Hong Kong, China: Rush hour traffic flows quickly through the Cross-Harbour Tunnel. It’s one of the world’s most traveled highways and connects Kowloon with Hong Kong Island (in the background).
Arteries Underground

Tunnel construction sites are extreme places that require complex solutions to make them safe. Even the later operation, of the underground facilities for transport and infrastructure, makes high demands.

Deep beneath the city center in London, UK, gigantic machines are working their way through clay and chalk. In spring 2012 the first of eight tunnel boring machines, from the German manufacturer Herrenknecht, began to drill more than 40 kilometers of rail tunnels under the British capital. These tunnels are at the heart of the Crossrail Project, which will channel long-distance rail transport under London in the future. The massive project is currently the biggest construction site in Europe.

Rapid Growth

Many new tunnels are being built in similar mammoth projects all over the world, because the future of transportation infrastructure lies underground. After all, high-speed rail lines and highways need tunnels; and high-performance transit systems in congested cities need underground tubes, so that they can go on growing. Besides tunnels for passenger transport, networks must also be built for data and energy transmission, water pipes, and sewer systems.

Tunnels are the arteries of cities, creating increasingly dense networks of structures beneath the earth’s surface. Hundreds of kilometers of tunnels are currently being built or planned worldwide. “The priorities are especially in Europe and Asia,” says the construction engineer Roland Leucker, Managing Director of the nonprofit Research Association for Underground Transportation Facilities (STUVA) in Cologne, Germany. “For everyone in the megacities, with their several Million inhabitants, there is a huge need for public transport tunnels.” But the new long-distance roads and rail tunnels need larger and greater dimensions.

As a result, not only the number of tunnels, but also their lengths are growing. One example of this is the 55-kilometer-long Brenner Base Tunnel, whose construction is soon to begin. The Brenner Pass currently the most important and busiest north-south connection in the Alps. Around two million trucks and 12 million cars drive through this bottleneck every year. The planned base tunnel, which will be solely for rail use, will run underground between Innsbruck and Franzenfeste, and should greatly reduce traffic congestion. Building on exploratory galleries began in 2007, and construction of the main tunnel will begin in 2013. The project, which will cost about eight billion euros, and is expected to be completed in 2022.

Rescue Concepts Required

Also the diameters are larger: Opened in 2009, the Changjiang Under River Tunnel in Shanghai is divided into two tubes, each with more than 15 meters in diameter. This provides enough space for a three-lane highway plus a subway line underneath. As tunnel projects become more ambitious, safety requirements increase as well—not only during construction, but also during later operation. The fact that safety at tunnel construction sites has to be further improved was emphasized by In-Mo Lee, President of the International Tunneling and Underground Space Association (ITA), at the World Tunnel Congress 2011 in Helsinki. “It’s essential for us to develop technologies that will en-
Mining and tunnel construction largely use the same technologies and tools

able us to protect and rescue people even more effectively after accidents, especially in the case of fire,” he said in an interview with the trade magazine tunnels et espace souterrain. This applies especially to very long tunnels, whose numbers are steadily increasing.

Conditions like those in a mine

The safety concept for the construction and operation of tunnels is complex, as is demonstrated by the large number of relevant ordinances and regulations. Because of the unusual conditions at the construction sites and in completed tunnels, many issues need to be addressed. They include occupational safety, accident prevention, fire protection, and safe escape routes.

The similarities to mining operations are especially apparent during a tunnel’s excavation and the building of its support structure. Perhaps that’s why the mining industry has often been a major source of inspiration for tunnel construction technology. The similarities, between these two types of excavation, have been a consistent feature ever since the first tunnels were built for irrigation purposes over 3,000 years ago. “For a long time, the methods and equipment used in excavations were largely the same as those associated with tunnel construction and mining,” says Dirk Bühler, Ph.D. Engineer and Tunnel Expert at the Deutsches Museum in Munich. “However, in terms of transportation, tunnel construction differed from mining with regard to slopes, cross-sections, and surface features.”

Werner Ochse, a tunnel expert at Dräger, adds, “There are also technical similarities between mining and tunneling when it comes to safety technology.” The Lübeck-based company’s long experience with mine rescue operations is the foundation on which the firm’s current range of safety equipment, for tunnel construction, is based.

An impression of how tunnel workers were protected in past centuries is presented by a replica of the Simplon Tunnel construction site, which can be viewed in the Deutsches Museum’s permanent exhibition. The first tube of this almost 20-kilometer-long tunnel connecting Switzerland and Italy was built between 1898 and 1912. The solid wood support structure leaves enough room for a mine railway in the lower half of the tunnel profile. Above it, numerous roughly cut tree trunks create a claustrophobic tangle of closely spaced pillars. If you add poor lighting and heat,
you can get an impression of the conditions under which the workers built the world’s first major traffic tunnel.

**Ongoing Construction Site Risks**

Conditions have changed considerably since then, thanks to electrical lighting, high-performance ventilation systems, and, above all, ultramodern tunnel excavation equipment. Tunnel construction was significantly transformed by large tunnel boring machines, which resemble underground factories consisting of everything from the tunneling shield to the tubing installation system. “In Germany, shield tunneling is used primarily to construct railway tunnels,” says Leucker. Road tunnels, on the other hand, are still often made using mining processes, due to the need to have flexible profiles. Open-pit construction also continues to play a major role; this technique is used for around 20 percent of the tunnel stretches built in Germany today.

The basic risks of tunnel construction have remained unchanged. The tunneling route has to be protected primarily against geological factors such as water penetration and rock pressure. In addition, workers have to be protected against the effects of blasting, tunnel boring, traffic, and the building of the support structures, as well as possible fires and their consequences. There are also specific risks associated with a hard-to-reach underground sites that depend on external energy supplies and ventilation.

In the early days of modern tunnel construction, working under high pressure was especially dangerous, because
> insufficient decompression could cause
the workers to suffer from Caisson Disease, which is similar to the bends. A milestone in the prevention of this disease was achieved by a physician couple during construction of the St. Pauli Elbe Tunnel in Hamburg, Germany. “For the first time ever, from 1909 to 1910 Arthur and Olga Adele Bornstein monitored the workers on a caisson or compressed air construction site. The couple systematically combated the disease, using methods that they enhanced themselves,” explains Dr. Jürgen Bönig from the Museum of Work in Hamburg.

**Working Under Pressure**

Nowadays, slurry-supported shield tunneling technology has reduced the importance of manual tunnel construction under high pressure, and the cutters in the cutting wheels of today’s tunnel boring machines can even be replaced at normal atmospheric pressure. This technology had its debut in the cutting wheel of Herrenknecht’s tunnel boring machine “Trude,” which was used to create the fourth tube of Hamburg’s new Elbe tunnel. However, tunneling work is still done using pressurized air in many places around the world.

Especially in recent years, one of the technical solutions used to improve safety at tunnel construction sites worldwide is the rescue chamber. These containers are pressure-sealed and gastight. They are equipped with an oxygen and energy supply system that is independent of the surrounding environment, and allow occupants to communicate with the outside world. The eight Herrenknecht tunnel boring machines being used in the Crossrail project in London are equipped with rescue chambers from Dräger. “This technology has great potential, considering how many tunnels are being constructed worldwide using shield tunneling,” says Werner Ochse from Dräger.

According to Dräger Sales Engineer Peter Medek, the organizers of a new tunnel construction project, or the upgrade of an existing system, should develop a consistent safety concept from the very beginning, on the basis of a specific hazard assessment. Medek understands these processes in detail, because Dräger has developed into a supplier of holistic safety systems for tunnel construction built on the foundation of its extensive portfolio of around 60 products and many services.

“We are already engaged in the early stages of new construction and or renovation projects so that we can provide all of the necessary services,” explains Medek. The tasks involved include providing consultation during the development of the safety concept, training workers and rescue crews, supplying rescue chambers and personal protective equipment, in addition to offering a flexible rental management system for a broad range of safety technologies. The services include making sure that the respiratory protection systems are always in working order for the fire departments that are responsible for the various tunnels. To ensure respiratory protection, Dräger supplies closed-circuit breathing apparatuses (e.g. Dräger PSS BG 4 plus) that can operate for up to four hours, enabling workers to work in typical scenarios involving long assignment times.

**Multistage Safety Concepts**

Preventive fire protection is necessary during a tunnel’s construction as well as its operation. However, the measures used for ensuring tunnel safety are different during operation than during the tunnel’s excavation and the building of its support structure. That’s because a tunnel is utilized by a great amount of people once it has been opened. These users have to be directed to safe areas if there is an accident or a fire. The differences between the various modes of transportation are much more apparent during a tunnel’s operation than when it is being built. The conditions in a pedestrian tunnel, for example, are very different from those found in a road tunnel or a railway tunnel.

The world’s longest tunnels are used for railway, and a variety of safety concepts have been established for them. Deutsche Bahn AG, for example, has developed a multistage safety concept for its tunnels. “The first stage consists of preventative measures, followed by event- alleviating actions,” explains Klaus-Jürgen Bieger, Head of Safety and Chief Fire Protection Officer of Deutsche Bahn AG. In the next stage, the victims either manage to flee from the accident site or are externally rescued. In order to prevent accidents and fires, trains with passengers and freight are not allowed to pass in long tunnels with high-speed rail lines. In addition, passenger rail cars have to comply with the Federal Railway Authority’s fire protection regulations in order to
Rescue chambers increase the level of safety

Following an accident in March 2012, rescue helicopters landed in front of the portal of the Sierre Tunnel in Switzerland.
Focus Tunnel

be approved for registration in Germany. These regulations are based on the DIN 5510 standard, supplemented by the current version, of the as yet unpublished, DIN CEN/ TS 45545-1 standard. If a fire should nonetheless break out on a train, measures such as an emergency braking override system will ensure that the train doesn’t stop until it has left the tunnel.

If all of these precautionary measures fail to prevent a critical incident from occurring in a tunnel, the passengers will either flee to safety or be rescued by firefighters. The rescue concept is supplemented by structural measures such as specially protected escape routes and lighting systems, escape route signs, emergency exits, and emergency telephones. In new tunnels such measures are augmented by additional features, such as built-in fire extinguishing pipelines including the reservoir, power supply systems, and wireless infrastructure.

Fast Rescue Trains

While the approaches to tunnel portals and rescue missions are designed to accommodate road vehicles, road-rail vehicles, and rescue trains, representing special types of rescue technologies. Germany has six rescue trains, which are stationed along the high-speed rail lines between Hanover and Würzburg and between Mannheim and Stuttgart. Schweizerische Bundesbahnen (SBB) in Switzerland operates a total of 15 firefighting and rescue trains. In 2006 SBB ordered eight new trains that were built by a consortium in which Dräger was responsible for the safety technology. These trains, which
Combating tunnel fires with water mist

From 2009 to 2012, the “Safety of Life in Tunnels 2” (SOLIT2) project investigated technical systems for fire protection in tunnels. As part of the project, which was financially supported by the German Federal Ministry of Economics and Technology, more than 30 simulations of major fires were carried out in summer 2011 in order to test the effectiveness of water mist fire fighting systems in connection with fire ventilation in highway tunnels. These simulations were carried out in the “Tunnel Safety Testing” test tunnel in San Pedro de Anes, Spain. In the process, liquid fires and solid material fires with fire loads of up to 100 megawatts were simulated.

At the STUVA conference in Berlin in 2011, Dr. Roland Leucker (Managing Director of STUVA) and Stefan Kratzmeir (Managing Director of IFAB – Institute for Applied Fire Safety Research) concluded that the project had been successful. They said that the use of water mist systems can favorably affect the development of liquid fires and solid material fires in a tunnel, as the finely distributed drops of water cool off the burning material and, its surroundings, and also alleviates the level of smoke. Additionally, the use of water mist reduces the danger of fire flashing over onto other vehicles. “In general, it’s important to activate the system as early as possible so that the positive effect of the cooling occurs sooner,” wrote the two experts in a joint article in the trade magazine Tunnel (issue 8/2011).
A low-frequency sound has proved to be effective as a subliminally alarm signal.

Final breakthrough on March 23, 2011

North portal
Erstfeld
Amsteg access
tunnel

Geology as a challenge: When the Gotthard Base Tunnel was being excavated, a whole range of rock had to be drilled through. This posed big challenges for the tunnel constructors. Among other things, they had to combine mechanical excavation and blasting technology.

Emergency station
Combined station
Shaft II
Shaft I

> lights, the escape door had a pulsating laser marking the exit across the tunnel.

12,000 New Sprinkler Heads

Technical aspects of fire protection play an important role in tunnel safety, beginning with pedestrian tunnels and large underground constructions that are used by many passers-by. For example, in February 2012 Munich’s municipal utility company was awarded the distinguished “Sprinkler Protected” seal of quality, from the Federal Association for Fire Protection Technology, for the fire protection system employed at the Stachus underground complex. The seal was granted after a renovation of the complex, which is one of Europe’s largest underground structures and includes about eight kilometers of underground escape routes. As part of the renovation, the fire protection system was upgraded and 12,000 new sprinkler heads were installed.

Another type of fire protection technology was chosen by the operators of the Dartford Tunnel and the Tyne Tunnels in the UK, which are part of the M25 and M9 highways. The Tyne Tunnels have been in
An overview of tunnel construction

Shield Tunneling: A tunnel boring machine mills off the surface soil with a rotating cutting wheel. The tip of the machine is surrounded by a cylindrical shield. Depending on the site’s geology, the tunnel face is supported by a slurry under pressure or by the excavated material itself. In solid rock, the excavated material can be simply crushed and taken away. As soon as the tunnel has been excavated, the tube is firmly secured and its inner surface is lined.

Mine Tunneling: In this traditional mining procedure, holes are drilled into the existing rock so that it can be blasted apart in a targeted manner. Subsequently the miners drill tunnels through the rock with hydraulic excavators. The modern version of this traditional mining technique is called the “New Austrian Tunneling Method.”

Cut-and-Cover: This type of construction is often used to build tunnels that lie close to the surface and for large underground constructions such as subway stations. An open excavation pit is dug, the tunnel is constructed, and finally the site is covered with a ceiling. In a variant process, only the walls and ceiling are built and the excavation of the tunnel is carried out underground.

Caisson Construction: Tunnels under rivers or estuaries can be constructed by connecting a series of caissons underwater. This was the procedure used for the first three tubes of the new Elbe Tunnel in Hamburg.

operation since November 2010, and the Dartford Tunnel tubes will be equipped with high-pressure fire extinguishing technology from Fogtec, a German firm. “The extinguishing water is atomized by means of special nozzles, so that a comparatively low amount of water with extremely high surface area combats the fire,” says Dirk Laibach, Technical Manager at Fogtec.

Sophisticated Fighting Technology

The company has installed the same technology in the Eurotunnel, which lies under the English Channel between England and France. Here there are four “safe stations,” into which the truck-carrying shuttle trains are automatically guided if a fire is detected on board. Once the site of the fire has been identified by the redundantly installed measuring technology, the fire extinguishing technology, around the site, is released with a valve pressure of up to 100 bar. The water mist that is released cools the surface of the burning object immediately and simultaneously reduces the influx of oxygen.

Roland Leucker, the Managing Director of STUVA, also mentions building fire protection measures based on, for example, the construction of the inner shells of tunnels with a type of concrete that has been mixed with polypropylene fibers. In case of fire, this prevents the concrete overlay from extensively spalling off from the steel reinforcements. This type of concrete has already been used in the Crossrail Tunnels in London. Peter Thomas

For information on Dräger products:
www.draeger.com/105/tunnel