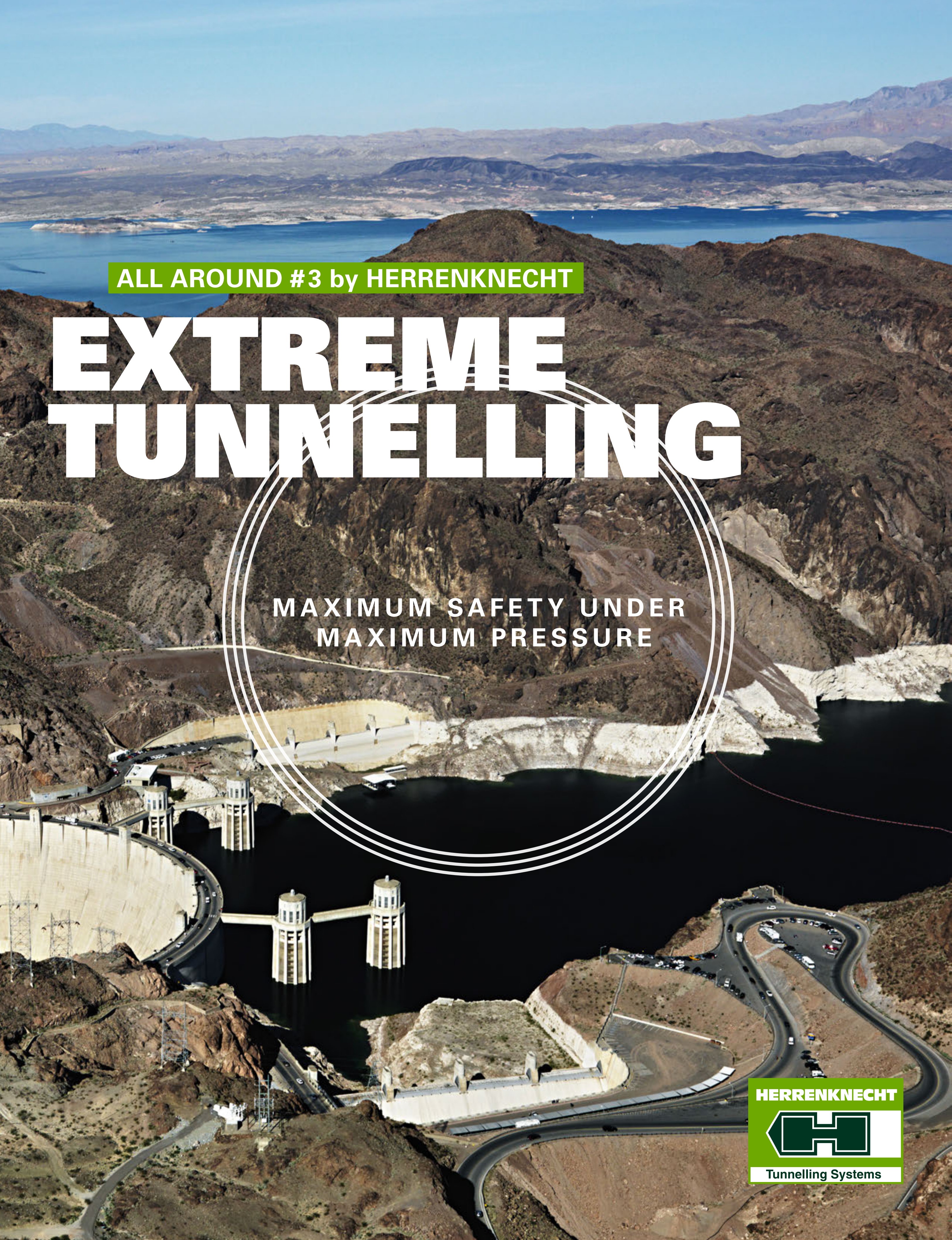

ALL AROUND #3 by HERRENKNECHT

EXTREME TUNNELLING

MAXIMUM SAFETY UNDER
MAXIMUM PRESSURE

HERRENKNECHT
Tunnelling Systems

LATEST TUNNELLING TECHNOLOGY FOR GROUNDBREAKING MISSIONS

Technical progress is driving tunnel construction forward. In partnership with clients, planners and construction companies, Herrenknecht is developing tunnelling technology to produce safe, reliably high quality and very long-lasting tunnel structures even in new, highly complex terrain. Here you get insights into high-profile pioneering projects and their technology that exemplify profound progress in tunnel construction.

◀ **A milestone in tunnelling:** Since 2013 a tunnel passes directly through the Hallandsås mountain range in Sweden — mastered with tunnelling technology from Herrenknecht.

▲ **Tunnelling at the limit:** in pioneering projects such as the Bosphorus crossing in Istanbul, safety for man and machine plays a crucial role.

BREAKING NEWS

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MAXIMUM SAFETY UNDER MAXIMUM PRESSURE

EXTREME TUNNELLING

Author: Georg Küffner

A large road tunnel deep beneath a strait, a railway tunnel through an enormously complex mountain range, a water tunnel under tremendous ambient pressures: mechanized tunnelling is penetrating into new terrain underground. True partnership with contractors and project owners leads to pioneering developments in machine technology. Integrating knowledge from professional offshore diving also contributes to significant progress in tunnel construction.

"That can't be done!" – This sentence is only true until the contrary is proved. For engineering achievements in particular: boundaries are motivation and never a limit. Bigger, faster, deeper, further – and at the same time always safer. That's the motto in mechanized tunnelling.

PUSHING THE BOUNDARIES OF THE POSSIBLE

The real engineering challenges await deep down in particular. In geologies under extreme pressures and where ground, sea or river water penetrating through fissures and other anomalies affect tunnelling. The example of a water intake tunnel under Lake Mead shows how the geotechnologically difficult excavation of such tunnels can be accomplished.

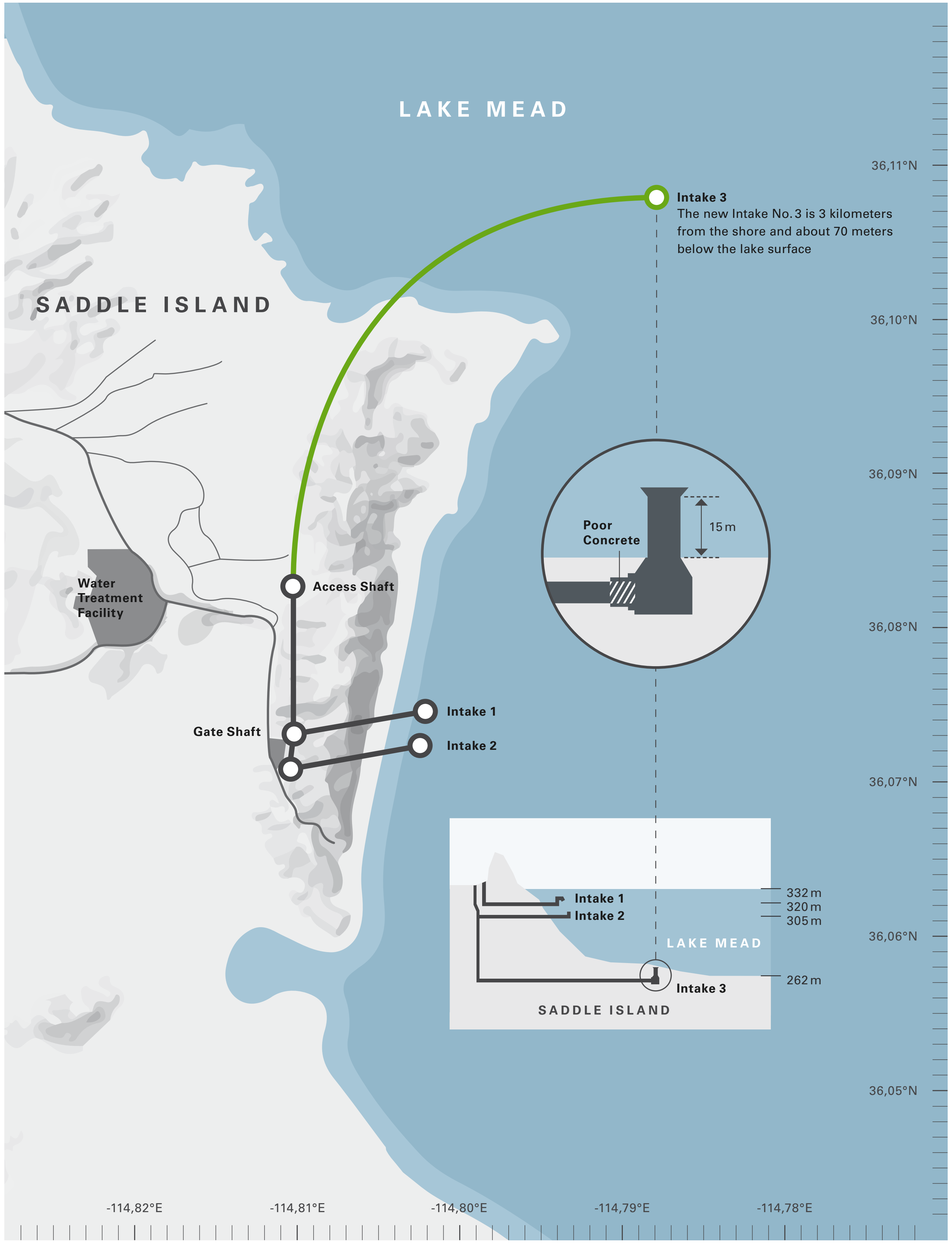
Like a blue diamond the largest reservoir in the United States lies about 50 kilometers southeast of Las Vegas, in the middle of the desert between Nevada and Arizona. Here the Hoover Dam, completed in 1935, dams the Colorado River: over a length of 170 kilometers and with a depth of up to 150 meters. The maximum storage capacity is an almost unimaginable 35 billion cubic meters of water – enough to supply Germany's private households for about ten years.

But Lake Mead is no longer full to the brim. Since 1998 its level has constantly dropped – as a result of a previously unprecedented drought phase. Meanwhile its water level is at an historic low: only 332 meters above sea level. This means the water stands just a few meters above the two existing intakes – and threatens the water supply.

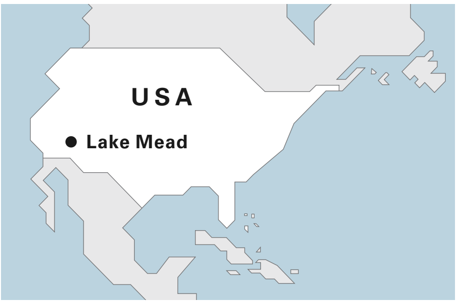
THIRD OUTLET TO SECURE WATER SUPPLY

A new, third outlet must be built. The planned "Intake No. 3" is approximately 70 meters below the lake surface and about 3 kilometers from the shore. The intake structure extending 15 meters vertically from the lake bed was lowered from a floating barge into a previously excavated pit. The foundation was then poured with underwater tremie concrete, fixing the structure in place.

The actual "Intake No. 3" consists of a 4.4 kilometer long, slightly ascending tunnel that the Herrenknecht TBM S-502 with an outer diameter of 7.2 meters excavated directly below the lake. Precisely to the centimeter it penetrated the specially made entry into the "soft eye" of the intake structure. Before that, for about three years the specially adapted Multi-mode TBM had worked its way through complex geologies with shattered rock and clay partly filled with water from the lake.



Lake Mead: The Lake Mead reservoir near Las Vegas is fed by the Colorado River and is the main water source of the gambling capital. Mineral deposits on the shores document the historically low water level.



The abrasive geology in conjunction with the high water pressures took **steel** and **seals** to the **absolute limit of their endurance.**

NEW RECORD FOR WATER PRESSURE

Due to the working depth – under water pressure rises one bar every ten meters – over large parts of the tunnelling route an enormous water pressure of up to 15 bars weighed down on the machine: an absolute innovation in mechanized tunnelling. Until then the record was 11 bar in places, set by a Herrenknecht TBM used to excavate the Hallandsås railway tunnel between Gothenburg and Malmö, completed in 2013.
The geological and hydrological conditions were very challenging to the construction team of Salini-Impregilo. On numerous occasions tunnelling had to be stopped and parts replaced. The abrasive rock under Lake Mead had destroyed the center disc cutters and parts of the cutterhead. Also the bearing seals were considerably affected by the high pressure and had to be replaced.

THE SEARCH FOR THE RIGHT SOLUTION

Everyone involved had asked themselves the right question long before the project began: how must a TBM be designed so it can constantly withstand such high, previously unmanageable pressures? On the one hand, by including more steel and making the walls thicker. After all, at 15 bar water pressure, 15 kilograms of pressure weigh down on every square centimeter of the shield – with a total length of 16 meters and a diameter of more than seven meters that adds up to a huge load. Secondly, with seals that are robustly designed, such as on the main bearing and the tailskin. Furthermore, it must be ensured that even under the extreme pressure conditions both routine work such as cutter changes and unscheduled maintenance can be performed. Based on the information gathered, Salini-Impregilo decided to use a Multi-mode TBM from Herrenknecht. In good, stable formations it worked in so-called open mode. Here the rock, broken into palm-sized chips by the cutterhead's disc cutters, is mechanically removed from the working area. That happens quickly and is efficient. The S-502 makes "way": four or five centimeters per minute. At times it ate its way forward by more than 100 meters a week through rough terrain.

After around <u>3 years of tunnelling</u>, in late 2014 the Herrenknecht <u>Multi-mode TBM</u> drove exactly through the entry construction of the new intake.

3

NOT EVERYTHING GOES ACCORDING TO PLAN

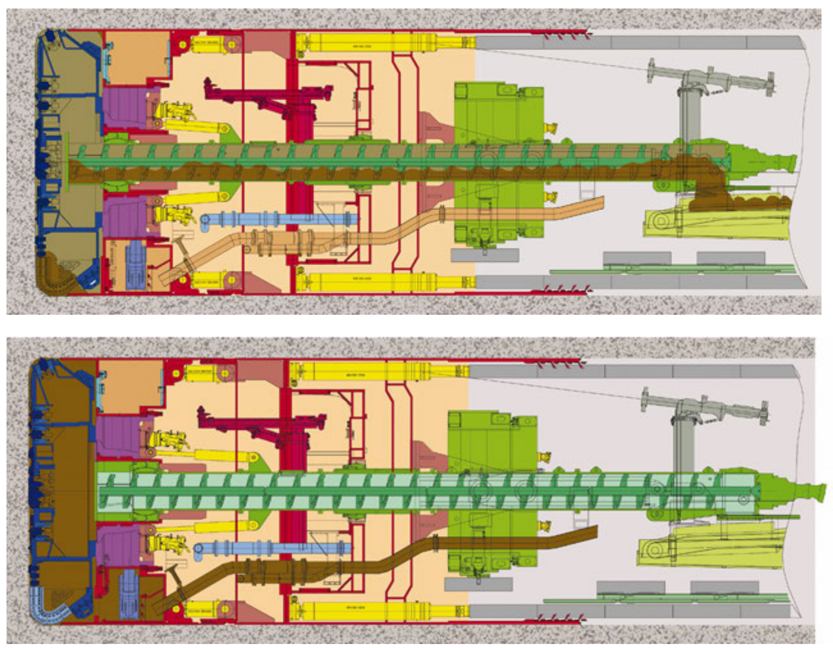
Only about 40 percent of the route could be driven at speed in open mode, however – instead of the planned 70 percent. The geology and the water inflow at the tunnel face made it necessary that the majority of the distance was completed in time-consuming and wear-intensive closed slurry mode. Here a liquid medium under pressure – usually a bentonite suspension – stabilizes the ground at the tunnel face. Together with the suspension the excavated material is pumped out of the working chamber via a slurry circuit. In this way even fluctuating pressure conditions can be controlled very precisely.

The change from open to closed mode has to be quick because of potential high water flows at high pressure. The specification for the Lake Mead TBM says the machine must be able to be sealed within 120 seconds. To do this the main chamber is locked by closing the rear discharge gate of the screw conveyor.

▼ Due to the changing ground conditions along the tunnel route, the contractor opted for a **Multi-mode machine** from Herrenknecht.

CHALLENGING CHAMBER INTERVENTION

Closed, safe, easy going? No way! Because even if the tunnel boring machine digs in the secured slurry mode, cutterhead and cutting tools require regular inspection and maintenance. Various monitoring systems collect all important tunnelling parameters in real time via sensors and record them. This data serves as a basis for the machine operator to decide when chamber interventions are necessary. But data analysis is only the first step. The actual replacing of the disc cutters, scrapers and buckets, however, is exhausting, time-consuming manual work.



▲ Depiction of the two **tunnelling modes** open (with horizontal screw conveyor) and closed (with slurry circuit).

▲ During assembly in Germany the further developed **lock systems** for the disc cutters were extensively tested.

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ATMOSPHERIC CUTTER CHANGE WITH LARGER DIAMETERS

When tunnelling under high pressure the concept of accessible cutterhead arms has proven itself. The special design feature was first used successfully at 4.5 bar during construction of the 4th Elbe River Tunnel in Hamburg with a Mixshield in 1998. In tunnel boring machines with a diameter ≥ ten meters the cutterhead arms can be formed as accessible hollow boxes. Under atmospheric pressure they are then accessible, worn or defective tools can be replaced relatively easily through the rear area of the cutterhead. Over the past two decades Herrenknecht has continuously developed this principle further and adapted it for significantly higher pressures.

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FRONT RUNNER

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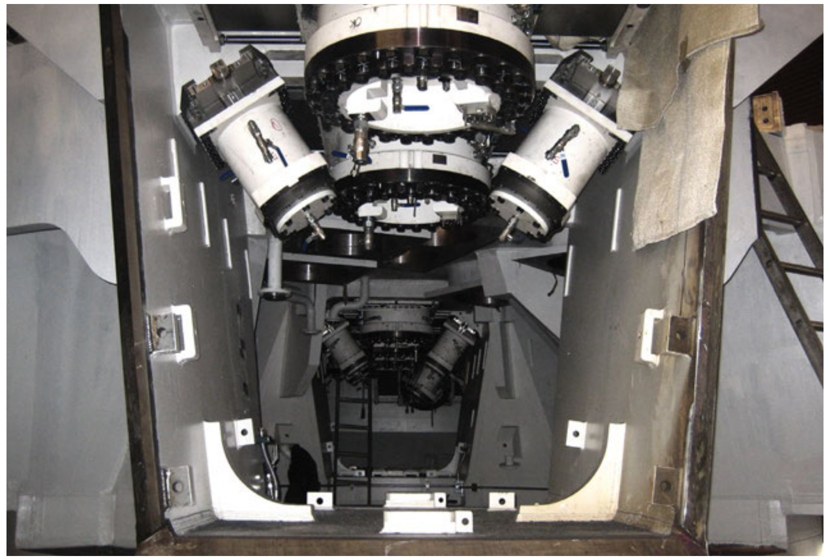
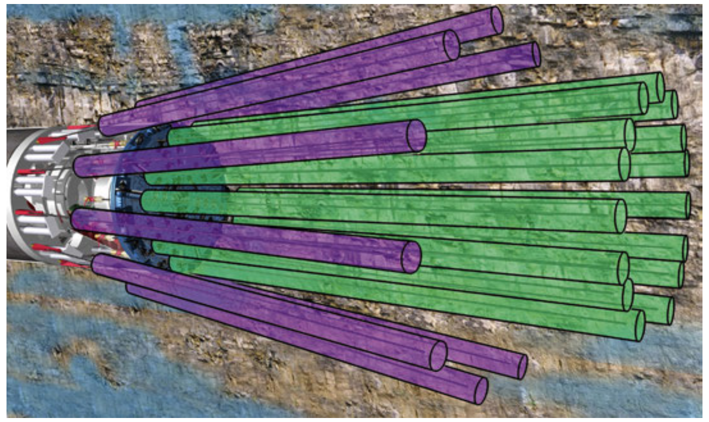


Starting at a diameter of about 10 meters, the cutterhead arms can be made accessible for atmospheric cutter change.

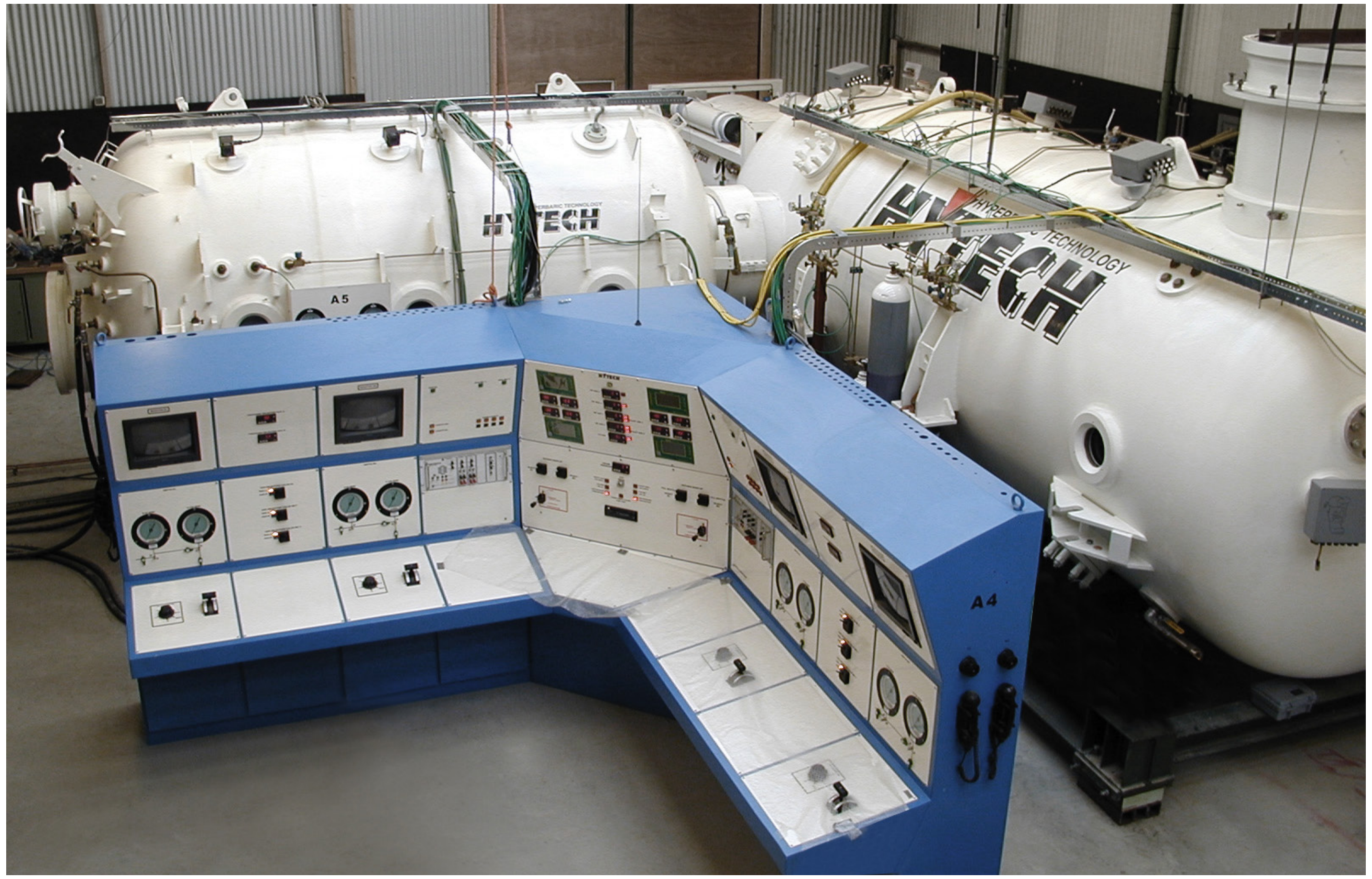
Maintenance work on the front of the cutterhead of the **Lake Mead TBM** in extremely cramped conditions in the shelter of a “safe haven”.



With the help of drilling rigs, **grouting** can be used to create artificial maintenance zones along the tunnel alignment. This method cannot always be used, however.

INTUITION NEEDED DURING TUNNELLING

Due to the cramped conditions, TBM diameters of less than ten meters do not allow accessible cutterhead arms to be included in the design – as at Lake Mead, for example. Atmospheric chamber interventions are not possible. In this case cutter changes or maintenance work can only be carried out in so-called “safe havens”. They allow safe access to the excavation chamber. Encountering such a natural, stable zone along a tunnel alignment, however, is a happy coincidence. It is not the rule.
Here the experience and intuition of all project partners is called for: do you take the risk and continue tunnelling a certain distance further in the hope of reaching a safe zone soon? Or are the cutters so worn that you have to act immediately? Safe havens can also be created artificially, for example by means of pre-excavation ground improvement with drilling rigs on the TBM or from aboveground. This is very time- and cost-consuming, however, and not always possible.



Saturation diving is an extremely complex process: from the living container (above) to the transfer shuttle to the TBM (right), everywhere project-specific special designs are necessary to maximize the safety of the divers.

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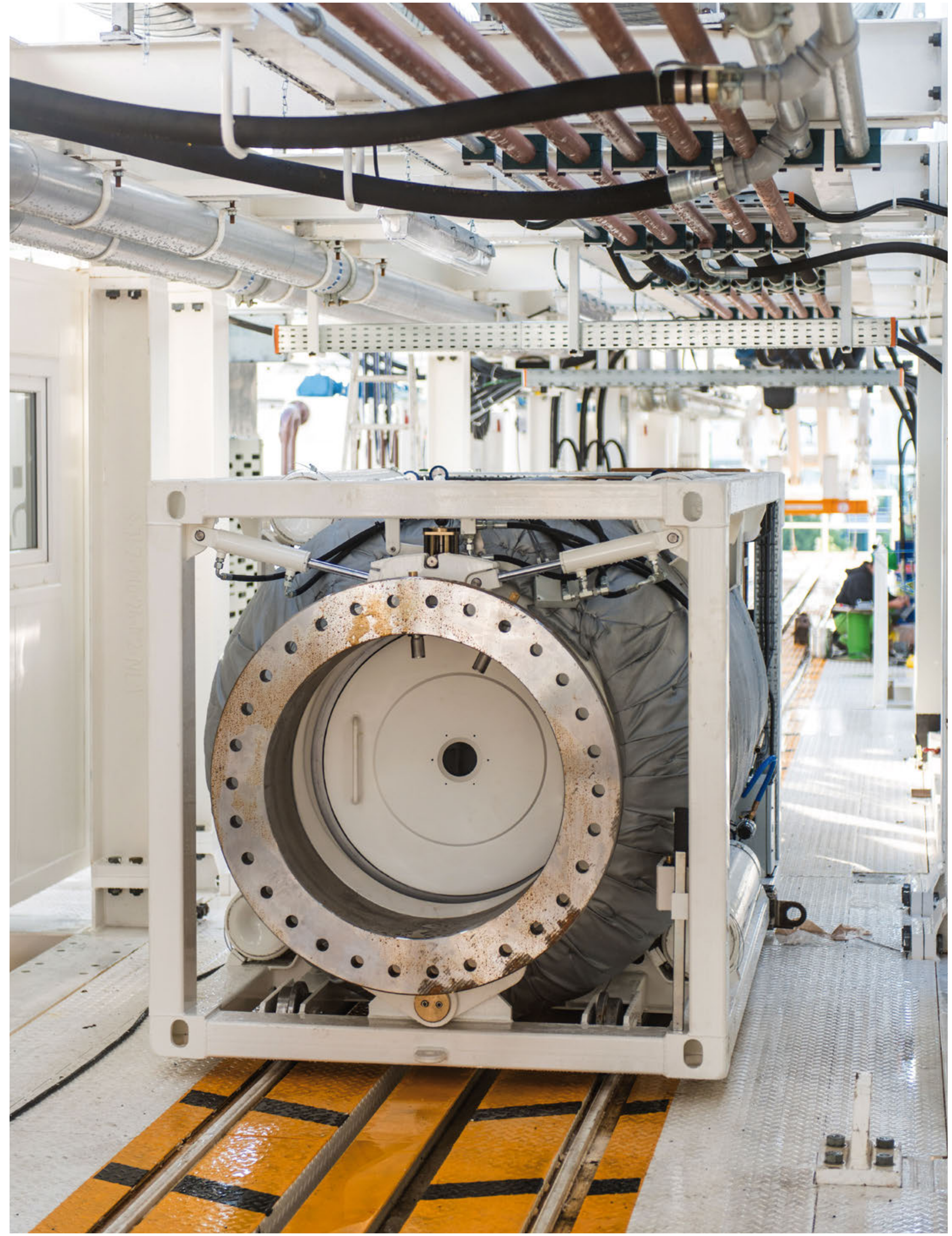
SATURATION DIVING AS A LAST OPTION

In the worst case you turn to the fallback solution: you send divers into the pressure area of the TBM. First experiences with this method were also gained during construction of the 4th Elbe River Tunnel in Hamburg. There the bucket supports needed to be rewelded and the buckets themselves replaced. The operation took six weeks – at pressures of up to 4.5 bar and thus in pressure ranges divers can only exceptionally still enter with "normal" compressed air.
At depths such as under Lake Mead and a pressure of up to 15 bar, that no longer works. Here you have to draw on experience from the "offshore sector". Saturation diving is the magic word. It makes use of the fact that under high pressure the gas intake of the human organism is eventually limited (saturated) – and hence decompression times have a natural, manageable limit.



▲ **A look inside a transfer shuttle.** Depending on the task, saturation divers spend up to several weeks at a time in positive pressure.

PREPARED FOR ALL EVENTUALITIES

At the Lake Mead project, jobsite and machine were ideally prepared for saturation diving up to 15 bar. For this a seamless positive pressure transport route was designed and implemented. This leads from the (pressurized) living chamber in the area of the launch shaft, in which the divers sometimes live for weeks, to the pressure lock in the front shield area of the TBM.

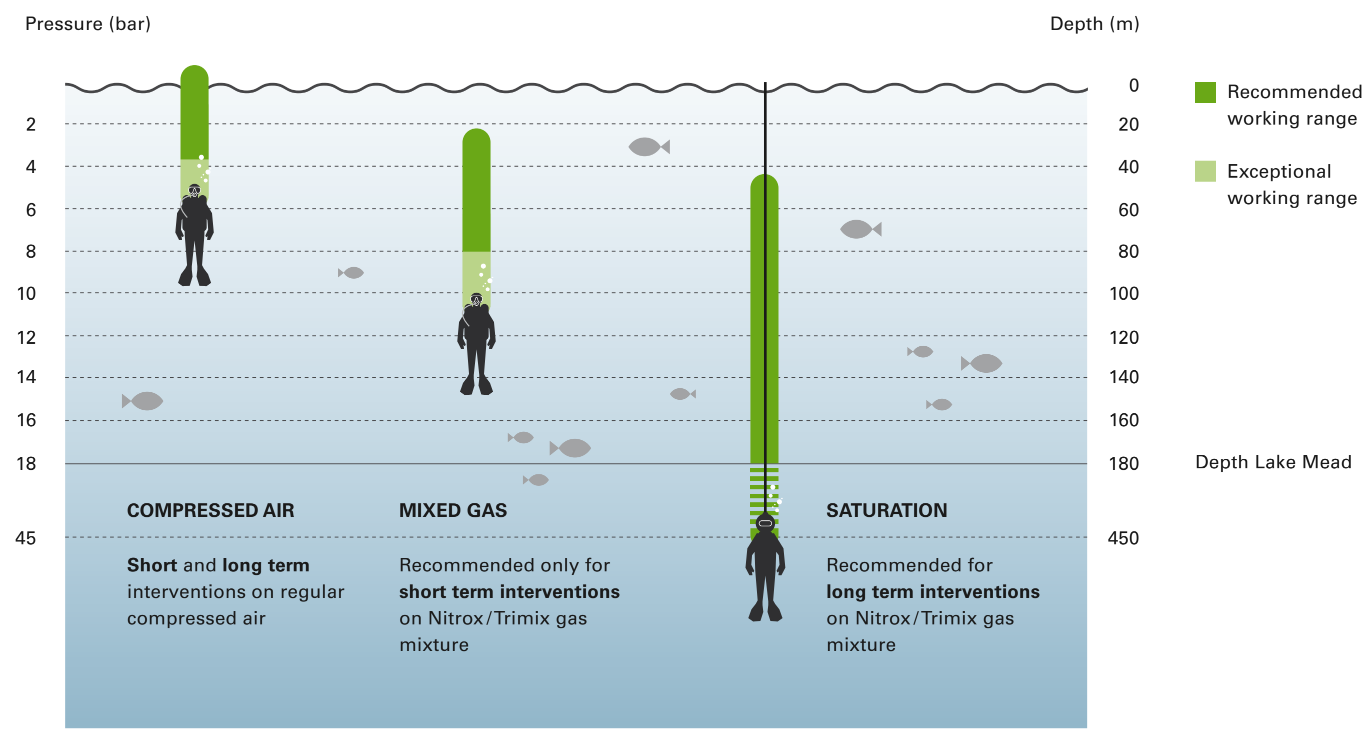
For a deployment the transfer shuttle must be transported through the entire back-up of the machine. Special design considerations are necessary for this so enough space for the shuttle remains open in the center. Only in this way can the quick and above all completely safe entry of the professional saturation divers into the excavation chamber be enabled. In normal operation, on the other hand, these facilities must cause minimal interference to the tunnelling process.

In the end, the complicated and time-consuming use of saturation diving was fortunately not needed during tunnelling under Lake Mead. Nevertheless, in such difficult pioneering projects at the limits of technical feasibility, in addition to plan A you always need to have a plan B or even plan C in your pocket.

In future it is therefore very likely that all tunnel boring machines underway deep below the earth's surface will be equipped with such technology reminiscent of space travel. Tunnelling depths of 200 meters are no longer a fantasy. On the dividing line between East and West, saturation divers are also the fallback solution: directly under the Bosphorus a 13.60 meter diameter Herrenknecht TBM is currently eating its way through the seabed between Europe and Asia – all possible facilities for chamber interventions are on board. At its deepest point the 5.4 kilometer long road tunnel of the "Istanbul Strait Road Tube Crossing Project" is about 100 meters below the water level.

Saturation diving

The deeper and longer a person dives, the more protracted is his return to the surface. The problem is the gas that he breathes. It dissolves in the body fluids and is deposited in the tissue – until the body is saturated. Hence the name: saturation divers. If you surfaced rapidly, the gas would be released too quickly, especially in the blood. Comparable to a soda bottle you shake before opening it. This would result in gas embolism, damage to the nerve tracts and in the tissue, with deadly consequences. The diver must therefore release the absorbed gas via his breathing in slowly decreasing pressure – which takes a while. Thus the decompression time after a dive to 200 meters can be up to seven days.



BACKGROUND

Lake Mead, Intake No. 3

Country, Location	United States, Las Vegas, NV
Client:	Southern Nevada Water Authority
Contractor:	Vegas Tunnel Constructors JV
Year:	2011–2014
Application :	Water
Geology:	Heterogeneous ground and rock (Basalt, sandstone, amphibolites, conglomerates)
Tunnelling length:	4,400 m
Machine data:	1× Multi-mode TBM
Diameter:	7,180 mm
Lining method:	Segmental lining

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(Responsible: Achim Kühn)

Outstanding success for the Herrenknecht Multi-mode TBM at Lake Mead: TBM in operation **under extreme water pressures up to 15 bar.**

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