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Compressed air work with tunnel boring machines

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ABSTRACT: In general diving and compressed air works are associated with works on offshore drill rigs and production platforms in the North Sea and Baltic Sea, national and international recovery operations, refurbishments of dams and works in contaminated waters, e.g. treatment plants. The use of divers in tunnelling first seems to be unusual. For more than one hundred years, however, compressed air works have been carried out on large construction sites during tunnelling works below groundwater level and nowadays, in particular, during river crossings at very high water pressures. The diving techniques employed in conjunction with mechanized tunnelling have included diving to depths of more than 50 m using mixed-gas or saturation diving. The tasks undertaken by the divers have included welding and cutting underwater; or in a bentonite suspension; surveying, welding inspections, removing and replacing tools on the cutting wheel. This report gives detailed information on the use of divers as well as the latest developments in construction and diving technology during very complex tunnelling projects at overpressures of more than 4 bars, referring to tunnelling projects such as the '4th Elbe Tunnel' in Hamburg (Germany), the 'Wesertunnel' (Germany) and the 'Westerscheldetunnel' (the Netherlands).

1 DIVING AND COMPRESSED AIR WORK IN TUNNEL BORING MACHINES

1.1 *General information on TBM design and diving operations*

The use of professional divers in mechanized tunnel excavation is usually limited to those machines that are deployed in very complex heterogeneous geological conditions at high water pressures: Mixshields. They can safely support the tunnel face by using a pressurized liquid. Here water-bentonite suspensions are often used for the support of the tunnel face. The bentonite is used because of its geomechanical characteristics, its plasticity and its swelling capacity in the support liquid. The pressurized suspension penetrates the ground and seals the tunnel face with a possibly thin, impermeable film, the so-called filter cake that is used to generate the support pressure. This process is carried out within a relatively short time span of 1 to 2 seconds. The support pressure balances the encountered ground and water pressure and avoids uncontrolled collapses and stabilizes the tunnel face.

The regulation of the support pressure in the excavation chamber is not directly carried out via the suspension pressure but via an air cushion between bulkhead and submerged wall. Fully automatic circuits, permanently controlling the pressure conditions at the face and generating the relevant counter pressure via the support media, allow for a precise support pressure control. Thus settlement or heave is avoided between the machine and the surface, which is especially important where there is low overburden.

In this operating mode, the bentonite suspension not only serves as a stabilizing support medium but also as a slurry transport medium to remove the material excavated at the tunnel face. The spoil is pumped through a slurry line to a separation plant that is normally located outside the tunnel, where the ground and the suspension are separated and the treated suspension is fed back to the slurry circuit.

Within the protection of the tailskin of the shield, the tunnel lining of precast reinforced concrete segments are put into position by the segment erector. For excavation, the tunnel boring machine is advanced by hydraulic thrust cylinders which push against the last-built segmental ring. The gap between the extrados of the segmental ring and the ground is continuously grouted as the tunnel boring machine advances to secure the ring and to support the surrounding ground.

1.2 *Compressed air works during mechanized excavation*

Work in compressed air (compressed air work) is carried out at an air pressure above atmospheric pressure. The compressed air work at overpressure in the excavation chamber can present serious health hazards to the personnel. Thus medical checks are mandatory prior to the works to ensure that the workers are fit for this type of work. Important health and safety regulations must be observed and complied with.

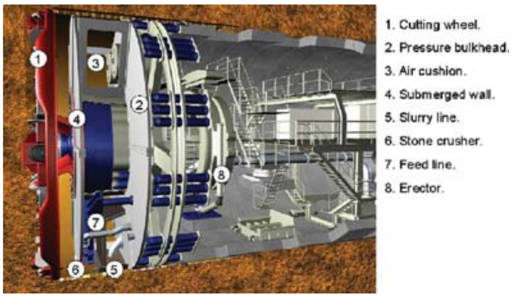

Figure 1. Functional Principle Mixshield (Shield Tunnelling with liquid supported tunnel face).

Divers also work under hyperbaric conditions as soon as they move below the water surface. The exposure to overpressure implies serious health hazards to the personnel even if the compressed air works are appropriately organized and monitored. According to the 'Regulations for Compressed Air Works – ('DruckluftV' of 1972) – the staff must not carry out works at an overpressure of more than 360 kN/m^2 (3.6 bars/52.2 PSI).

From 4.0 bars/58 PSI overpressure (40 m (131 ft) water column) upwards, the extended decompression times for the compressed air personnel and the reduced working time reaches a levels where it is no longer viable to carry out compressed air works in the conventional way. Here the use of divers is required. There is no pressure limit for diving. With compressed air as breathing air, the diving depth is limited to 50 metres (500 kPa or 5.0 bars overpressure). Breathing-gas mixes allow diving depths of more than 100 meters (328 ft) and operation times of several days or weeks using saturation methods.

Based on three prestigious projects, compressed air works and diving, that have become vital for mechanized excavation, will be explained in more detail.

1.3 *Compressed air works and diving during the '4th Tunnel under the River Elbe project'*

During the construction of the '4th Tunnel under the River Elbe', a Mixshield was deployed with a liquid supported tunnel face. The TBM was 14.2 m diameter and the special requirements of the project (an overburden of only 7 m between the top section of the tunnel and the river bed of the 'Elbe' at the most critical point) put the personnel and the technology to the test.

The geological conditions, in particular, the presence of large boulders, required a cutting wheel equipped with mixed cutting tools consisting of cutter discs as well as soft-ground cutting tools. The possibility to excavate boulders with sizes of 0.8 m up to 1 m with groups of cutter discs has been proven in practice.

The cutting wheel consists of five main and five additional spokes and is equipped with 120 soft-ground cutting tools as well as 31 cutter discs.

Due to the low overburden at pressures of up to 5 bars, a conventional access to the working chamber (lowering of the compressed air support) was considered critical. Since a cutting tool change had to be expected, a complete set of cutters was installed on two levels.

The first level comprised soft-ground cutting tools that were arranged correlatively with the cutter discs. The latter could only be exchanged after a conventional access.

The second level was equipped with cutting knives (scrapers) that could be exchanged from within the accessible spokes without lowering the slurry in the excavation chamber. This also applied for the cutter discs.

Additionally, the machine was equipped with all installations required for diving operations in the excavation chamber.

The cutter tools can partially be exchanged under atmospheric pressure from the five accessible main spokes and, in part, from the tunnel face under overpressure conditions.

To allow for a cutting tool change without lowering (fully maintaining the liquid support), another step (cutting tool change in the arm with exchange unit) was inserted between the conventional cutting tool change and the diving.

This was achieved through accessible spaces within the cutting wheel and depressurization valves located behind the cutters. The spaces within the cutting wheel could be accessed via the cutting wheel center, at atmospheric pressure or under hyperbaric conditions. Here the cutting tool change under atmospheric pressure in the cutting wheel arm was carried out as follows:

Each cutting disc is mounted in a pressurized housing with a hydraulically operated gate valve. The cutting disc is held in position by a hydraulic cylinder whilst the mounting bolts are removed. The cutting tool is then withdrawn and the gate valve is closed sealing the housing off from the face.

A crane attachment is then used to remove the worn cutting disc to be replaced with a new disc.

The same method is used for the replacement of scraper tools located in the five main cutting wheel spokes.

This development is part of the safety concept.

The tools on the first level could only be exchanged after a conventional access. Thus a new method for 'works in compressed air' was, for the first time, implemented during the construction of the project '4th Tunnel under the River Elbe'. During the planning phase, the use of divers was already considered for maintenance and repair works to the cutting wheel equipment. An operation program for potential diving

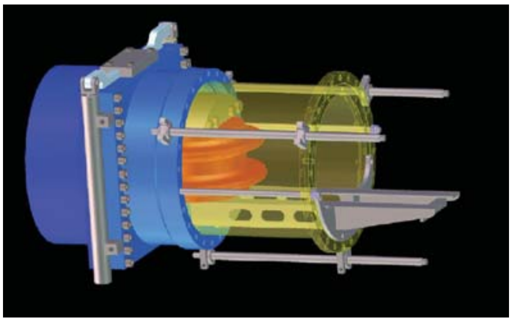

Figure 2. Cutting tool change under atmospheric conditions.

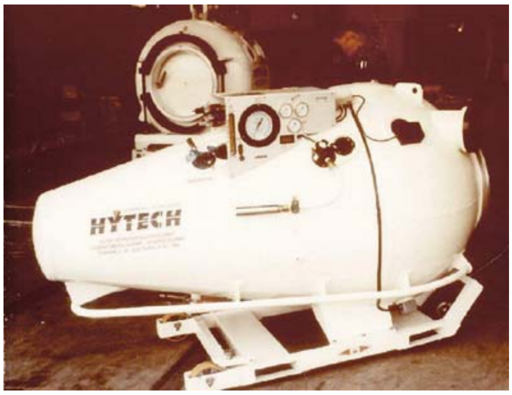

Figure 3. Emergency/Transport chamber to evacuate injured personnel from the pressurized zone to the surface.

works in bentonite as well as compressed air works at overpressures up to 5.5 bar was formulated in cooperation with the joint venture partners: 'Bilfinger + Berger', 'Hochtief AG', 'Wayss & Freytag AG', 'Philipp Holzmann AG', 'Dykerhoff und Widmann AG', 'Züblin AG', 'Heitkamp GmbH' (construction companies), the 'Amt für Arbeitsschutz' (Occupational Health and Safety Authority), the 'TBG' (The Employer's Liability Insurance Association for Underground Works) and the 'Nordseetaucher GmbH' (diving company).

A special team of nine divers was formed and prepared for the diving operations.

The tunnel boring machine was equipped with additional technology and a rescue system for the diving operations specially adapted to the machine. Claus Mayer working with 'Nordseetaucher GmbH' was senior manager in charge of this special operation.

Since the available decompression tables for works under hyperbaric conditions were insufficient, the works were partially based on the 'Druckluftverordnung für die Taucherarbeiten' (Regulations for Diving Operations in Compressed Air) and the French tables 'Air Oxy 12 M'.

For the diving operations, a special container with control and supply units was located on the tunnel boring machine, equipped with an individual air supply and communication system, independent from the Mixshield.

For the first time, a supply flange, specially adapted to the diving operations, was mounted on the bulkhead for:

- the supply of breathing and reserve air,
- the communication and lighting cables,
- the video and depth control units as well as
- the water and hydraulic connections for tools (impact drill, FLEX grinder and split-type drill rigs)

When accessing the excavation chamber for maintenance and repair works, the divers used specially adapted offshore diving helmets (Kerby Morgan 27), fitted with a water flushing system to prevent the breathing membranes of the air regulator from sticking together in the bentonite suspension.

The TBM is equipped with three man locks to pressurize the operating personnel and the divers, two man locks Ø2, 000 mm in the top section of the shield and one man lock in the center Ø1, 640 mm. The man locks consist of two independent chambers that are sequentially arranged (prechamber/main chamber). The prechamber serving all locks provides space for two persons, the main chamber (lock DN1600 mm) is designed for three persons and the main chambers (locks DN 2000 mm) for 5 persons each.

The prechambers are normally not be pressurized to allow additional personnel to access the main lock to assist with the evacuation of injured persons from the working chamber.

A door connects the main chamber to the working chamber in the cutting wheel. Each lock is equipped with a clock, a thermometer and the pressure gauges that display the pressures required for pressurizing and decompression. Each lock chamber can be pressurized or depressurized from the inside or the outside. A full-stroke safety valve limits the pressure to 5.5 bars.

Outside the man lock, additional pressure gauges are installed to display the air pressure measured in the pre- and the main chamber as well as in front of the bulkhead. A multi-band recorder registers the different pressures.

Optionally a transport chamber (with a Nato-connection flange) can be docked on to these locks during the works in compressed air to evacuate injured persons via the transport system (train) on the machine and out of the tunnel in an emergency. Above ground, the transport chamber can then be docked on to a recompression chamber where the necessary measures can be taken that are required for treatment. However, no emergencies occurred during the entire period of

Figure 4. Soft rock tunnel face – tool change at 3.5 bar at the 4th tube Elbe Tunnel (Hamburg, Germany).

the tunnelling works. The emergency chamber is part of the safety concept in order to safely evacuate injured persons from the pressurized zone to the surface.

During the tunnelling works on the site '4th Tunnel under the River Elbe' in Hamburg, a total of 10,920 hours were worked in compressed air, 6,603 of which in the pressure and excavation chamber. A total of 2,738 pressurizations of personnel were carried out, 237 pressurizations of which above 3.6 bars, 21 cases of decompression sickness occurred, all in a pressure range up to 3.6 bars.

Regarding the cutting tool change times, it needs to be mentioned that, approx. 13 hours were initially required for a cutting tool change under atmospheric conditions in the accessible spokes without particular complications. Since this time effort was considered too costly, several options were evaluated to reduce the working time. Through organizational improvements and modifications in terms of the existing cutter exchange design, the assembly time could be reduced from 13 to 6 hours.

With divers conventionally accessing the pressurized working area, approx. 8 cutter discs could be changed within about two hours compared with 2 to 3 hours required for a double disc cutter, depending on the type and volume of the muck to be cleared.

1.4 *Works in compressed air during the crossing of the river 'Weser' project in Mixshield mode*

In Dedesdorf, Germany, a Mixshield ø 11.67 m was deployed during the crossing of the river 'Weser'. Two parallel road tunnels, each with a length of approx. 1,635 m, were driven in very varying ground with heterogeneous formations.

The Wesertunnel is the first onshore traffic link north of Bremen crossing the river 'Weser'. Before, ferries connected the cities 'Nordenham-Blexen' and 'Bremerhaven', 'Kleinsiel' and 'Dedesdorf' as well as 'Brake and Sandsted'.

The shielded tunnel boring machine was designed for an operational pressure of 5.5 bars.

In this tunnelling mode, the support pressure is generated via an air cushion in the working chamber. The pressure communication between the chambers is carried out through the submerged wall opening. Even in case of clogging at the submerged wall opening, the pressure communication can still be maintained. This is achieved by additional compensation lines, connecting the invert area of the working chamber with the excavation chamber. The regulation of the air-cushion pressure is carried out through a redundant compressed-air regulator.

The 'Mixshield concept' allows for a pressure compensation from the atmospheric zone behind the bulkhead or from the working chamber, when the suspension level is lowered for accessing the excavation chamber.

Requirements such as low overburden and high water pressures, during projects with large TBM diameters, led to a situation where the suspension level can often be lowered by only one third in order to access the excavation chamber. In this case, it is mandatory to close the submerged gate valve. By closing the submerged wall gate valve, the principle of 'communicating pipes' is suspended. Additional units in form of pressure basins that are connected separately to the excavation chamber then serve as air cushion to support the tunnel face.

Maintenance and inspection works below the partially lowered bentonite level or at pressures higher than 3.6 bars were carried out by divers. The working chamber could be accessed via two double-chamber manlocks.

Regarding the diving operations, the following difficulties occurred during the compressed air works:

- tide-related pressure variation up to 0.4 bar per tide,
- compressed air works up to 4.5 bars for operations on the cutting wheel,
- compressed air works up to 5.0 bars for operations in the shield invert,
- use of divers up to 5.0 bars for operations in bentonite.

During the construction of the two 'Wesertunnel' tubes, the maximum admissible limit for compressed air works of 3.6 bars was exceeded at the deepest point due to compressed air operations at approx. 5 bars. Since the tunnel had to be driven 4 m below the planned tunnel alignment due to a modification of the operating program, the 'Druckluftverordnung für Arbeiten in Druckluft' (Health and Safety Regulations for Works in Compressed Air) and the H & S regulations 'VBG 39' (now 'BGV C 23') could, at times, no longer be observed. To be able to carry out compressed air works above the maximum admissible working pressure of 3.6 bars, a special authorization was required.

In cooperation with the responsible 'Occupational Health and Safety Authorities' 'TBG' and 'GAA-Oldenburg' as well as the 'Nordseetaucher GmbH' (diving company), a method was developed to comply with H & S regulations during compressed air works or diving operations at overpressure by the JV 'Wesertunnel' consisting of the companies 'HOCHTIEF AG', 'Philipp Holzmann AG', 'Ludwig Freytag GmbH & Co. KG', 'Heinrich Hecker GmbH & Co. KG' and 'Martin Oetken GmbH & Co. KG'.

During works at pressures of up to 5 bars, that had to be faced during this project, the ratio between the efficient working time at overpressure and the required decompression time has already now become uneconomical and borderline, e.g. reaching the physical limits of the personnel. Thus the involved parties ('Nordseetaucher GmbH', 'TBG' and 'GAA-Oldenbug', JV 'Wesertunnel', the hyperbaric doctor) issued the following framework regarding health and safety regulations for staff working at overpressure:

- common charts based on the 'Regulations for Works in Compressed Air' up to 3.6 bars and 'Air Oxy 12 M up to 5.0 bar'.
- in principle, depressurization with oxygen.
- an oxygen break of five minutes after a maximum of 30 minutes in compressed air.
- use of a 'hyperbaric assistant' as link between the personnel and the hyperbaric doctor.
- additional 'trial pressurizations' of the entire staff in the emergency chamber prior to the first operation above 3.6 bars.
- Reduction of the maximum working time at overpressure:
  - for the first exposure
  - after a longer working break
  - for extreme physical works.
- regular training of the tunnelling staff for operations at overpressure up to 5.0 bars.
- training of the doctors on call by the hyperbaric doctor.
- training and test of the personnel as to the appropriate conduct before, during and after pressurization/decompression.
- training of the lock attendant by the hyperbaric assistant and the hyperbaric doctor.
- regular assistance by the hyperbaric doctor of the compressed air works
- extension of the waiting time on site to 2 hours after an operation at an overpressure of more than 3.6 bars.
- a prophylactic 30-minute oxygen treatment at 0.9 bar in the emergency chamber for travel distances of more than 100 km after work.
- alarm system for the operating personnel, the doctors on call as well as the divers.

Figure 5. Special flanged connections installed at the bulkhead to allow manned interventions to be carried out in the bentonite.

Figure 6. Diving helmet for diving in bentonite.

This concept for Works in Compressed Air has been proven in practice and needs to be adapted to the information and conditions determined by the project requirements and the operation. Thus it is possible to safely access the working chamber at overpressure without exposing the 'compressed air personnel' to serious health hazards.

For diving in bentonite, special flange connections are installed at the bulkhead of the tunnel boring machine (figure 5), providing the divers and the personnel under hyperbaric conditions with breathing and reserve air, communication, lighting, video and data transmission as well as drinking water for the air regulators in the diving helmets.

The diving equipment consists of a diving helmet supplied through an 'umbilical'.

With pressures of up to 5 bars, the works were similar to offshore works. Thus a diving helmet (figure 6), comparable to those used during offshore diving, was specially adapted for the operations in bentonite. To make it easier for the divers to breathe in the bentonite suspension, the diving helmet was fitted with a water-flushing unit for the air regulator. The drinking water prevents the breathing membranes from sticking together. The diving helmet is designed as hard hat that is connected with a diving suit. The air volume within the helmet and suit is constantly flushed with compressed air.

The 'umbilical' (figure 7) is the 'umbilical cord' for divers consisting of hoses and cables for the supply of air, emergency breathing air, drinking water, communication, lighting, video and data transmission.

For works in the working chamber, the diving equipment and the required tools are pressurized via a material lock in the working chamber. Following this, the operating personnel are pressurized. The latter consists of two divers, one 'signal person' and one assistant. Prior to the works, the excavation chamber is inspected for possible overhangs and cloggings at the cutting wheel for risk prevention. The maintenance and repair works then start and the cutting tools are inspected for potential faults or damage. If a cutting tool change becomes necessary the required equipment, tools and auxiliaries are mounted on the submerged wall and the cutting wheel and the worn or defective cutting tools are exchanged and depressurized. Figure 7 shows a diver during a maintenance and inspection operation below the partially lowered bentonite level. After completion of the works, the required tools and auxiliaries are disassembled and the connection door to the excavation chamber is closed. The divers return to the lock, where they are depressurized.

At pressures between 4 and 4.2 bars, a cutter disc was changed within approx. 2 to 3.5 hours. The change of 12 soft-ground cutting tools could be carried out within 2 hours, depending on the type and volume of the clogging.

1.5 *Excavation with saturation diving during the construction of the 'Westerscheldetunnel'*

The most demanding diving operations in tunnelling were carried out during the project 'Westerschelde' in the Netherlands. Here the experiences gained during the projects '4th Tunnel under the River Elbe' and 'Wesertunnel' could be used. While pressures up to 5 bars had to be mastered on the 'Elbtunnel' site and overpressures of up to 5.5 bars during the 'Wesertunnel' project, hyperbaric conditions of up to 8.5 bars were expected on the 'Westerscheldetunnel'. During works at an overpressure of up to 8.5 bar, compressed air can no longer be used, since the nitrogen contained in the breath causes narcosis with increasing depth. The nitrogen is replaced by helium. During the design phase, the use of mixed gases was already planned. Mixed gases consist of oxygen with different inert gases. Depending on the pressure ranges that had to be expected, operation times of several days and weeks (saturation method) are possible. To smoothly carry out saturation diving, the TBM technology and

Figure 7. Use of divers for maintenance and repair work in the working chamber.

logistics needed to be designed in compliance with the requirements for saturation diving and rescue technology, already in the planning phase. The required technology was successfully designed and implemented by the diving company 'Nordseetaucher GmbH'.

Saturation diving is a long-term stay at overpressure. All tissues are 100% saturated with inert gases, i.e. an increase of the diving time leads to a longer decompression phase. This technology makes diving operations at depths of more than 150 m more efficient, since the divers can stay pressurized (depending on the working depth) until the completion of the works.

To allow the divers during the project 'Westerscheldetunnel' a long-term stay under hyperbaric conditions, a chamber system was planned, consisting of two pressurized living chambers outside the tunnel. This chamber system, containing all the necessary facilities such as berths, showers and toilets, can take on a maximum 12 divers and technicians.

Since it was not possible to install the saturation unit in the tunnel and to dock it on to the tunnel boring machine, a mobile transport system (shuttle) was manufactured. The shuttle can transport up to 4 divers under hyperbaric conditions. The shuttle collects the divers at the living chambers outside the tunnel (figure 8, right) prior to their diving operations. It transports the divers into the tunnel and docks on to the left manlock (DN 2000), in direction of advance (figure 9). This lock is equipped with a 'NATO' flange which allows the transport shuttle to dock on and also provides access to the working chamber.

In contrast to the 'Elbtunnel and Wesertunnel' projects, it was impossible to work at pressures of more than 4.5 bars with compressed air. Mixed gases were used instead, consisting of helium, nitrogen and oxygen. The special gas mixes reduce the absorption of the dangerous nitrogen in the blood. The oxygen content of these gas mixes is higher and its nitrogen content lower compared with normal breathing air.

Figure 8. Transport shuttle.

Figure 9. Transport shuttle before docking on the manlock.

The diving equipment is similar to the equipment that has already been successfully used during other tunnelling projects. For the works in the partially lowered conditions under the river 'Westerschelde', lightweight diving helmets used in the chemical industry were provided, specially adapted for this task. The special diving helmet is equipped with two air regulators and a controllable cooling system, since the temperature at the tunnel face can reach up to 60 degrees centigrade. All necessary tests prior to the works, were carried out at the Belgian Navy's Hyperbaric Center in Zeebrugge.

During the operation in the bentonite suspension, about 7 to 10 soft-ground cutting tools could be changed within 3 to 4 hours during one diving shift. The change of a double disc could be carried out in approx. 1.5 diving hours.

In total, five excursions in saturation were performed with a total saturation time of more than 40 days. The decompression time at working pressures

Figure 10. Special diving helmet (hyperbaric helmet) for application in hyperbaric conditions at 6.9 bars.

up to 6.9 bars was 4 days each time. In addition, six excursions were performed with mixed gas and 1,652 hours with compressed air involving 546 transfers. Five cases of decompression sickness (DCS) occurred, all of which could be treated in the on-site emergency chamber.

2 CONCLUSION

The above stated projects are exemplary for diving operations and compressed air works under extremely complex conditions at high pressures. Due to their technical profile, the qualified professional divers are an integral part of the day-to-day operations on a mechanized excavation site. The divers are permanently exposed to dangerous pressurization and depressurization transfers during their work in order to provide a smooth excavation process. State-of-the-art equipment is deployed, in accordance with the latest technologies in construction and diving and in compliance with national as well as international health and safety requirements. Good qualifications of the divers and compressed air workers involved, the permanent training as well as the adaptation of the tunnel boring machines to new requirements, make it possible to carry out technically challenging projects with success.

The experiences, that we have gained up to now, show that new methods for compressed air works in tunnelling were found that pave the way for increasingly complex projects with growing requirements in terms of TBM and diving technology. Only through a close cooperation between all parties involved in such a complex project, we will be able to continue a successful and innovative implementation of difficult projects.