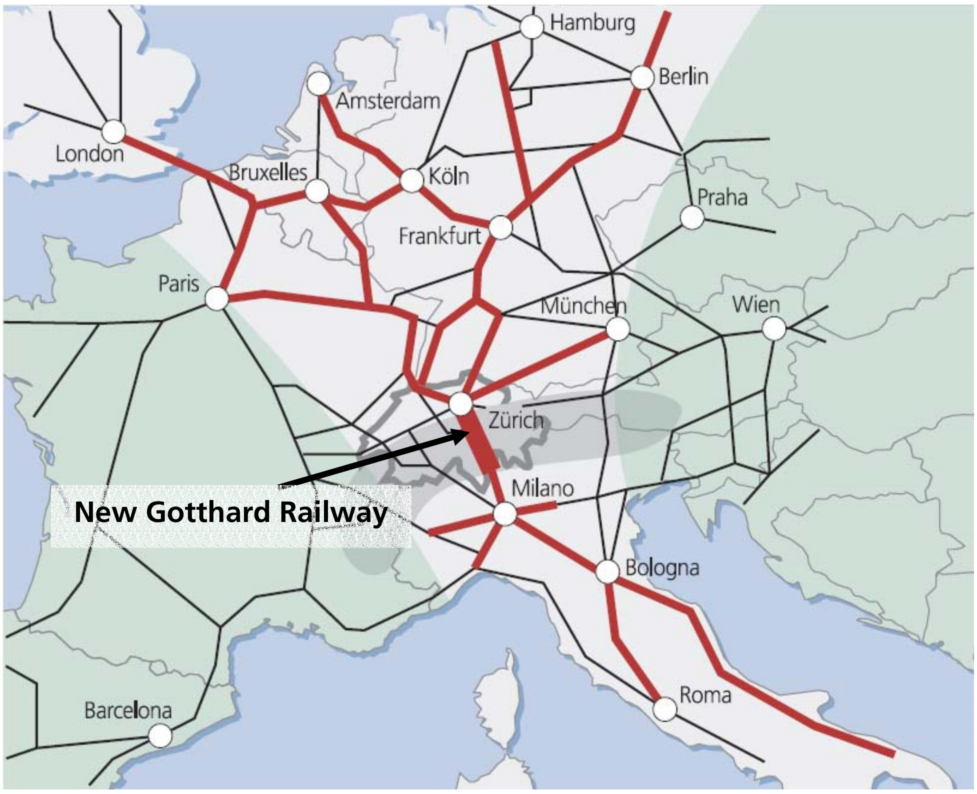

Figure 1: The New Gotthard Railway as a Central Link in the European Railway Network

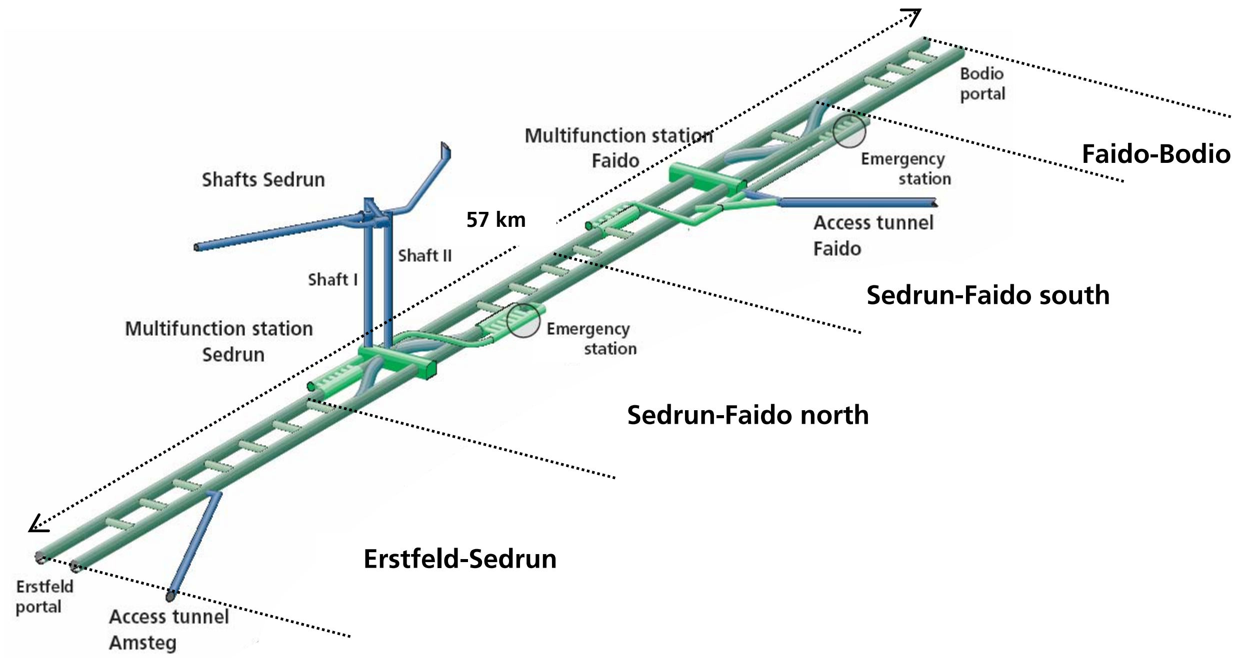

Figure 2: Schematic View of the Gotthard Base Tunnel System

The next major step will be to install the mechanical and electrical equipment. During the installation phase, more than 500'000 t of material, mainly trackway will be brought into the tunnel. Only a careful planning of this installation phase allows a reliable operation of the base tunnel at a later stage.

Since the installation of the equipment demands a huge amount of manpower, material and heavy machinery a sophisticated logistic concept is needed. To cope with the climatic requirements in the tunnel, the use of a ventilation and cooling system is unavoidably. Deployed diesel power of several 1000 kW and rock temperatures of up to 45°C due to high rock overburden of up to 2500 m (Busslinger et al. 2001 and Zbinden et al. 2002), requires both fresh air supply into the tunnel and extraction of heat out of the tunnel. Insufficient ventilation or cooling will cause unacceptable working conditions. This leads to forced stop of the work and failing of the installation schedule at high costs. Although the ventilation and cooling is only a temporary arrangement and will no longer be needed after the tunnel is completed, it is a crucial parameter for the completion of the tunnel on schedule.

As a basis of the call for tenders of the equipment installation as well as to estimate the costs, a preliminary design of the ventilation and cooling during the installation phase has recently been finished. This paper focuses on the experiences made during the design of the ventilation and cooling system for the installation phase of equipment of the Gotthard base tunnel.

OBJECTIVES

At construction sites sufficient climatic conditions have to be maintained. According to Swiss authority these conditions are defined by threshold values of maximum working environment concentrations. These values can only be examined under operation. Therefore special requirements are given to enable preliminary design of the ventilation and cooling systems underground. In Table 1 a brief summary of these requirements can be found.

Table 1: Climate Requirements on Tunnel Construction Sites

Requirement	**Threshold Value**	**Appliance**
minimum air flow rate according to engaged Diesel power	4 m^3/min/kW (full load) 2 m^3/min/kW (part load)	ventilation design
minimum air flow rate according to engaged manpower	1.5 m^3/min/person	ventilation design
maximum dry bulb temperature	28°C	venting and cooling design

A major objective of the ventilation and cooling system during the installation of equipment in the Gotthard Base Tunnel was to fulfil these regulations.

In addition the ventilation and cooling system had to support self rescue, evacuation and fire fighting in case of fire incidents.

DESIGN BASIS

Beside the regulations the concepts of ventilation and cooling must be based on the planned schedule of the equipment phase of the Gotthard Base Tunnel. The limited time span of transporting and installing the large number of equipment, relative to the small number of portals lead to a challenging schedule. As a consequence heavy transport traffic as well as intensive work on site are to be expected. Additionally the equipment phase can only begin when the previous excavation and construction work in the tunnel is finished. Since this will happen in a stepwise manner the installation of equipment in the Gotthard Base Tunnel will start at single tunnel sections and continuously take over the whole tunnel system. Figure 3 shows a simplified possible schedule of the equipment phase including the installation of the trackway and further equipment (catenary system, telecommunication systems, power supply, cabling, signals, auxiliary equipment, etc.) as well as transport activities.

To determine the needed ventilation and cooling power assumptions had to be made for the following parameters:

- power of the deployed diesel engines on site
- power of the deployed diesel locomotives
- heat release of all deployed technical equipment (engines, locomotives, ventilators, heat exchangers, lighting, etc.)
- heat release of the trackway concrete
- heat release and thermal properties of the rock
- meteorological conditions at the portals

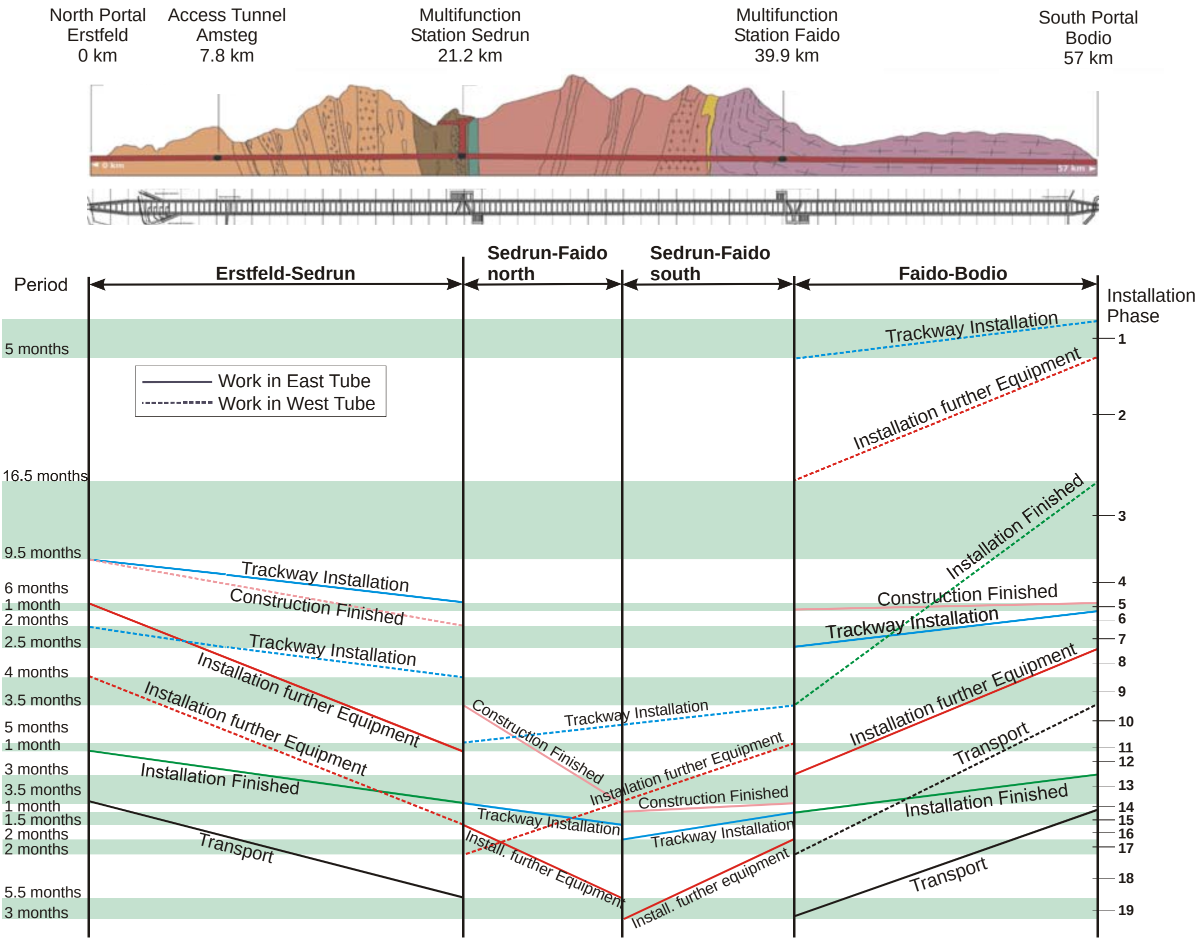

Figure 3: Schedule of the Installation Phase of Equipment in the Gotthard Base Tunnel and Separation of Installation Phases related to Ventilation and Cooling

CONCEPTS

According to the given objectives and design basis, concepts for the cooling and ventilation of the installation of equipment had to be developed individually.

Installation Phases and Sections

To assure a smooth ventilation and cooling performance during the whole installation of the equipment, the schedule of installation had to be divided into installation phases.

An installation phase is defined as the period during the equipment of the tunnel, in which the activities do not relevantly change, i.e. no changes of ventilation and/or cooling are necessary. The changes of activities may be the transition from "Installation Trackways" to "Installation further Equipment" or the like (cf. Figure 3; e.g. installation phase 1 to 2). Furthermore, relevant changes for ventilation and/or cooling might occur when the responsibility for a specific tunnel section is handed over from the construction phase to the installation phase (cf. Figure 3; e.g. installation phase 5 to 6).

For reasons of safety and to fulfil the requirements of the air quality, the tunnel was subdivided into 4 ventilation/cooling sections each of them between 10 km and 15 km long. These sections (cf. Figure 2) are:

- Erstfeld-Sedrun
- Sedrun-Faido north
- Sedrun-Faido south
- Faido-Bodio

This division of the tunnel leads to an optimisation of the volume flow of air needed in the tunnel. Moreover it would also limit the propagation of the smoke in the tunnel in case of a fire.

Concept of Ventilation

For each of the 19 installation phases and each installation section a distinct ventilation concept was defined. In addition to fulfil the objectives for the normal operation the concept design follows these principles:

- The system of ventilation should have the smallest possible influence on the installation of equipment in the Gotthard Base tunnel,, i.e. as few as possible air tubes, fans, etc. are placed in the main tunnels allowing efficient installation of the catenary system or the trackways.
- The time spans to adapt ventilation settings between two installation phases should be as small as possible.
- The individually ventilated installation sections along the Gotthard Base Tunnel are aerodynamically separated by air locks or air barriers.
- All available adits or shafts are used for fresh air supply or waste air disposal.
- Adits and shafts are adopted as soon as possible in the ventilations concepts, for concepts with air supply/removal only by the main tunnel portals have safety disadvantages (reduced pressurising, smoke extraction and accessibility of the tunnels).
- Due to safety reasons (redundancy) each installation section is ventilated at least by two fans.

In summary four basic ventilation concepts were adopted:

1. Air circulation at portal sections: Ventilation of tunnel sections near by the portal by fans in cross passages with fresh air supply/waste air removal through the portals of the main tunnel
2. Air circulation at inner sections: Ventilation of central tunnel sections by fans in adits with fresh air supply/waste air removal through the portals of the adits
3. Portal to adit ventilation: Ventilation of tunnel sections close to the portals by fans in adits with fresh air supply through the main tunnel portals and waste air removal through the portals of the adits
4. Adit to portal ventilation: Ventilation of tunnel sections close to the portals by fans in adits with fresh air supply through the portals of the adits and waste air removal through the main tunnel portals

A detailed illustration of a concept for the installation phase 15 is given in Figure 4.

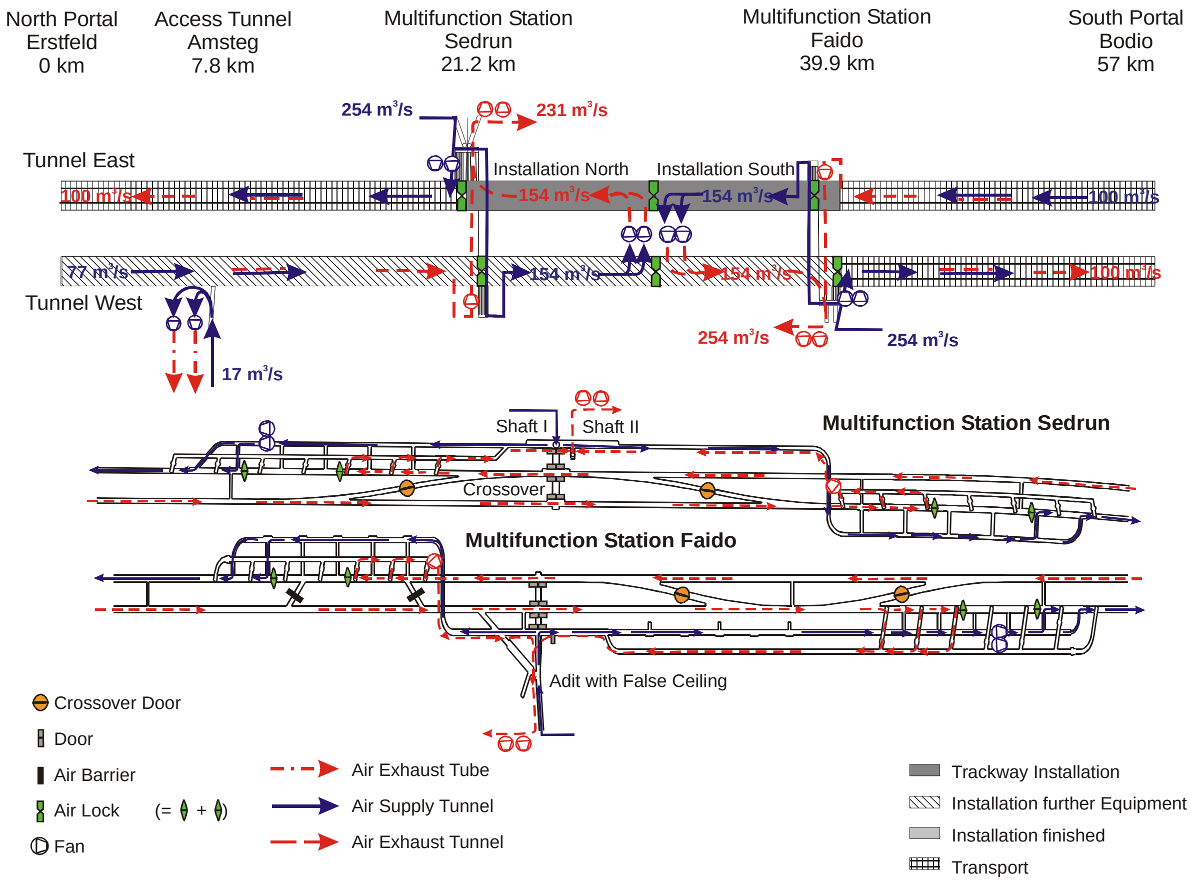

Figure 4: Ventilation Concept Installation Phase 15

The main activities in installation phase 15 include trackway and further equipment installation mainly in the central part of the tunnel system as well as transport of railway equipment through the portal sections of the tunnel. As mentioned before the tunnel is divided by air locks into 4 separately ventilated sections (cf. Figure 2). The ventilation of the sections in the vicinity of portals is based on the above defined concepts 3 and 4 whereas the tunnel sections between the multifunctional stations (MFS) are ventilated according to the concept 2. As most of the air will move through the multifunctional stations in Sedrun and Faido are these areas looked at in detail. The shown setting depends strongly on the availability of air ducts built for the future operation ventilation. In addition the adit Amsteg had to be supplied with fresh air by air tubes.

The marked air volume rates have been determined on the basis of the distribution of diesel and man power predicted for this installation phase (cf. chapter "Design Basis") and on the regulations related to ventilation (cf. chapter "Objectives").

Furthermore the concepts have to prove their reliability in case of emergency. As defined in the chapter "Objectives" the main incident to deal with is fire in the tunnel system.

Looking at this scenario the following basic requirements must be fulfilled by every concept:
- In most fire scenarios the non incident parallel tunnel is defined as the safe area where workers escape to. Thus the non incident tunnel must be kept smoke free.
- To determine the minimum air flow rate to eliminate smoke propagation or back layering into safe areas the critical velocity based on typical fire power in the installation phase must be considered.
- Non incident installation sections with separate ventilation must be kept smoke free.
- All engaged fans must be reversible to adapt the air flow direction in every installation section to fit the requirements during self rescue, evacuation and fire fighting.

In Table 2 a universal sequence of ventilation measures during the incident phases self rescue, evacuation and fire fighting is given.

Table 2: Sequence of Ventilation Measures in case of a Fire Incident

Incident Phase	**Ventilation Measures**
Self Rescue	The fans of the incident installation section are stopped and their dampers are closed. Smoke propagation in the tunnel is slowed down. Smoke layering in the soffit is supported whereas sufficiently low smoke concentration and high visibility in the remaining tunnel is obtained. If possible pressurising of the non incident tunnel starts.
Evacuation	By pressurising the non incident tunnel evacuation routes and safe areas of self rescue are kept smoke free.
Fire Fighting	The air flow rate and direction are controlled in correspondence with the fire fighting scenario. Smoke propagation against fire fighting is inhibited. Smoke extraction is realised through defined tunnel sections or adits.

The complex interaction of ventilation scenarios in different installation sections and for the defined incident phases can be seen in Figure 5. This illustration contains the sequence of ventilation measures in case of a fire in the section between the multifunctional station Faido and the portal Bodio during the installation phase 15 according to the introduced sequence in Table 2.

Right after the fire detection the self rescue of the workers takes place and the ventilation in the incident tunnel is switched off. The air flow is slowed down rapidly due to the closing of the fan dampers. As soon as possible a mobile fan is installed at the portal. Together with the fans in the multifunctional station Faido this allows an aligned pressurising of the non incident tunnel. This ventilation mode is kept running until the evacuation of all staff by train is completed. The pressurising protects both the involved employees and the evacuation team by keeping the non incident tube smoke free. Up to this point none of the neighbouring installation sections needs to be involved in the emergency scenario. During the fire fighting the ventilation must be controlled to protect the fire brigade and to extract smoke from the tunnel system. The air flow direction in the incident tunnel is reversed to transfer smoke to the nearby portal. The ventilation concepts of all installation sections connected to the multifunctional station Faido are affected. The staff of the neighbouring section is evacuated and its ventilation is stopped.

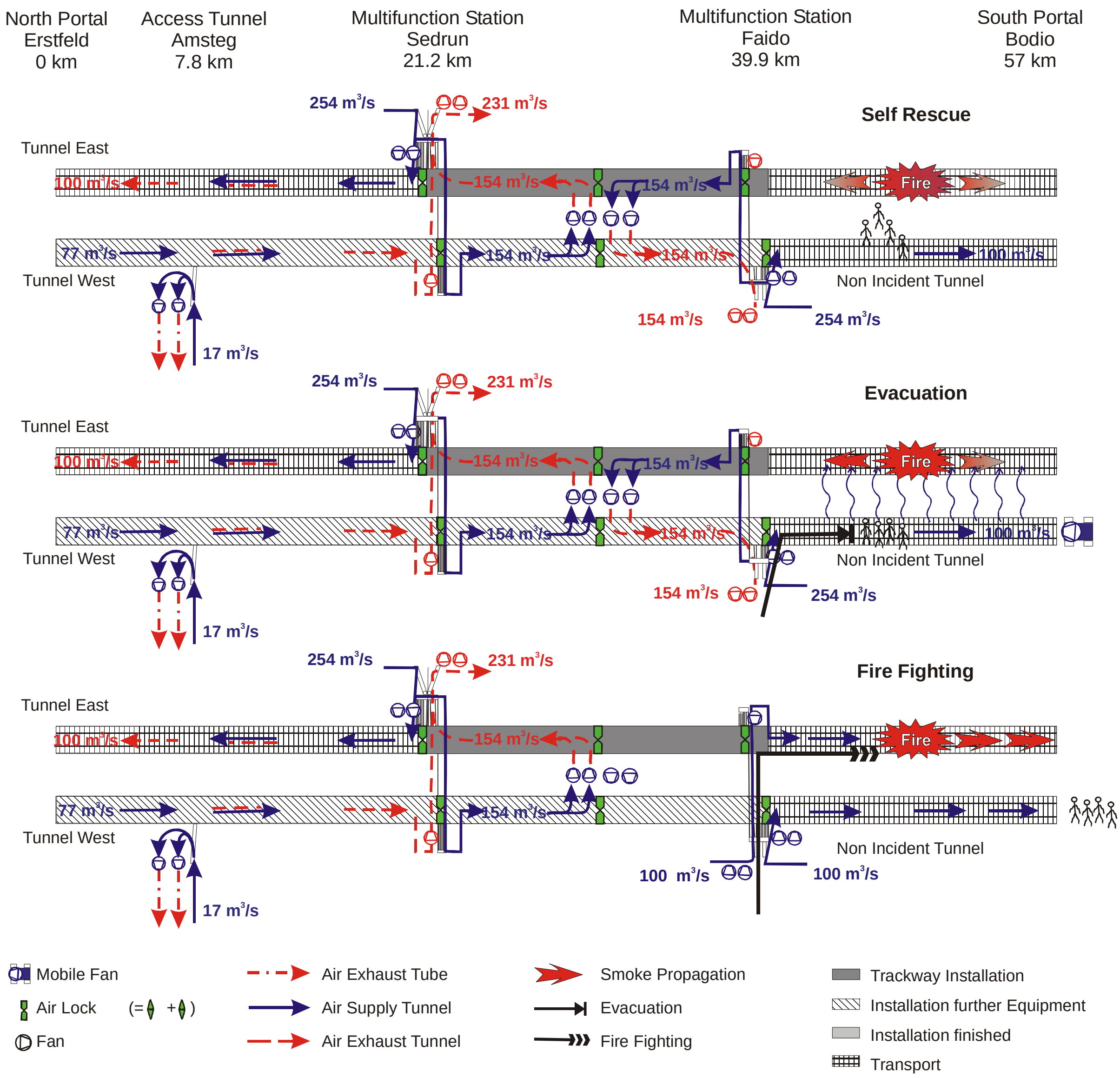

Figure 5: Ventilation Concept Installation Phase 15, Fire Incident

Concept of Cooling

Besides the need for fresh air in the tunnel a major demand is the sufficient heat removal, so that the temperature threshold will not be exceeded. It must be considered that the installation is a highly transient process. The location of men and machines varies consistently. To provide the cooling power at the right place and to the right time, a flexible concept was aimed for.

The cooling concept consists in the following basic principles:

- Cooling towers are located outside of the tunnel at the portals Bodio, Faido and Amsteg.
- A local cooling was chosen to adopt the cooling power where required.
- The cooling water system consists of 2 parallel pipelines, one for the supply of cool water to the mobile air coolers, one for the transfer of heated water to the cooling towers outside. These twin-pipes are only installed in one of the tunnels whereas the air coolers in the other tunnel are feed by branch pipes through the cross-passages.
- The mobile air coolers will be placed on the tunnel side strip. This causes as small as possible obstructions for the installation.
- To allow for high flexibility the air coolers can be connected to the cooling-water system every 100 m.

The concept for each particular installation phase was achieved as follows:

- Definition of the cooling power for each of the installation sections: This value is dependent on the type of work done in that specific section and the formerly evaluated air flow.

- Definition of the number of air coolers needed based on the assumption, that an air cooler unit provides 300 kW of cooling power
- Division of the installation sections into 3 subsections (cf. Figure 6; N: northern part of section; M: middle part of the section; S: southern part of the section).
- Distribution of the air coolers in an installation section on demand: To achieve a proper distribution 3 typical cases were defined (cf. Table 3)

Table 3: Definition of Cases for the Placement of Air Coolers

Case	Definition	Appliance for the Placement of Air Coolers
1	Installation along the air flow direction, where the installation induced heat sources move more or less continuously along the section.	- As long as the installation process hasn't reached the middle of the section: Placement of all the air coolers in the subsection (S or N), where the installation process begins, i.e. where the air enters the tunnel. - After the installation passed the middle of the section: Rearrangement of approximately half of the air coolers to the middle subsection (M).
2	Installation contrary to the air flow direction, where the installation induced heat sources move more or less continuously along the section.	- Placement of half of the air coolers in the middle subsection (M), the other half at the border of the subsection (S or N), where the installation process ends, i.e. where the air enters the tube.
3	Installation along or contrary to the air flow direction, where the installation induced heat sources are homogenously distributed along the section.	- Preferably equal distribution in all the subsections (S, M and N)

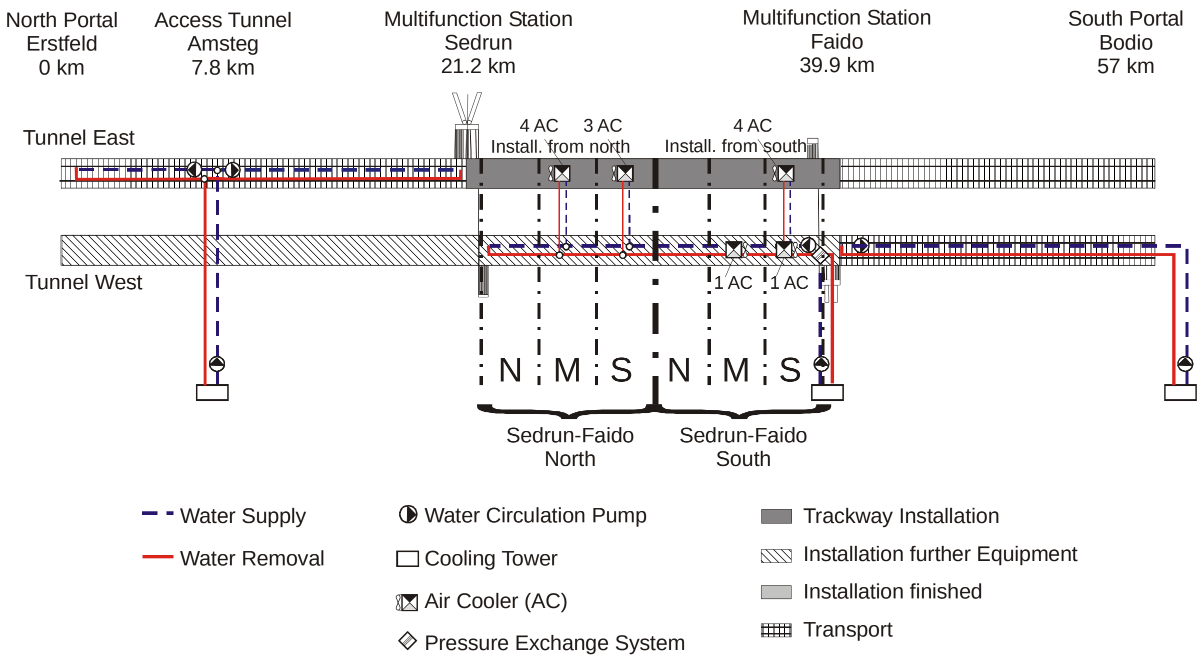

Figure 6: Cooling Concept Installation Phase 15

Figure 6 shows an illustration of the cooling concept with the alignment of the water pipes as well as the placement of the air coolers (AC). According to the rules in Table 3 the placement of the air coolers in the installation sections is as follows:

- Sedrun-Faido north: 4 AC in the middle of tunnel east, 3 AC at the south end of tunnel east, none in the tunnel west
- Sedrun-Faido south: 4 AC at the south end of tunnel east, 1 AC in the middle of tunnel west, 1 AC at the south end of tunnel west

The other sections (Erstfeld-Sedrun and Faido-Bodio) do not need additional cooling, i.e. the air flow is sufficient to remove the heat. This is due to the small heat input of the activities in this section on one side and the lower rock temperatures in that part of the tunnel on the other side.

Concept of Control

The ventilation and cooling during the installation phase are controlled by the temporary tunnel control centres established in the vicinity of the tunnel portals. Furthermore all ventilation and cooling services must be provided on demand as sketched in the flow chart of Figure 7.

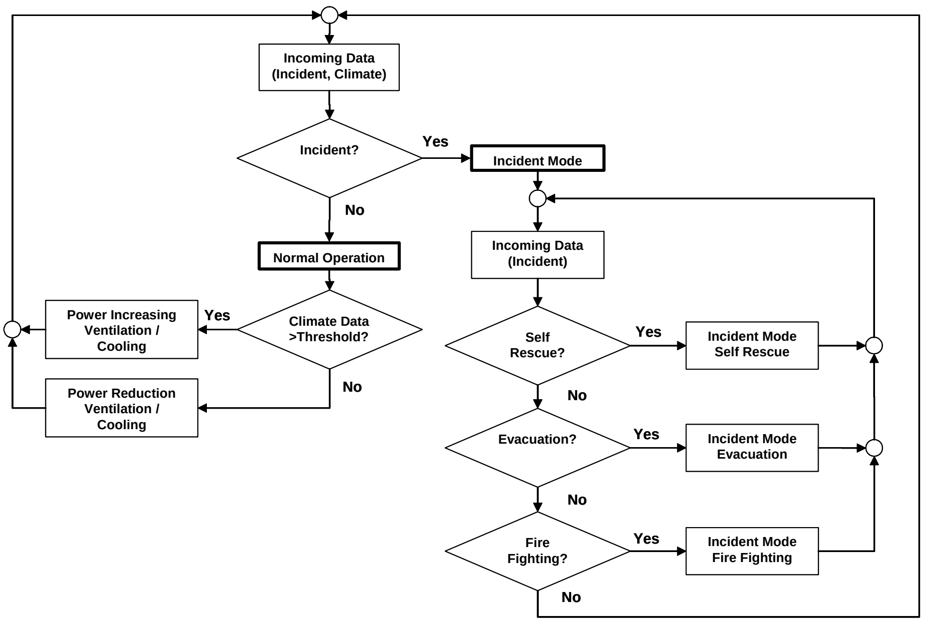

Figure 7: Flow Chart Control Concept of Ventilation and Cooling

In case of an incident (e.g. fire) the ventilation must be controlled as defined in the chapter "Concept of Ventilation". It will have highest priority within all control modes.

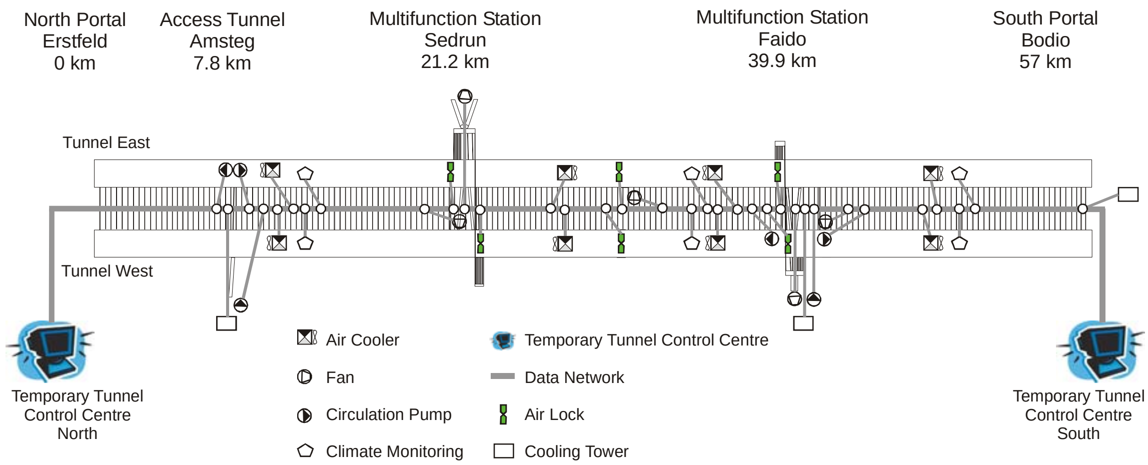

Figure 8: Control Concept of Ventilation and Cooling

During normal operation of installation the ventilation and cooling performances are adjusted to fulfil the climatic limits. Consequently a climate monitoring system in all installation sections is required to collect and transmit air speed, temperature, humidity and pollution data to the temporary tunnel control centre.

These basic requirements lead to the general concept of control shown in Figure 8. The main principles of this concept are the following:

- All elements of ventilation and cooling to be controlled or monitored (fans, air locks, circulation pumps, cooling machines, etc.) are connected by the data network to the temporary tunnel control centre.
- Every installation section is equipped with a climate survey system connected by the data network to the temporary tunnel control centre.
- The data network grows with the installation progress in the Gotthard Base Tunnel.

DIMENSIONING

The ventilation and cooling systems had to be dimensioned based on the defined concepts above. The necessary ventilation and cooling power relate strongly to each other. Typically the needed cooling power will be reduced by increasing the ventilation power and therefore the volume rate in a tunnel. Consequently the ventilation power of the equipment phase in the Gotthard Base Tunnel was determined first and then the cooling power had to be adapted to the given air flow rates.

Dimensioning of Ventilation

Within the concepts of ventilation the flow rates and flow paths of air was determined for every installation phase. Based on these data, as well as on the aerodynamically related parameters of the tunnel system, the specifications of the fans and further ventilation equipment could be found. In addition the pressure fluctuations caused by the moving trains had to be considered.

Furthermore the air locks and air barriers are dimensioned and positioned according to the requirements of the installation sections (train traffic, trackway installation, etc.) and of the temporarily nearby construction sections in the tunnel. In Table 4 all deployed elements of the ventilation are assembled in an overview.

Table 4: Overview of the Ventilation Elements

Element	Location	Number	Specification
air supply fan	multifunctional station Sedrun/Faido	4	reversible axial fan
air exhaust fan	multifunctional station Sedrun/Faido	4	reversible axial fan
circulation fan	cross passages	6	reversible axial fan
mobile fan	portals Erstfeld/Bodio	2	axial fan mounted on truck
air supply fan	adit Amsteg	2	reversible axial fan
auxiliary fan	multifunctional station Sedrun/Faido	6	reversible axial fan
air lock	tunnel	6	2 electric operated doors allowing train traffic
air barrier	tunnel and multifunctional stations	16	temporary air tight walls
air tube	adit Amsteg	2	1900 m of air tube

Dimensioning of Cooling

To specify the elements of the cooling system, the amount and distribution of the cooling power had to be calculated. For these calculations the software BAUKLIMA of HBI Haerter Ltd was used. BAUKLIMA allows for long term climate simulation in long tunnels. Substantially, it takes into account all essential construction activities, changing meteorological conditions at the portals and heat exchange with the surrounding rock. Air coolers can be placed in the system whereas their heat exchange with the water pipes and the temperature variation of the cooling water is considered. Moreover, BAUKLIMA is able to adjust the number and placement of a predefined air cooler type to fulfil a defined temperature threshold. Hence, BAUKLIMA is a suitable tool to estimate the cooling power needed for different phases (different activities, i.e. different heat emissions) during the construction and equipment of a tunnel.

For all of the 19 installation phases and the installation sections the needed cooling power was evaluated. Depending on the phase and the section, cooling power up to 4 MW was needed. For the installation section Sedrun-Faido south, the required cooling power (1030 kW) and the resulting air temperature will be shown below as an example.

According to Figure 9 the most cooling power is required in the east tunnel, where the trackway is installed. Additional cooling power is necessary at the fans (near the air lock) and in the tunnel west, at the location where further equipment is installed. As a result cooling powers of 880 kW for the east tunnel and 150 kW for the west tunnel are required.

Figure 10 shows the resulting air temperatures with the cooling deployed. The cooling power is adjusted to meet the threshold of the tunnel temperature. At the entrance portal (Faido) the air has ambient temperature. Along the tunnel system the air is heated up. As soon as the air reaches the technical heat sources, the temperature starts to increase rapidly. Only the use of air coolers prevents the temperature from exceeding the threshold value. In addition to the resulting air temperature the initial rock temperature is shown.

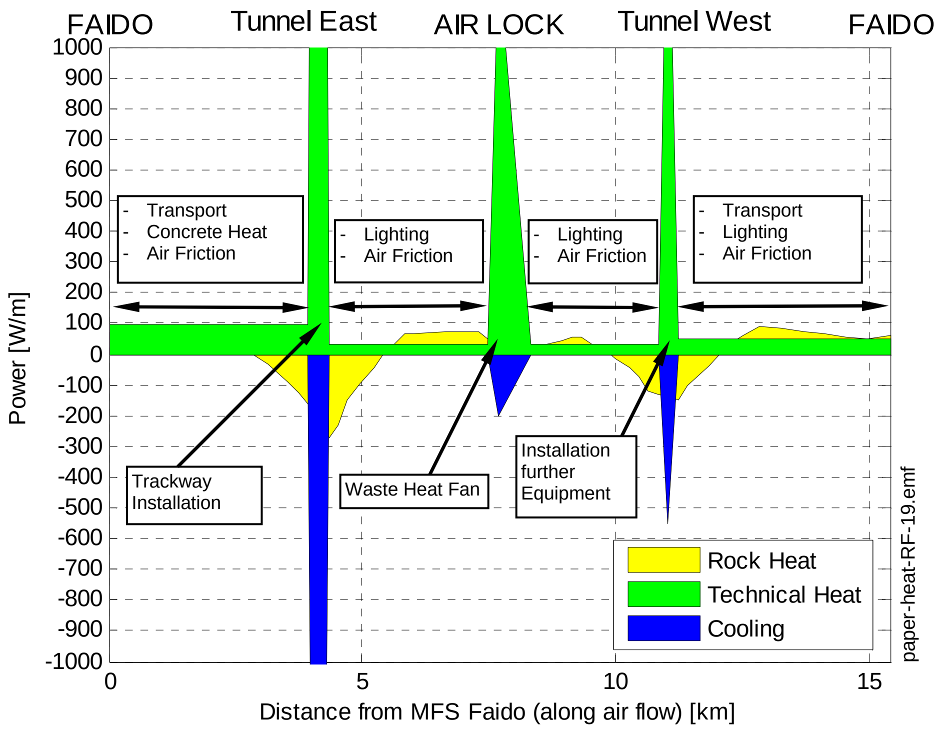

Figure 9: Distribution of Rock Heat, Technical Heat (Transport, Lighting, etc.) and Required Cooling Power in the Installation Section Sedrun-Faido South, Phase 15

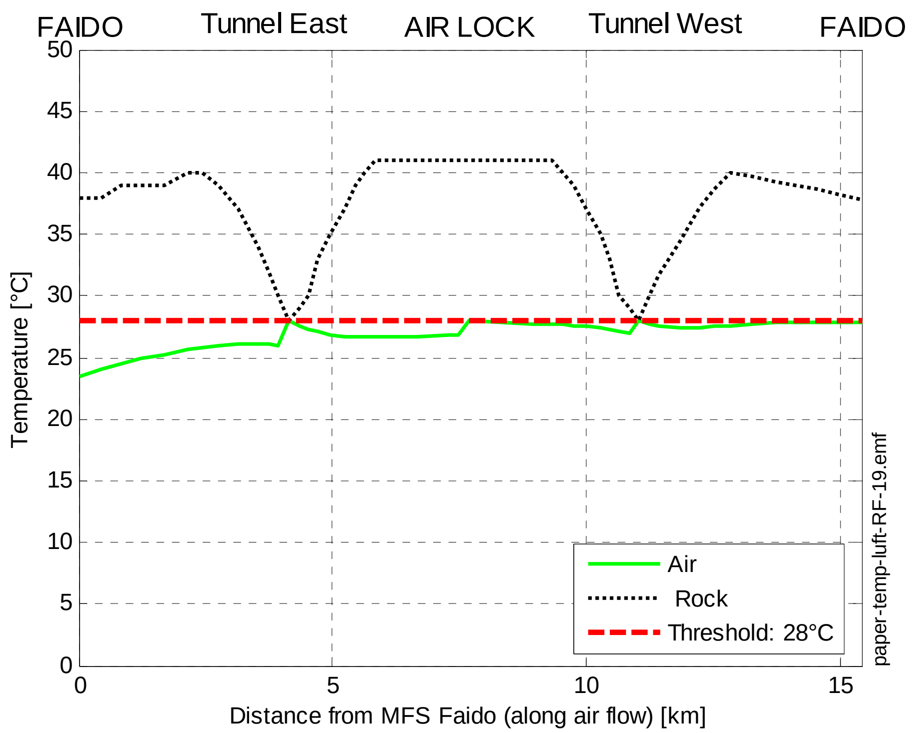

Figure 10: Temperature of Air and Rock in the Installation Section Sedrun-Faido South

In Table 5 all deployed elements of the cooling are assembled in an overview.

Table 5: Overview of the Cooling Elements

Element	Location	Number	Specification
air cooler	tunnel side strip	30	300 kW cooling power
fan	tunnel side strip	30	volume flow ca. 8 m^3/s

Element	Location	Number	Specification
water pipes	adits Amsteg and Faido	6 km	twin pipe 500 mm (supply and removal)
water pipes	tunnel side-wall	57 km	twin pipe 300 mm (supply and removal)
PES	multifunctional station Faido	1	pressure exchange system
water pump	portal Amsteg, Faido and Bodio	6	water circulation pump, primary
water pump	multifunctional station Faido, Amsteg	6	water circulation pump, secondary
cooling tower	portal Amsteg, Faido and Bodio	3	re-cooling of the water

CONCLUSION

The installation of the equipment for the Gotthard Base Tunnel is a time consuming and cost intensive issue. For the future operation the equipment has to be placed correctly and to schedule in the tunnel. All the more, the conditions (climate) during the installation phase are of crucial importance. The above described is the basis for the call of tenders. The planning of the ventilation and cooling, the prediction of flow rates, numbers of air coolers etc. allowed for an as precise as possible estimation of the system parts, and hence for a predictions of the cost.

The following experience was obtained during the project elaboration:

- Ventilation and cooling during the installation of equipment in tunnels can only be designed in close collaboration with the installation logistics. The main interfaces hereby are the schedule of installation, the installation methods (e.g. deployed engine power) and the emergency strategy.
- Especially for long tunnels the ventilation concept for incidents must be treated with care.
- The separation of the installation sites by air locks proved to be a simple method to reduce the locally maximum air flow needed. Moreover, it limits the propagation of smoke in case of a fire in the tunnel system.
- Special attention should be paid to the transition phases between preliminary construction and installation phase and between installation and future operation phase. The corresponding interfaces must be covered carefully to prevent major delays of working schedule and additional costs.
- Since the schedules of construction and installation are easily changed during the project phase, flexible or modular concepts of ventilation and cooling have great advantages and must be foreseen.
- The concepts of ventilation and cooling must be tailored to provide their services on demand. Otherwise no adaptations to the changing requirements during installation and no reduction of operation costs can be obtained.
- The concepts of ventilation and cooling especially concerning incident treatment should be discussed with responsible authorities as soon as possible.

Especially, it was learned that only a flexible cooling concept with a placement of the air coolers on demand is suitable for tunnels systems with long installation sections (limited access) and deep overburden (i.e. high rock temperatures). Furthermore, the necessity of a practicable tool (BAUKLIMA) to model various heat sources (rock, machines, air friction, etc.) and the changing of their location, the prediction of the cooling power to remove the heat as well as the verification of the defined air coolers was shown.

ACKNOWLEDGEMENT

The authors would like to thank the project management of the AlpTransit Gotthard AG in Lucerne for the permission of publication of their project results.

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