

# NEW SOLUTIONS IN THE PROCESS INDUSTRY— APPLICATION OF SIX-STAGE INTEGRALLY GEARED CENTRIFUGAL COMPRESSORS

by

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## ABSTRACT

At the end of the forties, the integrally geared centrifugal compressor was developed and initially used for air, and later for nitrogen and other gases. To date, about 10,000 units are in use working in the capacity range between 2,000 and 250,000 m<sup>3</sup>/h. The initial application was limited primarily to the sector of plant air. Within this realm, this compressor concept was not only convincing because of its high degree of efficiency and of its high control range, but, due to lower investment costs with extremely compact design, also compared to single-shaft machines. The logical further development of the integrally geared centrifugal compressor as a process compressor, particularly in its six-stage design, for further process applications such as ammonia plants and the importance of this development for the users of such plants, are detailed.

Technical development studies within the framework of a market-orientated machine design have pushed ahead by far the limits of application of geared centrifugal compressors with respect to achievable volumetric flows and pressure ratios, allowable inlet and discharge pressures along with attainable drive speeds. On the one hand, this was achieved due to advances in gear making technology and design leading to extremely compact models of high performance density with logical minimizing of mechanical losses. This type of integrally geared centrifugal compressor can have up to three pinion shafts for receiving up to six impellers.

The integration of such compact gearing with standardized low pressure and high pressure compressor stages offers very interesting combination possibilities. For example, those stages with high intake pressure can be used as discharge stages (five

and six stage) of an atmospheric intake compressor-discharge pressures up to 50 bar in integrally geared centrifugal compressors, with inlet volume flows of more than 100,000 m<sup>3</sup>/h can thus be achieved. Conversely, in the case of a four-poster integrally geared centrifugal compressor, which is working with high intake pressure as a recycle compressor in an air separation plant. A low-pressure stage combination intaking from atmosphere with high pressure ratio can be used as the fifth and sixth stages. The feed gas part, whereby, the installation of an additional centrifugal or screw compressor with corresponding high investment costs is not necessary.

Within the framework of this description, the design of such integrally geared centrifugal compressors and the corresponding areas of application are to be demonstrated by a few examples from the process industry. In addition to the actual technical design, questions relating to economy and reliability are considered.

Further, an overview of the areas of application of six-stage integrally geared centrifugal compressors using gases other than air and nitrogen, i.e., oxygen or hydrocarbon are included.

## INTRODUCTION

In the case of turbocompressors of the type under discussion, the integral gear unit not only performs the functions of power transmission and increasing speed, but also provides the means for incorporating between two and six turbomachine stages within what amounts to just one plant component. Moreover, the pinion shafts, can be employed both for inputting and outputting energy. The impellers may be of either centrifugal or axial type.

For the sake of clarity, the design of integrally geared centrifugal compressors will be explained using a cutaway drawing (Figure 1) of a four-stage machine. A central bullgear drives, by means of its helical gearing, a number of pinion shafts on which the impellers are mounted. The thrust forces resulting from the aerodynamics of the compression process and the gearing are absorbed by thrust bearings for the bull gear and, for the pinion shafts, frequently by thrust collars. The bull gear shaft generally drives the main oil pump via a gear unit. The volute casings are flanged to the gear housing and are equipped with flow-directing components such as guide units, and also connections for the suction pipes.

The advantages of this compressor design are illustrated in Figure 2. Each compressor stage features an axial and extremely homogeneous flow to the overhung impeller. The impeller can be constructed with very small tip-to-hub ratios, resulting in low Mach numbers at the intake area of the stages, with correspondingly small flow losses. The number of stages can be varied, as required, between two and six. The possibility of combining various impeller diameters and pinion speeds means that the compressor design can be readily adapted so that the impellers always operate within the range of maximum efficiency [1]. Further, with integrally geared centrifugal compressors, it is

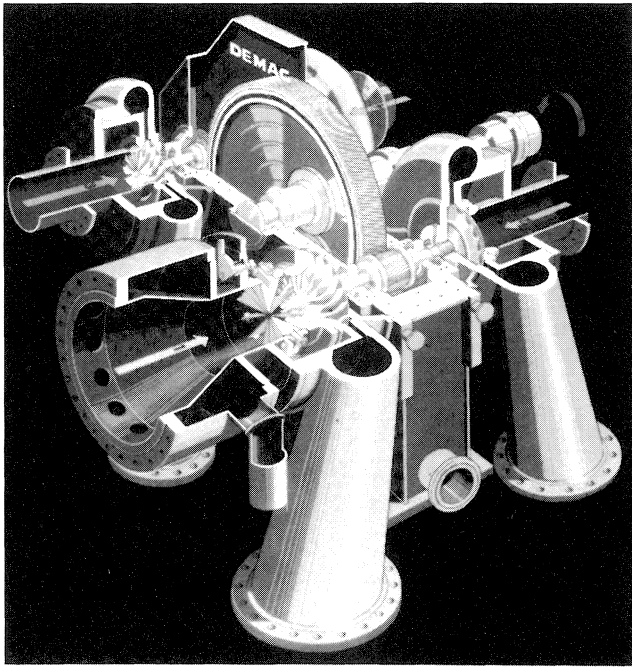


Figure 1. Four-poster Integrally Geared Centrifugal Compressors.

#### UNIFORM AXIAL INLET FLOW

→ low Machnumber, low flow losses

#### FREE SELECTION OF STAGE NUMBERS, DIAMETERS AND TIP SPEEDS OF IMPELLERS

→ optimum specific characteristic range

#### ADJUSTABLE INLET GUIDE UNITS AND DISCHARGE UNITS

→ low flow losses and optimum controllability

#### RECOOLING BEFORE EACH STAGE

→ nearly isothermal compressing process

Figure 2. Advantages of Integrally Geared Centrifugal Compressors.

possible to have inlet and outlet guide units at every stage to maximize compressor controllability and to optimize further the performance of the machine. In compressors of this kind, recoiling of the medium can be implemented ahead of each stage for very close approximation to the isothermic compression process.

For the compressor of designs discussed here, the step of adding a third pinion shaft to the original three-shaft gear unit to raise the number of possible compression stages to six is quite logical. The advantage of six-stage integrally geared centrifugal compressors lies mainly in their remarkable compactness and the efficient construction, depending on the process engineering. The compact and efficient design could mean that a second geared compressor or other type of compressor or turbine and the corresponding intermediate power transmission components could be eliminated. In addition to a reduction in the number of moving parts, an aspect which considerably improves the availability of a compressor installation, this would

also mean an increase in mechanical efficiency, because, for the fifth and sixth stages of the integrally geared centrifugal compressor, no further bullgear losses occur. The third pinion shaft requires a second split in the upper part of the gear unit casing along with mountings for connecting the volutes of the additional stages. The basic design of the gear unit, however, remains the same. The design and construction features of six-stage integrally geared centrifugal compressors are dealt with more fully later.

### FEATURES AND POSSIBLE APPLICATIONS OF SIX-STAGE INTEGRALLY GEARED CENTRIFUGAL COMPRESSORS

The usual ranges of application for integrally geared centrifugal compressors in the process industry are shown in Figure 3. Certain basic differences exist between compressors with low intake pressures—generally, machines operating at atmospheric suction pressure, and those receiving prepressurized gas in the first stage. Depending on the initial pressure and number of stages, either low, medium, or high-pressure stages are employed. Some of the characteristic features of these three types of stages are shown in Figures 4, 5, and 6. Apart from the basic design, all three can be equipped with adjustable inlet and outlet guide units. While in the low-pressure stages, closed and semi-open impellers are used, the medium and high-pressure types are equipped with shrouded impellers in order to reduce clearance losses. Particularly characteristic for the various types of stage are the shaft seals employed. Depending on the pressure level and the gas involved, various systems of non-contacting seals may be installed starting with the simple type, without intermediate bleed-off points, or buffer gas (Figure 4) to the multi-chamber types (Figure 6). If necessary, all the seals to the atmosphere and, above all, to the gearcase, can be of the buffer gas type. For a given basic configuration and seal size, either labyrinth seals with rotating tips or floating carbon ring seals are used.

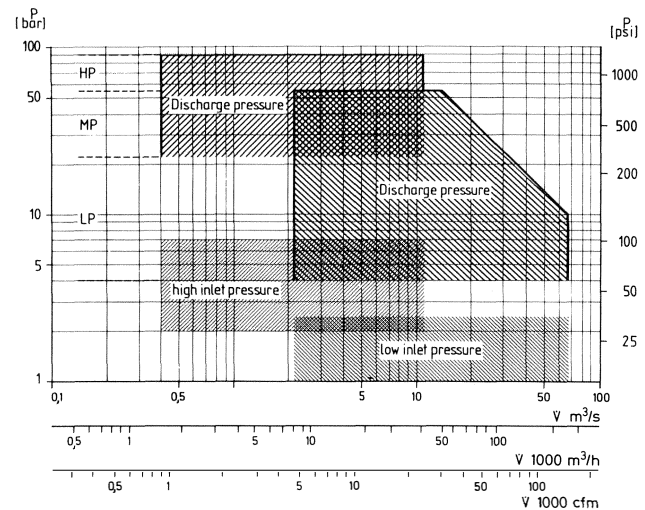


Figure 3. Working Range of Integrally Geared Centrifugal Compressors in the Process Industry.

#### Performance Features and Operating Characteristics

A summary of the most important performance and application features of integrally geared centrifugal compressors is shown in Figure 7. Another important characteristic of this type of compressor, its excellent operating behavior, is demonstrated in Figure 8, showing the total pressure ratio over

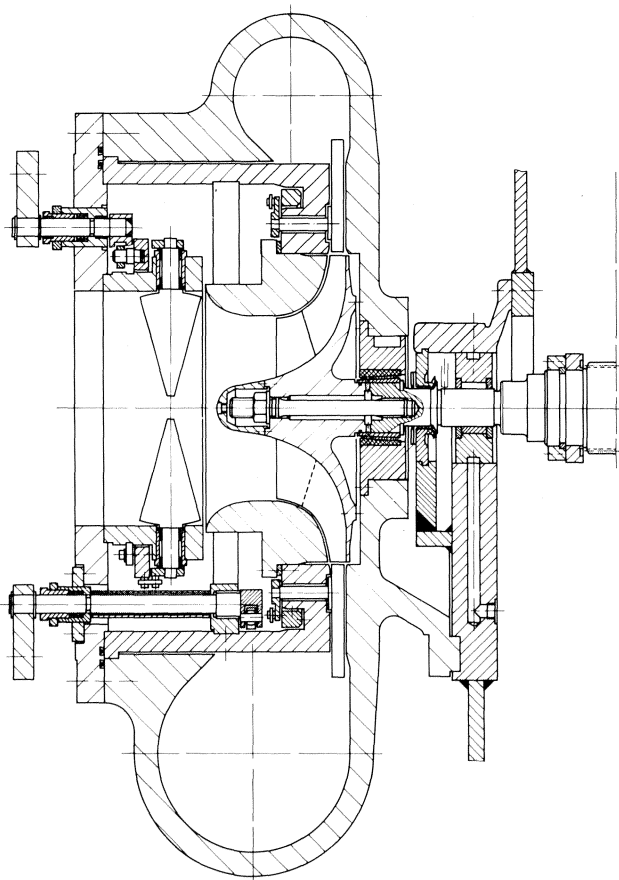


Figure 4. Compressor Stage for Low Intake Pressure.

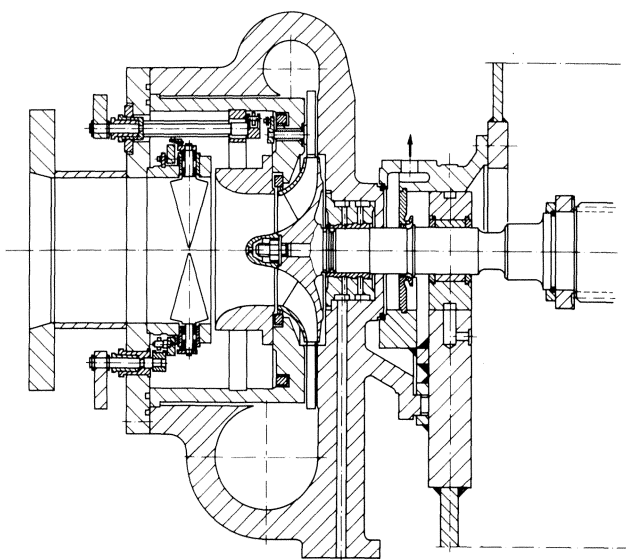


Figure 5. Compressor Stage for Medium Intake Pressure.

volume flow—referring in each case to the design point. As can be seen, the employment of an inlet guide unit ahead of the first stage (Figure 8a) permits variation of the intake volume flow between 60 percent and more than 105 percent of the design value for a given pressure ratio. This also results in a loss in efficiency (again related to the design point) of approximately eight percent towards the surge limit. The employment

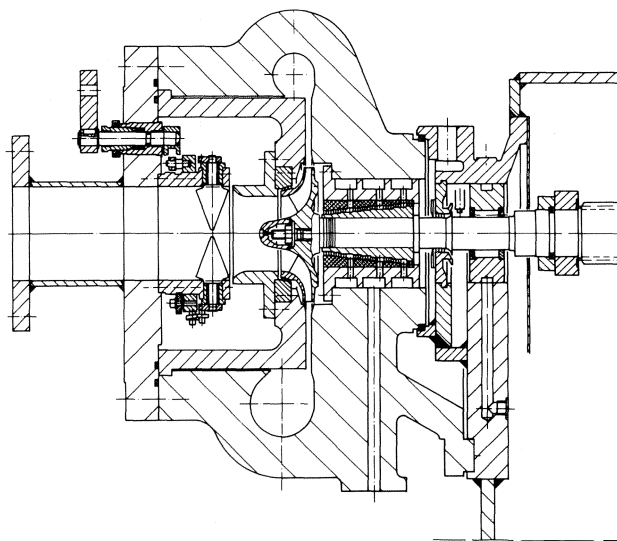


Figure 6. Compressor Stage for High Intake Pressure

	Low intake pressure	High intake pressure
Intake volume flow	→ 250000 m <sup>3</sup> /h → 150000 cfm	→ 40000 m <sup>3</sup> /h → 25000 cfm
Discharge pressure	→ 56 bar → 820 psig	→ 90 bar → 1300 psig
Speed*)	900 – 1800 rpm (50 Hz / 60 Hz)	
Drive rating	→ 30000 kw	
Medien**)	Air, N <sub>2</sub> , O <sub>2</sub> , H <sub>2</sub> O-Vapour	

\*) without additional or integral intermediate gears

\*\* ) using labyrinth- or carbon ring seals

Figure 7. Performance of Six-Stage Integrally Geared Centrifugal Compressors.

of intake guide units ahead of each stage increases volume flow controllability, as indicated in Figure 8b, to between 40 percent and 120 percent. Moreover, efficiency for a given pressure ratio is only reduced by approximately five percent towards the choke limit. Maximum expansion of the operating range combined with optimum efficiency is achieved by using coupled intake and outlet guide units at each stage (Figure 8c). With a given vane angle in the intake guide units, as in Figure 8 (a and b), and a constant pressure ratio, the intake volume flow can be varied from less than 40 percent to approximately 125 percent. The outlet guide units produce a substantial increase in efficiency even at the design point, and the drop in efficiency towards the surge and choke limits is considerably smaller than in the two previously mentioned cases [2].

#### Integration of Compressor Stages and Gear Unit

The central component of integrally geared centrifugal compressors is the gear unit, an integrated assembly which carries the compressor stages. The gearcases are designed for maximum interchangeability and combinability of stages. This is achieved on the one hand by adopting the modular construction principle with a very high degree of standardization, so that stage components feature standard interfaces such as impeller attachment, volute connections, guide unit mountings, and pipe connections. On the other hand, the existence of several series of gear units, each containing a number of gear unit sizes, ensures that the various compressor stages can be com-

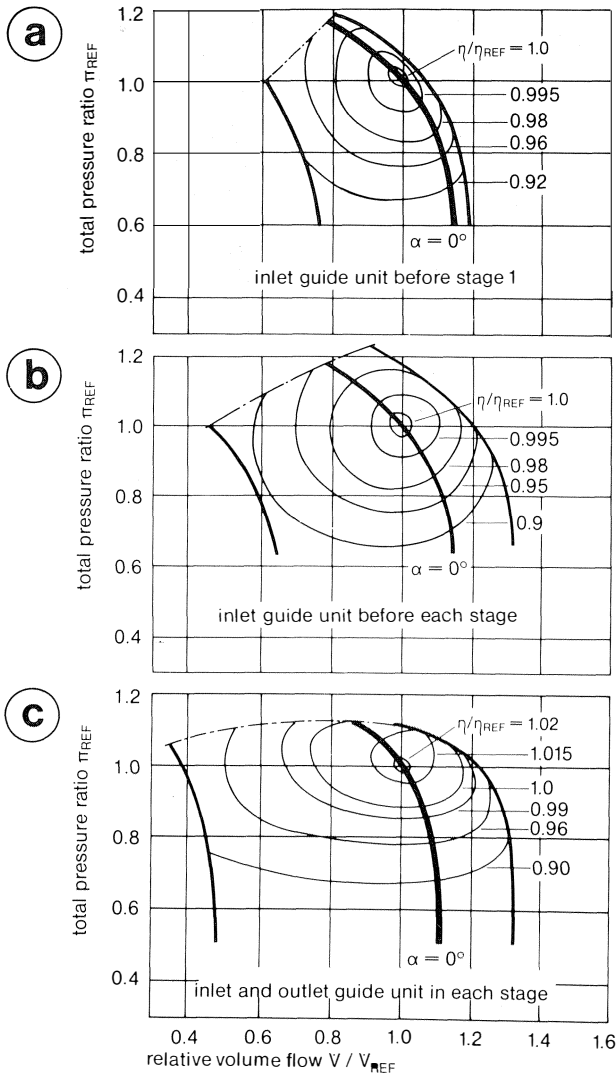


Figure 8. Operating Behavior of Integrally Geared Centrifugal Compressors.

bined to form an extremely compact unit while still taking into account:

- aerothermodynamic
- mechanical design
- rotordynamics

of the machine. Obviously, such an integrally geared centrifugal compressor is not limited to one compression process. The employment of individual stages means that several compression processes can be carried out by one compressor, the possibilities being:

- free choice of the pressure level
- free choice of the intake volume flows
- installation of process-specific gas-introducing side streams, gas extraction side streams and intercooling
- various media
- integration of expansion turbines.

The only limitation to the number of variations arises from the fact that the impellers which are mounted on the same pinion shaft, obviously operate at the same speed, so that adaptation of the impeller tip velocity can only be achieved by altering the impeller diameter. In that case, the specific diameters adopted must be such that optimum efficiency is still achieved.

Arrangement of Stages and Stage Groups

Some of the most important stage arrangement and stage combination alternatives are shown in Figures 9 and 10. The numbers indicate the compression sequence, while the letters A and B represent various processes or media. The stages are also marked according to whether they are of low, medium or high-pressure design. For the sake of clarity, also indicated are the drive shaft and coupling.

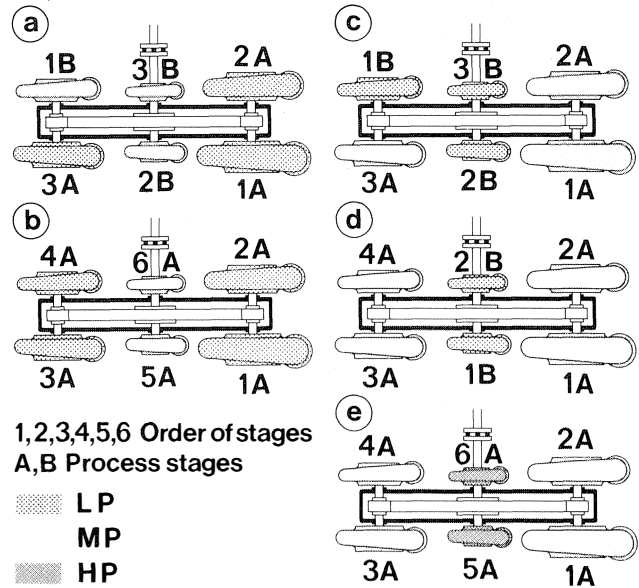


Figure 9. Stage Arrangements Possible with Six-Stage Integrally Geared Centrifugal Compressors [1].

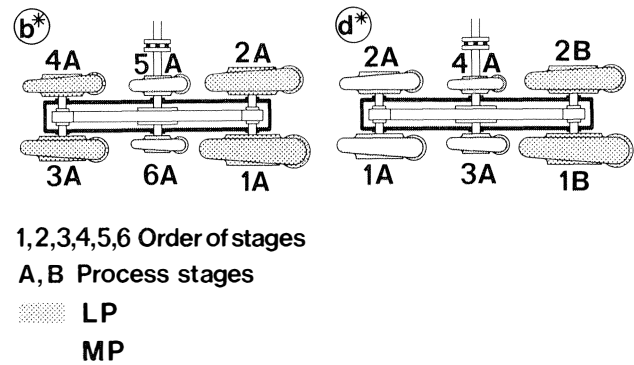


Figure 10. Stage Arrangements Possible with Six-Stage Integrally Geared Centrifugal Compressors [2].

A basic six-stage compressor in which a medium is compressed from a low intake pressure to a discharge pressure of up to 56 bar (820 psi) is shown in Figure 9b. The version depicted in Figure 9 (a) is made up of similar components but differs completely in terms of its function. Here, too, a mass rate of flow (A) is drawn in at low pressure, but this time it is only compressed to a discharge pressure of up to 11 bar (160 psi). A second mass flow (B) enters the machine at high intake pressure and, with a maximum pressure ratio of  $n = 5$ , reaches a discharge pressure of up to 56 bar (820 psi). Variant 9 (d) combines a four-stage compressor (A), having a high intake pressure and a discharge pressure of up to 56 bar, such as required of a recycle compressor in an air separation plant, with a two-stage unit (B) which intakes at atmospheric pressure. At a discharge

pressure of over 5 bar (75 psi), this would, for example, perform the function of a feed gas compressor in an air separation plant.

Version 9 (c) was derived from this configuration. Here, section A of the compressor has been reduced by one stage, so that three stages are available for the compression of medium B, a design which brings with it an additional intercooling operation and, assuming the same discharge pressure, lower impeller tip velocity. The result is a substantial increase in efficiency for compression process B, although process A is limited to a discharge pressure of 35 bar (510 psi).

If the two low-pressure stages of variant (d) in Figure 9 are replaced by high-pressure stages, the result is version (e), a six-stage integrally geared centrifugal compressor, which, depending on the intake pressure, will compress a medium to a discharge pressure of up to 90 bar (1300 psi).

In the case of large integrally geared centrifugal compressors in particular, the gear unit dimensions are no longer determined by the gear loads, but by the size of the volutes. In order to obtain as compact a machine as possible in such cases, i. e., with a gear unit which still represents minimum dimensions and mechanical power loss, the stage configurations (b) and (d) in Figure 9 have been rearranged in order to provide two further variants in Figure 10. In the case of variant b\*, the smaller sixth stage has been relocated to take the place of the fifth stage. Solution d\* comes into its own if the volume flow B in the low pressure unit is particularly high so that a position at the top of the compressor would make the gear unit dimensions unnecessarily large.

#### Compressor Design

Some of the special characteristics incorporated into the design of the six-stage version shows a cutaway diagram of such a compressor (Figure 11). The stage configuration corresponds to variant b in Figure 9.

The pinion shaft bearings of the fifth and sixth stages are installed in a second horizontal split in the gear case. The third pinion shaft is, like the other two, operating above the first

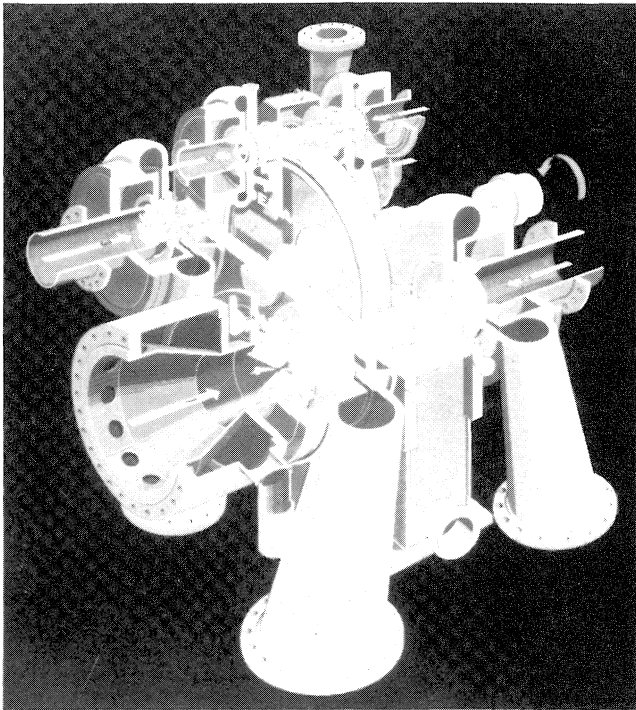


Figure 11. Six-Stage Integrally Geared Centrifugal Compressor.

critical lateral speed. In order to achieve maximum damping, tilting pad bearings are employed here, as for all pinion shafts. In the case of small integrally geared centrifugal compressors, the pinions shafts of the fifth and sixth stages achieve, in case of semi-open impellers, speeds of over 40,000 rpm.

With six-stage integrally geared centrifugal compressors, particular attention has to be paid to the distribution and draining of lube oil. Owing to the high-pitch-line velocities encountered in integrally geared centrifugal compressors of up to more than 150 m/s, the lubrication system must not only be such that it ensures sufficient lubrication at all points, but also that free and uncontrolled oil within the gear case is kept to a minimum. The interaction of such free oil with rotating components, and, particularly with the bullgear, contributes substantially to the degree of gear losses. In order to reduce these windage losses, the following are required:

- accurate calculation of the oil requirement of all lube points (bearings, thrust collars, gearing), precise dimensioning of oil pressure losses and controlled metering, in order to prevent excess oil from entering the gear case in the first place.
- the oil to lubricate the gearing and thrust collars must be ducted to as close as possible to the consumption point (e.g., gear meshing point) and injected in the direction of rotation (Figure 12).
- the return oil, particularly that running off the top pinion shaft, must be guided away by a system of baffles to prevent, as far as possible, any contact with rotating components (Figures 11 and 12).
- generous dimensioning of the oil drain aperture in the gear case; this should also be located perfectly in line with the oil slinging trajectory of the rotating bullgear (Figure 12).

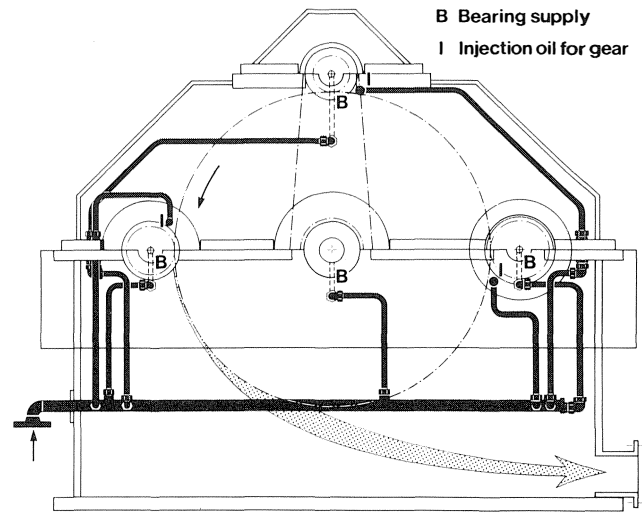


Figure 12. Lube Oil Distribution and Oil Drainage.

The pinion teeth are hardened and the bullgear is made from high strength quenched and tempered steel. The gearing of these turbo gear units is manufactured to DIN 3963, grade four, which corresponds to the AGMA grade 13. The tooth flanks are ground to produce a degree of longitudinal crown, in order to compensate for shaft displacement and thus prevent excessive edge contact.

The integrally geared centrifugal compressors are mostly fitted with thrust collars, to absorb the axial forces exerted by the pinion shafts. Thrust collars have the advantage over conventional thrust bearings, because they substantially reduce the mechanical losses resulting from bearing friction. This is due to the considerably lower relative velocities which occur

in the collar contact zones, as compared with the average rubbing velocities encountered in friction thrust bearings. The velocity ratios lie between 1:3 and 1:4, and the derived loss ratios correspond to the square of these figures.

A further significant advantage of thrust collars lies in their high load-bearing capacity. This is of particular importance in integrally geared centrifugal compressors with an odd number of stages, as the thrust from the single-impeller pinion shaft remains uncompensated through the lack of an opposing impeller. This situation also holds for the discharge stage. The problems encountered with regard to discharge stage thrust are as follows. The axial forces produced by centrifugal impellers are basically made up of two components:

- the thrust resulting from bending the direction of flow from axial to radial and the associated change in the axial flow momentum, and
- the thrust resulting from the axial distribution of pressure around the impeller; this force is generally dominant.

These two forces normally act in opposing directions and the resultant points away from the gear case. This applies to both impellers mounted on the same pinion shaft, so that the impeller thrust forces largely offset each other. If the compressor operates close to the choke limit with a high intake volume flow, e.g., with the inlet guide units set to full counter-rotational flow, the pressure rise in the last stage is minimal, and it may even be that expansion occurs. This causes a change in the direction of impeller thrust in the last stage so that the axial forces of the last and penultimate stages—assuming the impellers are located on the same pinion shaft—are no longer mutually compensatory. Instead, the impellers combine to increase the thrust in the direction of the penultimate stage. This phenomenon becomes more pronounced as the volume flow increases and the compressor discharge pressure decreases.

If friction-type thrust bearings are employed, the maximum permissible bearing load may be exceeded, and this may have to be avoided by establishing limits to the operating range. Increasing the bearing surface often has little effect, because this also produces an increase in the rubbing velocity. With high rubbing speeds, there is a reduction in specific bearing load capacity referred to the bearing surface, so that the increase in load-bearing capacity is often rather small, and there is considerable increase in the bearing losses.

Friction-type thrust bearings should therefore only be employed in very large integrally geared centrifugal compressors with relatively low pinion shaft speeds and low rubbing velocities at the bearings. Integrally geared centrifugal compressors with a high power density are, however, an area of application for thrust collars. With this solution, even critical operating ranges such as those described, are accommodated without difficulty or limitation.

In order to complete this description of the specific design features of six-stage integrally geared centrifugal compressors, the arrangement of the various operational monitoring points are shown in Figure 13 in the form of the bearing temperatures, shaft vibrations, key phaser signals and shaft position indicators. When using thrust collars, a shaft position indicator is only mounted at the bullgear shaft.

Further visual information as to the design of multi-stage integrally geared centrifugal compressors is provided in Figures 14, 15 and 16.

### SIX-STAGE INTEGRALLY GEARED CENTRIFUGAL COMPRESSORS IN INDUSTRIAL PROCESS APPLICATIONS

#### Air Separation Plant

The integrally geared centrifugal compressor is widely used in the air separation industry (Figure 17), where it has been

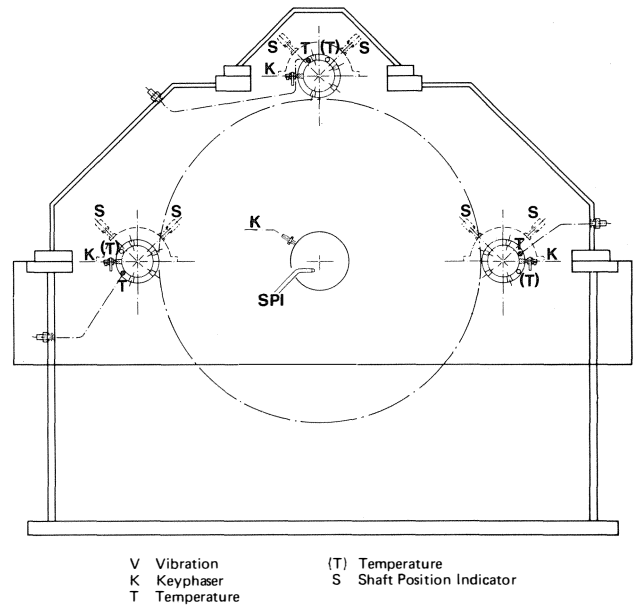


Figure 13. Arrangement of Measurement Points for Vibration and Temperature Monitoring, Shaft Position Indicator and Key Phaser Signal.

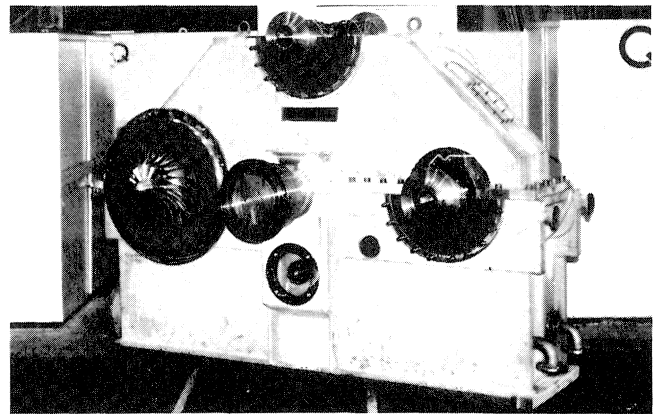


Figure 14. Six-Stage Integrally Geared Centrifugal Compressor for an Ammonia Plant.

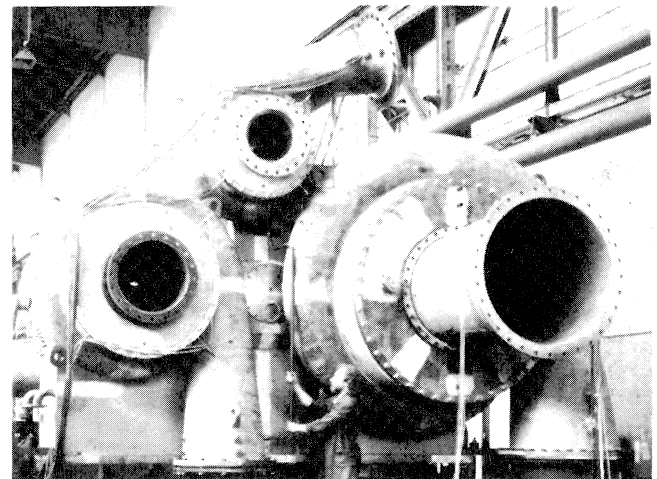


Figure 15. Lower Part of a Five-Stage Integrally Geared Centrifugal Compressor for Air,  $V = 135,300 \text{ m}^3/\text{h}$ ,  $p_1 = 13,150 \text{ kW}$ ,  $p = 1.013 \text{ Bar}$ ,  $p_2 = 13.2 \text{ Bar}$ .

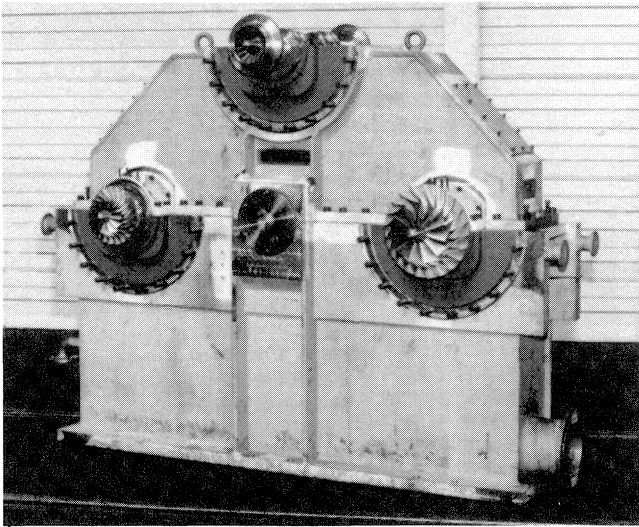


Figure 16. Six-Stage Integrally Geared Centrifugal Compressor for Nitrogen,  $V = 10,510 \text{ m}^3/\text{h}$ ,  $p_c = 2,480 \text{ kW}$ ,  $p_1 = 1.6 \text{ Bar}$ ,  $p_2 = 24.4 \text{ Bar}$ .

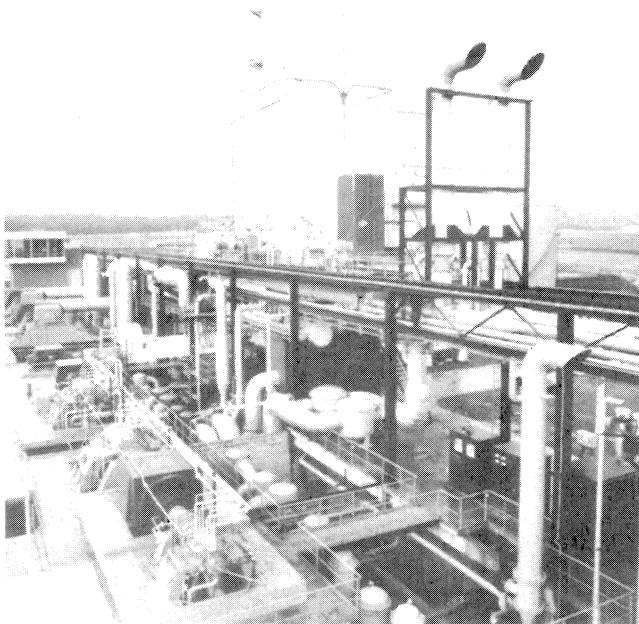
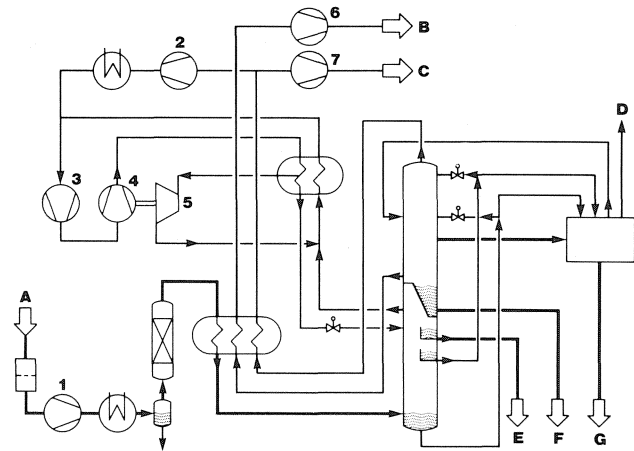


Figure 17. Air Separation Plant.

the standard solution for over 20 years. The reasons for this are obvious. The outstanding features of the integrally geared centrifugal compressor are its high operating cost-efficiency, coupled with a relatively low initial investment outlay. This type of compressor is, therefore, ideal for air separation applications where power costs amount to between 70 percent and 80 percent of total cost of production and the compressors themselves constitute up to 25 percent of the total investment cost of the plant.

The flow diagram of a typical air separation plant which uses the low-pressure process and a refrigeration circuit is shown in Figure 18 [3]. The various process variants are beyond the scope of this discussion, as they differ mainly in their air cleaning method and the types of heat exchanger employed (molecular sieve adsorbers, regenerators, reversing heat exchangers); otherwise, the plant components are virtually identical. The turbocompressors used are as follows (Figure 18):



- |                    |                               |
|--------------------|-------------------------------|
| A Air inlet        | 1 Air compressor              |
| B Oxygen/gaseous   | 2 Nitrogen recycle compressor |
| C Nitrogen/gaseous | 3 Nitrogen feed compressor    |
| D Residual gas     | 4 Nitrogen booster compressor |
| E Nitrogen/liquid  | 5 Expansion turbine           |
| F Oxygen/liquid    | 6 Oxygen compressor           |
| G Argon/liquid     | 7 Nitrogen compressor         |

Figure 18. Flow Diagram of an Air Separation Plant Low-Pressure Process with Refrigeration Cycle.

- Air compressor (1) with intercooling after each stage. The discharge pressure in the case of the most commonly used low pressure process lies in the range six to eight bar (85 to 115 psi), and is usually achieved with four-stage integrally geared centrifugal compressors. Where the operating pressures are very low, a three-stage unit is sufficient. In the case of the medium-pressure process, the operating pressure lies above the 50 bar mark (725 psi). Here, too, integrally geared centrifugal compressors can be employed, but this time, with six stages.

- Recycle compressor (3) for the nitrogen refrigeration circuit for the liquefaction of oxygen, nitrogen and argon. The recycle nitrogen is drawn from the pressure section of the rectifying column, supplied to the three or four-stage, intercooled geared centrifugal compressor at a pressure ratio of 4.5 to 6.5 bar (65 to 95 psi) and compressed to a discharge pressure of 30 to 40 bar (435 to 580 psi).

- The circuit booster compressor (4) brings the nitrogen up to a discharge pressure of 40 to 60 bar (580 to 870 psi)—the optimum figure from the point of view of investment and operating energy costs. This compressor is directly driven by an expansion turbine (5).

- The feed gas compressor (2) replaces the liquid nitrogen taken from the pressure section of the rectifying column, with gaseous nitrogen from the low-pressure column. This involves compressing the nitrogen gas from approximately 1.0 bar to the intake pressure of the recycle compressor of 4.5 to 6.5 bar. For this purpose, two and three-stage, intercooled integrally geared, centrifugal compressors are predominantly employed, although screw compressors may be used for very small volumes.

- Product compressors for gaseous nitrogen (7) and oxygen (6). The intake pressure of 1.2 to 1.8 bar (17 to 25 psi) and requisite discharge pressures of 40 to 60 bar (580 to 870 psi) again mean that six-stage integrally geared centrifugal compressors are particularly suitable for this application. A typical product compressor for nitrogen is shown in Figure 19. The stage configuration corresponds to variant b in Figure 9.

The advantage of using integrally geared centrifugal compressors as oxygen product compressors lies in their power consumption, as their coupling rating is about ten percent below

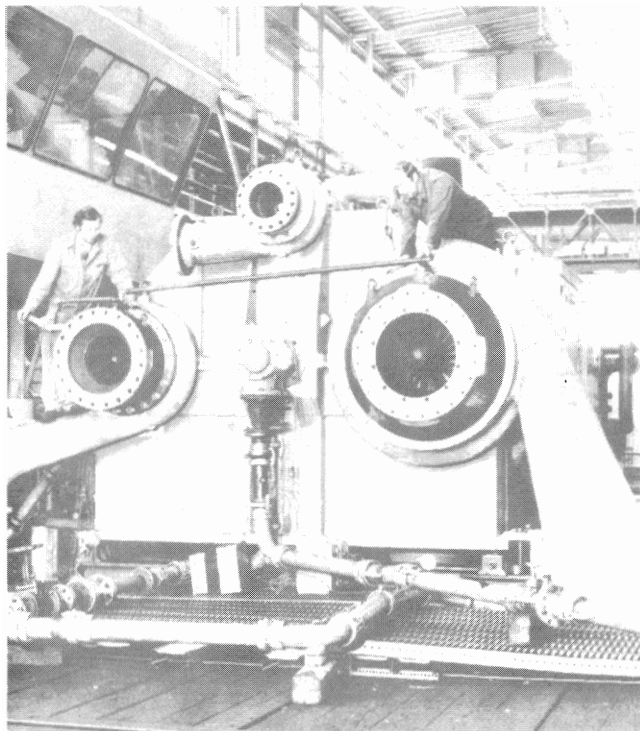


Figure 19. Six-Stage Integrally Geared Centrifugal Compressor for Nitrogen,  $V = 47,185 \text{ m}^3/\text{h}$ ,  $p_c = 8,950 \text{ kW}$ ,  $p_1 = 1.03 \text{ Bar}$ ,  $p_2 = 43.4 \text{ Bar}$ .

that of single-shaft compressors. Moreover, the six-stage integrally geared centrifugal compressor, as a single-casing machine with five intercoolers represents a lower investment outlay in the case of such pressure ratios for which a single-shaft compressor is usually designed with two casings.

A further and particularly attractive application for six-stage integrally geared centrifugal compressors involves the integration of the recycle compressor (3) and the feed gas compressor (2) within one machine. A typical multi-service compressor of this kind is shown in Figure 20. The stage configuration in these machines usually corresponds to variant (d) in Figure 9, and in certain cases to variant (d\*) in Figure 10. If the pressure ratios in the refrigeration circuit are not too high, three inter-cooled stages are sufficient for the recycle unit, as in the case of

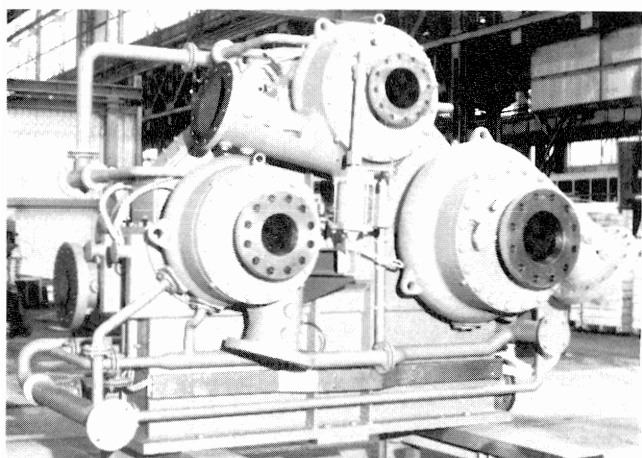


Figure 20. Six-Stage Integrally Geared Centrifugal Compressor for Nitrogen Recycle Feedgas Application,  $V = 5,807/5,602 \text{ m}^3/\text{h}$ ,  $p = 2,206/445 \text{ kW}$ ,  $p_1 = 5.6/1.0 \text{ Bar}$ ,  $p_2 = 33.5/5.8 \text{ Bar}$ .

variant (c) in Figure 9. A further stage with an additional inter-cooler is then available for feed gas compression, thus reducing the load on the feed gas stages (reduction of the impeller tip velocities) and substantially increasing the efficiency of these units. Depending on the feed gas volume, the employment of multi-service compressors of the type described in the place of multi-casing units in an air separation plant can mean a substantial reduction in investment costs for these compressors.

#### Ammonia Plant

A further example of the use of six-stage integrally geared centrifugal compressors in process applications is that of the air compressor in an ammonia plant (Figure 21). Turbocompressors have been operating in plants of this kind since 1964. To date, more than 300 such installations with daily capacities of between 500 and 1,500 metric tons are in operation. The turbocompressors employed in these plants are as follows (Figure 22):

- Air compressors with two or three intercoolers, discharge pressures of between 32 and 40 bar (465 to 580 psi) and discharge temperatures of between 170 and 250°C.
- Synthesis gas compressors with circulator for discharge temperatures of between 150 and 350 bar (2,175 and 6,525 psi).
- Ammonia compressors
- CO<sub>2</sub> compressors (low-pressure)
- Feed gas compressors (if the feedstock pressure is too low)

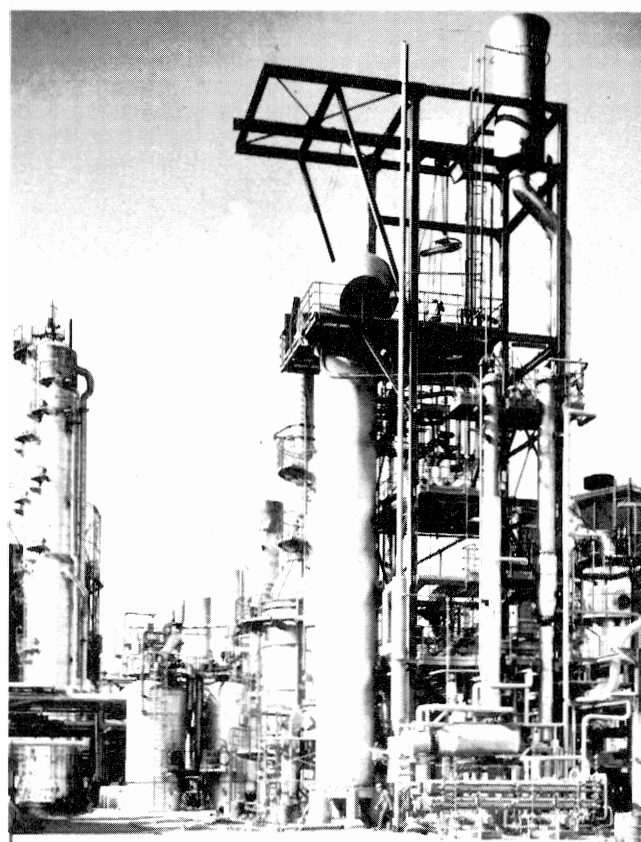


Figure 21. Ammonia Plant.

Increasing energy costs led to the adoption of a number of measures to improve ammonia plant efficiency. Those affecting the turbocompressors are as follows:

- The synthesis gas compressor discharge pressure was reduced. Today, it lies around the 100 bar mark (1,450 psi), and, in some cases, even lower.



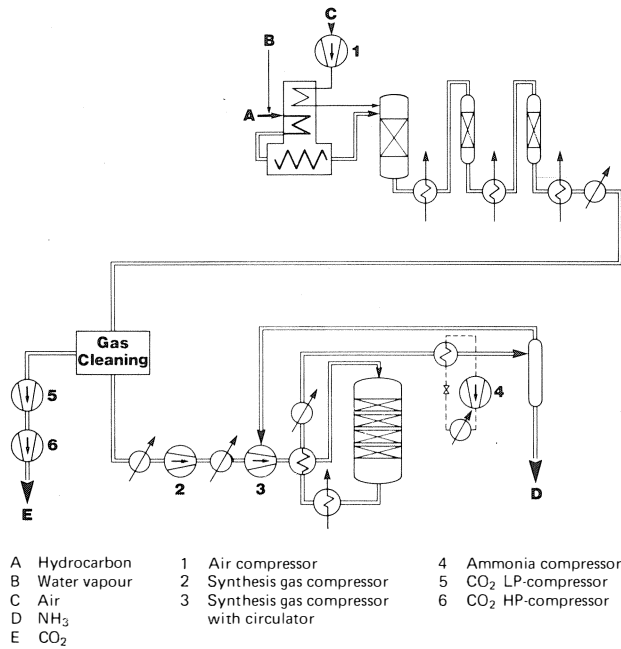


Figure 22. Flow Diagram of an Ammonia Plant.

- In the case of the air compressor, the number of intercooling operations was increased.
- There is an increasing tendency to use integrally geared centrifugal compressors as the air compressors instead of single shaft compressors.
- The air and synthesis gas compressors are now often driven by electric motors. In the case of the air compressor, gas and steam turbines are also used.

The size of the air compressors employed depends on the size of the plant. In the case of an ammonia plant with a daily capacity of 1,000 metric tons, approximately 62,000 kg/h of air is required, corresponding to a volume flow of approximately 54,000 m<sup>3</sup>/h.

A six-stage integrally geared centrifugal compressor of package design is shown in Figure 23. It has an inlet guide unit ahead of the first stage, and four intercoolers operating as the

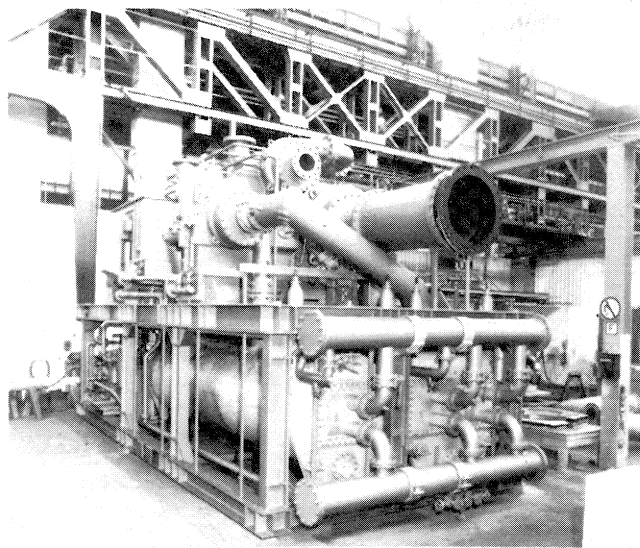


Figure 23. Six-Stage Integrally Geared Centrifugal Compressor for Air in an Ammonia Plant.

air compressor in an ammonia plant. The four cooler bundles are located in two cooler casings. This double-cooler design, coupled with other additional features, such as the integrated oil system module and common steel baseframe, render this machine extremely compact and easy to transport. Its stage configuration corresponds to variant (b) in Figure 9.

#### Comparison between Integrally Geared Centrifugal Compressors and Single-Shaft Compressors in Ammonia Plants

Finally, the advantages of integrally geared centrifugal compressors operating as the air compressors in ammonia plant are well illustrated by comparing them with their single-shaft counterparts in terms of power consumption and investment cost. In such an exercise, the number of intercoolers, the compressor discharge temperature and the type of driver employed must also be considered. The production parameters taken as a basis for the comparison are as follows:

- Ammonia production 1,000 metric tons/day
- Air consumption 62,000 kg/h
- Intake pressure 1.0 bar
- Pressure 35 bar
- Inlet temperature 30°C

As a comparison, a single-shaft air compressor with two casings and intermediate gear unit (Figure 24) and an integrally geared centrifugal compressor are considered.

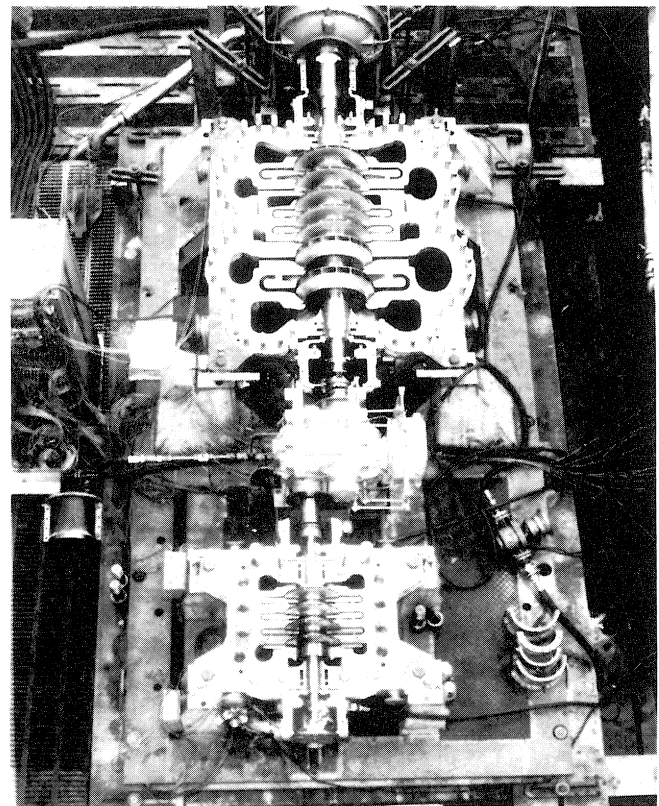


Figure 24. Single-Shaft Air Compressor for an Ammonia Plant.

The power requirement and discharge temperature as a function of the number of intercooling operations is shown in Figure 25. For comparison purposes, the performance data are indicated in dimensionless form; the reference data have been taken from a double-intercooled, two casing single-shaft compressor with a discharge temperature of 250°C. This reference compressor is driven by a steam turbine, i. e., no additional gear unit is required.

In the model considered in Figure 25, the number of intercoolers has been varied from two to five; the consequence of this progression is a drop in the compression discharge temperature from an initial 250°C to less than 100°C. The coupling power undergoes a corresponding change, although a differentiation must be made here between drivers which can be used without an additional gear unit. Generally speaking, this means steam turbines in the case of single shaft compressors, and electric motors for integrally geared centrifugal compressors, and those drive units, the speed of which has to be adapted to the requirements of the driven machine by means of a gear unit—electric motors and gas turbines for single-shaft compressors.

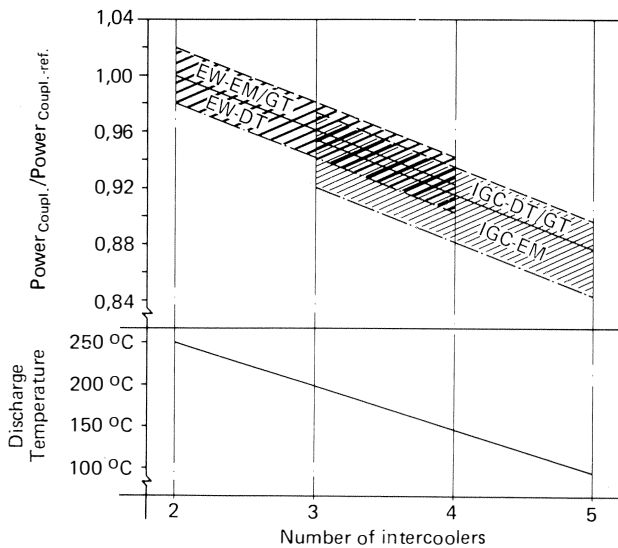


Figure 25. Comparison of Integrally Geared Centrifugal Compressors and Single-Shaft Compressors in Ammonia Plant.

sors, and gas and steam turbines in the case of integrally geared centrifugal compressors. In view of the fact that, owing to its design with several individual stages, the integrally geared centrifugal compressor is particularly suited to the introduction of intercooling, the six-stage integrally geared centrifugal compressor, with an electric motor driver, and as many intercoolers as possible, and therefore, a low discharge temperature—must take preference. This then requires an additional energy input for heating the air to the requisite process temperature of approx. 600°C, so that the availability of inexpensive heating energy, e. g., in the form of waste heat, must also be taken into account.

An analysis of the energy balance in respect of the compressor discharge temperature of the process air reveals that the saving resulting from the lower compressor power consumption and a reduction of the compressor discharge temperature from 134°C to 90°C is approximately 20 percent, with respect to the process as a whole. This result does not, however, necessarily mean that the incorporation of as many intercoolers as possible is undesirable, provided it is justifiable from the point of view of the investment costs involved. It is precisely here that the six-stage integrally geared centrifugal compressor offers considerable advantages over the single-shaft compressor. This cost advantage is due to the inherent design of the integrally geared centrifugal compressor, and above all its significantly smaller number of compressor stages. Whereas the integrally geared centrifugal compressor has six, equivalent single-shaft machines may have up to eleven. This can result in a quite considerable price advantage in favor of the integrally geared centrifugal compressor, depending on the plant engineering.

## SUMMARY AND OUTLOOK

Integrally geared centrifugal compressors are being employed for an increasing number of process applications in various branches of industry. The reasons for this include the high efficiency of these machines, their relatively low initial cost, and a high level of availability, as demonstrated over the many years in which they have been in service as standard components in the air separation sector. The importance of this latter aspect of availability of an air separation plant is roughly on a par with that of the availability of a refinery, as air separation plants are often responsible for providing the starting products for refineries.

The advantages and potential of this type of compressor are particularly noticeable in the case of the six-stage versions. On the one hand, their wide operating range renders them suitable for numerous new applications, and, on the other hand, their constructional versatility, achieved with just a limited number of highly developed and service-proven standard components, is leading to new solutions in process engineering, a trend which has been enhanced by the increasing use of electric motor drivers.

At the moment, labyrinth and carbon ring seals dominate in integrally geared centrifugal compressors. The range of process applications for which these compressors are suitable will continue to grow as these sealing systems are further developed. A double mechanical contact face seal and a dry gas face seal are shown in Figure 26. These are hermetic seals installed here in an integrally geared centrifugal compressor stage and used, for example, for hydrocarbons or toxic gases. Components of this kind mean that integrally geared centrifugal compressors can be used for a far wider range of media and can produce substantially higher discharge pressures.

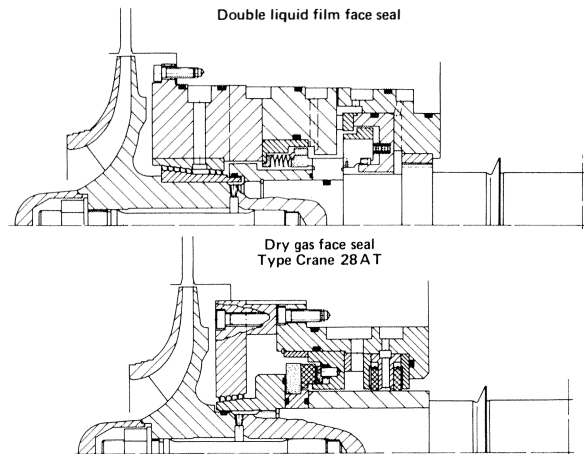


Figure 26. Hermetic Shaft Seals for Integrally Geared Centrifugal Compressors.

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