Engineered to the MAXimum
AIRMAX – the new standard for large ASU

Engineering the Future – since 1758.
MAN Diesel & Turbo
A True Game Changer
AR-MAX1 for large air separation units

Assembly of an AR105/06M MAC with six axial stages and one radial stage featuring a 3-D shrouded-type impeller

AR-MAX1 – the standardized axial/radial main air compressor can deliver volume flows up to 1.5 Mio. cubic meters per hour, pressures up to 25 bar and exhibits highest robustness: a piece of equipment our customers can rely on.

The family background
MAN Diesel & Turbo (MDT) offers leading air compression solutions for air separation units – ASUs –, either with a radial main air compressor or an axial/radial MAC for large units – the compressor type AR. MDT has more than 40 years of experience with large axial/radial main air compressors with 65 references in total until 2014. The latest reference with our conventional AR generation is successfully running in Qatar: QP-Shell Pearl, the world’s largest GTL plant. The air separation market for these large train sizes is continuously growing, driven by future-oriented applications like Gas-To-Liquid or Coal-To-Liquid.
AR-MAX1 – a true game changer
MDT has further developed its proven axial/radial main air compressor type AR by equipping it with the advanced axial blading generation MAX1. Besides the blade geometry itself all parts and design features are proven in a multitude of running references. AR-MAX1 is a fully API compliant standardized modular system with a simple layout and a reduced number of parts.

Benefits of AR-MAX1
AR-MAX1 features superior surge robustness. Also regarding compactness AR-MAX1 is a true game changer. Therefore, it is economic in CAPEX and has excellent transport features – the smallest and lightest concept in the market. Furthermore, AR-MAX1 exhibits potential for very high pressures for HP-ASU – also with 2 intercoolings – and for very large air compressor trains (7,000 t/d O₂ and larger). Such a “mega-train” featuring one AR-MAX1 is extremely economic in CAPEX compared to two “50%-trains”. A further benefit of a mega-train is the shorter delivery time and lower effort for site erection, operations and maintenance due to the lower train count in large plants.

All components of the main air compressor have been optimized for efficiency. The aerodynamical design of the new axial blading and the subsequent radial diffuser have been optimized with most modern tools and design methods used in the aero engine industry. The excellent operating range of AR-MAX1 – running at constant speed – is achieved by four variable guide vanes. For the standard ASU pressures AR-MAX1 features only one intercooler between the axial stage group and the radial stage, thus reducing complexity and easing assembly and maintenance. The diagonal inlet, the radial stage itself as well as the exit volute have been significantly improved with respect to their efficiency; resulting in a superior performance of AR-MAX1.
Ensuring the Leadership
AIRMAX – the new standard air compressor train for large ASU

AIRMAX trains serve the needs of today’s and future ASU plants. AIRMAX trains have already demonstrated their applicability to plants that until recently were considered large but now have become “standard”.

AIRMAX – the new standard air compressor train
In order to extend our leading position in the field of large ASU, MDT developed its new train concept called AIRMAX. AIRMAX trains – standardized in the sizes S to XL – consist of an AR-MAX1 and a geared-type BAC, both driven by a steam turbine positioned between MAC and BAC.

Benefits of AIRMAX
AIRMAX trains are very competitive regarding CAPEX and transportability due to the higher speed and power density of MAC and steam turbine. Regarding OPEX AIRMAX sets the benchmark, since the efficiency of the MAC has been further improved, and the steam turbine is now operating at its optimum speed with respect to efficiency.
AIRMAX Selection Diagram

AIRMAX Machine Frame Sizes, Volume Flow and Power

<table>
<thead>
<tr>
<th>AIRMAX Size</th>
<th>Oxygen Production [t/d]</th>
<th>MAC Type</th>
<th>max. Flow [m³/h]</th>
<th>BAC Type</th>
<th>ST Type</th>
<th>Power [MW]</th>
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<tbody>
<tr>
<td>S</td>
<td>3,000</td>
<td>AR100</td>
<td>558,000</td>
<td>RG45</td>
<td>DK080/190</td>
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<td></td>
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<td>AR105</td>
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<td>DK080/250</td>
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<td>813,000</td>
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<td>K</td>
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<td>L</td>
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1) For standard ASU pressure (approx. 6 bar). Assumption: BAC power = approx. 1/3 of total train power
2) Potential to be driven by electric motor with 3,600 rpm; 3) Potential to be driven by electric motor with 3,000 rpm

AR-MAX1 Dimensions and Weight

<table>
<thead>
<tr>
<th>AIRMAX Size</th>
<th>Oxygen Production [t/d]</th>
<th>AR-MAX1 Size</th>
<th>Length [m]</th>
<th>Width [m]</th>
<th>Height [m]</th>
<th>Weight [t]</th>
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<td>115</td>
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<td>7.2</td>
<td>5.3</td>
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<tr>
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<td>320</td>
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<tr>
<td></td>
<td></td>
<td>170</td>
<td>8.9</td>
<td>6.5</td>
<td>6.7</td>
<td>375</td>
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4) For standard ASU pressure (approx. 6 bar)
Uniquely Compact, Robust and Efficient
MAX1 – the hybrid axial-flow compressor blading

The new hybrid blading MAX1 represents a big step forward in power density and robustness – a unique combination of the advantages of proven industrial design and gas turbine technology.

**MAX1 – the hybrid axial compressor blading**
MDT has developed MAX1, the new hybrid blading based on proven industrial design and gas turbine technology, together with its development partner MTU Aero Engines. MAX1 combines the advantages of gas turbine technology – greater stage pressure ratios, higher speed and fewer stages – with the benefits of industrial axial compressors – high efficiency and wide operating range. The robustness could even be increased significantly.

**Uniquely compact, robust and efficient**
The two main design targets of the MAX1 blading – a big step forward in power density as well as in robustness – have both been fully achieved. A speed increase of approximately one third has led to a reduction in axial stage count by roughly one third and to a significantly smaller impeller diameter. The strongly increased power density drastically improves compactness, production cost and rotordynamics due to the shorter rotor. The novel blading generation combines the increased power density with further essential advantages, such as very high efficiency, good operating range and highest robustness – a unique combination of features in the market.

**Superior surge robustness in the market**
The MAX1 wide chord blading has a greatly improved robustness against all kinds of mechanical blade loads. MAX1 represents MDT’s latest generation of surge robustness. Extensive prototype tests and surge tests of the first customer machine have proven impressively that MAX1 exhibits superior surge robustness in the market.
Superior Results in Shop Verification Tests
12 AR-MAX1 have been thoroughly tested “first-time-right”

Superior test results of AR-MAX1
The final acceptance tests of the first order (AR105/06M) were successfully performed in MDT’s test center for large machinery trains in Oberhausen. The test bed was equipped with the job intercooler. The MAC was driven on the test stand by an electric motor. The very extensive test series was concluded with the mechanical running and performance test. In total 24 intensive measurement days were completed successfully. The performance of AR-MAX1 is significantly better than expected and the high expectations regarding robustness have been fully confirmed. In total 155 MAC surges were measured; all showed very low stresses in the rotor blades. AR-MAX1 is uniquely robust. It is much more surge robust than any other main air compressor in the market.

Performance prediction is highly reliable
All 6 trains of the 2nd order (AR115/06M) were successfully tested in their original configuration with MAC, job steam turbine and job intercooler. The performance tests again revealed a significantly better performance than projected, and the measurements show a very good repeatability amongst the individual compressors. Also the 5 MACs of the 3rd order (AR115/06M) were successfully tested in a configuration with MAC and electric motor drive (shop motor with shop gearbox). Again, the measured performance was significantly better than projected and the repeatability was excellent. Therefore, the design tools are fully proven by the performance verification tests of AR105/06M and AR115/06M. The performance prediction for future projects is highly reliable.
The First Reference
Air Products runs 4 AIRMAX S trains in Yulin, China

The AR-MAX1 story began with a successful launch project together with Air Products.

AR-MAX1 001 – serial number 1
Only a few weeks after the final sales release of the novel blading generation MAX1, MDT received the first AIRMAX order. The confidence that has been placed in us by Air Products and Chemicals at the beginning of 2012 is highly appreciated. The world-scale air separation plant in Yulin, Shaanxi, China is built, owned and operated by Air Products. The four AIRMAX S trains with a nominal output of ~3,000 t/d O₂ include an AR105/06M MAC, a RG45-6 BAC and a DK80/190R steam turbine. The entire project was a first-time-right success, running smoothly through the design and production phase in the Oberhausen and Berlin workshops. It was delivered to site on time.

The serial number 1 AR105-MAX1 has been tested successfully within a 24 day measurement campaign in the Oberhausen test center. The performance measurements have proven an even better operating range and higher efficiency and have confirmed the robustness of the machine during 155 MAC surges. Successful commissioning of the first train took place in April 2015.
The World’s Most Modern Large CTL Plant Uses AIRMAX
Shenhua Ningmei, China, with 11 AIRMAX M trains

One of the world’s largest CTL plants in Lingwu, Ningxia, China, owned by Shenhua Ningmei Coal Industry Group Co. Ltd.

The AR-MAX1 story was continued with the next size – AR115-MAX1.

MDT is proud to be part of Shenhua Ningmei CTL plant

In spring 2013 MDT received the order of 11 AIRMAX M trains from Linde and Hangyang for the new Shenhua Ningmei plant in the Ningxia region, China. The trains consist of an AR115/06M MAC, a RG56-6 BAC and a DK80/250R steam turbine.

MACs, BACs and steam turbines of all 11 trains successfully went through shop verification tests in the MDT Oberhausen test center. The performance of the AR115/06M was once more significantly better than projected – again a first-time-right result in all 11 MACs.

The project was conducted very successfully. All trains were delivered in time. MDT continues the work with the same effort in the erection & commissioning phase on site – up to the final customer satisfaction.

Fully assembled AR115/06M MAC
**Fully Industrialized**

The AR-MAX1 modular system is designed across all frame sizes.

**Definition of a specialized modular system for ASU**

In a comprehensive effort all sizes AR100-AR170 have been analyzed and optimized in detail regarding design, raw parts, suppliers and manufacturing of all MAX1 components and all systems components. Also assembly, balancing, testing, handling/logistics, erection/commissioning and the cost of all these steps have been analyzed in every detail. MDT’s testing facilities can test these large trains, but with the increasing number of units to be tested and the size of these compressor trains, the company needed to streamline its in-house facilities. The electric driving power will be significantly increased and a large-size intercooler will be permanently installed in the testing hall.

**High reliability of modular system preparations**

All MAC and system components have been analyzed to such an extent that the internal and external supply chain is 100% proven, the capabilities of different suppliers are known in detail and the costs are determined with high accuracy. For selected components samples have been manufactured in order to confirm quality and manufacturing costs in detail, e.g. for the rotor blades of stage 1 (see left figure).
The AIRMAX modular system enables train sizes up to 7,000 t/d \( O_2 \) and more – the ideal solution to realize the economies of scale.

**AR-MAX1 for the world’s largest CTL plants**
Large CTL projects show a clear trend: ASU train sizes are constantly growing to take advantage of economies of scale and – due to the lower train count in huge plants – also of shorter delivery time and lower effort for site erection, operations and maintenance. With the AIRMAX trains our customers are prepared for train capacities of 7,000 tons of oxygen per day or larger, which is an expected size in the foreseeable future.

Based on the already finalized design of the AR-MAX1 modular system across all frame sizes, the cost development of the MAC and the related system components over the MAC sizes is available. Together with the cost curves of BAC and steam turbine and all other system components, spare parts, testing and erection & commissioning the AIRMAX train prices have been analyzed. The diagram shows the specific train price related to the MAC volume flow (train S/AR100 = 100%). It reveals a significant price advantage of larger ASU trains.

Replacing 2 AIRMAX 50% trains by 1 large AIRMAX 100% train results in a cost saving of more than 25%, offering an ideal option for our customers of large scale ASU plants to save cost.

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**Economies of Scale**
Large AIRMAX trains help to reduce cost significantly

*Example: Replacing 2 AIRMAX trains M / AR110 by 1 AIRMAX train XL / AR160 results in a train cost reduction of > 25%*
AIRMAXe
AR-MAX1 in a perfect combination with electric motor drives – featuring the largest reference AR140-MAX1

AIRMAXe offers multiple options for efficient and economic air compressor trains with electric motor drive.

**AR-MAX1 with direct 2-pole-motor drive or 4-pole-motor drive with gear box**

AIRMAXe trains are a smart supplement to the steam turbine driven trains due to the shorter plant erection time in cases a reliable power grid is available. MDT has long and successful experience with ASU trains driven by large electric motors.

Generally, all AR-MAX1 compressors can be driven by an electric motor drive with an additional gear box. The example in the left figure shows an AR140-MAX1 driven by a 4-pole-motor with a gear box in between, which is a very economic solution with only slightly increased mechanical losses. The electric motor is rated at 65 megawatts driving the AR140-MAX1 with more than 1 Mio. m³/h effective volume flow.

This AIRMAXe solution with an AR140-MAX1 represents the first AIRMAXe order placed by Air Liquide in the beginning of 2015. It will serve the world’s largest Air Separation Unit with a capacity of 5000 t/d O₂ in Secunda, South Africa. The AR140-MAX1 delivers 100% of the ASU flow in a single train. It represents the largest reference so far and will be the biggest axial flow compressor ever used in an industrial application.

An AIRMAXe train featuring a double-intercooled AR130 with a 2-pole-motor direct drive is shown in the right figure, representing the solution with the lowest number of rotating parts and with the highest efficiency. Direct drives are suitable for larger trains as AR130/AR140/AR150 with a speed of 3,600 rpm or AR150/AR160/AR170 with a speed of 3,000 rpm.
AR-MAX1 – Made for HP-ASU
It’s all in the same modular system – AR-MAX1 enables highest pressures

AR-MAX1 – the flexible modular design system allows various combinations of axial and radial stages plus 1 or 2 intercoolings to cover the needs of all applications from LP-ASU to HP-ASU.

AR-MAX1 with increased numbers of axial and radial stages
High pressure ASU is characterized by an elevated pressure in the cold boxes and thus the discharge piping of the MAC. For a constant oxygen production this cost driven solution reduces all piping dimensions significantly. With AR-MAX1 a very flexible modular system is available up to pressures of 25 bar and with 1 or 2 intercoolings. The figure shows an example with 8 axial and 3 radial stages and 2 intercoolings, one after the axial stage group and one upstream the last radial stage.

The possibility of cooling the air twice during compression translates into power savings in the order of at least 4% compared to a single intercooled configuration. Operating costs will reflect a reduction in power consumption of several megawatts due to the size of these machines. HP-ASU MACs with two intercoolers are not new at MDT. In the previous generations, due to the number of axial stages required, the last impeller was mounted overhung, but on the MAX1 all stages are within the bearing span. The reduced number of high efficiency axial stages and a staggered layout of the outlet and inlet nozzles in the radial section have allowed MDT to maintain a short bearing span so as to operate the machine far below its critical speed. The other characteristic features of the MAX1, superior surge robustness, high performance and compactness, thus economic in CAPEX, are unchanged.
**AR-MAX1 – a First-Time-Right Success**

Excellent order execution and very positive customer feedback

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**Team spirit as a basis for success**

Team spirit, discipline, management attention as well as excellent collaboration with our customers – these are the decisive factors for the first-time-right success of the first ARMAX orders.

An internal MAX1 event for the entire Oberhausen MAX1-team was held on 25th of September 2013 in Oberhausen. It was a celebration of the first AR105-MAX1 compressor and a recognition of the performance of the whole Oberhausen team. More than 400 participants showed that the entire team is fully committed to AR-MAX1.

A MAX1 international end user event was held on 25th and 26th of September 2013 in Oberhausen. Heart of the event was the presentation of the first AR-MAX1 to guests from end users from four continents, including important synthetic fuel producers. MDT received an extremely positive customer feedback.

The first AR115-MAX1 was presented at the Volkswagen and MAN Annual Shareholder’s Meeting in Hannover on the 13th and 15th of May 2014. AR-MAX1 raised a high interest of the shareholders and the MAX1 team was pleased to give a lot of explanations about MDT’s new high-tech product.

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*The Oberhausen AR-MAX1 team after the successful test of the serial number 1 compressor in Oberhausen, September 2013*
**AR-MAX1 – reviewed and recommended by major technical experts**

MAX1 successfully passed through a profound technical review process with well-known technical experts and institutes in the turbomachinery area. The Southwest Research Institute (SwRI) certifies that the MAX1 blading gives the customer a very high level of safety. John W. Fulton (former senior engineering advisor from ExxonMobil) recommends MAX1.

Large turbomachinery for mega size plants are clearly in the focus of MDT, having a lot of experience with large compressor trains in the applications ASU, PTA and FCC. MDT has the best experience in large ASU with axial compressors (since 1970). The competence has been recently proven by the largest GTL plant, QP-Shell Pearl in Qatar, and the first AIRMAX orders. The MDT axial compressor modular system is developed up to the frame size 170 and referenced up to frame size 140. With the introduction of our latest technology step – the improved axial blading MAX1 – significant benefits can be exploited in all axial compressor applications.

At MAN Diesel & Turbo we are dedicated to innovation and the continuous improvement of our products to meet the challenges of tomorrow.

**AR-MAX1 – the air compressor technology of the future.**
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