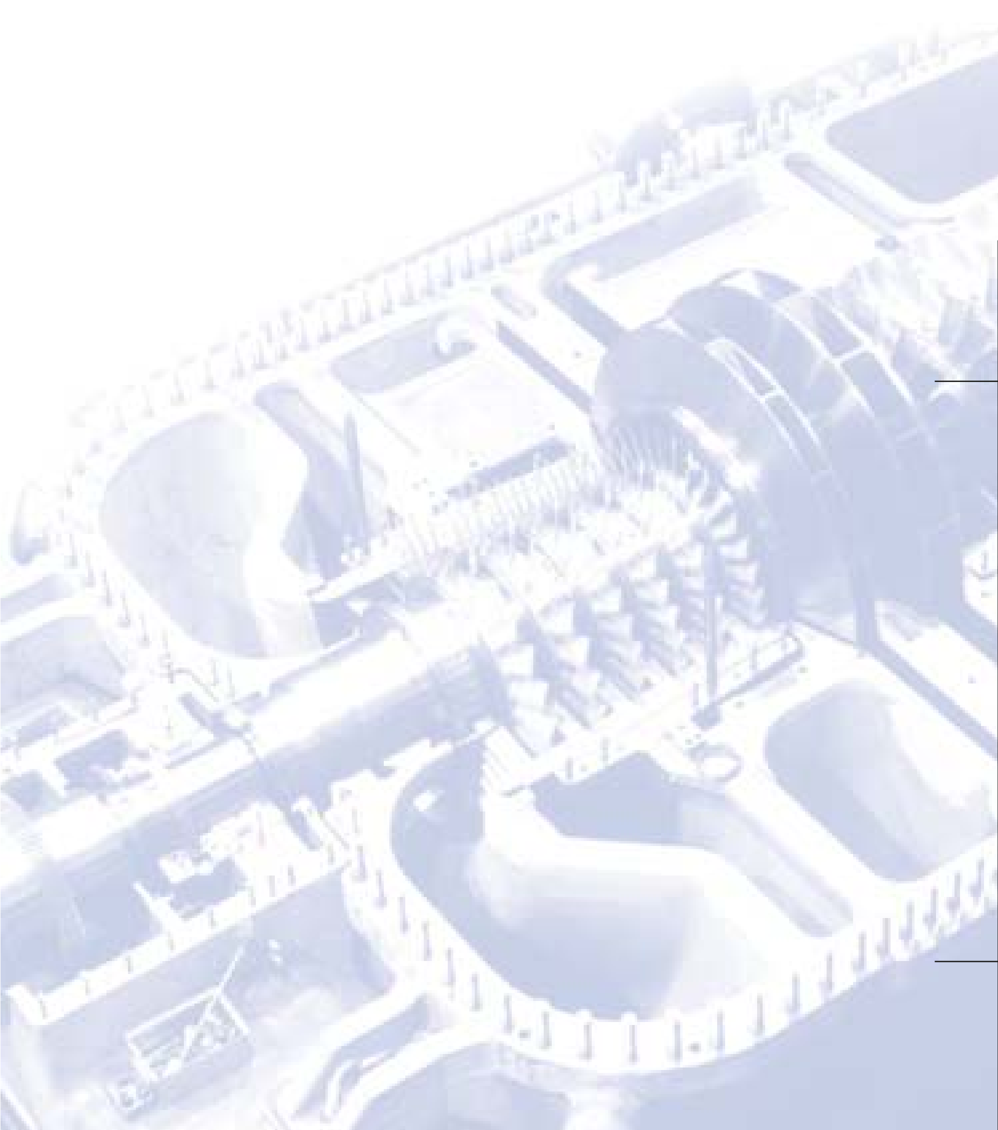
# Turbomachinery for the world's largest nitrogen plant

## Enhanced Oil Recovery to increase the output in the Cantarell oil field, Mexico



# Turbomachinery for the world's largest nitrogen plant Enhanced Oil Recovery to increase the output in the Cantarell oil field, Mexico

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## Summary

As part of a project to increase the production output of PEMEX's Cantarell offshore oil field, situated in the Gulf of Mexico, the world's largest ever nitrogen plant has been constructed. It was designed, built, owned and operated by Compania de Nitrogeno de Cantarell S.A. de C.V. (CNC) an international consortium of BOC Gases of Great Britain, Westcoast Energy of Canada, Marubeni of Japan, Linde Germany and ICA Fluor Daniel of Mexico.

For this project, MAN Turbomaschinen AG GHH BORSIG was awarded the order to supply, supervise the erection of and commission the air compressors for the air separation plant and the nitrogen product compressors including their drivers for the delivery of the high purity nitrogen to the oil field. The total installed driver power for compression exceeds 400 MW.

This paper contains a brief description of the plant as a whole, details of the turbomachines supplied and the results of their workshop trials.

## Introduction

Methods of introducing nitrogen under high pressure into oil fields with a low well pressure or to increase production can be used for enhanced oil recovery either if there is insufficient gas available for reinjection, or the associated gas is to be used for another purpose. Petroleos Mexicanos (PEMEX), the Mexican state oil company, is utilizing these methods to increase its future production capacity in the Cantarell oil field.

PEMEX's production output to date from its main oil field accounts for a third of total domestic oil production. The Cantarell oil field is located offshore in the Bay of Campeche, in the southern Gulf of Mexico **(Fig. 1).**

Roughly 1.4 million barrels per day of crude oil have been produced here on average in previous years. In addition to other measures to increase the daily output to around 2 million barrels per day, the diminishing well pressure of the crude oil is to be increased to approx. 84 bar and maintained at that level by injecting highly pure nitrogen into the rock formations containing the oil. To do this, around 1.3 million Nm$^3$/h or roughly 40,300 tonnes per day of nitrogen are required, which are produced from atmospheric air in an air separation plant and following compression in turbocompressors to 121 bar is transported to the offshore injection facilities in a 36” subsea pipeline approx. 92 km long.

source: www.enr.com

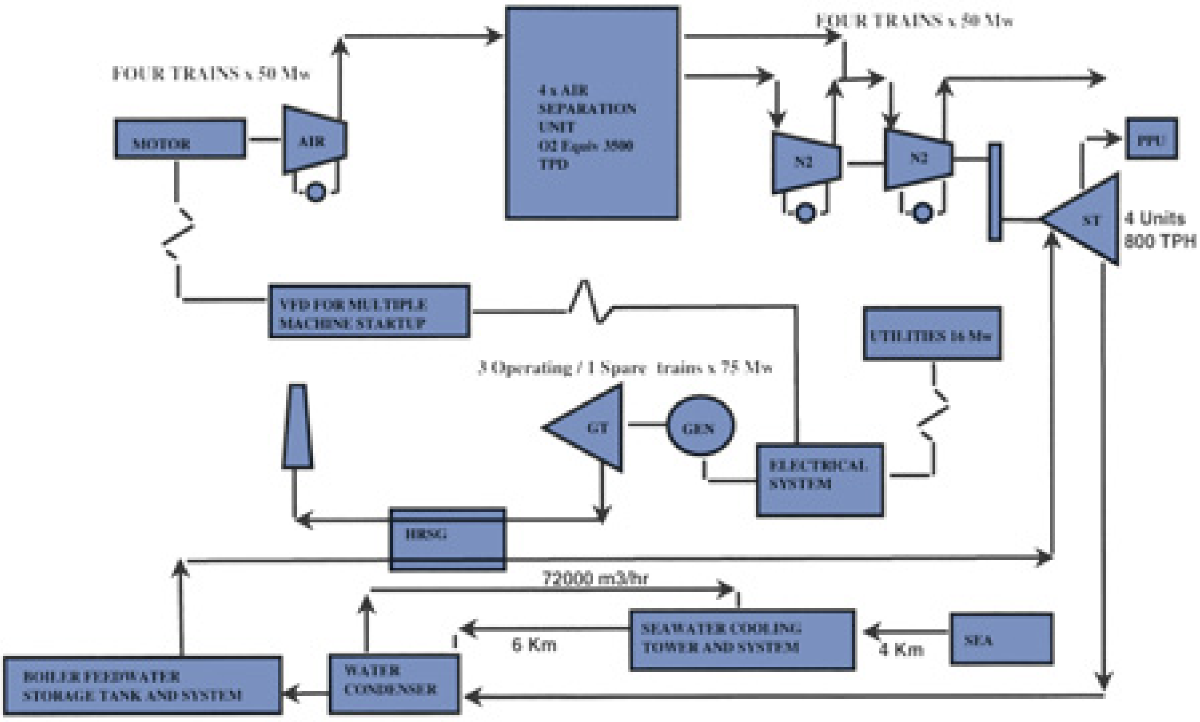
Fig. 1: Location of the Cantarell Oil Field

The scope of the project won comprises, as shown in **Fig.2,** a natural gas fired gas turbine COGEN power plant, an air separation plant to produce the nitrogen, seawater and treated water cooling systems including the subsea water pipes, turbocompressor sets and pipelines to the platform. It was constructed on the Atasta peninsula on the Gulf of Mexico, not far from Cuidad del Carmen, by CNC, an international consortium made up of the following companies:

**BOC Gases**/Great Britain
**Marubeni Corporation**/Japan
**Westcoast Energy Inc.**/Canada
**Linde AG**/Germany
**ICA Fluor Daniel S. de R.L. de C.V.**/Mexico.

The last-named company is a joint venture between Constructoras ICA (Mexico) and Fluor Daniel (USA). At the end of 1997, ICA Fluor Daniel, in consultation with BOC, awarded the contract to supply the turbocompressor sets on either side of the air separation plant to MAN Turbomaschinen AG GHH BORSIG, which was also contracted to supervise erection of the compressors and to commission them.

Fig 2: Plant Schematic



## Plant concept

Pemex awarded the CNC consortium, led by BOC, a gas supply contract for a period of 15 years. This decision was based on the lowest gas price coupled with design, construction and operating experience. Key to this award was experience of the components including the machinery, minimum fuel consumption measured in energy units per unit capacity of nitrogen,and a predicted high level of availability of the plant.

The facility was built on a green field site provided by Pemex. There was no infrastructure or utilities, with the exception of natural gas which is used to fuel the gas turbines. Owing to this lack of infrastructure at the erection site, the plant in its entirety, including the gas turbine cogeneration plant, was designed as an island solution.

In designing the plant, it was recognised that minimum energy usage combined with the best economic solution could only be accomplished by a high level of integration which would balance the optimum air separation cycle with the optimum energy supply cycle. As BOC had experience successfully designing, building and operating such facilities e.g. their integrated gas turbine cogeneration and ASU facility at Gresik Indonesia, another facility using MAN GHH BORSIG's compressors and steam turbines, BOC led this activity. Using proprietary computer programs, in excess of 40 combined energy and ASU cycles were evaluated including variation of process cycles, variations of compressor types and cooling arrangements, simple cycle, combined cycle, and cogeneration gas turbine arrangements before the optimum solution was decided on an NPV and experience basis. The solution eventually implemented as the most economical is based on a four ASU-train version as follows:

- Four (three operating/one spare) gas turbine generators with heat recovery steam generators (HRSGs) connected downstream to the gas turbine exhausts to generate steam
- four motor driven intercooled air compressors,
- four air separation plants to produce the nitrogen and
- four steam turbine driven intercooled nitrogen compressors.

Splitting the total production between four units that can be operated independently also provides the required flexibility of the nitrogen plant in the event that the oil field requirements vary.


source: Fluor Daniel

Fig. 3: Nitrogen Production Plant

**Fig. 3** shows a photograph of the nitrogen production plant. The four gas turbine units – gas turbines, generators and HRSGs – are on the left hand side of the picture. The machine house can be seen opposite these, in the middle of the picture. The four turbocompressor sets – four air compressors with motor drive and the four nitrogen compressor sets with condensing steam turbines, gear units and low- and high-pressure nitrogen compressors – are housed here. At the right-hand side of the picture are the four air separation facilities, and the sea water recooling system with cooling towers in all is located in the left-hand section. The area as a whole is roughly 6 km from the coast. Water is piped from 5 km offshore of a sump at the beach where it is pumped to the cooling towers for use in the intercoolers and condensers.

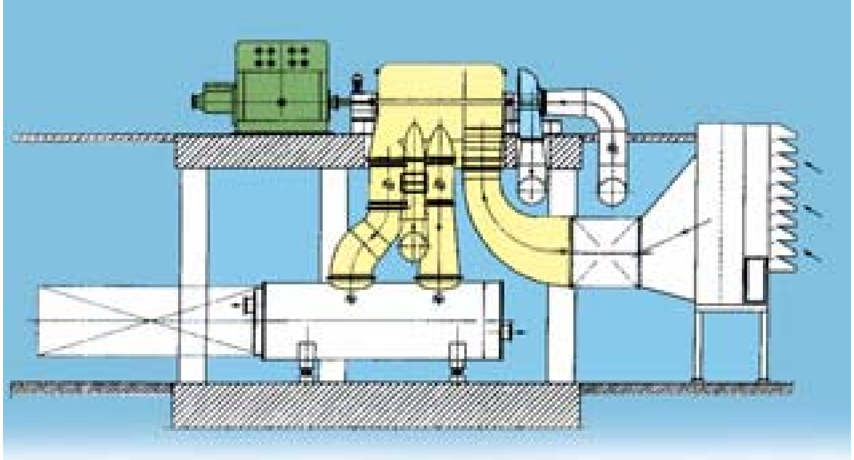


Fig. 5: Axial Flow Compressor Arrangement

# Turbomachinery

MAN Turbomaschinen AG GHH BORSIG supplied the following 16 turbomachines for the nitrogen plant: Four intercooled axial flow air compressors consisting of two back to back axial stage groups and one overhung radial stage driven by ABB two pole synchronous motors, and four intercooled centrifugal nitrogen compressor trains. Each nitrogen compressor train consists of a low pressure casing driven by a condensing steam turbine through a step up gearbox with each low pressure casing directly connected to a high pressure casing. The following is a more detailed description of these turbomachines:

## Axial flow main air compressors

MAN GHH BORSIG is the market leader in the construction of axial compressors for industrial applications. Axial compressors were developed at the start of the 1950s and have since been introduced very successfully into various market segments of the process industry. While their primary use initially was in blast furnace applications, the emphasis has shifted over time increasingly to the chemical and petrochemical sector, and also to the “air separation plant” segment of the market.

Thus since 1977 MAN GHH BORSIG has supplied a total of 14 identical axial flow compressors, each with 36 MW (48275 HP) drive power, to the world’s largest oxygen plant in Sasolburg, South Africa. These compressors have now successfully clocked up around 2 million operating hours. The compressor design is described in detail in [1].
The axial flow compressors used for the air separation plant on Atasta are virtually identical to those for the Sasolburg installation. Each of the four machines operates at over 50 MW (67050 HP) with suction volumes in excess of 600,000 $m^3/h$ (353100 acfm) depending on plant demand and ambient conditions.
The power required is supplied by a synchronous motor directly driving the compressor at 3,600 rpm and started by a soft starter. Its rated drive output is 52 MW (69733 HP).

The air is taken in via a radial inlet casing **(Fig. 4)** and following compression in seven axial stages and a final radial end stage in the low-pressure section, is conveyed to the intercooler located beneath the compressor **(Fig. 5)**. Following further compression in the intermediate-pressure section (six axial stages and radial end stage) and further stage of intercooling, final compression is carried out in the overhung-mounted radial stage with axial intake.

Fig. 4: Intercooled Axial Flow Compressor

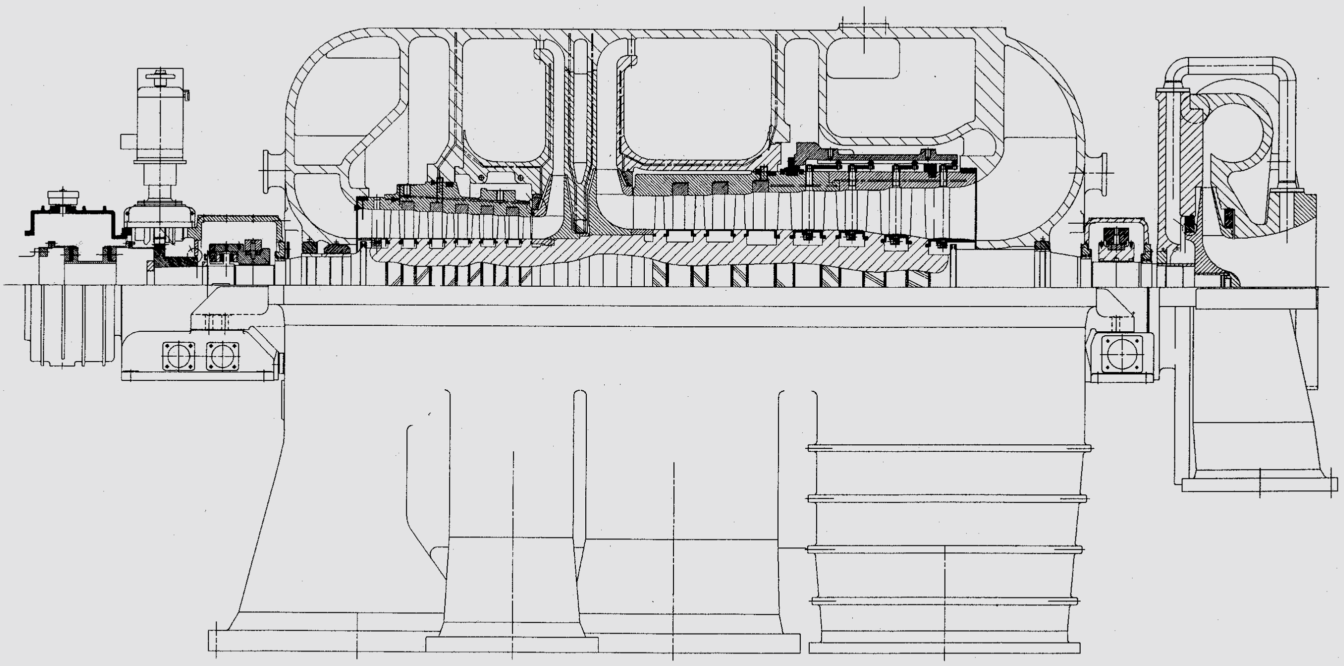


Fig. 6: Nitrogen LP Compressor

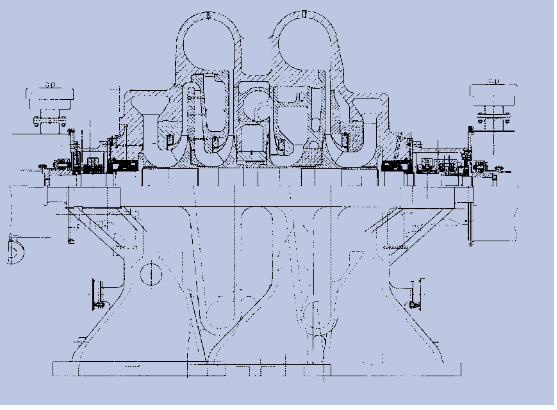


Fig. 7: Nitrogen HP Compressor

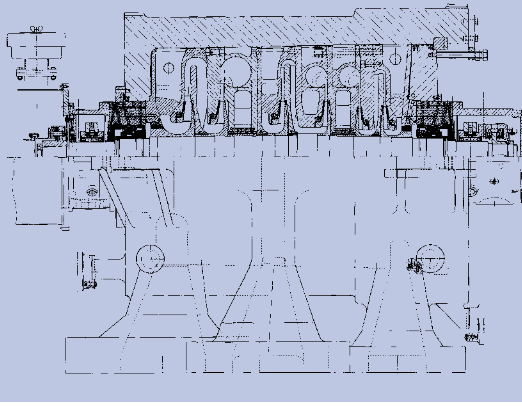
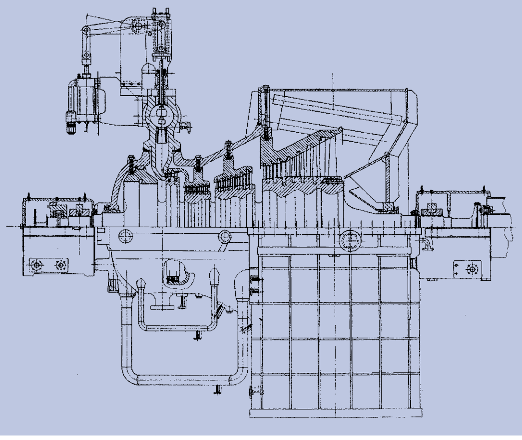


Fig. 8: Condensing Steam Turbine



The wide range of compressor performance data required can be delivered with just four synchronously adjustable rows of stator blades at the inlet to the low-pressure section. The reasons for the superb partial load characteristics lie in the moderate aerodynamic loading of the blading of the low- and intermediate-pressure section together with the stage characteristics of the HP stage.

The dimensions of the axial flow compressor can best be characterized by the distance between bearings of around 6 m, the outer diameter of the largest centrifugal impeller of 1.64 m and the transportation weight of roughly 180 tonnes.

## Centrifugal type nitrogen product compressors

Each of the four centrifugal compressor trains designed to API Standard operates at up to 48 MW depending on the well demand profile and compresses in excess of 335,000 Nm$^3$/h (300 million standard cubic feet per day) at pressures up to 121 bara (1755 psia).

The low-pressure compressor, two times intercooled, contains four impellers with a nominal outer diameter of 750 mm **(Fig.6)**. The two external volutes with a circular cross-section are typical of the cast casing with a horizontal split joint and are connected to the vaneless diffusers of the respective stages.

The high-pressure compressor is provided with two stages of intercooling **(Fig.7)** and contains three stage groups, each comprising two impellers with an outer diameter of 660 mm. The casing of cast steel is designed as a barrel with a single cover. On this compressor also, volutes with a circular cross-section and a connected conical diffuser optimize efficiency in transferring the compressed nitrogen to the coolers located beneath the machine. The initial stages of the three HP stage groups have vaned diffusers. The HP compressors are constructed without an internal casing; in place of this, the internals are connected via special tie-bolts to form the axially removable barrel.

Both compressors have single dry gas seals at the shaft ends to seal the gas chambers relative to atmosphere.

To achieve optimum efficiency of the selected compressor configuration, the flow-conducting components were produced with a particularly high-grade surface finish, especially on the HP compressor.

Because of the power required by the compressors, their rotor lengths and, for the nitrogen compressor, the pressure at which it worked, special attention was paid to the rotordynamics. The design was carried out in accordance to API 617 including both unbalance response analysis and log decrement analysis to confirm stability.

## Steam turbines

Each of the steam turbine drivers for the nitrogen compressors obtain their steam from waste heat boilers connected to each of the gas turbines. Each steam turbine can expand more than 160 t/h of high pressure/high temperature steam to produce up to 55 MW (73755 HP) at 3,200 rpm.

**Fig.8** shows a section through a typical, reaction-type condensing steam turbine for mechanical drives. With an isentropic efficiency rating of almost 85%, this turbomachine also meets the high standards expected with regard to optimum energy utilization by the overall plant.

The 23-stage turbine blading is divided into four sections. The rotor blades of the two-stage control wheel, the HP and IP part and the first three stages of the LP part have integrated shrouds, into which damping wires are caulked in a circumferential direction. Only the last four rotor blades of the LP part are free-standing. All blades up to the end stage are held in the rotor by T roots or double-T roots. The end stage has a finger root fixing which is attached to the rotor by two pins. The guide vanes are connected in segments on the rotor side to riveted shrouds, against which sealing strips caulked into the shaft run.

Four control valves are used for partial load control. These are connected to one another by a balance beam control system, which is actuated by hydraulic oil. The control valves are coordinated so that a virtually linear connection is created between the steam throughput and valve stroke.

Special features of the steam turbine design include the welded joint between the cast turbine casing and welded exhaust casing, and the bearing housings set up separately to the turbine casing. The first of these features contributes substantially to the tightness of the horizontal split joint, even when the turbine is started up and stopped frequently; the second facilitates simple alignment of the casing and rotor, which is retained even during transient operating conditions.

The nitrogen compressor train arrangement is shown in **Fig.9.**

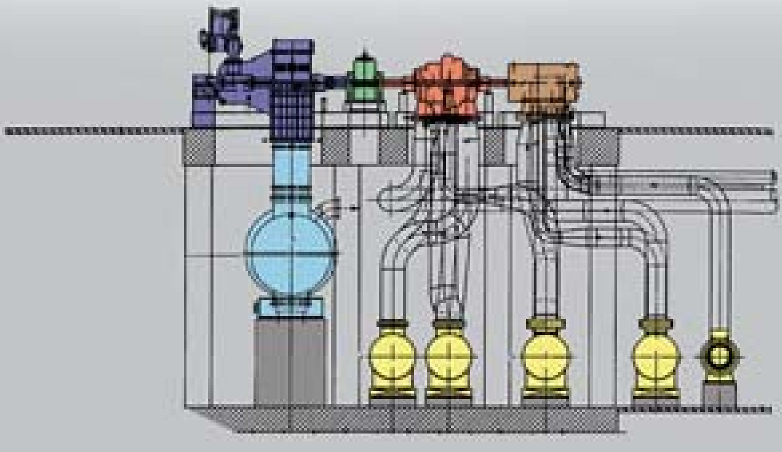


Fig. 9: Nitrogen Compressor Train Arrangement

## Plant dynamics and control

The definition of plant dynamics here means the analysis of transient operating states of turbomachinery installations such as occur during start-up and shutdown, in control processes and in the event of system malfunction. MAN GHH BORSIG began at an early stage to analyse the behaviour of turbomachinery systems under aforementioned operating conditions [2], [3]. One aim of these investigations is to ensure a mode of operation for compressor installations that excludes unstable events such as “surging” even for transient operating states.

In dynamic simulation, the thermodynamic attributes of the compressors in the form of performance data, the characteristics of the drive units, the mass moments of inertia of all rotating components, the storage volumes of the gas coolers and the gas-carrying pipelines, plus the attributes of the controllers used, and the corresponding valves and fittings as related to one another by means of a system of differential equations, which are solved digitally. As a result of this simulation, all the important time-dependent parameters, such as speeds, pressures, volume flows etc. in the transient behaviour of the installation are available for further evaluation. By varying elements of the plant, e.g. the arrangement and attributes of valves and fittings, this behaviour can be influenced in a targeted manner even at the plant design stage.

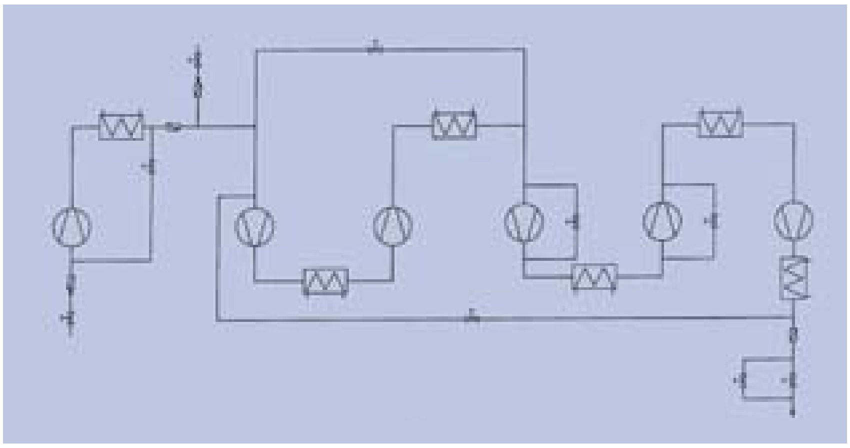


Fig. 10: Nitrogen Compressor Loop

One example of using this simulation system is shown in **Fig. 10**, showing the system design of the nitrogen compressors. To avoid “surging” of individual stages or stage groups in transient processes, recycle valves are provided for certain stage groups, which open automatically when required. **Fig.11** shows as the result of such simulation how the transient effects of a shutdown process – in this case by means of turbine tripping – can be traced in the performance map of the 6th stage group of the nitrogen compressor set.

The turbomachinery and related units are controlled and monitored by the proven turbolog DSP machine control and protection system, which was developed in-house. Linked to the digital control and monitoring system of the overall plant, turbolog DSP protects the air and nitrogen compressors against surging, controls the position of the variable stator vanes of the axial flow compressors, the speed of the steam turbines, monitors and controls all the other components, and last but not least handles the visualization of the operating data required for smooth, uninterrupted production.

## Workshop trials

Workshop trials of the compressors and their drivers serve to demonstrate the guaranteed mechanical integrity of the finished product as well as the guaranteed thermodynamic properties prior to dispatch to the site as it has long been recognised that it is easier and more cost effective to fix a problem in the factory rather than in the field. For such large units the cost of one weeks delay can result in over $1 million in lost revenue. These test runs are to be regarded as a comprehensive quality assurance measure at the end of the design and manufacturing process. The procedure and content of mechanical and thermodynamic trials are precisely stipulated in various internationally approved acceptance codes for the respective machine types. Customers and those they commission to carry out acceptance therefore devote particular attention to these test runs.

MAN GHH BORSIG has met the growing market demand for test runs to be carried out by continuously expanding the number of test stands available for such tests [4]. Drive outputs of 14 MW (electric motors), 16 MW (steam turbines) and 25 MW (gas turbines) are now available in the plant for works test purposes, along with an open-air area for compressor trials involving combustible gases. The following programme of trials was conducted for the turbomachines described in Chapter 3:

Mechanical testing of all
- compressors as per API 617,
- steam turbines as per API 612 and
- gear boxes as per API 613,

and thermodynamic test runs each involving one axial flow compressor, one LP centrifugal compressor and one HP centrifugal compressor as per ASME PTC-10.

Fig. 11: Result of Dynamic Simulation

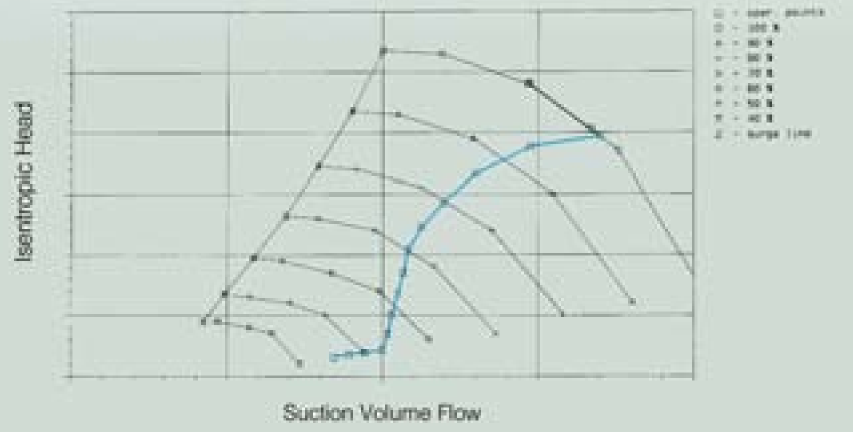


Fig. 12: Test Arrangement of Axial Flow Compressor

For this project BOC also required that one of the nitrogen HP compressors be tested under full load and full pressure (121 bara/1775 psia). A complete, dedicated FT8 gas turbine package on one of the test stands with a drive output in excess of 25 MW was made available as the drive for this test [5].

The five following pictures show some of the turbomachinery to be tested on the test stands:

The erection of the axial flow compressor behind the 16 MW test stand steam turbine can be seen in **Fig. 12**. The two job coolers were used for the tests. The second intercooler is positioned next to the steel foundation, whilst the first intercooler, not visible in the picture, is located underneath the axial flow compressor.

The two following pictures **13 and 14** show the LP centrifugal compressor and the HP centrifugal compressor in the test stand. **Fig. 15** shows a view of the split joint on the condensing steam turbine.

The full load test of the HP centrifugal compressor under design basis conditions was carried out using nitrogen in a closed loop, the job intercoolers again being used. **Fig. 16** shows the test set-up of the HP compressor. The casing, with downwards facing intake and discharge connections in the original build, was rotated 180° upwards, to simplify the pipework for the test set-up. The gas turbine already mentioned above was used as the drive for the full load test, with a drive speed of 5,500 rpm a 25 MW test stand gear box was used to match the compressor speed.

Fig. 13: Nitrogen LP Compressor

Fig. 14: Nitrogen HP Compressor on Test Field

Fig. 15: Condensing Steam Turbine on Test Field

Fig. 16: Arrangement of HP Compressor for Full Load Test

## Results

Of the large number of results obtained from the workshop trials, only those which apply directly to the operating ranges originally quoted for the air and nitrogen compressors will be mentioned here.

All guaranteed thermodynamic values were met without the need to draw on manufacturing or measuring tolerances. Analysis of the official acceptance trials and the large number of internal measurements also carried out yielded the overall performance data shown in **Figs. 17 and 18** for the compressors. A comparison of the tender performance data and so called “as built” performance data is provided.

The predicted surge limit was safely achieved both on the air compressors and the nitrogen compressors. Even the shape of curves of the measured characteristics is a good match for the precalculated characteristic curves, if the deviations between measured and calculated in the case of the axial flow compressors above the pressure limiting line specified by a safety relief valve are disregarded. The overload range is well covered for both compressors.

The rotors demonstrated a high level of stability especially during the full load, full pressure test of the high pressure nitrogen compressor. **Figs. 19 and 20** are examples of the Bode plots from the tests.

The plant as a whole meets the high expectations of the operating company and its end customer PEMEX. Oil production in the Cantarell field has been increased markedly by this investment of one billion US $ [6].

MAN Turbomaschinen AG GHH BORSIG has contributed to this success by supplying a total of 16 turbomachines with an installed maximum drive power in total of 428 MW (573957 HP). The efficiency and availability of the turbomachines supplied, together with MAN GHH BORSIG’s competence in handling the order up to commissioning, qualify the company as a mayor turbomachinery supplier for future challenges of a similar nature.

**Acknowledgements**
The authors would like to congratulate the many people who contributed to make this project such a success.

Fig. 17: Predicted and “as built“ Performance Map of Axial Flow Compresor

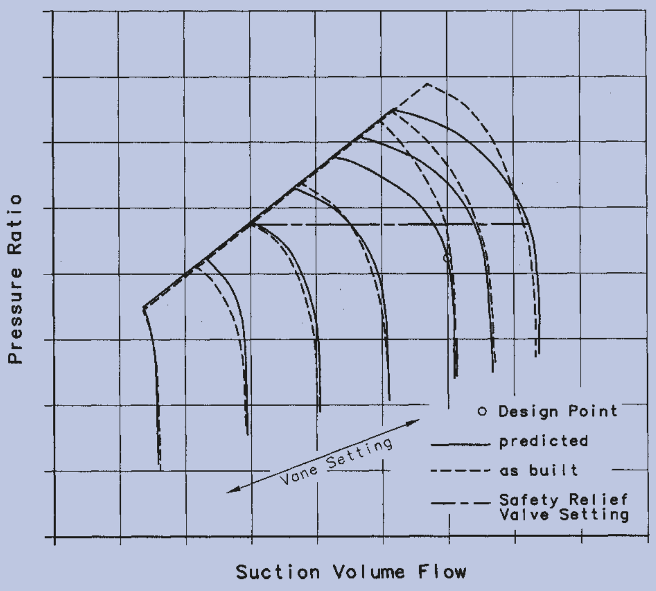


Fig. 18: Predicted and “as built“ Performance Map of Nitrogen Compresor

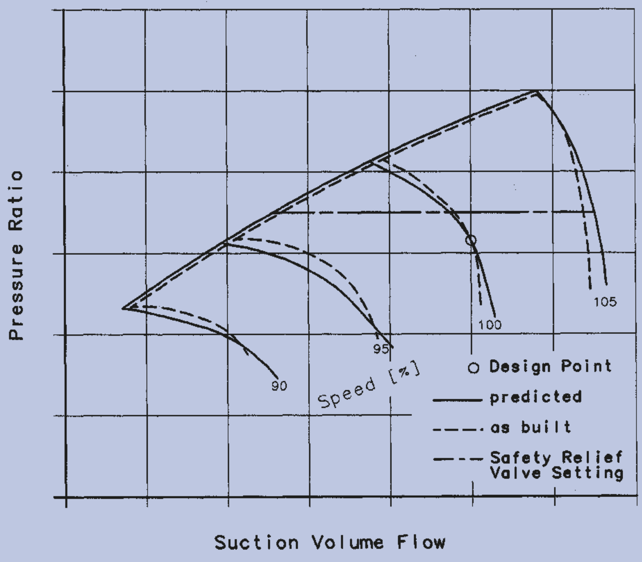


Fig. 19: Rundown of Axial Flow Compressor after Mechanical Running Test

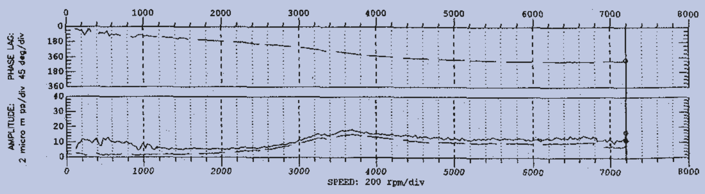
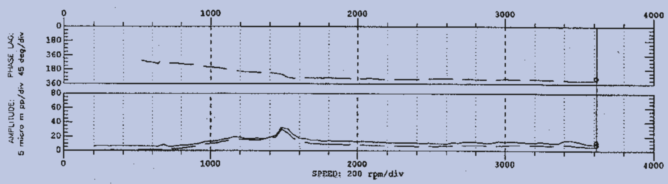


Fig. 20: Rundown of Nitrogen HP Compressor after Full Load Test



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