STANDARDIZED INTEGRALLY GEARED TURBOMACHINES—TAILOR MADE FOR THE PROCESS INDUSTRY

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ABSTRACT

For more than 40 years, integrally geared centrifugal compressors have been in use worldwide, in the plant air sector first, and increasingly in the process industry. Apart from reliability, efficiency and operating range, the most striking features of this compressor concept, particular when used in the process industry, are the versatility and configurability of the machine. Today, all sorts of process gases, including toxic and flammable ones, can be compressed or expanded using integrally geared centrifugal compressor and expander units.

The high level of modular construction employed in integrally geared turbomachines (IGTMs) allows for a high degree of standardization; the resulting building block system makes it possible to adapt the machine concept to each field of application and, in particular, to the customer's own requirements. Of prime importance here are the definition and geometry of the interfaces between the individual modules and equipment units, such as compressor and expansion stages, gear case, pinion shafts, seal systems, etc.

The integrally geared centrifugal compressor has conquered many ranges of application in the process industry starting with compressors operated purely on air, followed by nitrogen and then carbon monoxide, carbon dioxide, chlorine, hydrocarbons, acetylenexide, and isobutyric aldehyde, and so forth. A recent success involving the compressing of high purity oxygen to high discharge pressures using integrally geared centrifugal compressors deserves special mention. It had been thought that this could only be achieved using single shaft compressors. This means that for oxygen, too, the advantages of integrally geared centrifugal compressors such as efficiency and very broad operating ranges can be used, as in the case of variable oxygen supply systems (varox) in air separation plants.

Energy recovery in the process industry has presented integrally geared centrifugal compressors with a new task. Tail gases often have high energy contents which can be returned directly to a compression process in the same machine through addition of expander stages.

In its original concept, the integrally geared centrifugal compressor is primarily suitable for the use of low-speed drive units. By using "free" pinion shaft extensions or additional pinion shafts, high speed drive units without an external intermediate gear can also be used. This aspect, together with the integration of expander stages already mentioned, leads to a very interesting and economical application of integrally geared centrifugal compressors: alongside compression and expansion functions, IGTMs can be used for mechanical output power distribution in sophisticated process equipment such as dimethylterephthalate (DMT) and pure terephthalic acid (PTA systems).

FUNCTION AND DESIGN FEATURES OF MODERN INTEGRALLY GEARED CENTRIFUGAL COMPRESSORS

Integrally geared centrifugal compressors offer the possibility of mechanically coupling several compressor or expander stages via a central, single or multistage spur gear. In some cases, combinations of spur and planetary gears are used. To date, such gears have been fitted with up to five pinion shafts on which one or two radial or axial flow impellers are overhung. In the case of an additional third pinion shaft bearing, more than two impellers per pinion can be used. Moreover, the possibility exists of supplying or taking off mechanical power not only via a central bull gear but also via one or several pinion shafts.

The fundamental design of IGTMs is characterized by the centrally arranged gear casing [1] on which the individual compressor and expander stages are fixed (Figure 1). One or two horizontal splits are often provided here for two or three pinion shafts. If a further pinion shaft is used, whether for power input or application of further stages, then this can also be designed as a stub shaft.

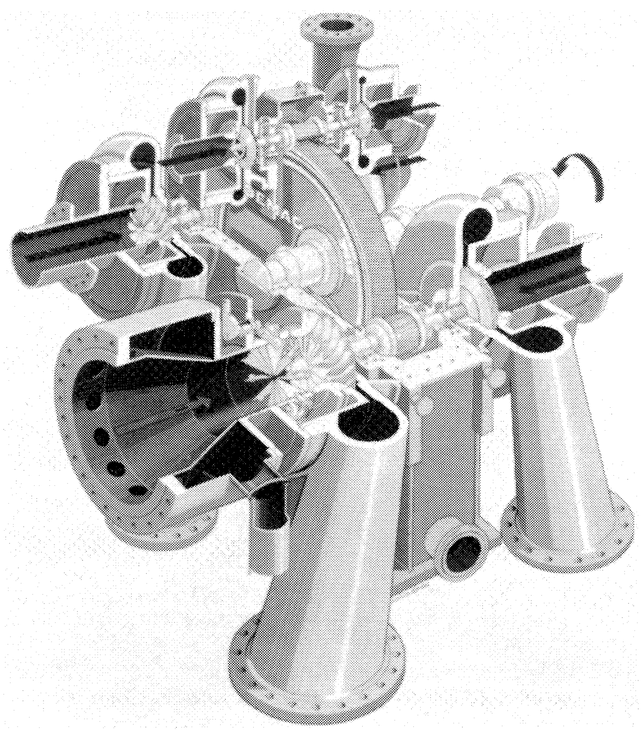

Figure 1. Six Stage Integrally Geared Centrifugal Compressor.

A very important design element of such multiservice turbomachines is a thrust collar for absorbing the axial forces occurring in the pinion shafts (Figure 2). This results firstly in the situation that the axial gear forces are contained within the rotating parts (in principle like with double helical gearing). Furthermore, compensation of the axial thrust (axial gas forces) is not only possible for one pinion shaft, but for all shafts in contact with each other via thrust collars. This is of great importance, particularly with very unsymmetrical axial force distributions within a pinion shaft (e.g., only one impeller, compressor and expander wheel on one shaft or a combination of low and high pressure compressor stage). A further advantage in this connection is the rather constant axial thrust behavior over the operating range typical for back-to-back arrangements of impellers. A free choice of the helical direction and angle of the toothing offers a very intricate possibility of thrust collar relief; which does, however, require accurate predictions of all occurring forces any resulting thrust unbalance is absorbed by the bullgear, both as moment on the radial bearings and axial load on the thrust bearing.

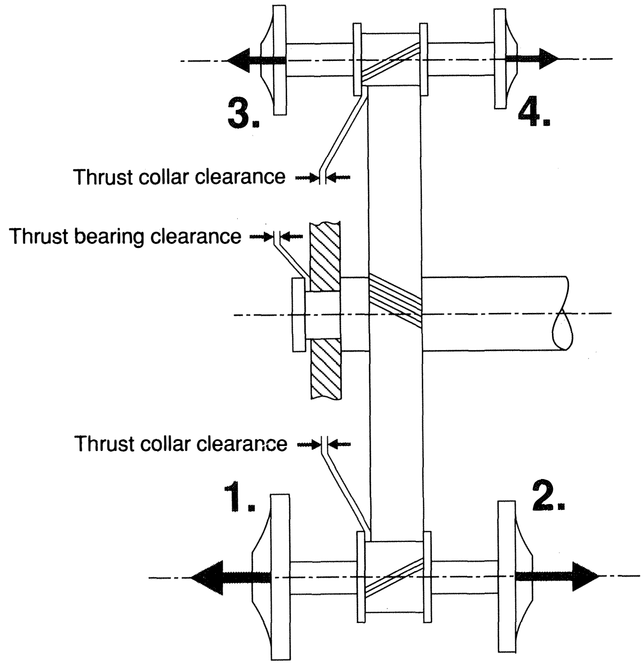

Figure 2. Thrust Collar Design.

A further design feature of central importance is the connection between impellers and pinion shafts.

Besides the functions of torque transfer and impeller centering, it is advantageous to be able to mount the impellers on the installed pinions. This permits use of one-piece seals particularly, such as, for example, liquid mechanical and dry mechanical seals. The use of self centering spur gears in connection with necked-down stretch bolts has proven to be excellent; the Hirth serration is to be mentioned in particular. Such impeller connections, which require only very small hub bores, lead to very low hub ratios (ratio of smallest to greatest diameter of blading) of in some cases below 20 percent. Thus, the suction volume capacity of an impeller is not limited by the shaft diameter, as for instance with a single shaft machine (Figure 3), but by cross section or fabrication related limits in the impeller inlet area. This applies particularly to milled radial impellers with large flow rate parameters.

MATCHING TO ACTUAL REQUIREMENTS AND VARIABILITY OF IGTMS

The outstanding feature of integrally geared turbomachines is the capability of selecting the speeds of the pinion shafts such that impeller specific speeds lie in the range of highest efficiency. These and also other advantages are reported by Rothstein [1] and Simon [2]. Moreover, another feature of this type of turbomachine is of great importance, especially for process applications. Dimensioning of the individual stage elements (such as impellers, volutes, inlet guide vane units, and vaned or vaneless diffusers) must match the respective compression or expansion process and the, thus, related volumetric change of the fluid. With IGTMs this can be achieved to a high degree with standardized components, because of the separate stage arrangements. In the case of single shaft compressors, suitable compromises with respect to stage

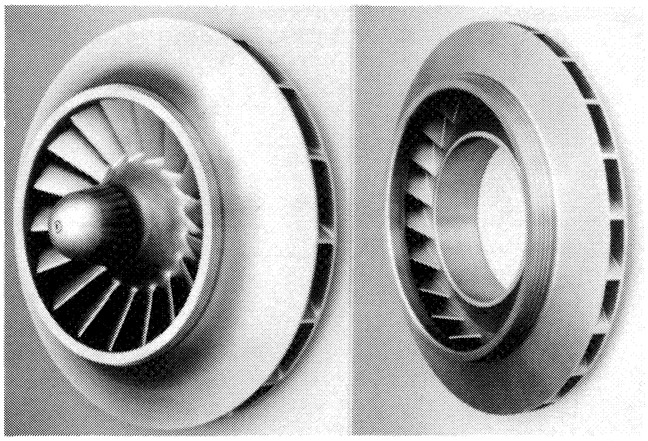

Figure 3. Typical Impeller Contours for Single Shaft and Integrally Geared Centrifugal Compressors.

design are required which have imposed limits of efficiency and control ranges. For integrally geared turbomachines, this means a considerable capability of variations which, starting from a relatively small number of standard components with frequent recurrence and correspondingly high degree of reference, leads to a large number of application variations.

Three preconditions must basically be met for implementing and mastering such a modular system:

• The available sizes of the individual components should cover the relevant design parameters over the entire range of the product application program. This is shown schematically in Figures 4 and 5 for compressor and gear components. With respect to closeness of size increments, aspects of economy on the one hand and the necessity for precise adhesion to the customer request (tailormade design) without concessions on the level of efficiency and control range are to be taken into consideration on the other hand.

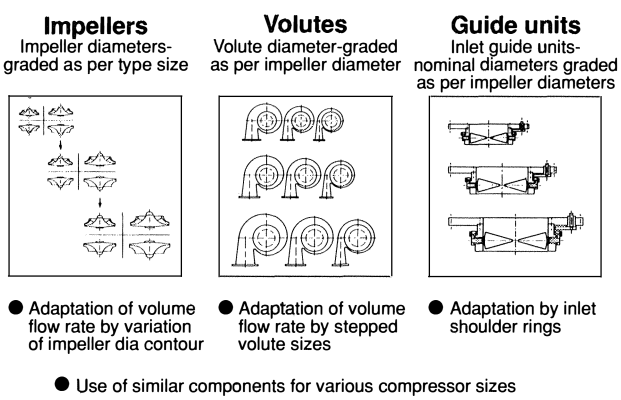

Figure 4. Design Systematics of Compressor Components.

• The component interfaces are to be defined and organized such that a maximum range of variation is available with respect to:

· volume flow rate.

· pressure ratio.

· maximum operating pressure.

· control range.

· type of fluid.

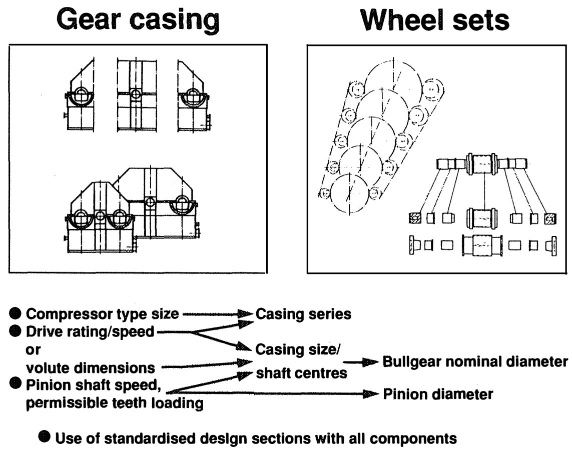

Figure 5. Design Systematics of Gear Components.

· efficiency requirements.

· combination of various processes—compression and expansion.

· type of drive and speed.

· compactness of entire machine.

· observation of general and customer specifications.

Sections through an LP compressor and an expander stage in an integrally geared turbomachine are shown in Figures 6 and 7.

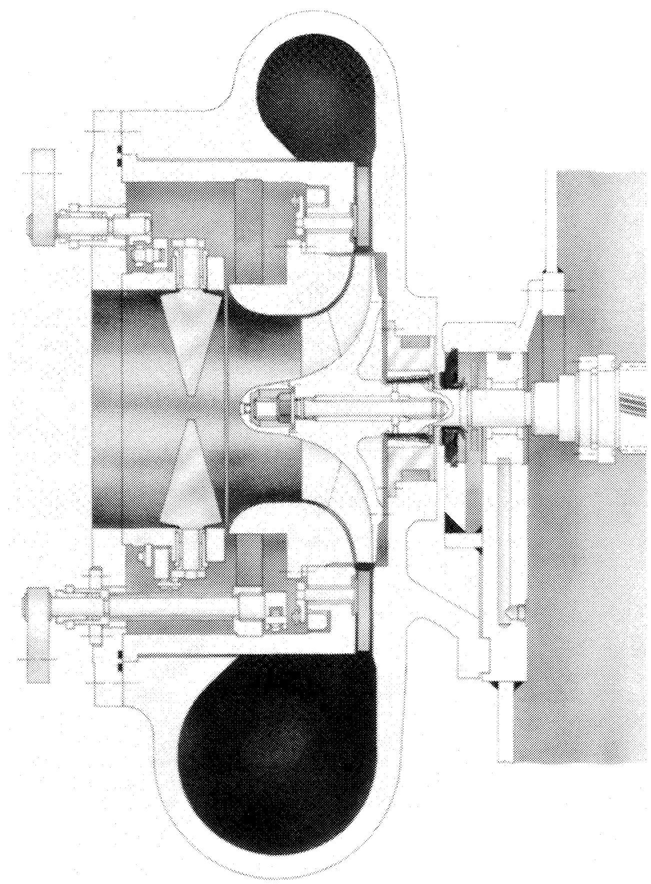

Figure 6. Typical IGTM Compressor Stage.

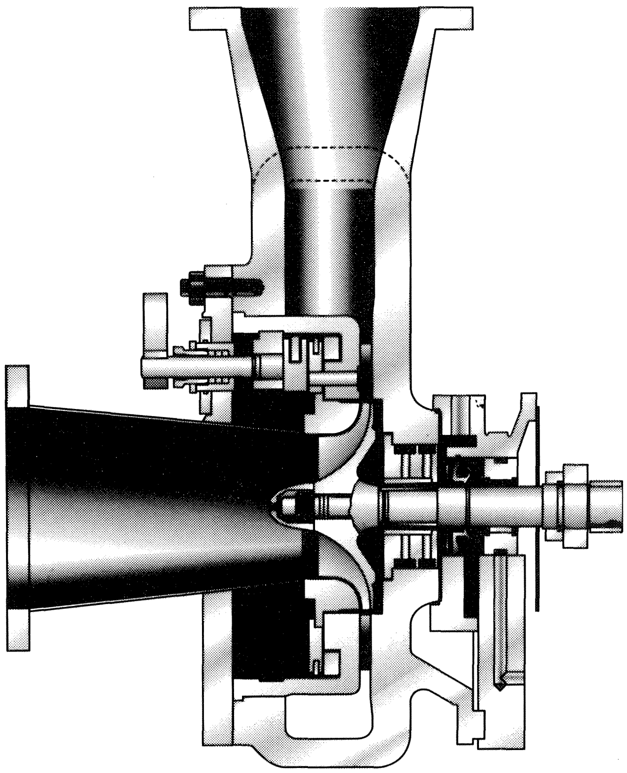

Figure 7. Typical IGTM Expander Stage.

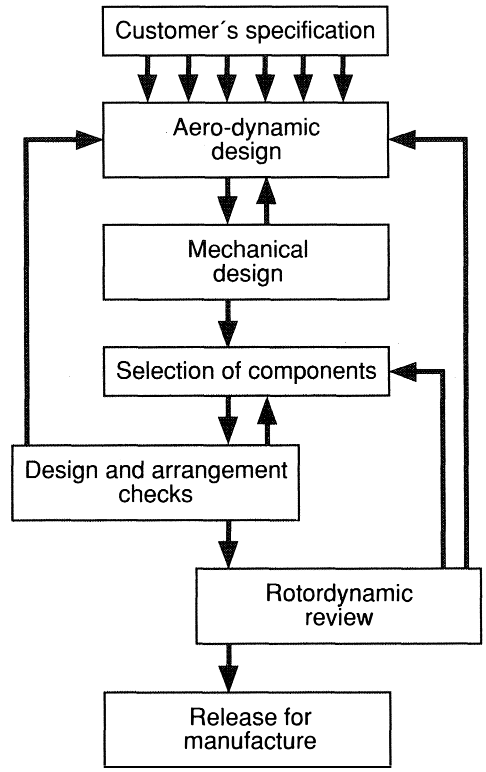

Figure 8. IGTM Design and Construction Based on a Modular System.

The design aspects illustrated include:

- impeller—pinion shaft.
- volute/inlet casing—gear casing.
- inlet guide unit—impeller.
- inlet guide unit—vaned diffuser—volute casing, etc.

• The combination of the components to form a complete and functional machine has two aspects, first, the logistics of the modular system, this is all data which define component design and the reliability and second the design systematics, i.e., consideration of all aspects regarding:

- aerothermodynamics.
- mechanical design.
- rotordynamic.
- specification related requirements.

This complex task, which has to be resolved in the project planning phase in order to ensure implementability of a proposal, requires highly developed design programs. The structure of such a design system is shown schematically in Figure 8. The use of expert systems with suitable decision optimization should prove to be path breaking for the future; the results of tests with less complicated systems than shown here are promising.

In summary, integrally geared turbine machines on the basis of a modular system of the type presented here meet the following requirements:

• IGTMs are suitable for a wide range of applications in the process industries. General application features for integrated compressor and expander stages are tabulated as:

	Compressor Stage	*Expander Stages*
LP side volume flow rate	300,000 m^3/h max.	150,000 m^3/h max.
HP side stage pressure	90 bar max.	25 bar max.
LP side stage temperature	– 196°C	– 196°C
HP side stage temperature	300°C max.	300°C max.
Power per stage	10,000 kW max.	7,000 kW max.
Speeds	50,000 rpm max.	50,000 rpm max.
Impeller peripheral speeds	450 m/s max.	450 m/s max.
Control range	$40\% < V/V_0 < 125\%$	$25\% < V/V_0 < 120\%$
Process technique	intercooling	interheating
Media	air, N_2, O_2, CO, CO_2, C1, ethylene oxide, (also with H_2S) isobutyraldehyde hydrocarbons (also with H_2S), steam, etc.	tail gases (rich N_2, NOX) hydrocarbons steam, etc.

• IGTMs accurately meet specified and guaranteed requirements, thanks to the use of standardized components: the extensive employment of identical components permits a detailed selection of a base design. The great number of recurrent uses provides a wide range of reference data in respect of operational behavior and reliability.

• They allow fast and high quality planning. The planning data are, to a great extent, suitable as design data.

• Economy benefits, such as short delivery and reduced manufacturing costs.

What are the features of an integrally geared turbomachine as a process machine?

In order to answer this question, a process machine must be defined. The essential criteria and features for a process machine are summarized in API 617 [3]. Added to this are further specifications for important components such as:

· gears (API 613 [4])

· oil supply systems (API 614 [5]),

· vibration monitoring (API 670 [5]), and

· couplings (API 671 [7]),

along with general requirements arising from the mode of operation of process industry facilities. Besides special requirements, adherence to certain inspection intervals are to be mentioned in particular: Modern integrally geared turbomachines by some manufactures are designed for a service life of at least 20 years, whereby an uninterrupted, maintenance free operation of at least three years is guaranteed. A few important steps in attaining this aim are:

• The integral gears are designed principally to have strength well above the endurance limit, whereby the calculations are to be performed in accordance with DIN 3990 [8] or AGMA 421 [9]. With respect to starting up and shutting down the machines, two starts per day should be assumed as a design basis. In the case of driving with synchronous motors, for example, the transient loads (oscillating torques) arising during acceleration are to be simulated by cumulated cyclic loads, which include in the load cycle five times the nominal loading (seven times in special cases) for at least 10^5 load cycles. Similar considerations apply to abnormal operating conditions such as network switching in phase opposition or short time power interruption. Compared to electric motors, gas or steam turbine drives are not a problem in this regard.

• Tilting pad bearings are used to support the pinion shafts and for the axial thrust of the bull gears. The bearing loads are not to exceed 50 percent of the manufacturer's rating.

• If gear couplings are used on the drive end, then for maintenance reasons, these should be oil lubricated and not grease lubricated; alternatively, dry couplings (flexible disc) are to be provided.

• Fouling factors for the oil and intermediate cooler are to be set at 0.35 m^2K/kW.

The points just listed simply represent a selection of the most important design criteria.

USE OF INTEGRALLY GEARED TURBOCOMPRESSORS

With regard to the preceding characteristic properties of integrally geared turbomachinery and the requirements which they are able to meet, the possible uses and designs of this machinery type are explained on the following pages using latest applications.

The principal domain of integrally geared turbocompressors is air separation plants. The air, nitrogen, and oxygen compressors in such plants are usually machines with nonhermetic seals, which are fitted out with a product loss recovery seal system. Safety reasons dictate that the oxygen compressor is equipped with a buffer gas system.

The main air compressors are integrally geared turbocompressors for intake volumes up to 300,000 m^3/h (Figure 9). They are mostly driven by electric motors and have three to five intercooled compression stages. Adjustable inlet and outlet guide vanes can be adapted to all stages where high partial load requirements must be satisfied [1].

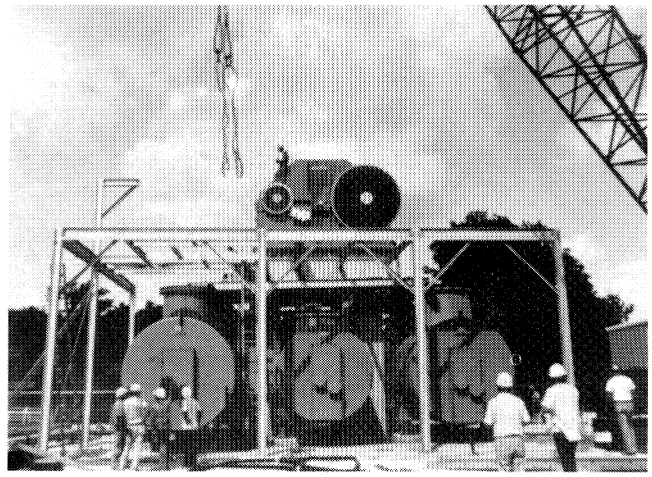

Figure 9. Four-stage Integrally Geared Centrifugal Compressor in an American Air Separation Plant; V_c = 240,000 m^3/h; P_C = 19,000 kW.

In liquid oxygene (LOX) facilities, which exclusively or mainly produce liquid oxygen, a dry air recycle compressor is used in addition to the main air compressor (wet air). Both applications are integrated today in a single casing multiservice compressor.

N_2 integrally geared turbocompressors are employed in liquid nitrogen (LIN) facilities as recycle compressors. In facilities with a high liquid nitrogen capacity, and in particular with simultaneous liquid argon generation, an N_2 feed gas compressor is also used. An amplified process diagram of a LIN facility is shown in Figure 10. Feed gas and recycle compressor are designed as a single casing multiservice compressor.

With regard to oxygen compression (air separation plants, partial oxydation) it should be noted that recently highly pure oxygen was compressed to high discharge pressures in integrally geared turbocompressors (Figures 11 and 12), an achievement that had only been reserved to single shaft compressors before. This

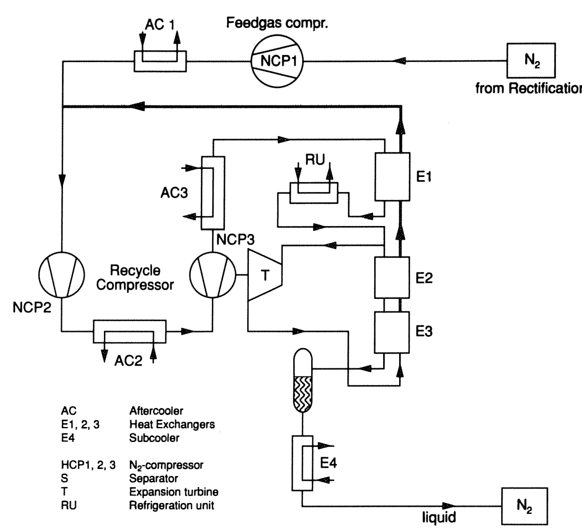

Figure 10. Liquid Nitrogen Plant Simplified Process Diagram.

means that the advantages offered by integrally geared turbocompressors, such as their high efficiencies and their wide control range, are now also available for oxygen service. The oxygen demand may fluctuate considerably in some industries. The demand may fluctuate about a given average value, for example in steel plants, or perhaps at a low or a high level during prolonged periods of time, depending on capacity utilizations. Variable oxygen supply units (varox units) specially designed for such requirements, are used in these cases [10]. Varox units have tanks for liquid oxygen and nitrogen instead of the customary gas pressure vessels. When the oxygen demand is high, evaporation from the tanks is utilized in addition to the normal oxygen production rate. The evaporation heat is extracted from gaseous nitrogen, which in turn is liquified and supplied to the N_2 tank. In the event of low oxygen demand, the O_2 production is reduced, and excessive amounts of oxygen are sent to the O_2 tank.

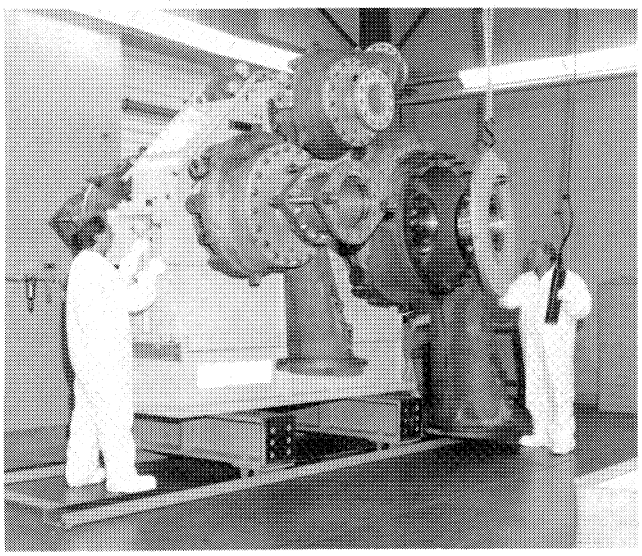

Figure 11. Assembly of an Oxygen Geartype Compressor in the Clean Room.

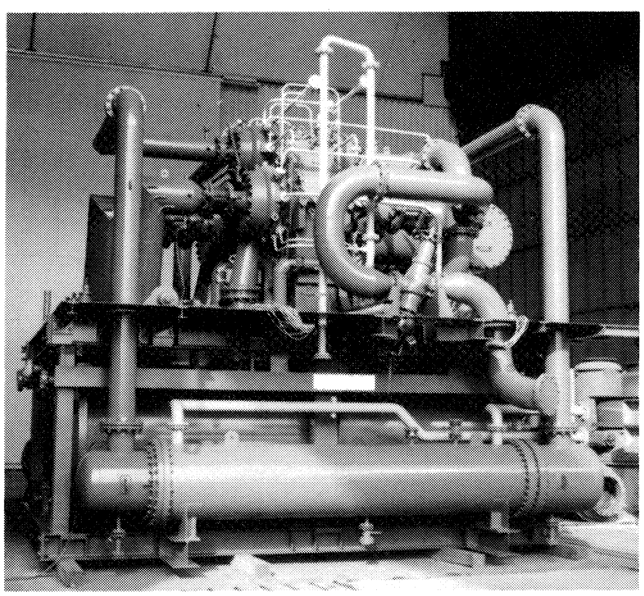

Figure 12. Complete Package of a Six Stage IGTM for Oxygen $V = 25{,}000\ m^3/h$; $= 17.0$; $P_C = 5.500\ kW$.

Such considerable fluctuations in oxygen demand require significant flexibility of the oxygen product compressor.

Here, the user of such an installation can benefit by the enormous operating range advantages which integrally geared oxygen compressors offer over conventional single shaft compressor trains (Figure 13).

A typical comparison is shown in Figure 13 between the operating range of a single casing six stage integrally geared turbocompressor and that of a two casing single shaft compressor train with six impellers arranged in three stage groups per casing. The single shaft compressor is equipped with a main and an intermediate gear unit.

Each compressor installation, the integrally geared turbocompressor and the single shaft compressor, is equipped with five intercoolers.

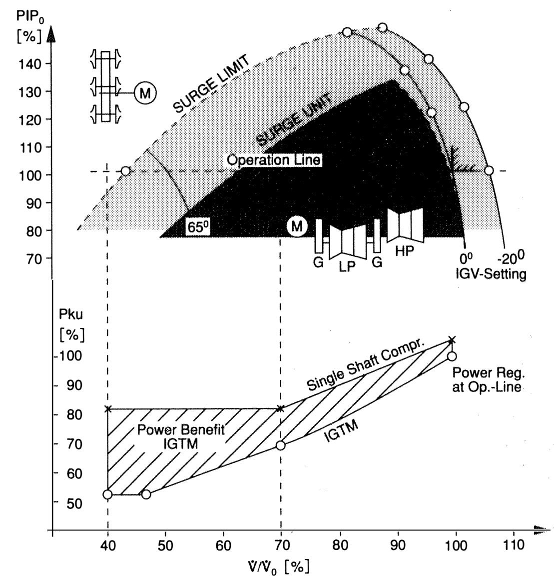

Figure 13. Typical Operating Range and Power Requirement of an IGTM Unit and a Single Shaft Compressor.

The operating range of the integrally geared compressor is of light color and that of the single shaft compressor is dark in the illustration. Since the operating cases for oxygen product compressors are mostly at constant pressure ratio in air separation plants, the same operating method is used here for comparison purposes. The integrally geared turbocompressor, related to its design point, features a turndown range of 45 percent V/V_0 with guide vane setting before all six impellers, while the variation range of the single shaft compressor, equipped with suction throttle control as is typical of the single shaft type, is only 66 percent V/V_0. Moreover, counter rotational flow setting of the guide vanes of the integrally geared compressor offers an overload range of some 110 percent V/V_0, which range is not available in a single shaft compressor without intake guide vanes. The aerodynamic advantages of integrally geared turbomachines lead in the reference point to efficiency and, therefore, power advantages of up to 10 percent depending on the application. The curve map comparison (Figure 13) shows also the power requirements of both application examples at a constant pressure ratio, in addition to the operating ranges.

The minimum power difference of five percent is assumed for the reference point. For 70 percent delivery, the power difference is approximately 12 percent and for a 40 percent delivery, the power difference is approximately 30 percent. On the assumption of identical periods of time for each of the 100 percent, 70 percent and 40 percent operating cases, and allowing for a power requirement of 4000 kW for the reference point of the integrally geared compressor, the cost advantage in favor of the integrally geared compressor is $700,000, based on the usual cost to power ratio of 10 ct/kW-h, calculated for two years uninterrupted time. It has to be pointed out again that the data mentioned are typical of such applications.

Whether the machines are single shaft compressors or integrally geared turbocompressors for oxygen, all components, such as impellers, bearings, seals, and casings, they are designed and made in accordance with the same high safety aspects.

The paired materials are silver and monel wherever contact between rating and stationary parts cannot be ruled out.

The impeller and the shaft seal of the third pinion of an integrally geared oxygen turbocompressor are shown in Figure 14. All labyrinth seals in contact with oxygen or nitrogen are of the stepped type to reduce leakage. An overview representing the oxygen sealing system of a six stage compressor is shown in Figure 15. The breakdown of the oxygen pressure in up to three cascades provides efficiency optimized and product saving leakage rate handling. Stepped breakdown to the high pressure, the medium pressure, and the low pressure level is also shown in Figure 15. The high pressure leakage, which occurs in the fifth and the sixth stage only, is returned to the fifth stage inlet. The medium pressure leakages of stages three to six are returned to the third stage suction, and the low pressure leakage of all six stages is fed back to the first stage inlet. A vent port is arranged after the intermediate sealing ports as seen in the leakage direction followed by a nitrogen buffer port. All remaining oxygen leakage, together with part of the nitrogen buffer gas, are piped and vented to atmosphere. The positive differential pressure between the buffer port and the vent port is one of the most significant safety features of an oxygen compressor. Moreover, additional nitrogen buffering is provided for all shaft seals of the gear case (Figure 15). As an additional safety device, this results in a nitrogen atmosphere in the gear case. The outer nitrogen leakages escape between the volutes and the gear box into the atmosphere respectively, are evacuated through the oil drain and an ejector. The buffer gas for the compressor stage and for the bearing may come from different sources, depending on the operator safety philosophy.

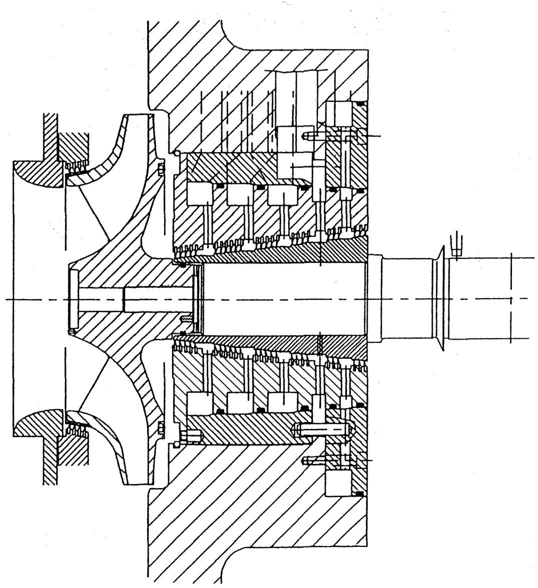

Figure 14. Integrally Geared Centrifugal Compressor for Oxygen Impeller and Shaft Seal.

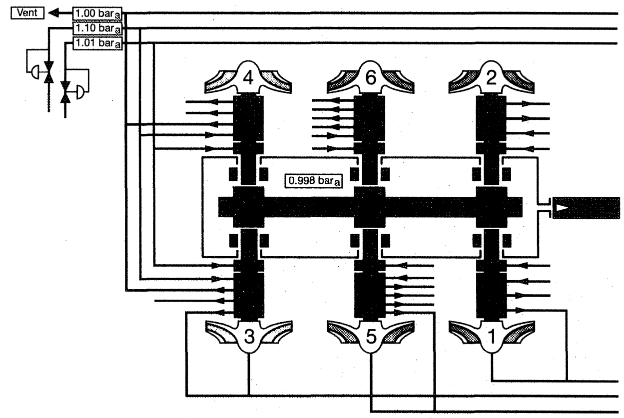

Figure 15. Integrally Geared Centrifugal Compressor for Oxygen Sealing System.

IGCC POWER PLANTS

"The future belongs to those who prepare for it" is the heading of a publication [11] which appeared in August 1990 and in which a 250 MW integrated gasification combined cycle power station erected in Holland was described.

This project represents the final demonstration phase to justify coal gasification commercially. A typical process diagram of such plant is shown in Figure 16. Its main advantages are:

- High plant efficiency of approximately 43 percent.
- Reduced pollutant emission.
- High quality of the process residues, namely slag and sulphur, facilitating disposal and sale.

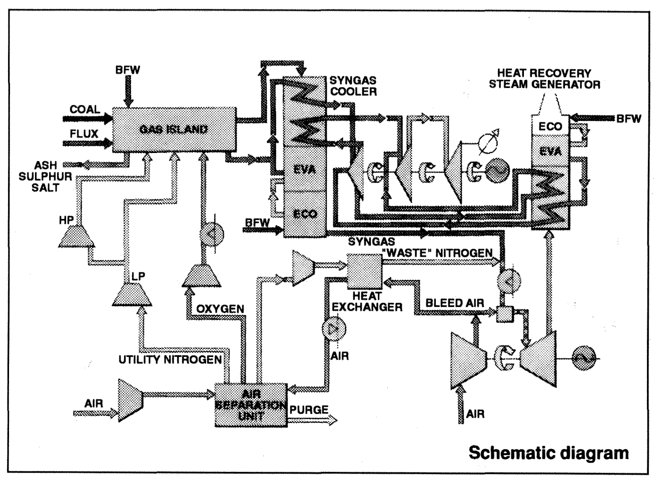

Figure 16. Process Diagram IGCC Power Plant (Integrated Gasification Combined Cycle).

The three main components of the plant are:

- Coal gasification unit.
- Power station with gas and steam turbines.
- Air separation plant.

The air compressor of the gas turbine supplies part of its air to the air separation plant at a pressure of approximately 10 bar. The oxygen obtained in the separation plant is compressed to about 28 bar and blown into the gasifier together with pulverized coal [11].

Great amounts of nitrogen at about 16 bar pressure are necessary for the dilution of the coal gas, which is subsequently burned in the gas turbine. Dilution with nitrogen means that the formation of NO_x in the offgas is largely prevented.

The turbocompressors used operate in the following power ranges:

Medium-pressure nitrogen compressor Power requirement: up to 13,000 kW	(combustion gas conditioning)
High pressure nitrogen compressor Power requirement: up to 2,500 kW	(pneumatic transport)
Medium pressure oxygen compressor Power requirement: up to 7,000 kW	(coal gasification)
Low pressure air compressor Power requirement: up to 6,000 kW	(air separation unit startup)

In view of the high cost-to-power-ratio of 10 ct per kWh, calculated for three years uninterrupted time, it was quite logical to build the nitrogen compressors and the startup air compressor as integrally geared machines. So about 75 percent of the compressor power is required by this machine type. During plant startup, the medium pressure nitrogen compressor is operated on air as a booster of the startup air compressor.

Common to all integrally geared compressor applications described until now is the fact that intercooling is provided after each machine stage. The same process technique is also applied in the following cases:

Air compressors	in protein plants
Nitrogen compressors	as nitrogen pipeliners delivering up to 80 bar discharge pressure
Oxygen compressors	for all steelmaking plants

PROCESS AIR AT HIGH DISCHARGE TEMPERATURES

Chemical industry processes frequently demand process air at high discharge temperatures. Integrally geared turbocompressors are now available for maximum discharge temperatures of 300°C. In fluid catalytic cracking (FCC), uncooled two stage compressors can be used. Their drivers are usually steam turbines. For maleic acid plants (synthetic resin production), the machines are also uncooled two stage units. The drivers are either motors or steam turbines.

The integrally geared turbocompressors of NH_3 plants are six stage machines to cope with the higher compression ratios. A six stage air compressor supplied for an NH3 plant in Great Britain is shown in Figure 17. It compresses 36000 m^3/h of air to a discharge pressure of 41 bar. The optimum discharge temperatures of the machine are about 220°C. The air is, therefore, cooled after the first and the third compressor stage, but is compressed further in stages four to six without any intercooling. Air compressors in ammonia plants are either motor-driven or turbine driven.

COMPRESSION OF TOXIC AND FLAMMABLE GASES

Contrary to inert gases, which do not require hermetic compressor sealing, no leakage to the outside whatsoever must occur where toxic and flammable gases are used in the process industry. Hermetic sealing is achieved, for instance, by liquid mechanical seals or by nonhermetic seals with a buffer gas safety feature, in other words labyrinth or dry mechanical seals.

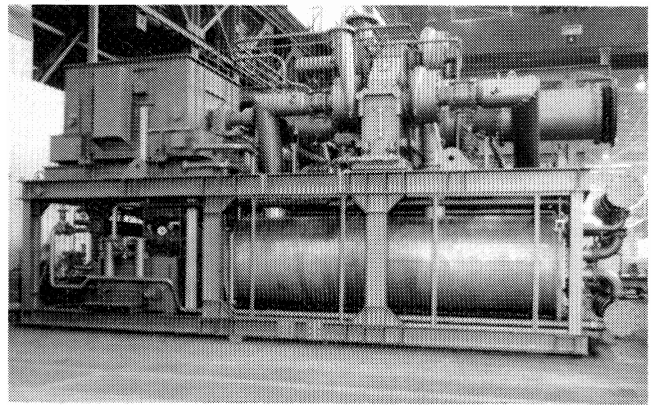

Figure 17. Six Stage Air Compressor for an NH_3-Plant $V_C = 36000\ m^3/h$; $P_C = 42$; $P_C = 6400\ kW$, $T_D = 220°C$.

The pinion shown in Figure 18 is of a two stage integrally geared turbocompressor used for the compression of isobutyraldehyde for the heat pump loop in an OXO plant. The seals are of the liquid mechanical type. The lubricating oil and the sealing oil flow in a combined system. Where the gas contains corrosive constituents, separate systems can be installed for the lubricating oil and the sealing oil.

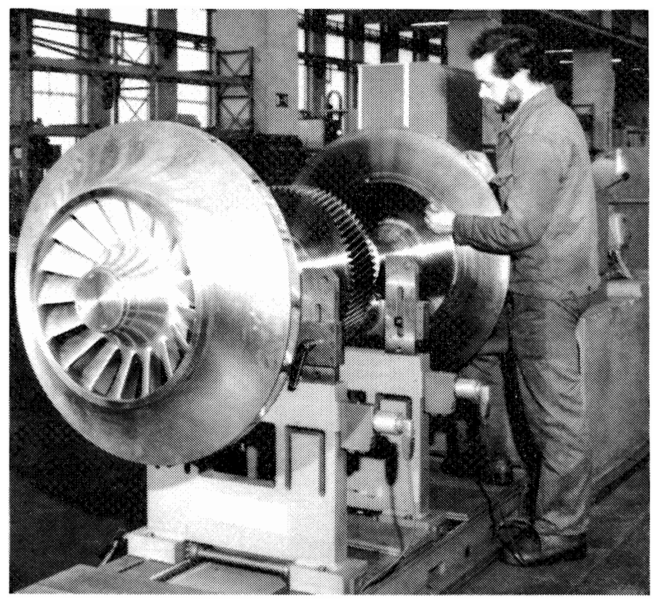

Figure 18. Shaft of a Two Stage Integrally Geared Centrifugal Compressor in an OXO-Plant. $V_C = 60000\ m^3/h$; $P_C = 3.5$; $P_C = 3800\ kW$.

Carbon monoxide and hydrogen are nowadays required in great quantities for the most varied industrial purposes. For instance, carbon monoxide is used in the plastics industry for the production of isocyanates, and hydrogen is required in NH_3 synthesis, in numerous hydrogenating reactions, and for oxyacethylene welding and cutting. Capital intensive plants in which pure H_2 and CO are separated from gas mixtures rich in H_2CO, necessitate the use of radial compressors of high reliability and a wide control range to ensure cost effective operation.

The integrally geared turbocompressors used in such plants are most often equipped with five or six impellers, all provided with intake guide vanes (Figure 19).

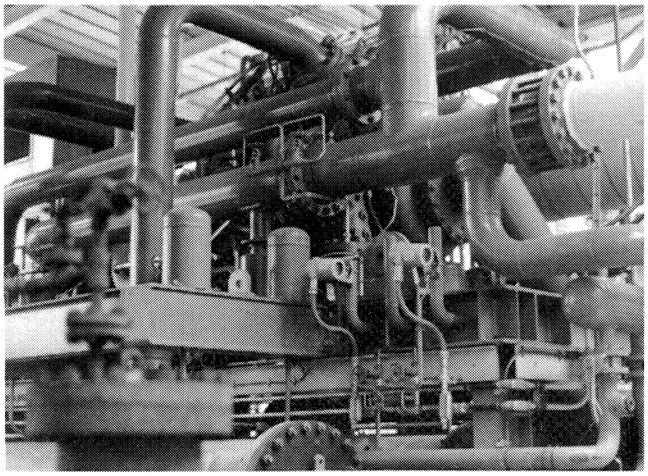

Figure 19. Five Stage Integrally Geared Centrifugal Compressor for CO. $V_C = 12300\ m^3/h$; $P_C = 14$; $P_C = 2700\ kW$.

The seals are nitrogen buffered multiple port labyrinth seals. As product costs are very high, the use of gas seals should be considered, through which much less product is lost.

Gas seals of the most varied types (Figure 20) can be employed, depending on the media handled and the pressures which act on the seals. The three most frequent gas seal types are shown here: typical applications for double seals with additional buffer gas feature (GDDS, Figure 20) are processes in which the pressures to be contained are low and neither external clean gas is allowed in the process nor process gas is allowed as secondary leakage gas. The majority of gas seal applications are simple gas seals with the additional buffer gas feature (GDES, Figure 20) and tandem gas seals with internal labyrinth (GDTL. Figure 20). They are used where the differential between the compressor discharge pressure and the pressure in the flare burner, used for the primary leakage disposal, is in excess of 0.5 bar. In a tandem seal, buffer gas is admitted between the internal labyrinth and the secondary seal, which means considerable reduction of the buffer gas flow. In single seals, the same function is performed by a gas buffered floating carbon ring seal.

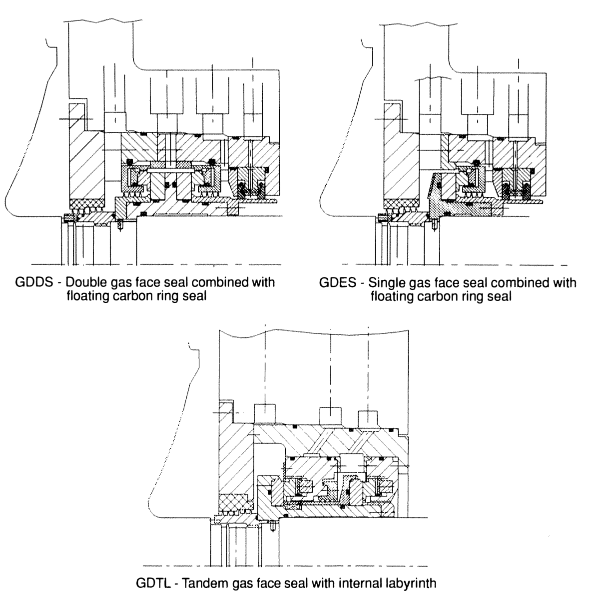

Figure 20. Gas Sealing Systems for Flammable/Explosive Gases.

APPLICATIONS OF INTEGRALLY GEARED EXPANDERS

The authors distinguish between two main applications of process gas radial flow expanders. One is cryogenic in the air separation for the purpose of nitrogen liquification and for liquifying natural gases and the second is energy recovery with the following sectors:

- Nitric acid plants (HNO_3-synthesis)
- Dimethylterephtalat (DMT) and pure terephtalic acid (PTA-plants)

(Raw material synthesis for synthetic fibre production)

- Fluid catalytic cracking (FCC) plants
- Furnace top gas systems
- Pressure reduction in natural gas piping

With the exception of large nitric acid and FCC plants, where the process gas expanders are multistage axial flow type for powers up to 20000 kW, single stage and two stage radial flow expanders of 500 to 10000 kW range are employed in most cases. The expander stages are inward flow stages, as shown in Figure 7. The process gas is distributed from a header to the inlet nozzles, which may be fixed or may permit angular adjustment (Figure 21). A high prerotation is imparted to the fluid. As expansion proceeds, the prerotation is converted into mechanical energy in the downstream expander wheel. When the medium leaves the expander stage, it is almost rotation free. A downstream outlet diffusor is provided for maximum utilization of the contained pressure energy.

Figure 21. Adjustable Inlet Nozzle for a Radial Expander.

Important applications in energy recovery are presented in the following text. In the case of large HNO_3 plants, for example, the residual energy is utilized for driving the process compressor train. In small plants, the available process energy is often used for power generation. In DMT plants and PTA plants, the waste air from the catalyzer is available for the recovery of energy. Because of their excellent flexibility, integrally geared turbomachines are, in these cases, ideal for an optimum utilization of the energy, with full integration into the process.

The driver of the multistage process air compressor is usually an electric motor. The tail gas or waste gas from the process is expanded on a radial flow expander and the gained mechanical energy is used to reduce the power consumption. Where no process energy is available to the expander for operation related reasons, drive is provided by the electric motor alone. Where the compressor and the process gas radial flow expander are attached to a gear box (Figure 22, top), the installation is referred to as a single casing design. Where the compressor and the expander are attached to a separate gear case (Figure 22, bottom), the installation is referred to as a two casing construction.

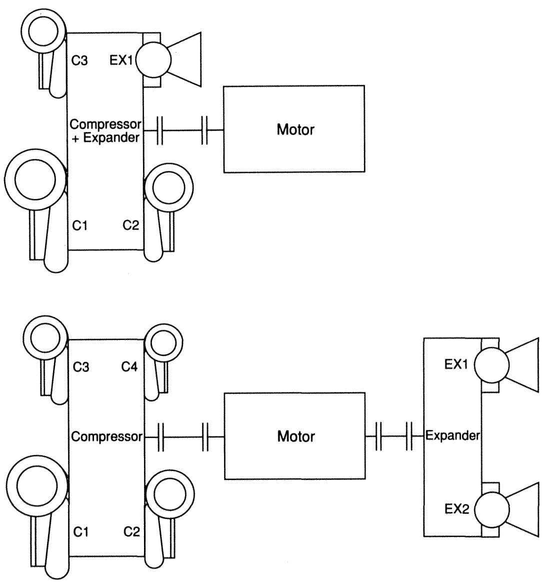

Figure 22. Possible Arrangement for Compressor and Expander Stages.

There are two types of the single casing constructions. The first is characterized by the fact that the expander wheel is mounted with a compressor stage on one common pinion shaft (Figures 23 and 24). The expander power input is consumed in part, or even fully, by the compressor stage, which means that the gearing design for the pinion shaft may be based on the maximum differential power. Since both wheels run at identical speeds, a compromise is necessary in this respect. The compressor stage and the expander stage are possibly not operated at their optimum efficiency specific speeds. If such a compromise is not acceptable, then the expander stage may be mounted on a separate pinion shaft of the integrally geared multistage turbocompressor, which is illustrated in Figures 25 and 26. Then, both the expander and the compressor stages can be designed for optimum specific rotational speeds. The diameters of expander wheel and of the compressor impeller and their speeds can be determined to meet individual requirements.

Since there is a limit to the number of integratable compressor and expander stages, the two casing construction (Figure 27) is a logical consequence. Basically, the preceding information is also applicable to the separate casing type. However, separation of the expander gear case from the compressor gear case means that both units can be uncoupled mechanically. The compressor can then be operated without the expander. Since the stage arrangements of the compressor and the expander portion are fully independent of each other, the two casing construction is ideal for large stage sizes, i.e., large volume flowrates (compressor/expander). The arrangement and integration of the expander stages follows the same criteria as

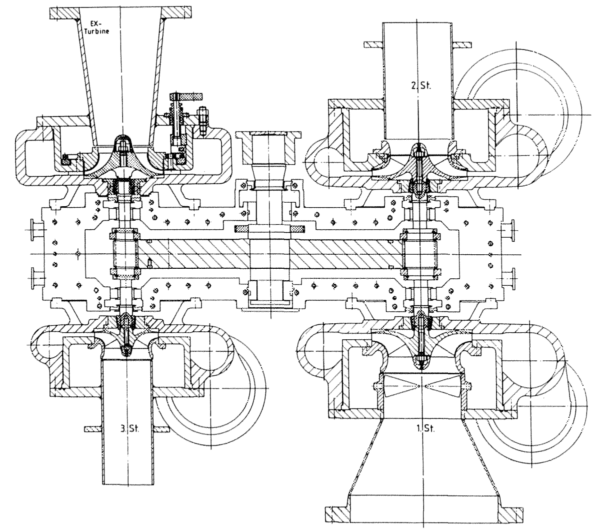

Figure 23. Three Stage Integrally Geared Centrifugal Compressor with Radial Expander Stage.

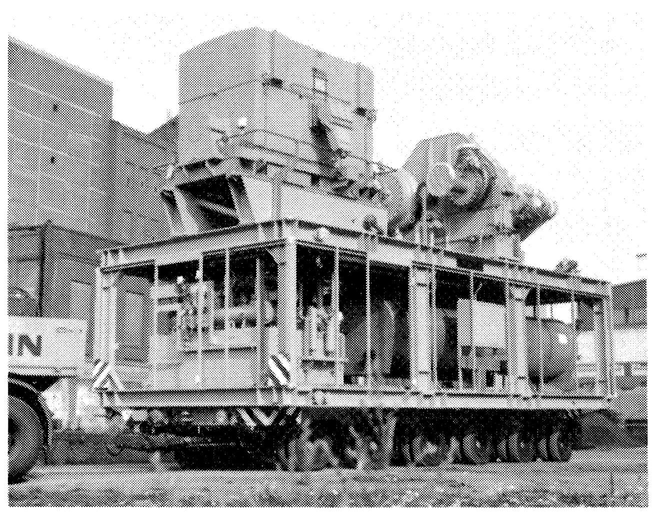

Figure 24. Three Stage Integrally Geared Centrifugal Compressor with Radial Expander Stage V_C/V_E = 38000/25000 Nm^3/h; P_C/P_E = 4800/1100 kW.

those of the compressor stages. Some of the important aspects (Figure 8) to be repeated are:

- Aerodynamic Design.
- Mechanical design.
  - toothing.
  - axial thrust.
  - bearings.
- Component arrangement checks.
- Rotordynamic design.

Great numbers of stage arrangements are available to create optimum conditions for each particular application in respect of:

- Efficiency and control range.
- Mechanical loading.
- Construction expenditure.

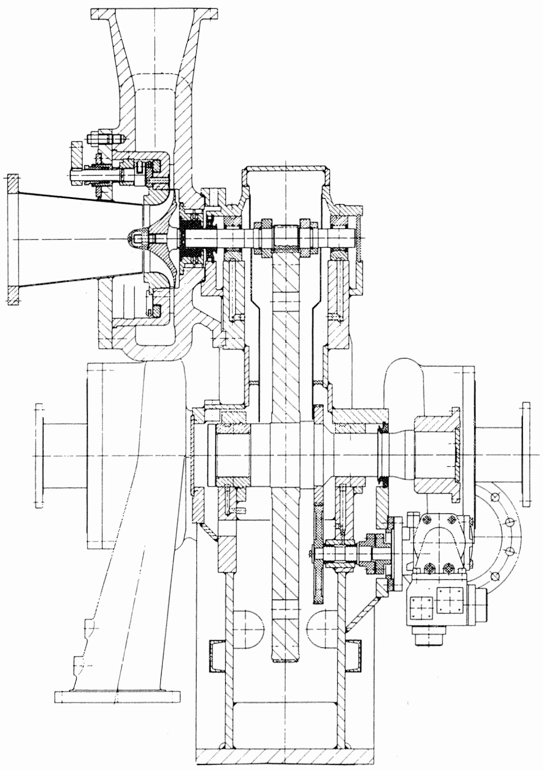

Figure 25. Four Stage Integrally Geared Centrifugal Compressor with Radial Expander Stage.

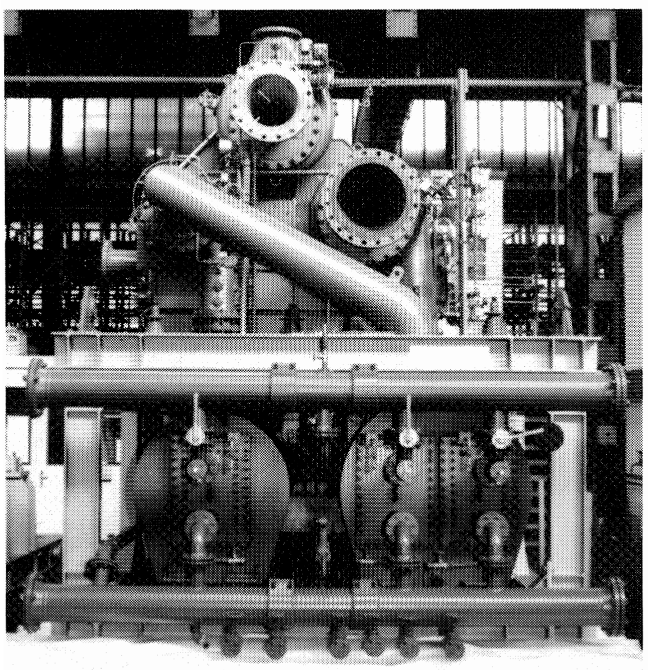

Figure 26. Four Stage Integrally Geared Centrifugal Compressor with Radial Expander Stage V_C/V_E = 9000/12600 Nm^3/h; P_C/P_E = 1100/600 kW.

This is demonstrated by means of the two stage process radial expanders illustrated in Figures 28 and 29. The axial thrust is largely eliminated as part of the construction detail in the case of

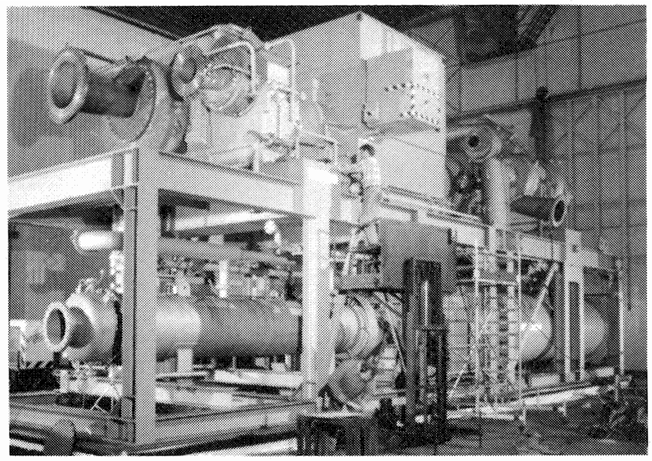

Figure 27. Two Casing IGTM Package (Compressor and Expander) with Electric Motor for a DMT Plant V_C/V_E = 120,000/80000 Nm^3/h; P_C/P_E = 17000/6000 kW.

the single shaft type (Figure 28). The main reasons for choosing the stage arrangements shown in Figure 29 are the possibility of individual speed adaptation and toothing load reduction, as previously mentioned. A typical single shaft design in actual use can be seen in Figure 30.

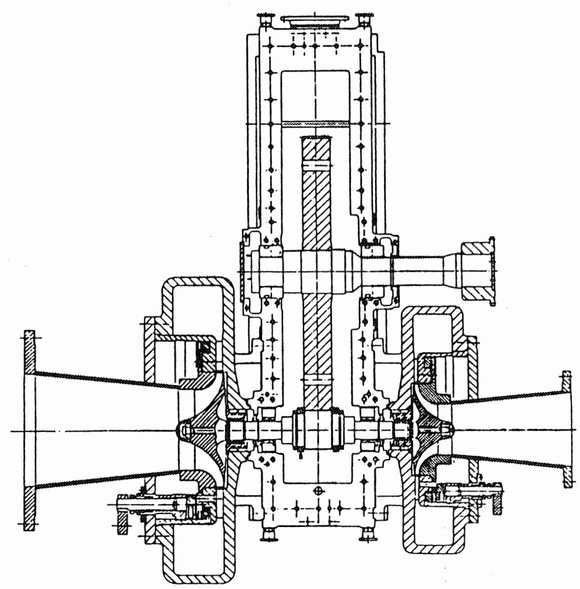

Figure 28. Two Stage Integrally Geared Radial Expander with One Pinion Shaft.

DRIVE AND INSTALLATION POSSIBILITIES

IGTMs excel in their high flexibility, as shown previously, whether as power supplying expander or power consuming compressor. Additional aspects of this machine construction, such as the trend towards higher operating speeds, etc. will be explained. The machines previously mentioned were chiefly designed for motor drivers. The input speeds of medium and large size IGTMs are 1,800 rpm maximum. Therefore, steam and gas turbines could hardly be employed for this machine type as direct drivers. Present possibilities of machine design and manufacturing quality, together with a high degree of adaptability and reliability, allow new

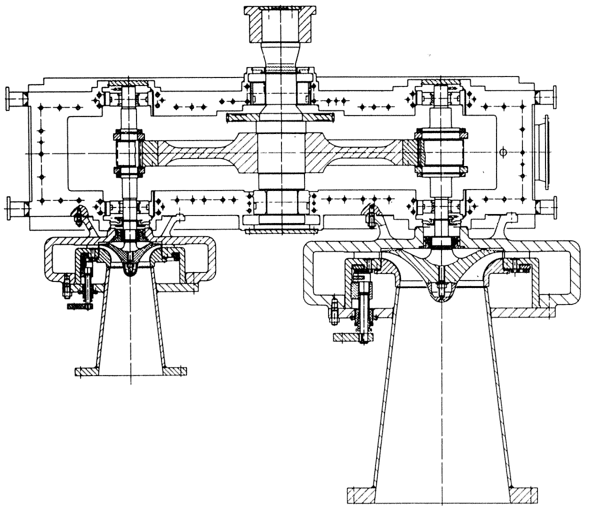

Figure 29. Two Stage Integrally Geared Radial Expander with Two Pinion Shafts.

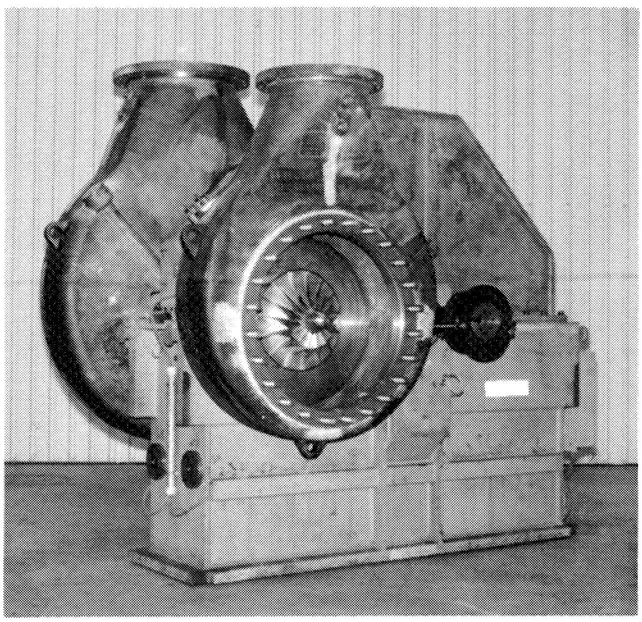

Figure 30. Two Stage Integrally Geared Radial Expander with One Pinion Shaft.

drive and arrangement options, some of which are explained in the following paragraphs.

If an integrally geared turbomachine is driven through a pinion shaft, the input power can be transmitted to one extension of a shaft whose other end carries a compressor impeller or an expander wheel. This leads to optimum gearing utilization in respect to the number of stages, but restricts the selection of input speeds. A compromise must be found between the optimum driver and the optimum stage speed. Such problems can be solved by transmitting the drive power to a pinion shaft which is only used for the power input. The pinion shaft may be located in the bottom or the top casing split (Figure 1). Another solution is the use of a stub shaft in the lower part of the gear unit (Figure 31). Up to six compressor expander stages can be connected in this case, where the driver is a high speed unit. Should the input power fully meet the IGTM requirement, no further bullgear shaft coupling is necessary (Figure 31). It is, nevertheless, possible to supply power

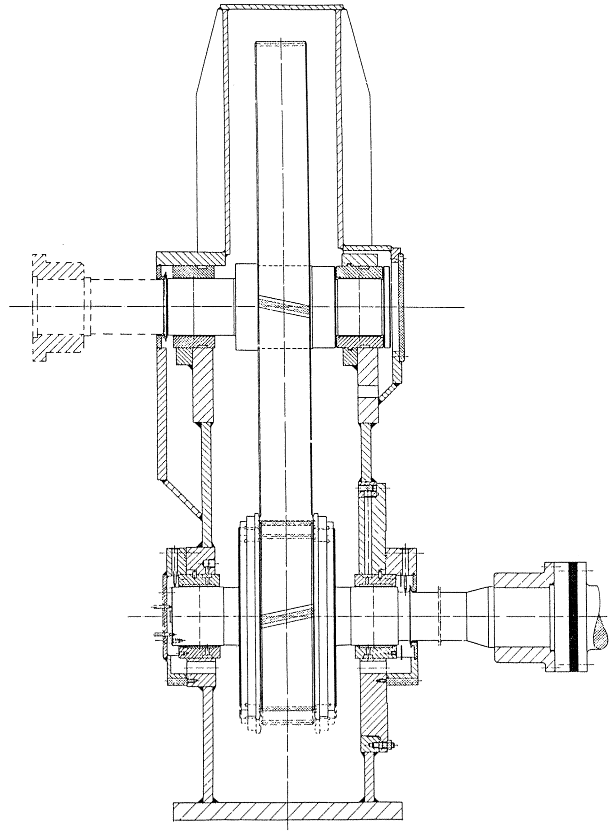

Figure 31. Gear Casing for IGTMs with Plug Shaft Drive.

through a gear shaft coupling in addition to the high speed driver, or give off excessive power at a low speed, for example to a generator or another integrally geared turbocompressor.

This leads us to another very important aspect of integrally geared turbomachinery use: The distribution of the power to various consumers. A large four stage integrally geared turbocompressor of more than 130,000 m^3/h capacity (illustrated in Figure 32) is driven by a gas turbine through stub shaft arranged in the lower part of the gearcase. About 50 percent of the gas turbine power is reduced to a lower speed level in the integrally geared turbomachine and transmitted by the gear shaft to a four-stage integrally geared HP turbocompressor. The gas turbine is a model LM 2500 machine.

Another highly interesting application is illustrated in Figure 33. A six stage axial flow compressor is motor driven through an integrally geared turbocompressor. The power required by the

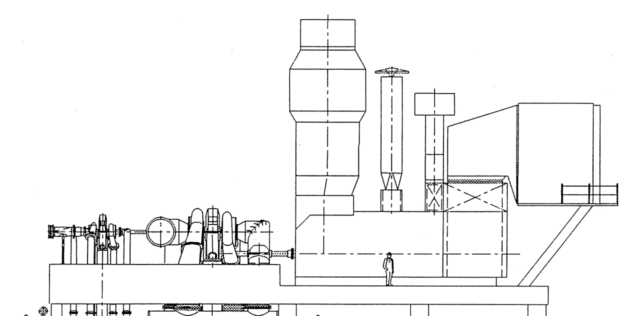

Figure 32. IGTM String with Gasturbine Drive.

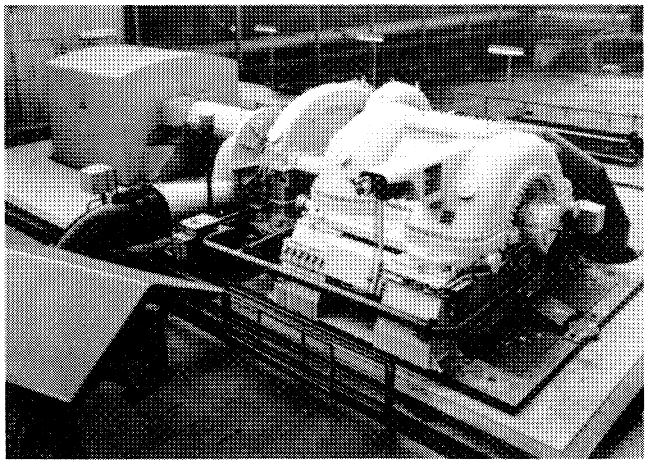

Figure 33. Six Stage Axial Compressor Driven by a Three Stage IGTM; $C = 250{,}000/Nm^3\ h$; $P_C = 7.5$; $P_{Mot}/P_{AX} = 23000/9000$ kW

axial flow compressor is about 9000 kW, and the total drive power is 23000 kW.

Finally, another gear design should be mentioned in connection with integrally geared turbocompressors, the idle gear unit, sometimes referred to as five shaft gear unit (Figure 34). Its characteristic feature lies in the fact that an intermediate gear wheel is arranged between the bullgear and the pinion shaft of an integrally geared four stage turbocompressor. This serves a double purpose. The centerline spacing of the pinion shafts in large integrally geared turbocompressors is no longer dictated by the gear loading (chiefly toothing and bearing forces), but by the dimensions of the volutes. Consequently, the input speeds must be reduced as volume flowrates increase in order to keep gear pitchline velocities at acceptable levels. On the assumption of the present achievable maximum pitchline velocity level of about 190 m/s and a minimum driving speed (60 Hz mains) of 900 rpm, centerline spacings of more than four meters are realistic. Such a centerline distance is sufficient for an integrally geared turbocompressor of over 400,000 m^3 capacity. However, if it is intended to reduce gear unit ventilation losses (which chiefly depend on the pitchline velocity and amount to a high percentage of the total gear unit loss), or where higher input speeds are specified (smaller volume motors), the gear unit type with intermediate gear wheels shown in Figure 34 must be employed. To put it simply, only half the pitchline speed of a conventional three shaft gear unit is necessary with identical centerline spacing. Moreover, input speeds are achievable for integrally geared turbocompressors equipped with five shaft gear units which correspond to those of gas or steam turbines of the referred power range. In addition to the above advantages, the significant reduction in the mass moment of inertia must be emphasized at any rate. Its consequence is a reduction in the maximum startup power.

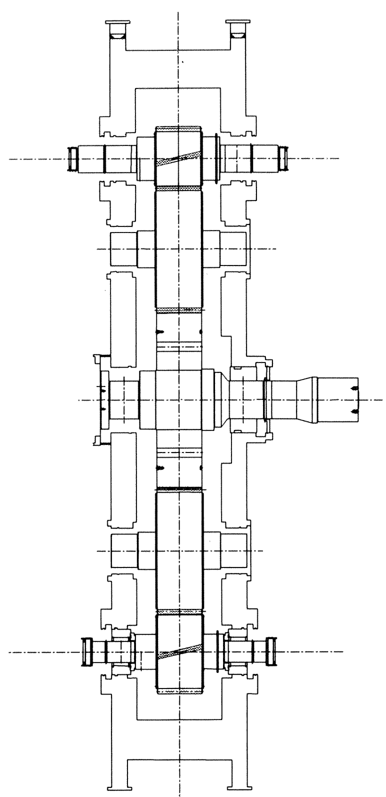

Figure 34. Gear Casing with Integrated Intermediate Gearing (Five Shaft Gear).

SUMMARY

A comprehensive overview of the configurations and options of modern integrally geared turbomachinery has been attempted, with reference to the use of both turbomachine versions, the compressor and the expander. The main emphasis lies on the great number of IGTM varied application possibilities, based on a proven number of modularized and standardized components. The arrangement options and the requirements to be satisfied by the modular construction principles and the modular design methods used for configuring integrally geared turbomachines in a manner best suitable for each particular purpose have been discussed.

The application range of this turbomachinery group extends from the meanwhile classic use in air separation plants to a great number of modern process industry sectors. It should be mentioned in respect to air separation plants that integrally geared turbocompressors assist in, and sometimes even allow, new process techniques, such as varox (variable oxygen supply). Similarly, the demands of the process developments instigate or accelerate further developments of the integrally geared turbomachine, such as the multiservice compressors in cryogenic circuits, or the first application of integrally geared machines to highly pure oxygen compression.

In addition, the options of this compressor concept in the compression of the most varied gases of the process industry have been explained with those of a number of typical examples, which initiated the successful employment of new components, such as gas seals or special materials.

Special mention has been made of the important role which integrally geared turbomachines play in the development of new technologies. One example is the use of several entirely different integrally geared turbocompressorss parts of integrated gasification combined cycle (IGCC) power plants. Economic considerations, in particular, favorable cost to power ratios, wide operating range capabilities, and the power plant specific need for high reliability and availability clearly favor the integrally geared turbocompressor solution. Another field of application where the modular concept of integrally geared turbomachines is an advantage is the recovery of energy by residual gas or tail gas expansion in process radial flow expanders. Both integrated compressor and expander concepts and expanders with separate gear units have been presented. These energy saving concepts are of great interest in this time of constantly rising energy prices. The possibilities offered by the most varied modular configurations of the gear units, compressor stages, expander stages and drives have been described in detail. When considering the technological and conceptual developments of integrally geared turbomachinery during the past three or four years, as described here, and allowing for the constant development of new component features, such as seals, toothing, bearings, etc., it is felt that the prediction is justified that continuing developments, especially in the fields of process and energy industries, will provide a considerable potential for integrally geared turbomachinery applications.

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