INTEGRALLY GEARED API 617 PROCESS GAS COMPRESSORS

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ABSTRACT

Integrally geared (IG) centrifugal compressors, originally developed for plant and instrument air service, continue to gain acceptance in process gas applications as an alternative to other types of centrifugals, and in many instances, reciprocating compressors. Manufacturers have developed a class of integrally geared compressors that have demonstrated high levels of safety, reliability, and robustness; these machines are routinely specified for process gas services.

The API Standard 617 (Draft) has recently been revised (Seventh Edition) and now addresses IG centrifugal compressors for process gas service. This tutorial describes important technical features of IG compressors, and compares them with traditional API 617 beam-type compressors.

INTRODUCTION

This tutorial discusses the application and use of integrally geared (IG) centrifugal compressors in the petroleum, chemical, and gas service industries. Traditionally, single shaft, multistage, between-bearings, horizontal split case, or barrel compressors have been applied in these services (Figure 1). Frequently referred to as inline or beam-type compressors, they often employ a separate speed-increasing gearbox to achieve the desired rotational speed. Integrally geared compressors combine the gearbox and compression stages into one compact unit (Figure 2).

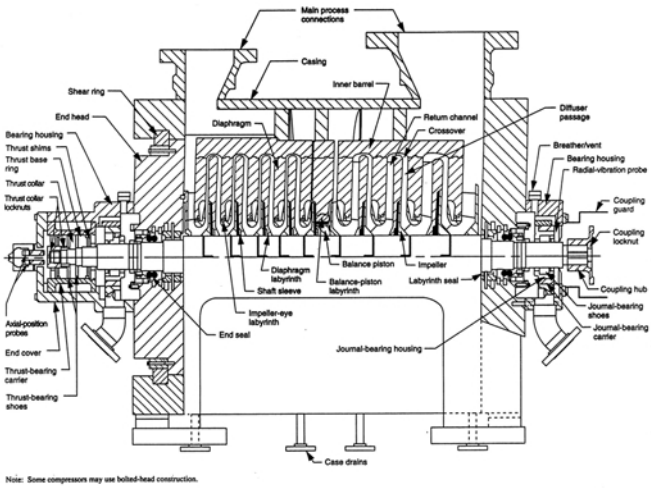

Figure 1. Beam-Type Compressor.

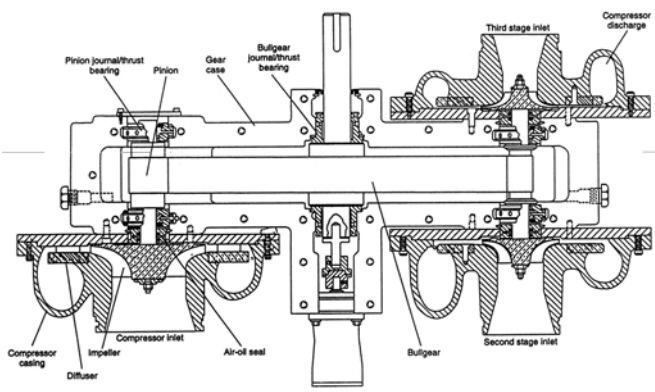

Figure 2. Integrally Geared Compressor.

In recognition of the many successful, safe, and reliable installations of integrally geared compressors, API Standard 617, Seventh Edition, Chapter 3 (Draft), specifically addresses this type of equipment, helping assure users that IG compressors are properly specified, designed, and tested. The history, performance capabilities, technical features, and highlights of API 617 Chapter 3 (Draft) compressors are discussed, along with cost of ownership, to help the user evaluate alternatives.

HISTORY AND PERFORMANCE CAPABILITIES

What is an integrally geared compressor? Quite simply, the IG compressor has merged the speed-increasing gearbox with the compression sections to create a compact and efficient package. Developed and patented in 1948 by Dr. Otto Schirl, Technical Director of Demag AG, the first IG "centrifugal flow compressor with not fewer than four stages installed in sequence" was a result of Mr. Schirl combining a number of single-stage compressors, each with an axial intake and single gearbox housing (Figure 3). This first IG compressor, which was the precursor to thousands that have been built, was supplied to a coal pit in Ahlen, Germany, and had the following performance:

- Air
- Suction capacity: 9000 m^3/h (5300 cfm)
- Discharge pressure: 7 bar (100 psi)

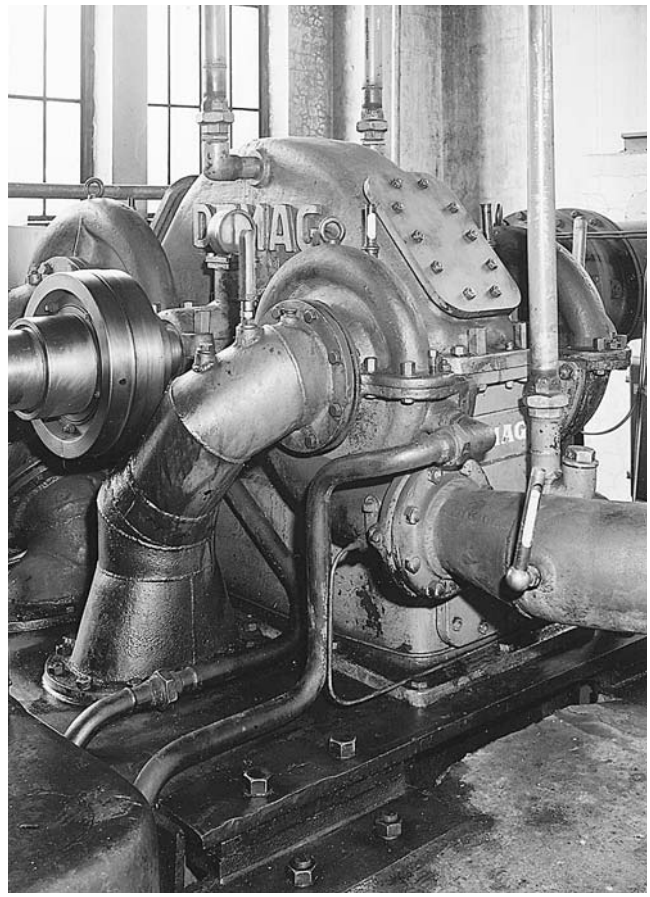

Figure 3. First Integrally Geared Compressor.

Although first patented by Demag, the race was on by several additional manufacturers, Joy, Delaval, Hitachi, and Borsig to introduce IG compressor configurations that avoided any patent conflicts. Initially these new IG compressors were used in mines and in the automotive industry to supply air. Originally, the impeller blades were made of riveted-in strips of steel, but increasing flow and pressure ratio demands resulted in extremely high loads on the impellers. This led to the development of rotor disks milled from solid forgings. Rivets then attached the cover, which was quickly adopted and became the standard for IG compressor impeller manufacturing. With the increase in reliability, new markets such as air separation and the chemicals industry were opened up.

Within a few short years, IG compressors became the compressors of choice for air separation plants where the prime objective is maximum efficiency since the feedstock—air—is free. Fortunately, IG compressors can achieve excellent efficiency due to the axial intake, ability to aerodynamically optimize pinion-shaft speeds, and an isothermal compression process. As a result of air separation plant growth, IG compressor suction capacity capabilities have steadily increased from 100,000 m^3/h (60,000 cfm) in 1962 to over 400,000 m^3/h (240,000 cfm) in 1999 (Figure 4).

Similar to flow capacity increases, IG compressor discharge pressures have dramatically increased from the original 7 bar (100 psi) to achieve levels of 200 to 300 bar (2900 to 4350 psi)

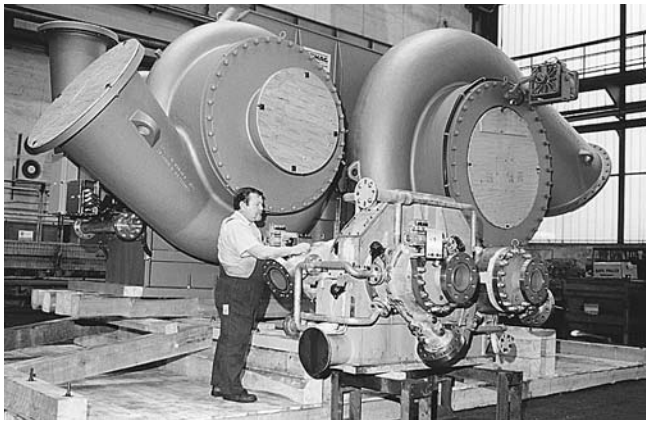

Figure 4. High Capacity Integrally Geared Compressor.

(Figure 5). Recently, an IG compressor was developed with five pinions or 10 stages driven by one gearbox to provide a 200:1 pressure ratio. Of course, commensurate with the flow and pressure increases, power levels have risen as well. Today, power levels up to 34,000 kW (45,500 hp) have been accomplished on very diverse gases such as hydrogen, ethylene, oxygen, and natural gas. Figure 6 shows an oxygen compressor being assembled in a clean room.

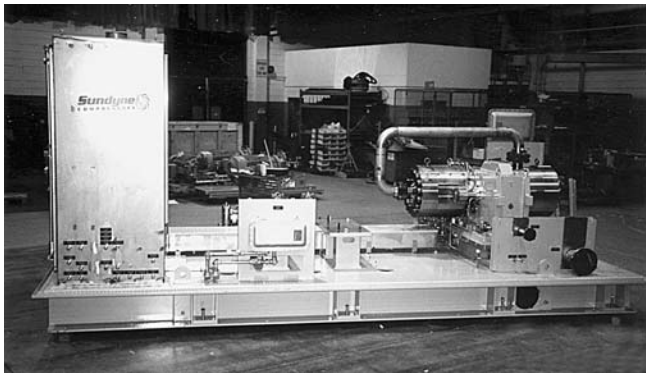

Figure 5. High-Pressure Integrally Geared Compressor.

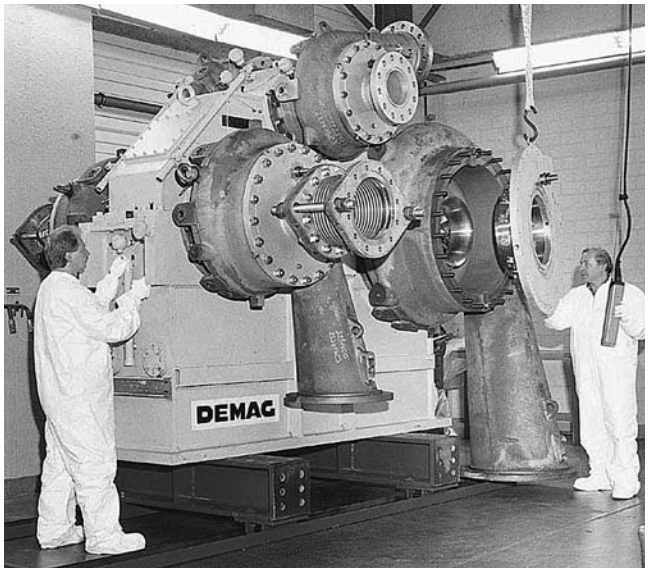

Figure 6. Oxygen Compressor Cleaning.

To satisfy the refining and petrochemical industries need to reduce gas emissions, dry gas mechanical seals were first available in IG compressors in 1965. These seals, which use various face patterns to achieve lift-off, offered a safe, reliable, and simple arrangement to contain toxic and hazardous hydrocarbon gases. Expensive and cumbersome oil seals could now be eliminated. Two of the more common face pattern geometry's are shown in Figure 7.

Figure 7. Dry Gas Seal.

Not only can additional pinions and stages be connected to increase the pressure ratio, but also the stages may be arranged to provide multiple compressor services. For example, a classic three-pinion six-stage IG compressor could be installed as two three-stage units, or one four-stage and one two-stage, or one four-stage and two single-stage compressors. All of these combinations can be achieved with a single machine thus allowing different gases to be compressed simultaneously. Further advances have even allowed power recovery turbines to be installed on the same gearbox to reduce power consumption (Figure 8).

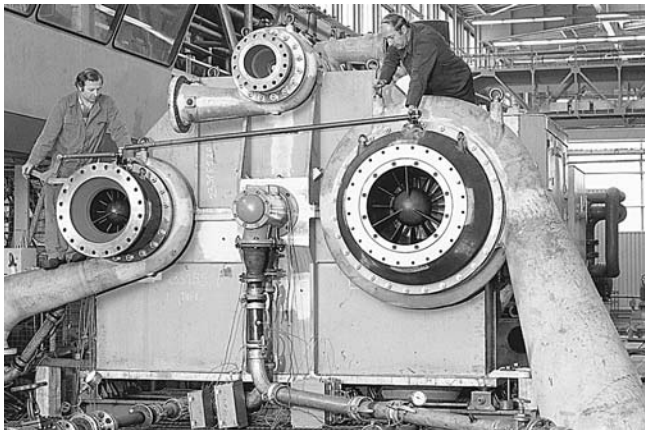

Figure 8. Compressor with Recovery Turbine.

Performance Flexibility

Centrifugal compressors increase the gas pressure by imparting kinetic energy via the impeller blades, and convert the kinetic energy into useful static pressure by a downstream element called the diffuser. Since the amount of energy added is predominately a function of the impeller tip speed, the higher the impeller tip speed, the more pressure ratio a given stage can develop. Further, impeller tip speed is proportional to the operating speed and diameter, but often restricted by material stress limits. Traditional single-shaft multistage compressors use closed or fully shrouded impellers to facilitate the stack up of several impellers on the shaft while maintaining aerodynamic efficiency and adequate clearances from the stationary diaphragms. Accomplishing the proper stack up is difficult with more than one impeller on the shaft. Even though the cover or shroud helps to minimize the axial thrust, the maximum impeller tip speed will be less than for an open style impeller due to the higher stresses compared to the open style of impeller. Although both impeller types are used in integrally geared compressors, most often the open impeller style is selected to maximize the impeller tip speed and hence pressure ratio.

Modern shrouded impellers produce pressure ratios in the range of 1.5:1 to 2:1, while open impellers can easily generate pressure ratios as high as 4:1, depending on impeller tip speed and gas conditions. Compressor manufacturers of either beam-type or IG compressors try to maximize the stage pressure ratio to minimize the number of stages. Beam-type compressors may simply add stages to achieve the desired overall pressure ratio, but are frequently limited by the axial length between the bearings, which negatively affects shaft rotordynamics. Since an IG compressor with an open impeller can generate a higher pressure ratio per stage for the same overall service, fewer stages are required.

Depending upon the volume flow rate, for the same pressure ratio requirement the IG compressor can be several points more efficient than the beam-type compressor. To better understand how this is possible, a brief discussion on compressor aerodynamics is needed. Regardless of the centrifugal compressor type, maximizing compressor efficiency, while obtaining the desired headrise or pressure ratio, frequently requires trade-offs when selecting speed, impeller diameter, and the number of stages.

Specific speed, defined in Equation (1), is a parameter that relates speed, inlet volume flow rate, and headrise or pressure ratio. Armed with specific speed versus efficiency (Figure 9), the aerodynamicist may begin to optimize compressor specific speed and efficiency by iterating on the individual stage speed and the number of stages to determine the best possible compressor configuration. As the gas is compressed from stage to stage, the volumetric flow decreases in the later stages, which often forces the specific speed and efficiency to be less than optimum for a beam-type compressor, since all stages operate at the same speed. Integrally geared compressors, however, with multiple pinions have the flexibility to operate the impeller at the most optimum speed to maximize efficiency and pressure ratio. It is for the reason of optimizing specific speed and maximizing compressor efficiency that the later stages of an integrally geared compressor frequently operate at a higher speed than the first stages.

$$\textit{Specific Speed} = Ns = \frac{N * \sqrt{Q}}{H^{3/4}} \qquad (1)$$

where:
N = RPM
Q = Stage inlet flow
H = Stage headrise

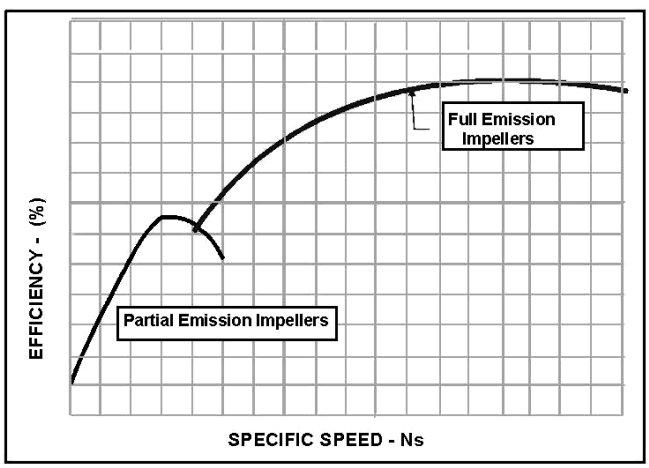

Figure 9. Specific Speed Versus Efficiency.

The exact flow rate and headrise that each compressor type begins to compromise performance with respect to specific speed is difficult to pin down, but generally for "low flow-high head" services the single shaft multistage compressor will begin to compromise compressor efficiency much earlier than the integrally geared compressor.

FEATURES COMPARISON OF BEAM-TYPE AND INTEGRALLY GEARED COMPRESSORS

Integrally geared and beam-type compressors have been in widespread use for many years but in different industries. Beam-type designs have been prevalent in the oil, petrochemical, and gas industry while integrally geared designs have been predominant in the air separation, pharmaceutical, and to some extent, the petrochemical industry. This section is directed at discussing the basic design differences as well as some the advantages and disadvantages of each type of compressor.

The following configurations were considered as a basis for comparison.

- A single integrally geared stage versus a beam-type multistage section producing the same flow and pressure.
- A single-stage beam-type versus a single-stage integrally geared. These are normally configured as a single-stage overhung or an integrally geared unit.
- Multiple intercooled integrally geared stages versus an intercooled multiple section beam-type type.

The factors considered in the comparison:

- *Design differences*—The normal execution of both designs considering flow, pressure, turndown, specific power consumption, thrust loading, variable speed, rotordynamics, cleanliness requirements, startup and shutdown, as well as typical maintenance issues.
- *Purchasing*—The specification, purchase order, expediting, inspection, testing, and shipping to site.
- *Commissioning*—Erection and startup of the unit.
- *Operational differences*—The differences in operation of both types.
- *Maintenance*—The basic steps taken in disassembling and reassembling both types.
- *Uprate capability*—The ability to change the compressor's rated capacity and head rise to meet new conditions of service.

Design Differences

- *Flow*—Integral gear designs are generally capable of higher volume flow rates, especially multistage, because of their impeller axial inlet orientation and higher rotational speeds. Typical beam-type compressors are limited to a maximum rotational speed of approximately 16,000 rpm due to shaft rotordynamics, while IG compressors routinely operate up to 50,000 rpm.
- *Pressure*—Although both are capable of high pressure ratios, beam-type, especially barrel-type, are capable of much higher pressure levels due to their casing design that tends to be cylindrical rather than the more complex three-dimensional shape of an integrally geared unit. The more simple cylindrical shape reduces the stresses, although 300 bar (4350 psi) has been obtained with an IG compressor.
- *Turndown*—In general, beam-type machines have a broader operating range because of the lower head per stage and the almost exclusive use of vaneless diffusers. Integrally geared machines can increase the operating range through the use of variable diffuser guide vanes; however, this adds considerable complexity and cost to the design.
- *Specific power consumption*—In general, integrally geared units have lower specific power consumption due to the shorter internal flowpath and lower turning losses. As a practical matter, variable inlet guide vanes can be used on one or multiple stages (unlike beam-type machines) to provide more efficient performance at reduced flows.
- *Thrust loading*—Beam-type units are inherently thrust balanced because of impellers on opposite ends of the double shaft end and

so do not need special consideration at startup other than the normal driver startup limitations. However, during operation it is common practice to use a balance piston, with its associated protective alarms, to counteract the aerodynamically induced thrust loads. Integrally geared machines must account for the high startup thrust loads. However, balance pistons are generally not needed as the aerodynamically induced thrust loads on a single integral gear stage are lower and can be counteracted by the gear helix angle forces that are present in direct proportion to the input power to the stage. Two approaches exist to absorbing the final thrust load on the high-speed pinion. One method simply uses high-speed thrust bearings, while the other method transfers the thrust from the high-speed shaft via thrust collars or rider rings to the low-speed shaft. Each works effectively well.

- *Variable speed operation*—This is commonly used on beam-type machines to provide flow control over the normal operating envelope and to allow for variations in the compressor inlet conditions. This works well for nonintercooled units having only a few stages, but is inefficient where intercooling and/or a high number of stages are required. Integrally geared units, generally, are not variable speed, especially in multistage configurations. The use of variable inlet guide vanes achieves equivalent performance with these machines, with the exception of increased flow that can be achieved at overspeed.

- *Rotordynamics*—Integrally geared compressor rotors generally operate above their first rigid body mode in single-stage configurations and above their second rigid body mode in two-stage configurations. Operation above the first bending mode is also common. Beam-type compressor rotors usually operate above the second rigid body mode and not uncommonly above the first bending mode. However, because of the inherent low film stiffness of the bearings, this mode acts more like a rigid body mode and is therefore highly damped. Prediction of rotordynamics behavior of integrally geared rotors tends to be somewhat more accurate due to the greater certainty of the actual bearing stiffness and damping coefficients. The higher loading condition of the bearings due to gear forces results in less dependence on bearing preload and clearance in determining the stiffness and damping characteristics, which have a strong effect on the location of the various lateral modes. Torsional analysis for IG compressors is also simpler due to simpler rotor models and only one coupling.

- *Cleanliness*—Integrally geared compressors generally are less tolerant to liquid and solid particle ingestion due to the higher impeller tip speeds. They are, however, more resistant to fouling due to the shorter flowpath, fewer turns, and higher flow velocities.

- *Startup and shutdown*—Both compressor types are suitable for full pressure startups and shutdowns. Recommendations for reduced pressure startups are based more on the driver limitations rather than any inherent limitation in either compressor type. IG compressors do have higher startup inertia when compared to an equivalent beam-type multistage section due to the presence of a higher speed ratio.

- *Maintenance issues*—Both compressor types will respond basically in the same manner to abnormal conditions, but not surprisingly, there are some differences.

  - Beam-type compressors:

    – Damage to bearings (both compressor and gear) due to high speed coupling misalignment.

    – Fouling of gas path due to condensable liquids in gas stream.

    – Erosion of labyrinth seals at interstage and balance piston locations due to particle ingestion (resulting in performance degradation and thrust overload).

    – Rotor damage due to a bearing failure may damage all stages since they are on a single shaft.

  - Integrally geared compressors

    – Erosion of impeller blades due to liquid and/or particulate ingestion at high impeller speeds.

    – Deposits in radial bearings due to high surface speeds, which makes the bearings more sensitive to lube oil quality.

    – Thrust overloading due to high settle-out pressures or overpressure at startup.

    – Impeller/bearing failures may result in damage to the gearing.

Purchasing

- Specifications of both types involve the same elements; therefore there should be no difference.

- Expediting and inspection may be more complex with beam-type compressors due to the significantly larger number of parts, and the supply and testing of the separate gear.

- Testing of both types involves similar elements, however, complete package testing of the beam-type type involves considerably more setup due to the additional alignment required of the high-speed coupling(s). Beam-type units tend to occupy considerably more floor space, therefore, interconnecting multiple modules may be necessary due to transport size limitations.

Commissioning

- Erection of either type involves the same elements, however, as beam-type units tend to occupy considerably more floor space. Interconnecting multiple modules may be necessary due to transport size limitations.

- Startup for both types involves the same tasks such as cleanliness checks alignment, instrumentation calibration/check-out, subsystem check-out, and actual starting of the machine. However, beam-type compressors require precision alignment because of possibly multiple high-speed couplings in addition to alignment of the driver coupling. While integrally geared compressors only require a single, less precise alignment of the driver coupling.

Operation

- Full load operation and control are essentially the same for both types.

- Partial loading of an integrally geared compressor is somewhat similar to the variable speed operation of a beam-type compressor such that crossing of rotordynamic modes may occur. In the case of a beam-type compressor the speed is actually varying and the modes are only moving as a result of a speed change. In the case of an IG compressor the reduction in load results in a reduction in the bearing loads, which causes the modes to shift more dramatically then from just the speed change alone. In other words, as an integrally geared compressor is unloaded the primary rotordynamic modes will reduce in frequency (but become more damped). This phenomenon is most common on the nonimpeller shaft end of a single-stage rotor where under fully loaded conditions the rotor is operating below the second rigid mode while at unloaded conditions it actually operates over the second mode.

Maintenance

- Inspection or replacement of bearings

  - Integrally geared compressors require removal of the gearbox cover similar to a standalone gearbox.

  - Beam-type compressors may require removing the high-speed coupling hub and end covers in addition to removing the cover from the standalone gear.

- Inspection/cleaning of impellers/flowpath

  - Integrally geared compressors involve removal of the stage inlet spool or pipe and removal of the stage inlet shroud.

  - Beam-type compressors involve possibly removing the section inlet and discharge spool pieces or piping as well as the casing half. On barrel compressors (a form of beam-type compressor) all bearings and the entire rotating element and diaphragms must be removed and either the diaphragms split or the rotor unstacked.

- Inspection of shaft end seals

  - Some integrally geared compressors have split shaft seals (labyrinth type) that can be removed from the gearbox side without disturbing the gas path while others require removing the impeller from the shaft (dry gas and carbon ring type).

  - Beam-type compressors require removal of the high-speed coupling hub and bearings.

Rerate Capability

- From the standpoint of future rerates, either an increase or decrease in flow and/or pressure, the beam type compressor has an advantage over the IG compressor. Although the IG can accomplish more head rise per impeller, this may limit the overall range compared with a multi-impeller beam compressor. The beam compressors can usually accommodate a change in capacity (±20 percent) by just changing impeller widths and/or diameters.

- Depending upon the originally selected compressor casing, aerodynamic changes may actually be simpler with the integrally geared type because there are fewer stages to change. Significant increases in head for fixed speed drivers are limited with both types because the increased impeller diameter will impact the casing or volute sizing. Generally, integrally geared compressor casings can accommodate a 10 to 15 percent future increase in capacity without adversely affecting the efficiency. However, if a greater than 15 percent flow capacity increase is contemplated, changing the compressor casing volutes is usually not easy, especially if larger volutes must be installed. The larger cases may dictate new gear center distances, or else a compromise in head/flow/efficiency will occur if the original gear casing is retained.

- Of primary importance in any uprate (be it beam or integrally geared) is the mechanical uprateability. In either compressor type provisions should be made in the original design to allow oversizing of the gears, bearings, and driver for rerating.

API 617 SEVENTH EDITION CHAPTER 3 HIGHLIGHTS

The Seventh Edition of API Standard 617 (Draft), which is nearing publication, includes a new chapter on integrally geared compressors. Major features are discussed here.

- *Compressor case mounting*—Referring back to Figure 2, one can see that the compressor case is mounted directly to the gearbox housing. While the case and supports shall have sufficient strength to avoid problems, the allowable forces and moments are generally less than a beam-type compressor.

- *Alignment*—The gearbox/compressor unit is fixed and not moved during alignment. The driver is adjusted to achieve the proper coupling alignment.

- *Gear rating methodology*—Not surprisingly, this topic provided the most spirited discussions among the Task Force members. API 613 (1995) gears may readily increase the rating without much regard to the resulting gear face width, or gear tooth temperature rise. However, due to the often high rotational speeds and gear pitchline velocities of IG compressors, different gear design approaches are necessary to compensate for the bull gear centrifugal growth and heating of the individual gear teeth. Table 1 indicates the rating methodology to be used for IG compressors. Units in the field rated under this methodology have demonstrated the desired reliability and robustness to process upsets.

Table 1. API 617 Integrally Geared Compressor Rating Methodology.

	GEAR RATIO < 7:1	GEAR RATIO >7:1
Applicable Life	20 years	20 years
Rating Criteria	API 613	AGMA 2101
Evaluation	One mesh	Each mesh
Gear Quality	API 613	ISO 1328, Grade 4 (AGMA Q13)

COST OF OWNERSHIP AND EXAMPLES

Integrally geared centrifugal compressors can achieve very high efficiencies (80+ percent) because:

- Each impeller has an axial intake;

- Each impeller can be run at the optimum speed;

- Intercooling between stages provides near-isothermal compression.

For chemical plant service, efficiency is usually subordinate to maintenance and reliability, whether the compressor is handling process air or a more demanding gas. Corrosive, toxic, and other difficult-to-handle gases can be safely and reliably compressed by IG compressors. Of course, materials of construction, shaft sealing, and other features can and *must* be specified on par with traditional API-type centrifugals.

Integrally geared centrifugal compressors can be shipped ready-for-operation on a steel frame, complete with all auxiliary and ancillary equipment. In some situations major items such as the oil system, gas coolers, and piping are fitted at the factory but shipped separately. Erection time and costs are still considerably less than for conventional compressor installations since frequently the entire package may be set and grouted into place at one time (Figure 10).

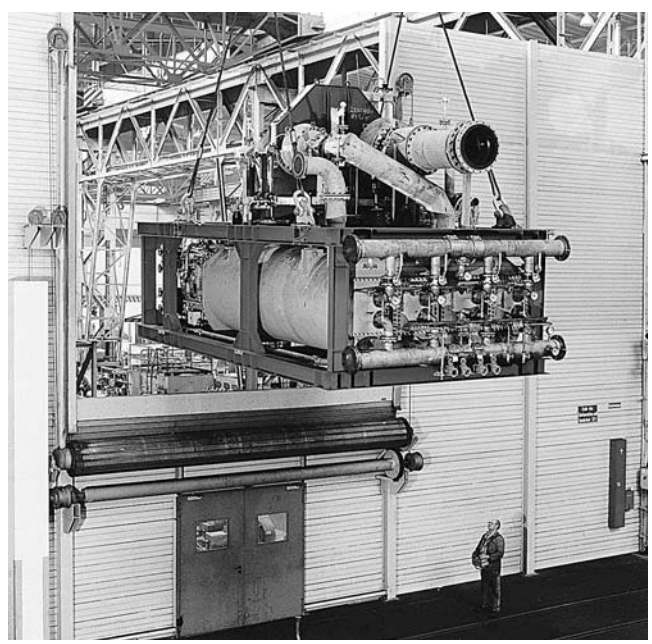

Figure 10. Packaged Integrally Geared Compressor.

Integrally geared compressors have the advantage of great flexibility. As discussed earlier, the bullgear can drive two or more pinions, each with two impellers (or stages). Thus the IG compressor can handle two or more gas streams simultaneously,

making it possible to do the job of several other compressors, substantially reducing both the purchase price and total installed cost since additional compressors, drivers, and peripheral equipment are eliminated.

Although IG compressors are typically motor-driven, the type of driver does not limit them. Steam turbine drives are often used, alone or in combination with an electric motor. A turbine/motor/compressor combination is often specified.

Integrally geared centrifugal compressors are especially attractive economically when:

- One or two stages efficiently replace a multistage, beam-type type of compressor, especially if an entire compressor body can be eliminated.
- Several gas services are combined into one machine, doing the job of two or more beam-type centrifugals.
- They can efficiently meet the process requirements that otherwise would require a more expensive reciprocating compressor (i.e., low molecular weight gases, like hydrogen). Due to the inherently higher online availability of centrifugal compressors compared to reciprocating compressors, an entire installed spare can be avoided, significantly reducing investment.

Numerous applications exist where IG compressors have been purchased and installed according to API 617 (Draft) specifications, and have provided the same degree of reliability as traditional API centrifugals:

- Process air for a wide variety of petrochemical applications, including PTA and nitric acid
- Air, recycle gas, and off-gas expander stages combined in one machine for nitric acid and other speciality chemical processes
- High-pressure booster applications (above 100 bar) are now routine due to the advent of reliable high-speed dry gas shaft seals. This service previously required reciprocating or beam-type barrel-type centrifugal compressors.
- Hydrogen recycle units are in service up to 300 bar (4350 psi).

Examples

Case A

A single-stage IG centrifugal was installed to circulate a corrosive gas (MW = 3.5) around a reactor operating above 150 bar (2200 psi). The process gas is sealed against atmosphere and has a constraint for near-zero leakage. These requirements would have been difficult and very expensive to meet using any other type of compressor. Installed cost of the IG compressor with a tandem dry-face shaft seal was $1.5 million compared to more than $4 million for two reciprocating compressors. Cost of energy was not an issue.

Case B

A two-stage, intercooled IG compressor for nitrous oxide gas was installed for $1.8 million compared to over $3 million for an intercooled, beam-type compressor. The IG compressor also had better efficiency, which decreased the operating costs.

Case C

This is a very good example of the versatility of an IG compressor. Basic data for a new chemical process called for:

- A motor-driven air compressor
- A recycle compressor driven by a steam turbine, using steam generated by cooling the process reactor
- A steam turbine generator to utilize excess reactor cooling steam

The estimated price of these three machines was more than $12 million. By comparison, a single train consisting of an IG compressor, motor-generator, and steam turbine was installed. The IG compressor has two stages of air and one recycle stage. The arrangement allowed the addition of a reactor off-gas expander stage, which previously could not be justified, recovering 1.8 MW of power. The purchase price of this train was $5.7 million.

Furthermore, total cost of the plant was reduced more than $10 million, and complexity was reduced:

- One induction motor-generator versus a motor and separate generator
- One lube oil system versus three
- One steam turbine versus two
- One control panel versus three (although control logic remained the same as for three separate trains)
- Less real estate required
- 1.8 MW of power (avoided electric cost) was recovered for negligible incremental investment

A multiservice integrally geared compressor is shown in Figure 11.

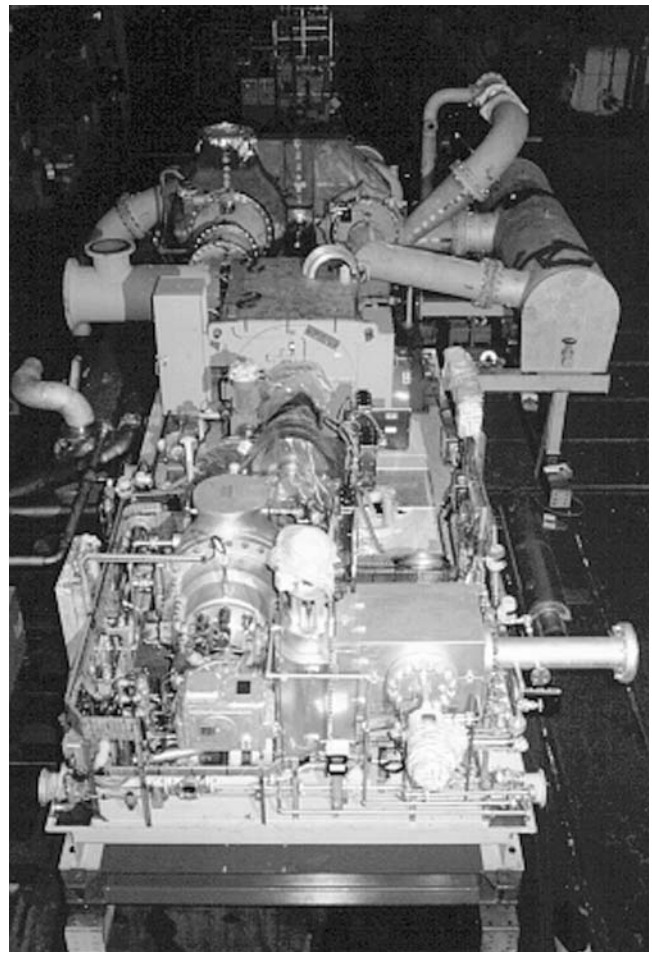

Figure 11. Multiservice Integrally Geared Compressor.

Case D

A six-stage integrally geared compressor is under evaluation for boosting natural gas from 9 bar (130 psi) to 170 bar (2500 psi) or nearly a 20:1 pressure ratio. Due to the pressure requirements, a tandem beam-type compressor arrangement (two units coupled together) is necessary, where a single IG compressor can meet the conditions of service. Table 2 summarizes the two compressor arrangements under consideration.

Table 2. Integrally Geared Versus Beam Compressor for P_r = 20:1.

	INTEGRALLY GEARED	TWO BODY SINGLE SHAFT MULTISTAGE + GEAR
Number of Stages	4	14
Number of Bearings	2 Input, 4 High speed	4 - Gear, 4 – Compressors
Number of Couplings	1 Low Speed	1 Low Speed, 2 High Speed
Number of Process Seals	4	4
Shaft Speeds	Pinion #1 = 36,000 rpm Pinion #2 = 44,000 rpm	14,000 rpm
Intercooling	Yes	Yes
API 614	Yes	Yes
Floor Space	3.5 m x 6 m (50% less)	4.5 m x 10 m
Estimated Purchase and Installation Costs	$1.8 MM	$2.6 MM

CONCLUSIONS

Considering all aspects, it is clear that both IG and beam-type compressor designs have advantages that must be evaluated in the context of the intended service. The categories for consideration are capital and installed cost, operating cost, durability, downtime, and maintenance costs.

• *Capital and installed cost*—Integrally geared compressors may be considerably less expensive than their beam-type counterparts. If prepackaged at the factory, installation costs can be reduced compared to the beam-type arrangement with a separate gear.

• *Operating cost*—Integrally geared compressors can optimize the individual pinion rotational speeds, and therefore maximize stage efficiency. This results in low specific power consumption and good operating range. If power is less of a concern compared with a very wide range of operation, a beam-type compressor might be the better choice.

• *Durability*—Beam-type compressors are often more resistant to process abnormalities and upsets, so for processes whose cleanliness and stability cannot be maintained, they are usually the better choice. However, if the process is capable of damaging both compressor types, the integral gear type is a better choice from the standpoint of easier maintenance.

• *Downtime*—Damage resulting from gas path contamination typically requires replacement or refurbishment of a rotor assembly. The change out time for an integrally geared rotor is typically much shorter than that of a beam-type compressor.

• *Maintenance cost*—IG compressors have fewer stages for the same pressure rise, and the rotor assemblies are significantly less expensive than beam-type compressors, even with the gear on the pinion shaft. Spare rotating elements for gearboxes are reduced to only a bull gear because the pinions are part of the rotor assemblies. The inventory of spare stationary components is also substantially less due to less complexity.

APPENDIX A—
TOTAL EQUIPMENT OWNERSHIP COST EVALUATION

Comparing offers from different suppliers is difficult enough even when the equipment is similar in design, and evaluations are further compounded when different technologies are available for the same service. To assist users in this intricate decision making process, a brief and simplified total equipment ownership cost (TEOC) example using the model presented by Thorp, et al. (1997), is provided. As seen in Equation (A-1), TEOC is the sum of all of the costs throughout the life of the equipment, and on a percentage basis illustrated by Figure A-1.

$$TEOC = C_a + C_o + C_m \qquad (A\text{-}1)$$

where:
C_a = Acquisition costs (engineering, inspection, procurement, equipment, installation)
C_o = Online costs (utility and user operating)
C_m = Maintenance costs (labor, material, aftermarket)

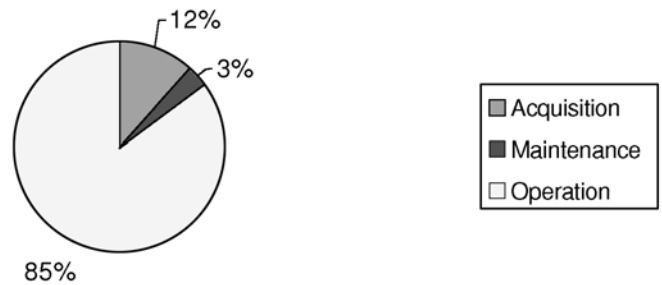

Figure A-1. Percentage Breakdown of Ownership Costs.

In this example, it is assumed that the application falls within the low flow-high head regime where the efficiency has been compromised 75 hp on the traditional horizontal single-shaft compressor. Table A-1 summarizes the various cost components to demonstrate that the integrally geared multishaft compressor can be competitive.

Table A-1. Simplified Total Equipment Ownership Cost Comparison.

	Beam-type Compressor	Integrally Geared Compressor	Comments
Brake Horsepower	1500 hp +1.5% gear loss +2% thrust brg loss	1425 hp	Approximately 5 points in gas efficiency difference.
Acquisition Costs + Differential Installation Cost	$1,000,000 +500,000	$925,000	IGC has a lower installation cost (foundation and labor)
On-line Costs	$15,000,000	$14,250,000	20 year life. $500/hp/year electric energy cost.
Maintenance Costs	$500,000	$500,000	Assumed equal Mean Time Between Repairs and costs.
TOTAL EQUIPMENT OWNERSHIP COSTS	$16,700,000	$15,875,000	For simplicity, the time value of money has been ignored.
Lifetime Cost Savings		$825,000	

Clearly this example shows that the integrally geared compressor results in a substantial savings. This is not always the case and the user is encouraged to conduct his own total equipment ownership cost evaluation to determine which equipment is best suited for the application.

REFERENCES

API Standard 613, 1995, "Special Purpose Gear Units for Petroleum, Chemical, and Gas Industry Services," Fourth Edition, American Petroleum Institute, Washington, D.C.

API Standard 617, Draft, "Centrifugal Compressors for Petroleum, Chemical, and Gas Service Industries," Seventh Edition, American Petroleum Institute, Washington, D.C.

Thorp, J., West, D., and Carlson, J., 1997, "A Systems Approach to Optimizing Total Equipment Ownership Cost and Revenue," Proceedings of the Methods, Strategies, and Technologies to Reduce Total Equipment Ownership Cost, Houston, Texas.