2

RECIPROCATING PROCESS COMPRESSOR DESIGN OVERVIEW*

The reader may best be introduced to the subject of this chapter by way of a component or construction feature review. We may note that today's reciprocating process compressors are the result of many years of development and experience. As of 2006, one U.S. manufacturer alone had manufactured reciprocating engines and compressors for over 100 years with well over 50,000 process units shipped.

Reciprocating process compressors are a very efficient and reliable method of compressing almost any gas mixture from vacuum to over 3000 atm. They have numerous applications in refining, chemical, and petrochemical plants. Power ratings vary up to 18,000 kW, with capacities up to about 35,000 m^3/h at compressor inlet conditions.

Reciprocating compressors have great flexibility. Being positive displacement compressors, reciprocating units can easily compress a wide range of gas densities, from hydrogen, with a molecular weight of 2, to gases such as chlorine, with a molecular weight of 70.

Reciprocating compressors can quickly adjust to varying pressure conditions with stage compression ratios ranging from 1.1 on recycle services to over 5 on gases with low k values or low ratios of specific heat. Typical compression ratios are about 3 per stage to limit discharge temperatures to perhaps 150 to 175°C (300 to 350°F). Some reciprocating compressors have as many as six stages, to provide a total compression ratio over 300.

Conservative rotative and piston speeds are used for process compressors, as most units operate continuously for many years with only occasional shutdowns for maintenance. With many applications the gases can cause problems because of being corrosive, containing entrained liquid and/or foreign abrasive particles. For these reasons, low- to medium-speed compressors are used, which have rotative speeds from 275 to 600 rpm, with piston speeds varying from 3 to 5 m/s (600 to 1000 ft/min) and compressor strokes from 150 to

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460 mm (6 to 18 in.). Normally, for higher-kilowatt-rated units, a longer strokes and slower speeds are used. Also, for nonlubricated applications, lower rotative and lower piston speeds are recommended to obtain improved piston and packing ring life.

The most common reciprocating compressor in use today is the balanced-opposed design (Figs. 2.1 through 2.3). This design maximizes the operating life of larger reciprocating units by minimizing unbalanced forces and moments. Two to 10 cylinders are used, with the reciprocating and rotating weights balanced as closely as possible. Also, single-cylinder units can be built with opposed balance weight crossheads used as necessary. Figure Y and similar vertically arranged reciprocating compressors are shown in Figs. 2.4 through 2.8.

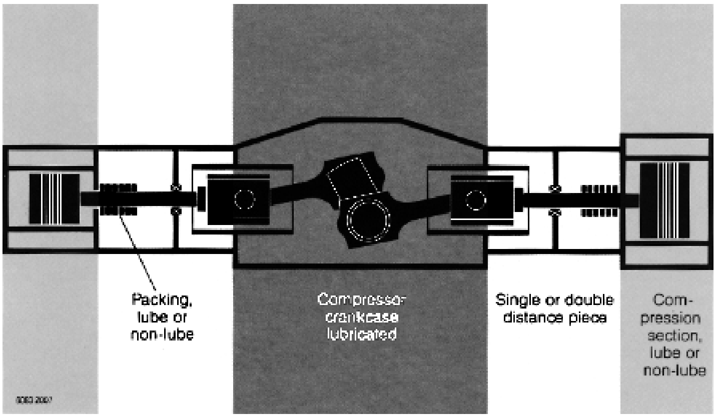


FIGURE 2.1 Principle of a balanced-opposed reciprocating process compressor. *(Sulzer-Burckhardt, Winterthur and Basel, Switzerland)*

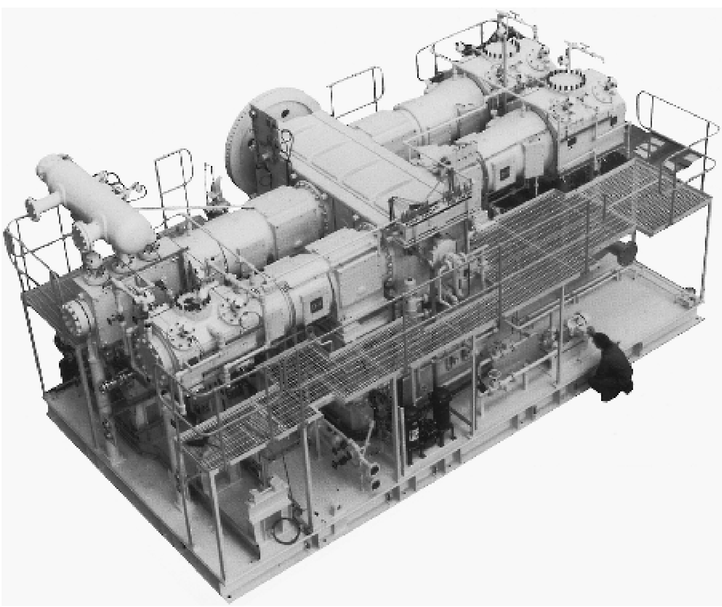
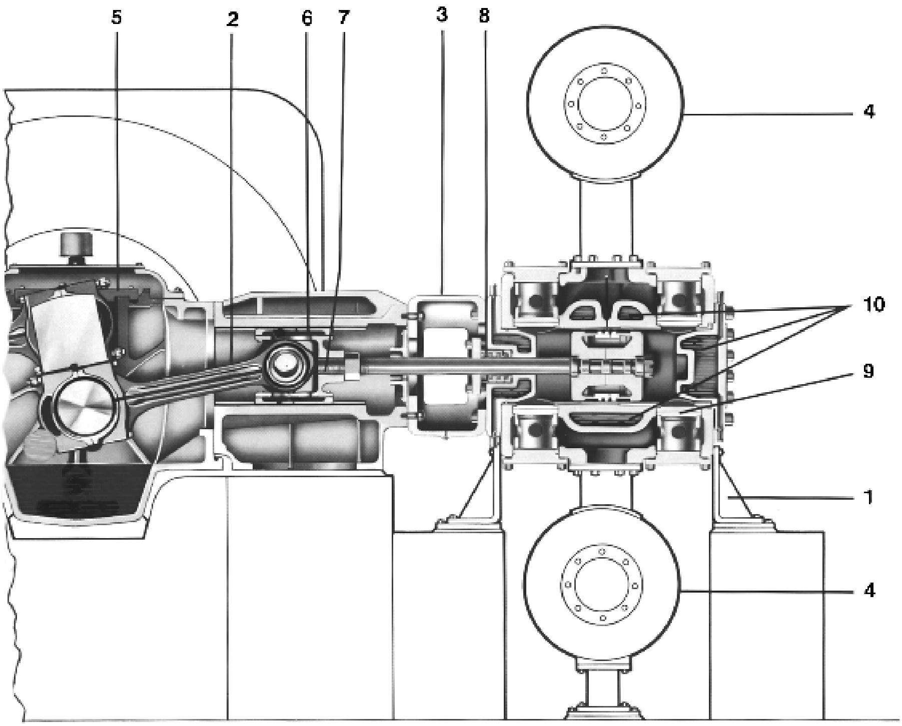


FIGURE 2.2 Balanced-opposed reciprocating compressor package. *(Dresser-Rand Company, Painted Post, N.Y.)*



1 = Cylinder support
2 = Connecting rod
3 = Distance piece
4 = Pulsation
5 = Frame
6 = Crosshead
7 = Piston rod
8 = Packing
9 = Valves
10 = Water jackets

FIGURE 2.3 Right-hand portion of a balanced-opposed reciprocating compressor. *(Dresser-Rand Company, Painted Post, N.Y.)*

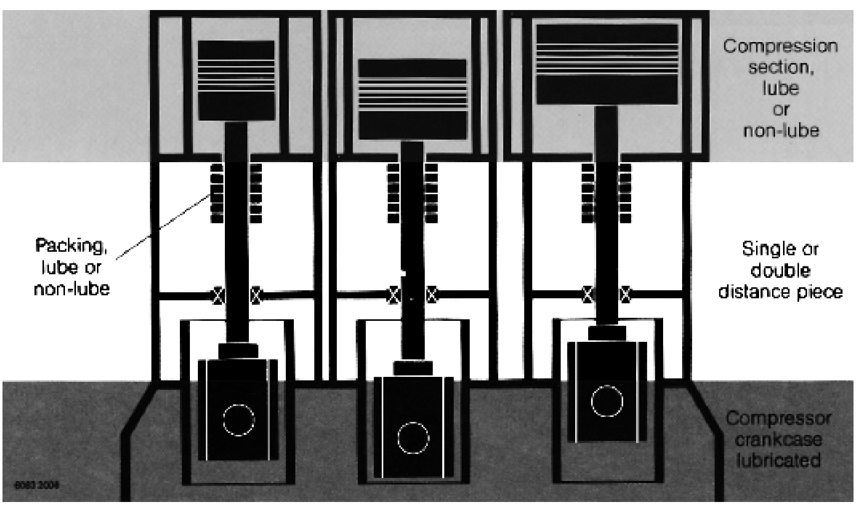


FIGURE 2.4 Vertically arranged compressor cylinders. *(Dresser-Rand Company, Painted Post, N.Y.)*

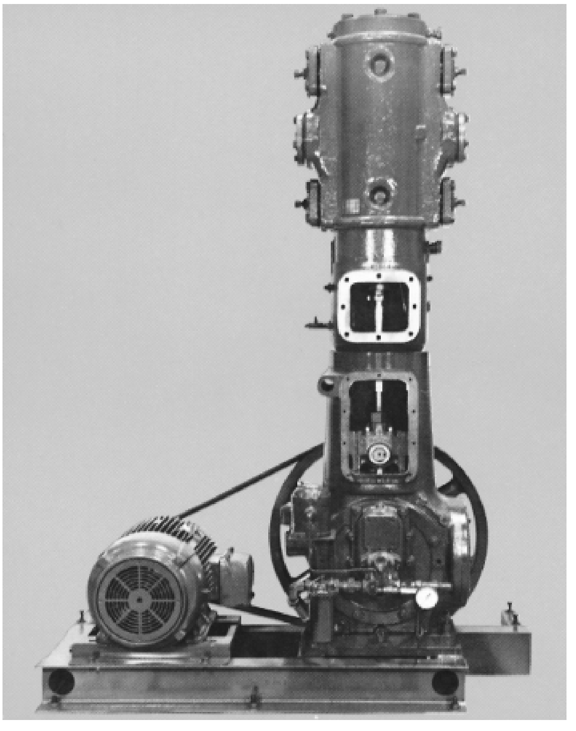


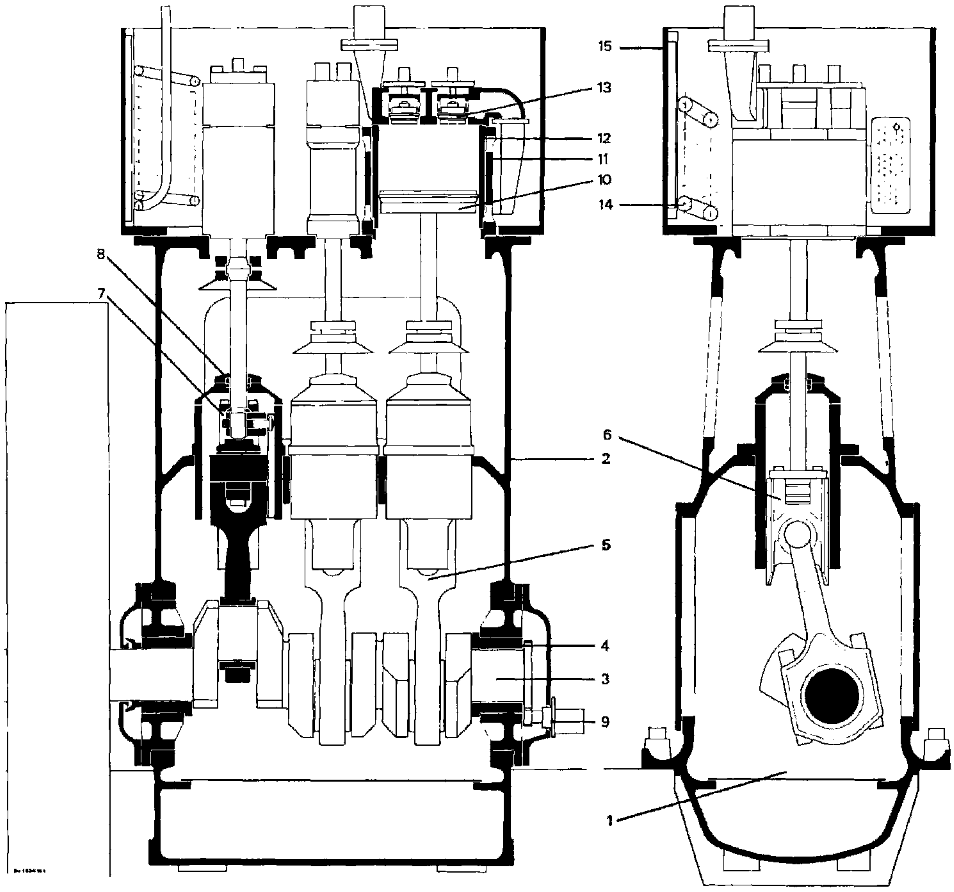
FIGURE 2.5 Vertically oriented reciprocating compressor. *(Cooper Cameron Corporation, Cooper-Bessemer Reciprocating Products Division, Grove City, Pa.)*

Unbalanced forces are produced by reciprocating and rotating masses. Reciprocating forces occur in all compressors from acceleration and deceleration of the reciprocating weights (piston and rod, crosshead, and a portion of the connecting rod). A compressor designer tries to equalize the reciprocating weights on each crankthrow to balance the forces. Rotating forces result from the centrifugal force produced from the unbalanced weights of the crankthrow and part of the connecting rod.

Only primary unbalanced forces occurring at the compressor speed and secondary unbalanced forces occurring at twice the compressor speed are considered significant in compressor foundation design (refer to Fig. 2.9). Unbalanced primary and secondary moments also exist in most compressors. With a two-cylinder unit having equal reciprocating weights on crankthrows set at 180° to each other, all primary and secondary forces cancel each other. Only couples or moments are transmitted to the foundation. With good foundation design, these moments are not harmful.

Only six crankthrow units can be perfectly balanced, with all unbalanced forces and moments zero. However, perfect balance is normally required only for offshore platform installations or for foundations installed without the use of piles on extremely poor (swamp-like) soil conditions.

Compressors installed on well-designed foundations over compacted soil or rock will withstand the normal unbalanced forces and moments of a reciprocating compressor. Multiple compressors should be installed on foundations tied together with a common concrete mat to spread out the area resisting any unbalanced forces and moments. Compressors are designed to withstand these forces and moments and merely transmit them to the foundation. However, it is very important that a strong grout bond be obtained between the compressor frame and the foundation. Epoxy-type grouts are highly recommended.



1 = Crankcase
2 = Frame
3 = Crankshaft
4 = Bearing
5 = Connecting rod
6 = Crosshead
7 = Ratchet drive for rotary motion of piston
8 = Cover
9 = Crankcase lubrication group
10 = Piston
11 = Cylinder
12 = Cylinder liner
13 = Valves
14 = Gas cooler
15 = Cooling-water tank

FIGURE 2.6 Sectional drawing of a water-lubricated vertical reciprocating compressor used in oxygen service. *(Sulzer-Burckhardt, Winterthur and Basel, Switzerland)*

2.1 CRANKSHAFT DESIGN

Up to 10 crankthrow units have been supplied for large compressors. The cranks are arranged with equal angles between each crank to provide optimum unbalanced forces and the smoothest overall crank effort torque (see Fig. 2.10). Even-number crankthrow units are arranged with 180° opposed pairs of cranks to cancel out inertia forces; odd-number crankthrow units require special crank-angle layout or dummy crossheads, as shown in Fig. 2.11.

Cylinders create pulsating compression forces and vibratory torque on the crankshaft with peaks that can exceed the average compressor horsepower torque by up to five times. The crankshaft design must be conservative to withstand these crank effort and vibratory

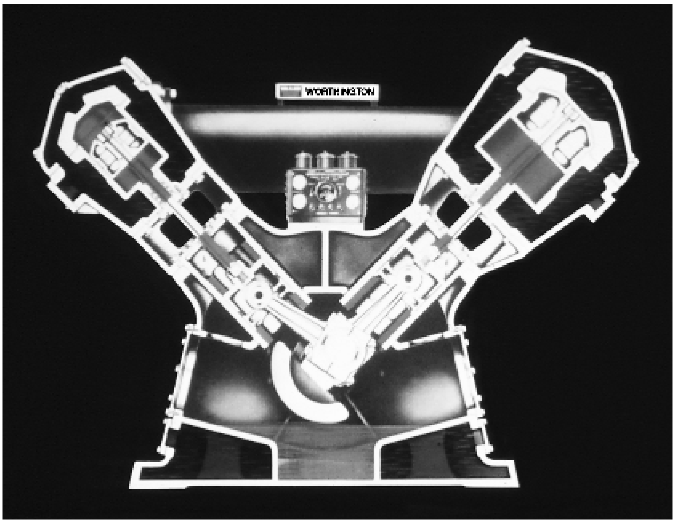


FIGURE 2.7 Reciprocating compressor with Y arrangement of cylinders. *(Dresser-Rand Company, Painted Post, N.Y.)*

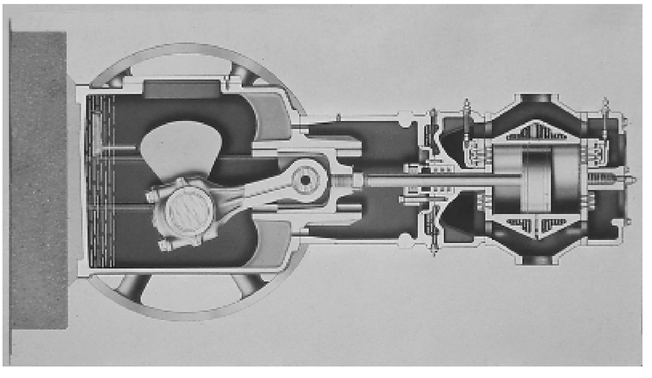


FIGURE 2.8 Reciprocating compressor with vertically arranged cylinders. *(Dresser-Rand Company, Painted Post, N.Y.)*

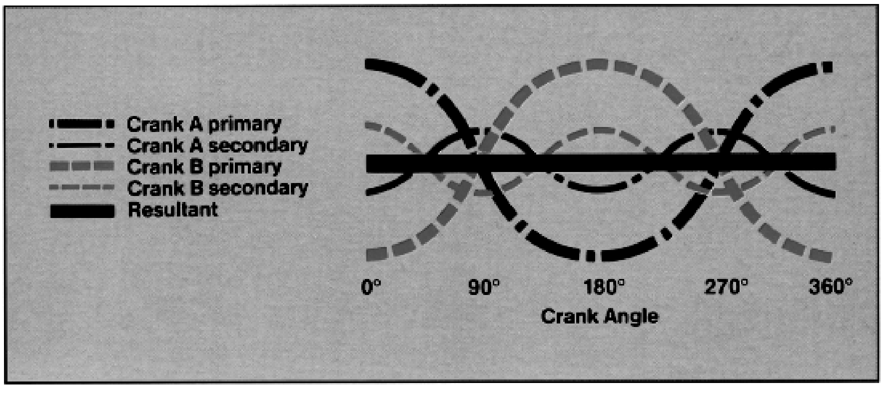


FIGURE 2.9 Crank-angle diagram demonstrating how primary and secondary forces balance each other out by acting in opposite directions. *(Dresser-Rand Company, Painted Post, N.Y.)*

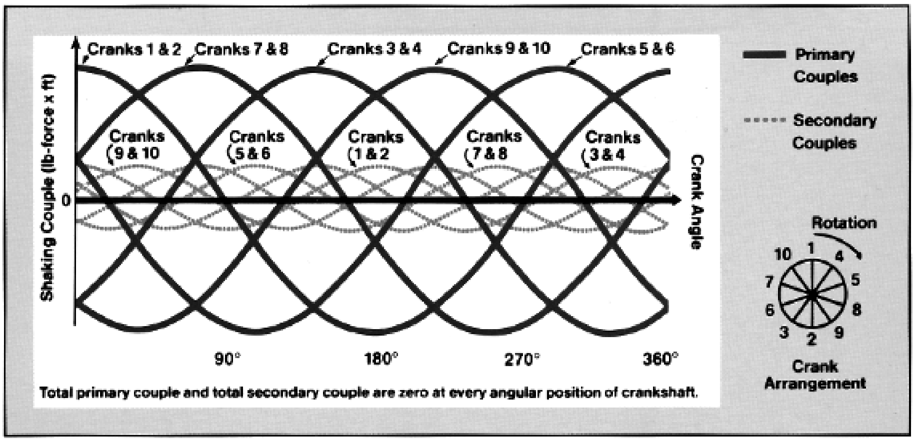


FIGURE 2.10 Preferred crank arrangement and resulting couples for a 10-throw compressor. Pairs of cranks are uniformly displaced at 36°. Therefore, reciprocating and rotating weights in opposing cylinders will not normally be equal. A variety of techniques are used to add weights to reciprocating parts to achieve the desired balance. *(Dresser-Rand Company, Painted Post, N.Y.)*

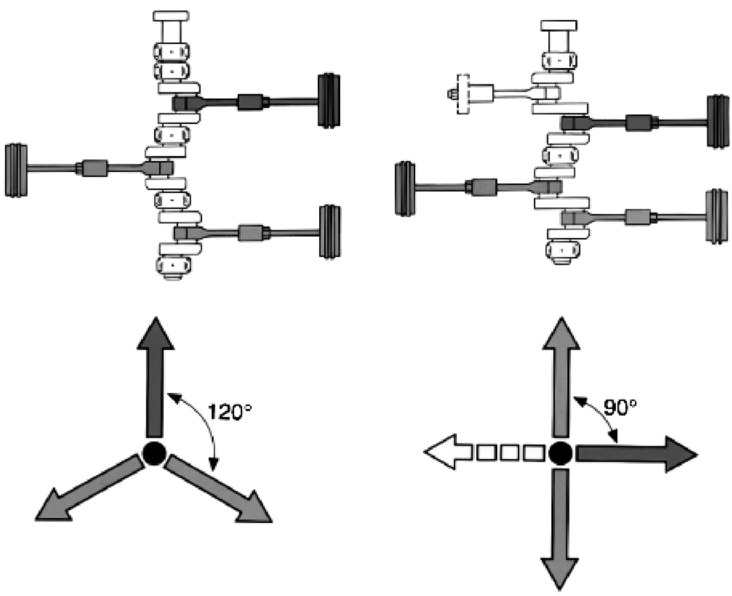


FIGURE 2.11 Three-throw crank angles at 120° (left) vs. 90° (right). Note the dummy crosshead required on the right. *(Dresser-Rand Company, Painted Post, N.Y.)*

stresses. For compressors over a small size of about 150 kW per crank, the crankshafts should be forged steel.

A customarily applied American Petroleum Institute specification (API 618) requires all crankshafts to be forged steel and heat-treated with ground bearing surfaces. Experienced manufacturers further require the cranks to be upset forged from the steel billet to provide

FIGURE 2.12 Two-throw crankshaft. *(Dresser-Rand Company, Painted Post, N.Y.)*

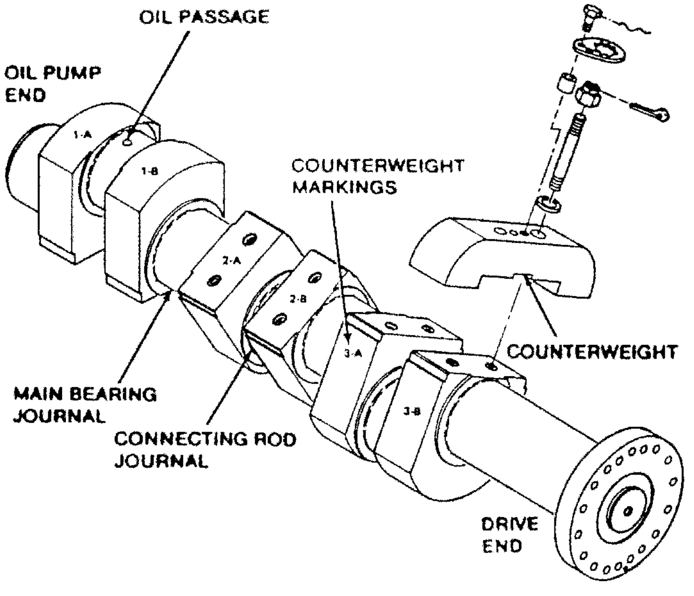


FIGURE 2.13 Three-throw crankshaft showing oil passages and counterweights. *(Dresser-Rand Company, Painted Post, N.Y.)*

stronger grain flow through the crank webs and cranks instead of machining the cranks from a billet. Materials used are alloy steel AISI 1045 or AISI 4140 with ultrasonic inspection by the crankshaft supplier. Crankshafts are purchased completely finished from suppliers who have special facilities to upset forge and grind the journals and crankpins. Also, special attention must be given to providing polished radii between the cranks and crank webs. Oil passages are drilled to permit oil flow from the journals to the crankpins. The intersections of these holes must be radiused and polished to prevent stress concentration points. Separate bolted-on or integral counterweights are used to help offset unbalanced forces and moments (Figs. 2.12 and 2.13).

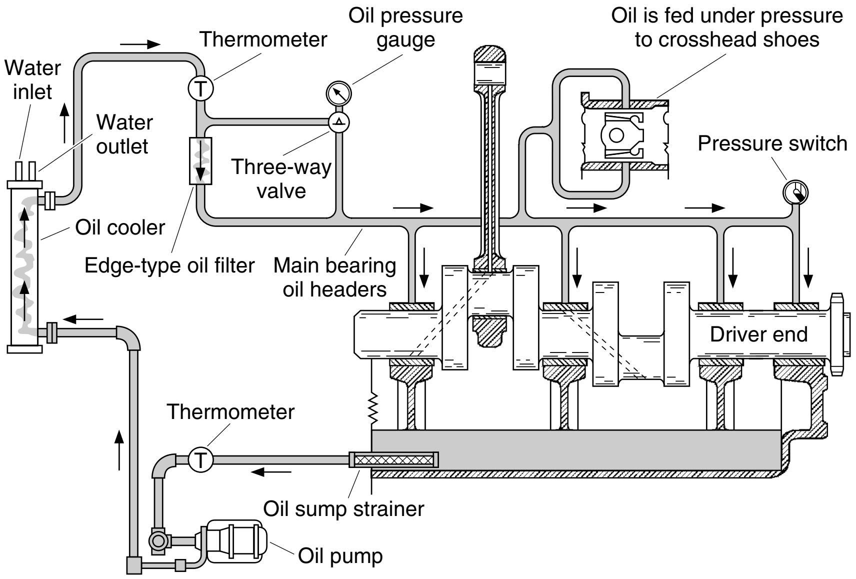


FIGURE 2.14 Force-feed lubrication system for reciprocating compressor. *(Dresser-Rand Company, Painted Post, N.Y.)*

2.2 BEARINGS AND LUBRICATION SYSTEMS

Most units have replaceable precision-bored sleeve-type aluminum alloy crankpin and main bearings. No field fitup or adjustment is necessary. Aluminum alloy has a high bearing load capability and is not likely to score the crankshaft surface should a bearing failure occur. Other bearing materials used are steel-backed aluminum, steel- or bronze-backed, babbitt-lined, and trimetal (steel–bronze–babbitt). With any of these bearings systems it is very important to maintain clean oil piping and filters and specified lubrication pressures and temperatures.

All large process compressors require forced-feed lubrication with a minimum scope of supply, as shown in Fig. 2.14, including oil pump, oil cooler, and oil filter. Redundancy and instrumentation requirements are governed by the criticality of a given process, and API 618 covers available options.

2.3 CONNECTING RODS

Connecting rods (Figs. 2.15 and 2.16) on process reciprocating machines are typically made of forged steel and manufactured with a closed die to provide good grain flow throughout the piece. Forced lubrication oil passages are drilled the length of the rod to permit oil flow from the crankpin to the crosshead pin bushing. Crosshead bushings are made of replaceable bronze. Connecting rod bolts are special forgings, and larger sizes have rolled threads for maximum strength.

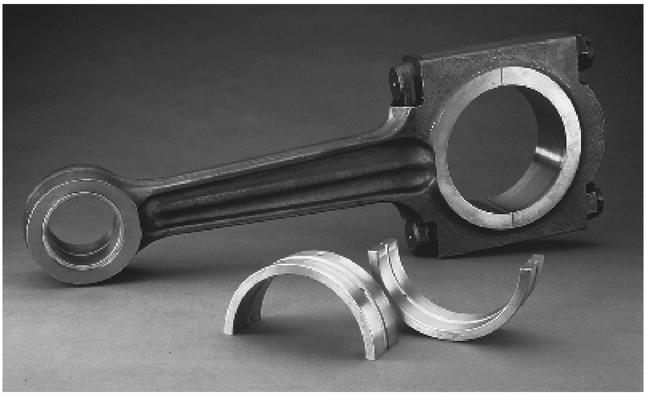


FIGURE 2.15 Typical connecting rod. *(Dresser-Rand Company, Painted Post, N.Y.)*

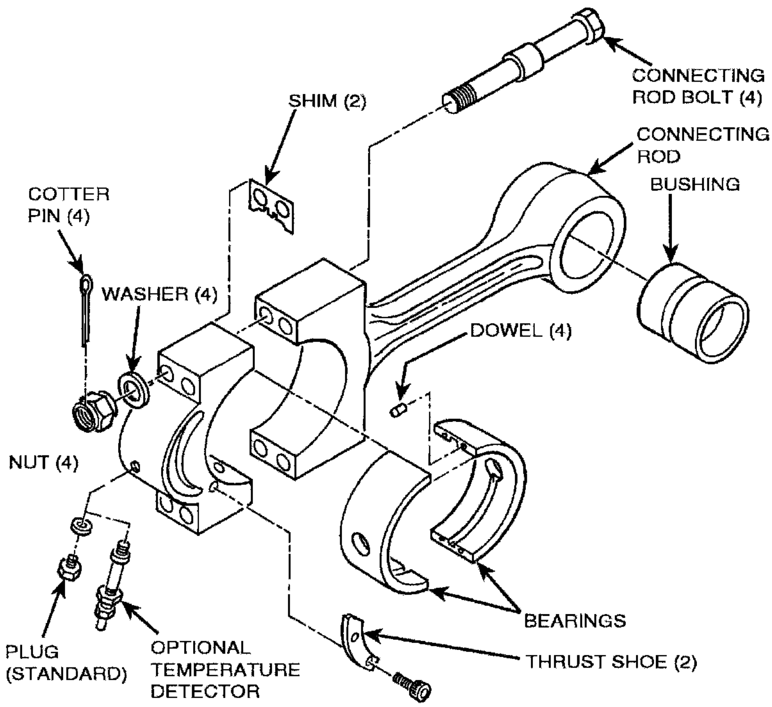


FIGURE 2.16 Component parts of a typical connecting rod. *(Dresser-Rand Company, Painted Post, N.Y.)*

2.4 CROSSHEADS

A crosshead is a sliding component typically manufactured of cast steel, or cast or ductile iron, with options for cast steel to meet API 618. For units over 150 kW, replaceable shim-adjusted top and bottom crosshead shoes are supplied. Most crossheads are of floating-pin design (Figs. 2.17 and 2.18); however, some larger units use a fixed-pin design. Either type is acceptable for reliable long-term, operation.

FIGURE 2.17 Crosshead for a reciprocating compressor. *(Dresser-Rand Company, Painted Post, N.Y.)*

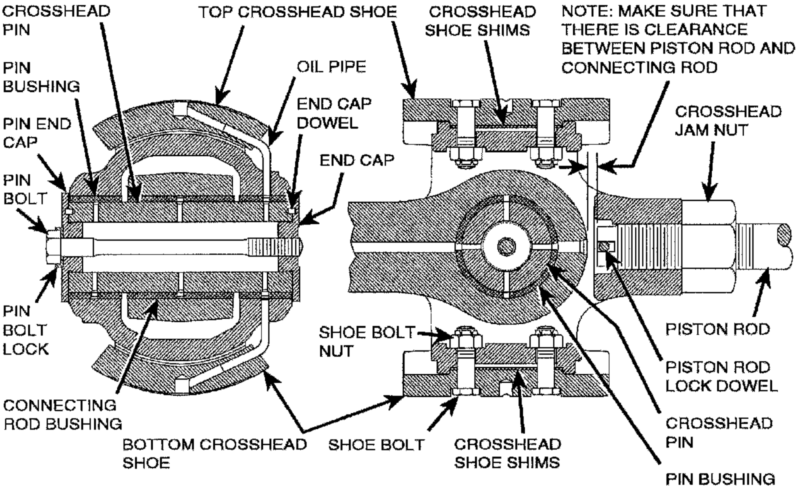


FIGURE 2.18 Cross-sectional views of crosshead components. *(Dresser-Rand Company, Painted Post, N.Y.)*

2.5 FRAMES AND CYLINDERS

Although a few manufacturers have offered fabricated, or welded, equipment frames; the majority of compressor frames are of cast iron (Fig. 2.19). Frames have suitable ribbed bearing supports to eliminate frame deflection and maintain crankshaft alignment under all operating conditions. Frames over 750 kW have either a tie-rod or a tie-bar over each main bearing to prevent deflections from the inherently high horizontal gas and inertia forces. Frames are totally enclosed to withstand outdoor conditions and have large maintenance access covers.

Each cylinder must be designed for the capacity, pressure, temperature, and gas properties of a specific project. Available cylinder materials include cast iron (Figs. 2.20 and 2.21), ductile

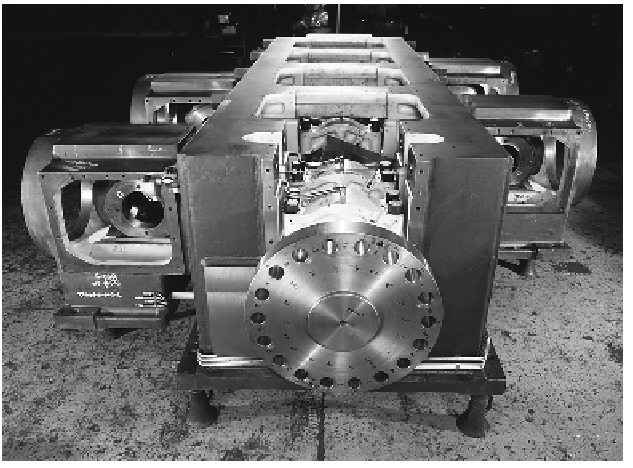


FIGURE 2.19 Cast iron compressor frame assembly showing double bearings at the drive end. *(Dresser-Rand Company, Painted Post, N.Y.)*

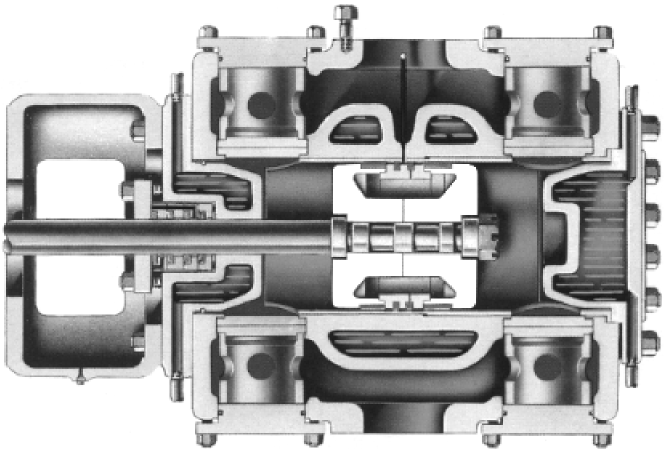


FIGURE 2.20 Low- or medium-pressure double-acting cylinder with a flanged liner and a three-piece piston. Liberally sized jackets reduce thermal stresses and aid in heat dissipation. *(Dresser-Rand Company, Painted Post, N.Y.)*

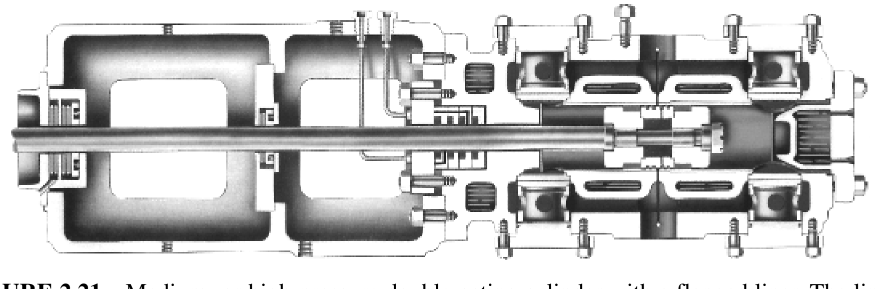


FIGURE 2.21 Medium- or high-pressure double-acting cylinder with a flanged liner. The liner is locked in place by a flange between the head and the cylinder barrel. A two-compartment distance piece designed to contain flammable, hazardous, or toxic gases is illustrated. *(Dresser-Rand Company, Painted Post, N.Y.)*

or nodular iron (Fig. 2.22), cast steel, and forged steel (Figs. 2.23 and 2.24). Manufacturers such as Dresser-Rand have also built large numbers of fabricated (welded) compressor cylinders (Fig. 2.25), with carbon and stainless steel being the primary materials.

Tandem cylinders (Fig. 2.26) are supplied where space and cost savings are important. Similar considerations may lead to the selection of step or truncated cylinders (Fig. 2.27).

Cylinders normally have separate force-feed lubrication systems using special oils. However, many services can be supplied nonlubricated. Nonlubricated service requires

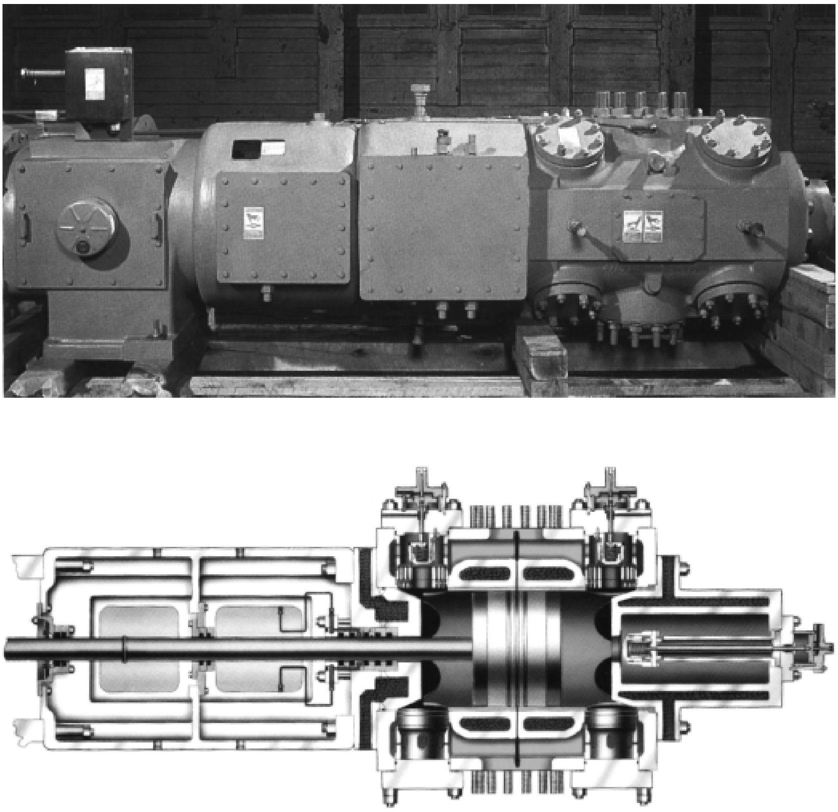


FIGURE 2.22 Cast iron or nodular iron cylinders shown with a two-compartment distance piece and frame extension. Pressures to 1500 psi are typical. *(Dresser-Rand Company, Painted Post, N.Y.)*

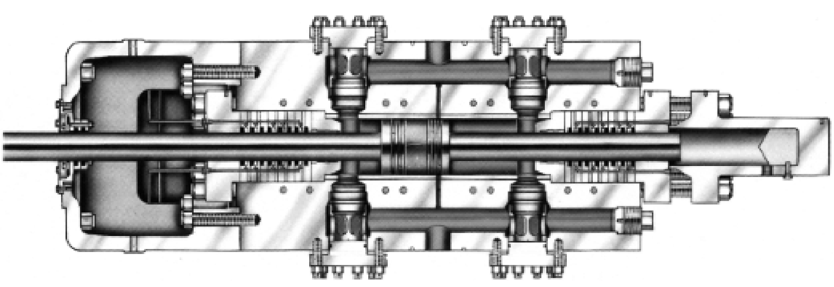
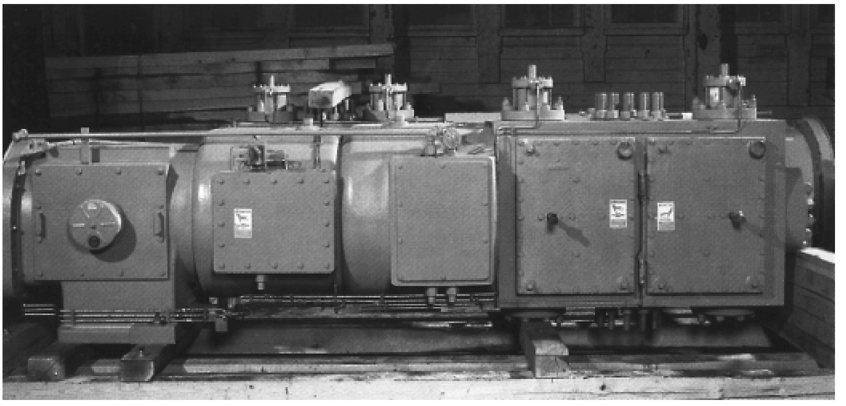


FIGURE 2.23 Forged steel cylinder with a tailrod design for pressures to 7500 psi. Tailrod construction is used to pressure-balance a piston or to achieve rod load reversals. This load reversal may be needed to properly lubricate the crosshead pin bearing. *(Dresser-Rand Company, Painted Post, N.Y.)*



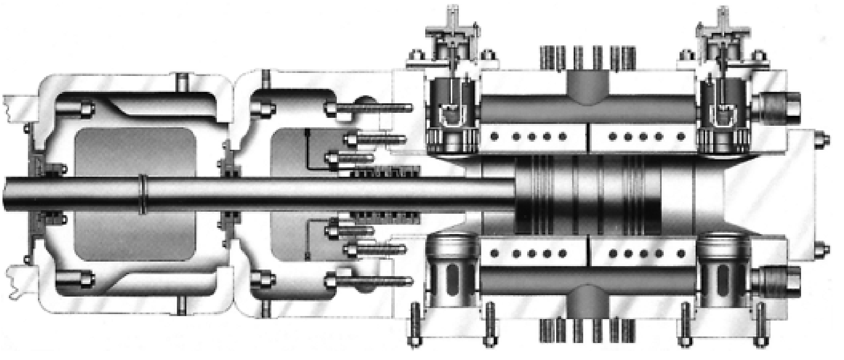


FIGURE 2.24 Forged steel cylinder with two-compartment distance pieces and a frame extension for 3000-psi refinery service. *(Dresser-Rand Company, Painted Post, N.Y.)*

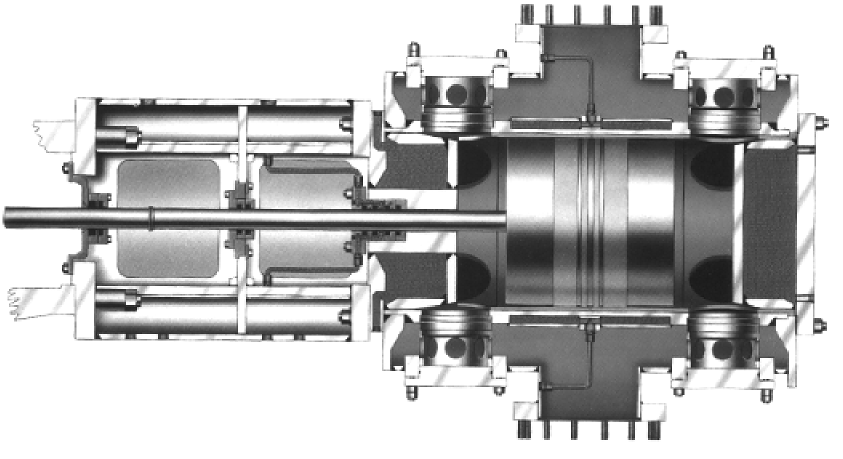


FIGURE 2.25 Fabricated carbon or stainless steel cylinders for special applications. *(Dresser-Rand Company, Painted Post, N.Y.)*

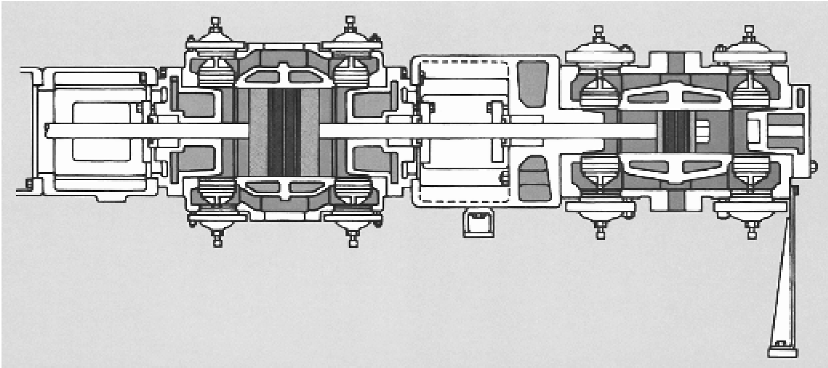


FIGURE 2.26 Tandem cylinders are furnished with a second piston connected in-line with the first piston. *(Dresser-Rand Company, Painted Post, N.Y.)*

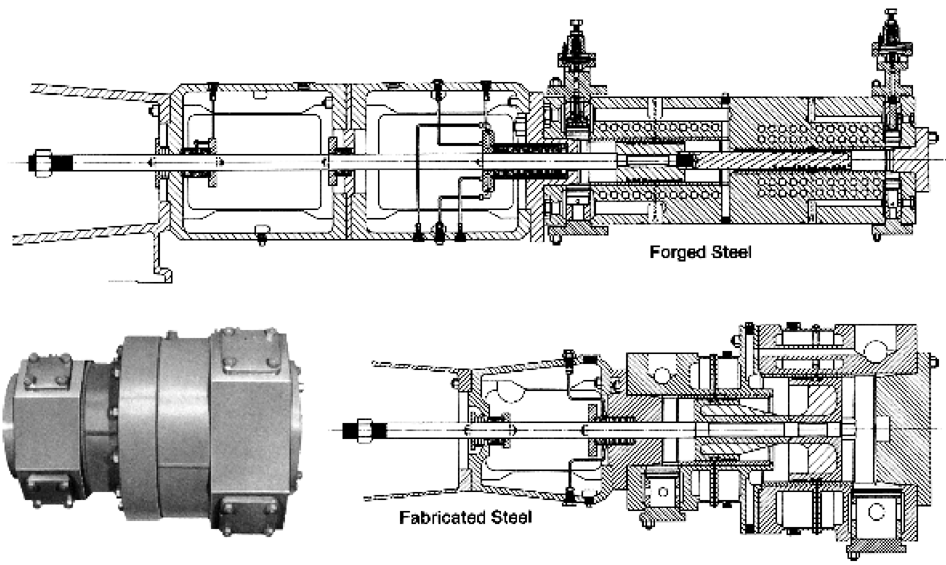


FIGURE 2.27 Truncated or step cylinders allow for space-saving multistaging. *(Cooper Cameron Corporation, Cooper-Bessemer Reciprocating Products Division, Grove City, Pa.)*

very clean gas by suction filtration to 1 μm if necessary and piston speeds reduced to below 4 m/s (700 ft/min) for acceptable piston, rider, and packing ring life. (Labyrinth piston compressors represent a special and important subcategory of nonlubricated process gas compressors and are covered later in the book).

Most cylinders are double-acting: that is, compression takes place in one half of the cylinder as the piston moves toward the cylinder head and also as the piston moves toward the crank end of the machine. However, cylinders can be made single-acting for special applications such as for high pressures such as those used in automotive fuel gas compression, where only a small displacement is required. Both conventional and tandem cylinders are shown in Fig. 2.28, which depicts a trunk piston compressor. Trunk piston machines resemble automobile engines in that they do not incorporate crossheads.

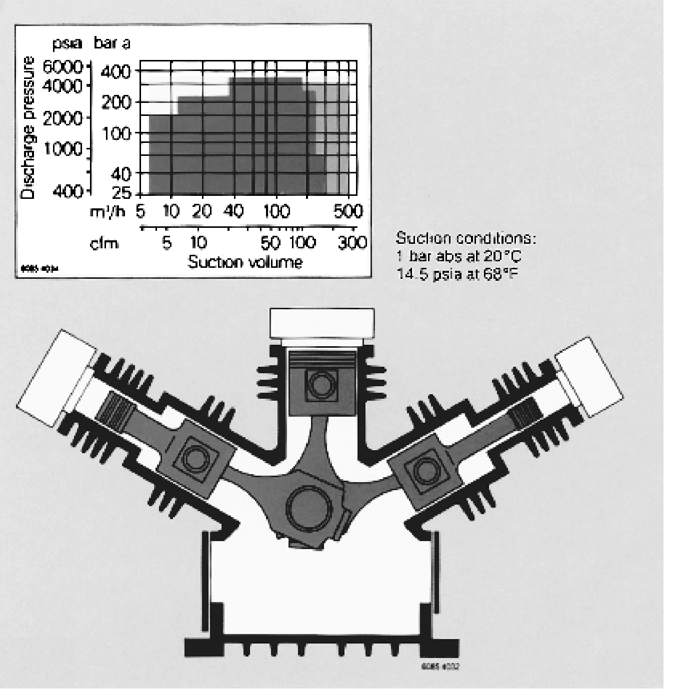


FIGURE 2.28 Trunk piston compressor with conventional stage 1 and step-type higher-stage pistons. *(Sulzer-Burckhardt, Winterthur and Basel, Switzerland)*

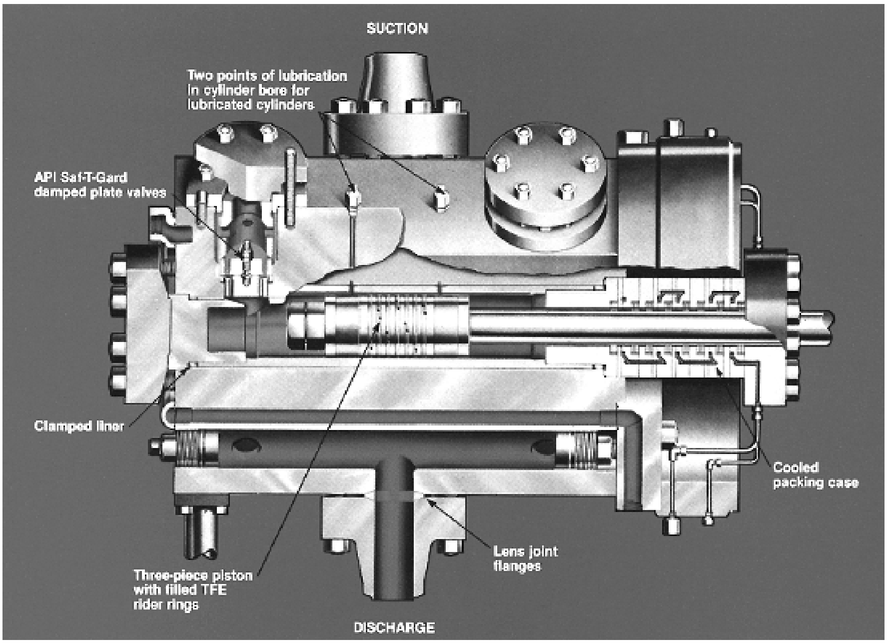


FIGURE 2.29 Compressor cylinder with clamped liner, cooling, and lubricating provisions. *(Dresser-Rand Company, Painted Post, N.Y.)*

Most process gas cylinders on large double-acting compressors are equipped with replaceable full-length liners that are held in place to prevent end movement or rotation. Liners (Fig. 2.29) are always used in steel cylinders. Standard liners are centrifugal cast iron, which provides a good dense bearing surface. Other materials, such as NI-resist, are available for special applications.

2.6 COOLING PROVISIONS

For large process gas compressors, forced cooling through the cylinder barrel and heads is most common (Fig. 2.30). If water is used, it is very important that clean treated water be used. Untreated river water is not acceptable because excessive deposits and fouling buildup will occur in the cylinder jackets, creating serious damage from cylinder overheating. A closed cooling system with a tempered water–glycol mixture is highly recommended to minimize deposits and prevent liquid dropout from saturated gases in the cylinders. A typical cooling system as shown in Fig. 2.31 may be used for one or more units.

The purpose of cylinder cooling is to equalize cylinder temperatures and prevent heat buildup. This cooling removes only the frictional heat. The heat of compression is removed by the inter- or aftercoolers. Thermosyphon or static-filled cooling (Fig. 2.32) can be used for cylinders having discharge temperatures below 88°C (190°F). The coolant supply temperatures should be at least 6°C (10°F) above the gas inlet temperature to prevent formation of liquid in the cylinder gas passages, which can cause serious valve and piston problems.

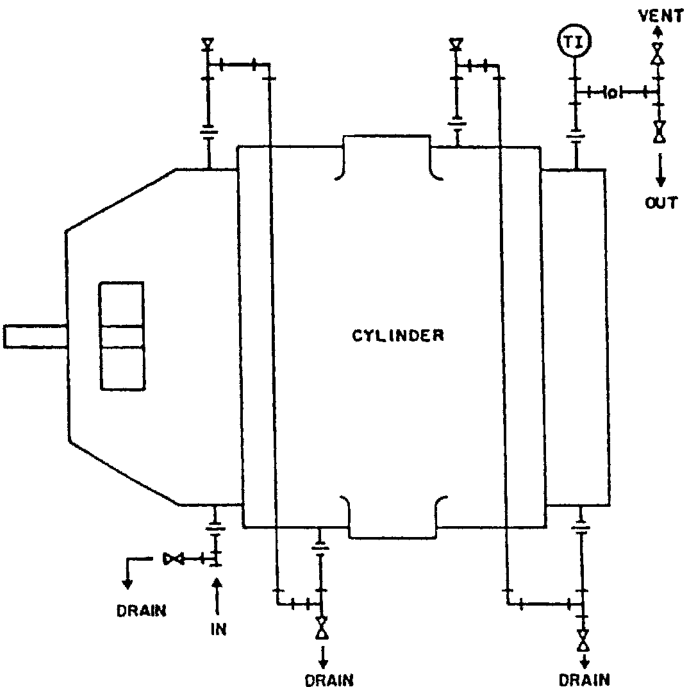


FIGURE 2.30 Forced cooling arrangement for large compressor cylinders. *(Dresser-Rand Company, Painted Post, N.Y.)*

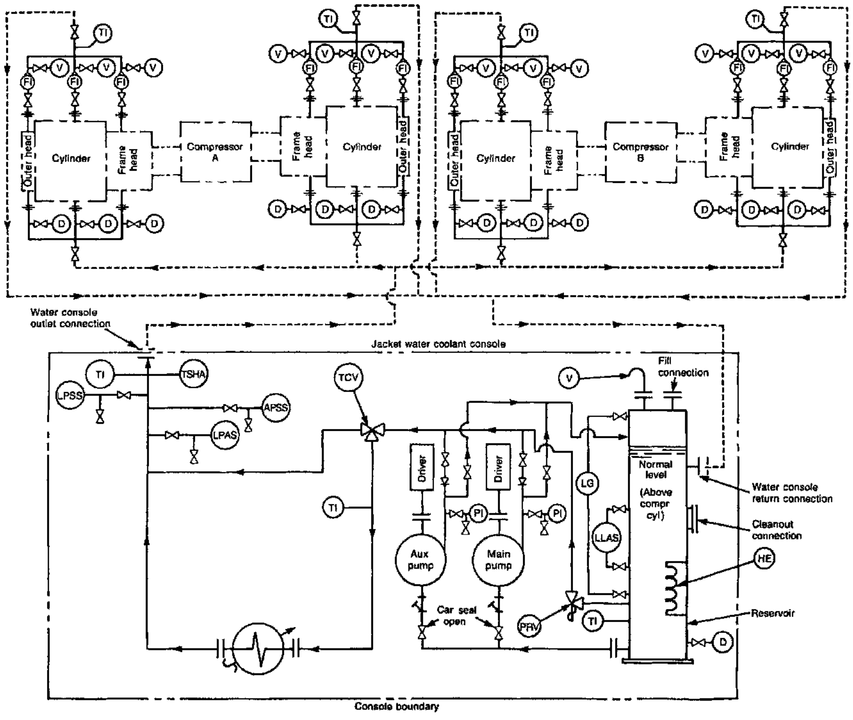


FIGURE 2.31 Closed cooling water system per API 618. *(American Petroleum Institute, Washington, D.C.)*

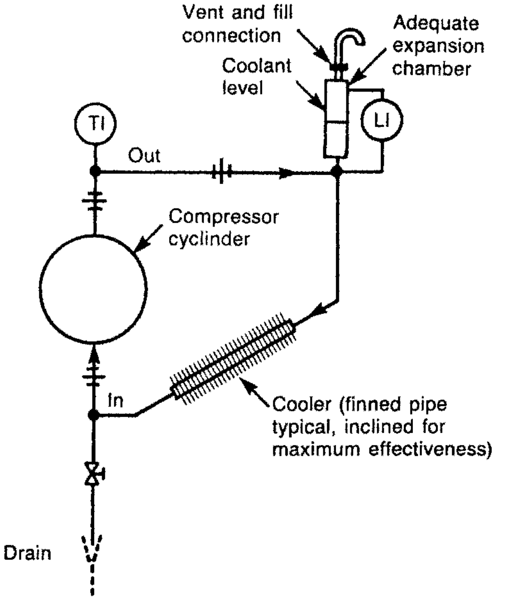


FIGURE 2.32 Thermosyphon cooling arrangement per API 618. *(American Petroleum Institute, Washington, D.C.)*

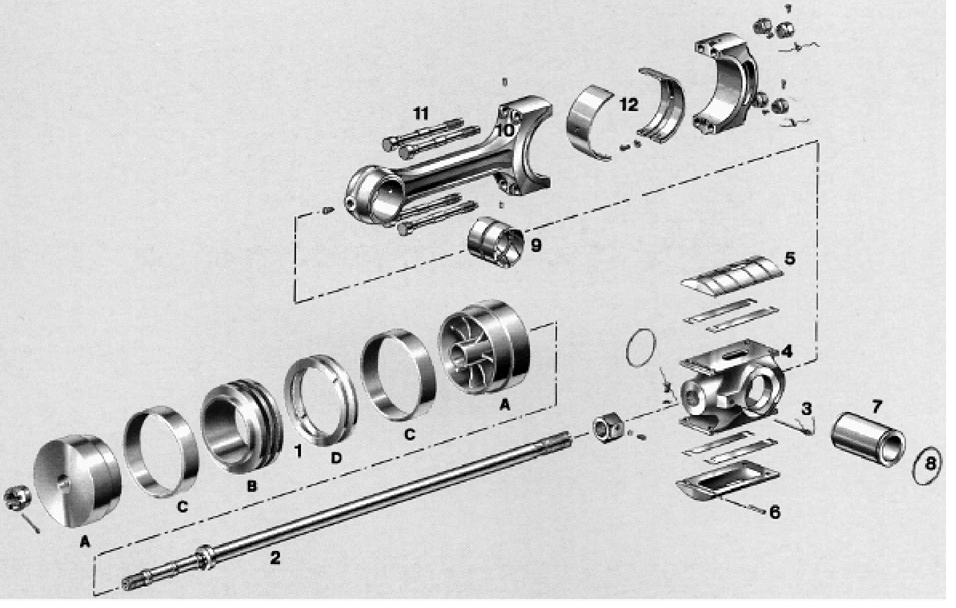
2.7 PISTONS

Cast iron is the piston material of choice for most applications. Aluminum is used for large pistons and on higher-speed units to reduce and balance inertia forces. For some high-pressure applications, over 150-atm absolute pressure one-piece integral steel piston and rod construction is used for higher piston strengths.

2.8 PISTON AND RIDER RINGS

Most process units today are equipped with Teflon (PTFE) or other high-performance polymer piston rings. Normally, two or three single-piece diagonal-cut rings without expanders are used. For some high-pressure applications (over 300 atm absolute) three-piece bronze segmental rings are used. Also, for some nonlubricated applications other special plastics or high-performance polymers have been used. One typical assembly is illustrated in Fig. 2.33.

For many lubricated and all nonlubricated applications, TFE rider rings are used. The rider rings support the weight of the piston and piston rod. Rider rings may be split type, located in the center of the piston (Fig. 2.34), or band type, stretched onto the piston. The bearing pressure on rider rings is normally below 0.7 kg/cm^2 (10 lb/in^2). As noted earlier, it



1. **3-piece piston** allows for two solid slip-on Rider Bands.
   A. Piston end bells
   B. Ring carrier
   C. Solid rider bands
   D. Piston rings
2. **Piston rod**
3. **Dowel pin** so piston rod can not turn
4. **Box-section crosshead**
5. **Babbitt-faced cast iron cross-head slippers**
6. **Crosshead slipper key**
7. **Full-floating crosshead pin**
8. **Crosshead-pin retainers**
9. **Renewable crosshead pin bearing**
10. **High-strength connecting rod**
11. **Connecting bolts**
12. **Split crankpin bearing**

FIGURE 2.33 Reciprocating components of a typical compressor. *(Dresser-Rand Company, Painted Post, N.Y.)*

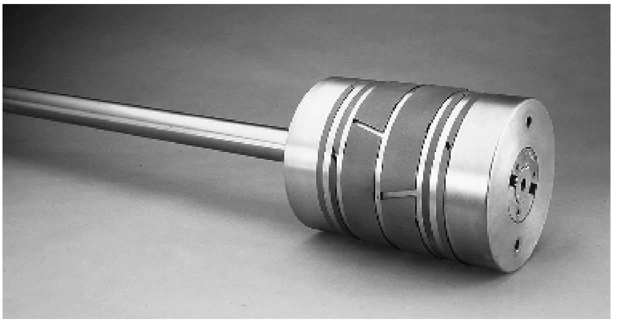


FIGURE 2.34 PTFE rider bands used to support pistons of contact-type nonlubricated compressors. *(Dresser-Rand Company, Painted Post, N.Y.)*

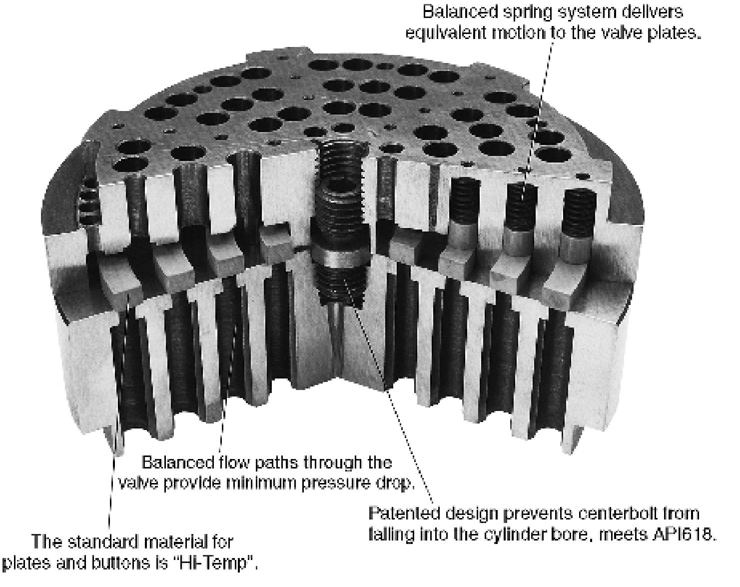


FIGURE 2.35 Plate valve. *(Dresser-Rand Company, Painted Post, N.Y.)*

is critical to have clean gas for long piston, rider, and packing ring life. Dirt or piping rust and scale carryover into cylinders will cause very rapid ring, cylinder bore, and valve wear.

2.9 VALVES

Virtually all process gas and moderate size-to-large air compressors use spring-loaded gas-actuated valves. Two of the many basic valve configurations are depicted in Figs. 2.35 through 2.39. Although certain claims and counterclaims are made by the various manufacturers, they share a desire to provide durable configurations compatible with gas composition and pressure. Also, valves are almost always symmetrically placed around the outer circumference of the cylinder and can normally be removed and serviced from the outside.

Good specifications mandate configurations and arrangements that will preclude installation errors. Reversing a suction valve could make it function as a discharge valve, and

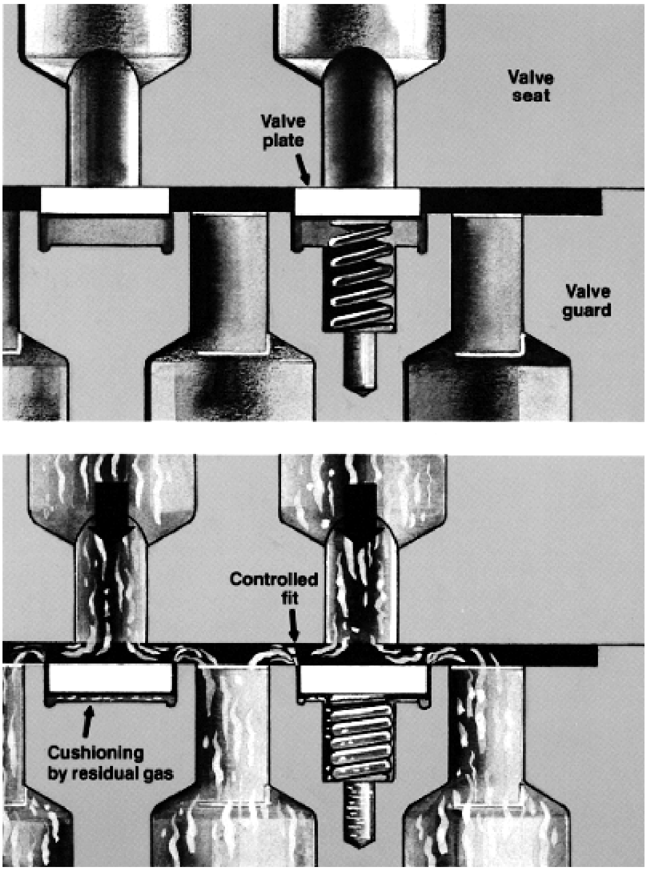


FIGURE 2.36 Cutaway of the closed and open positions of a damped plate valve, illustrating the pneumatic damping feature. *(Dresser-Rand Company, Painted Post, N.Y.)*

vice versa. Similarly, a bad valve design might risk deteriorating components falling into the compression space of a cylinder. Quite obviously, catastrophic damage and safety incidents could be the end result.

To ensure against structural failure of the guard or seat, API-compliant valve designs feature the use of a center bolt. The bolt is designed so that even in the event of its failure, it cannot drop into the compression chamber. The center bolt provides a very important part in valve fixed-clearance and physical strength. Without the bolt, all of the differential pressure would be sustained by the valve seat alone. The center bolt allows the designer to use the physical strength available in the guard since the center bolt ties the guard and seat together. The result is smaller clearance volumes, which result directly from thinner seats and guards than would be possible with designs not using a center bolt. Poorly designed valves can also cause noticeable decreases in compression efficiency; valve lift and valve area affect gas velocity and must be dimensioned properly.

Figure 2.35 depicts a plate valve. Enhanced versions of plate valves will sometimes apply the principle of pneumatic cushioning by allowing a small amount of gas to be trapped, as shown in Fig. 2.36. Deck-and-a-half and double-deck valves (Figs. 2.37 and 2.38) are designed to incorporate larger flow areas and thus improved efficiency.

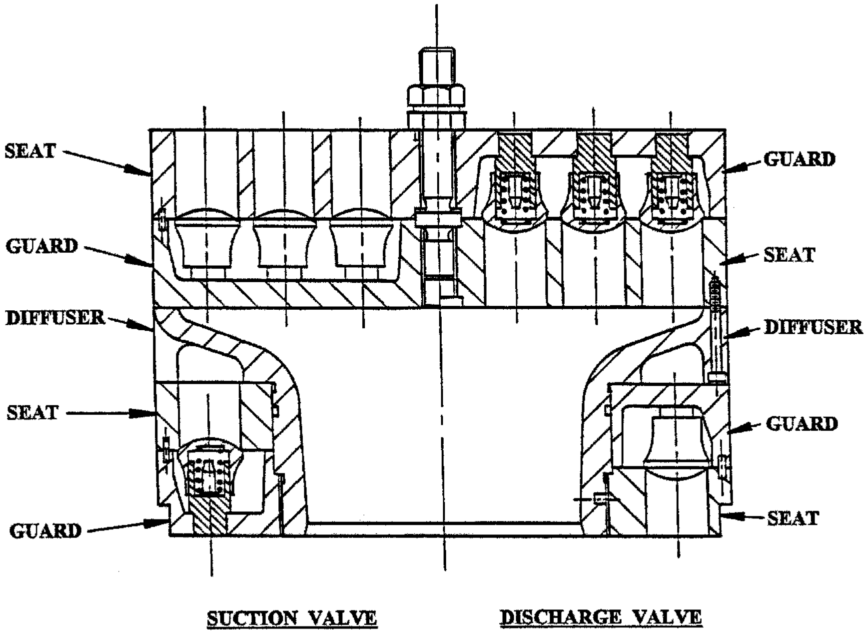


FIGURE 2.37 Deck-and-a-half compressor valve. *(Anglo Compression, Inc., Mount Vernon, Ohio)*

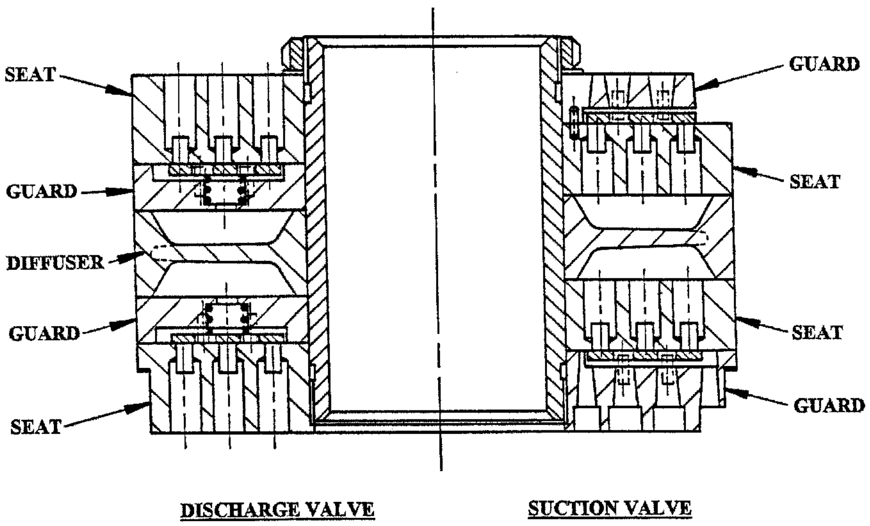


FIGURE 2.38 Double-deck valve, ported plate, opposed-flow type. *(Anglo Compression, Inc., Mount Vernon, Ohio)*

Although the description of valves has emphasized the plate-type design, circular channel ring-type valves as well as poppet designs are available. Straight channel, circular channel ring, and poppet designs were created primarily for high- and medium-pressure low-ratio applications, respectively. Many valves incorporate components made of high-performance polymers. PEEK (polyether ether ketone) is a typical material.

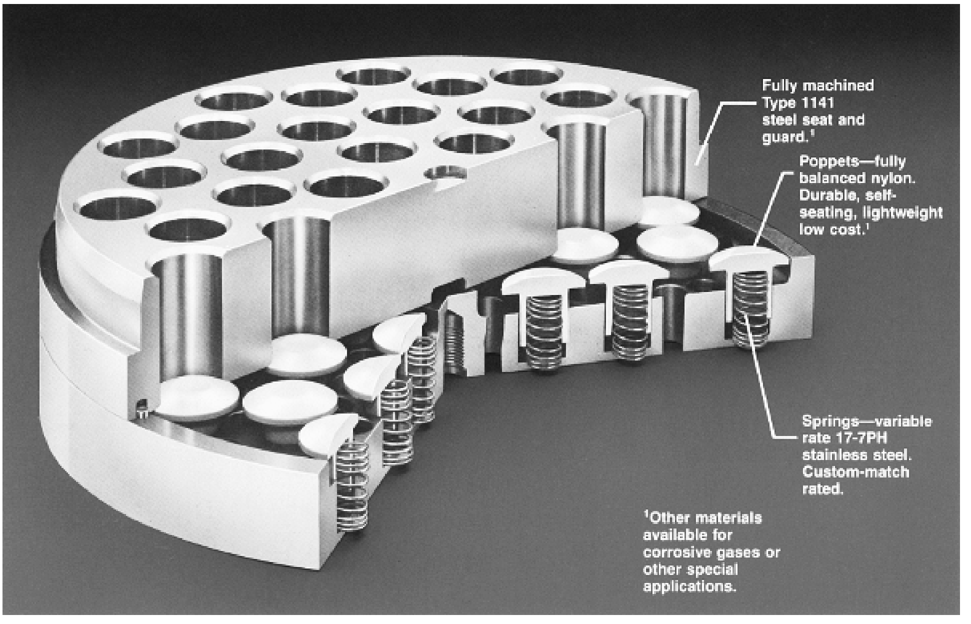


FIGURE 2.39 Poppet valve. *(Cooper Cameron Corporation, Cooper-Bessemer Reciprocating Products Division, Grove City, Pa.)*

In most high-pressure applications the damped valve has replaced the channel design. The lower plate mass, the greater damping, and a plate with fewer stress concentrations have led to the success of the damped valve over the channel design. The poppet valve has been applied primarily to low-ratio slow-to-medium-speed gas transmission service. Because of the alignment problems of valve seat to valve guard, maintenance has occasionally been a problem. Nevertheless, well-designed poppet valves (Fig. 2.39) are widely used in the application range illustrated in Fig. 2.40. It should be noted that valve designs continue to improve. As an example, the Cook Manley Company manufactures elastomer-enhanced Moppet compressor valves, which have produced outstanding results in the field.

The basis for a valve or compressor manufacturer's dynamic calculations is depicted in Fig. 2.41. Poor valve designs are revealed in lift vs. crank-angle diagrams (Fig. 2.42) and *p–V* diagrams such as those shown in Fig. 2.43 and in Figs. 3.10 through 3.20.

2.10 PISTON RODS

The standard recommended piston rod material is AISI 4142 alloy steel, induction hardened throughout the packing travel to a Rockwell hardness 50C minimum. Other materials, such as stainless steel, are available for increased corrosion-resistance properties. However, these materials cannot be hardened above Rockwell hardness 40C. Special hard coatings, including tungsten carbide and ceramic materials, are available as well. High-quality process compressors incorporate piston rods furnished with precision-controlled rolled threads (Fig. 2.44) that offer much greater fatigue strength over cut threads. API 618 also specifies the use of rolled threads.

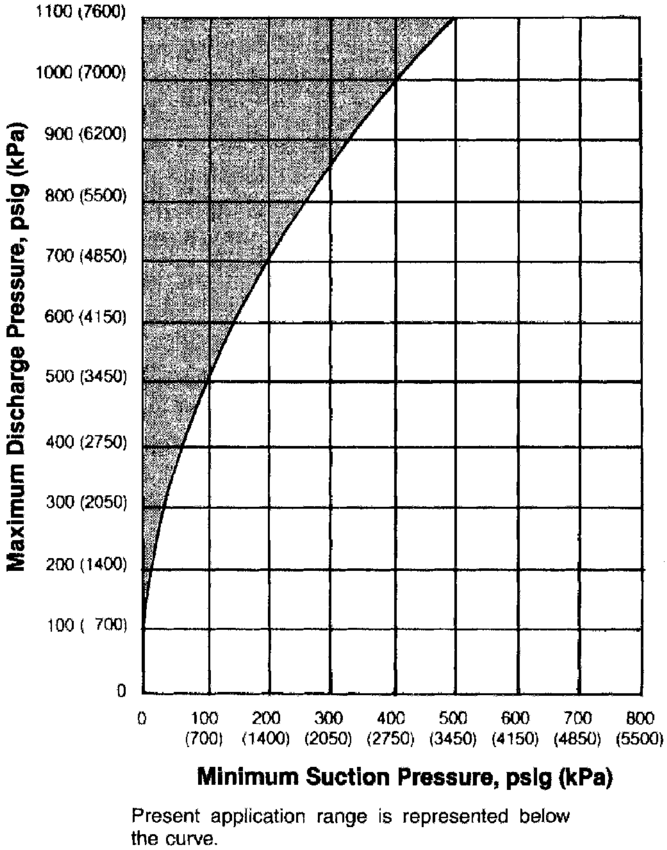


FIGURE 2.40 Poppet valve application range. *(Cooper Cameron Corporation, Cooper-Bessemer Reciprocating Products Division, Grove City, Pa.)*

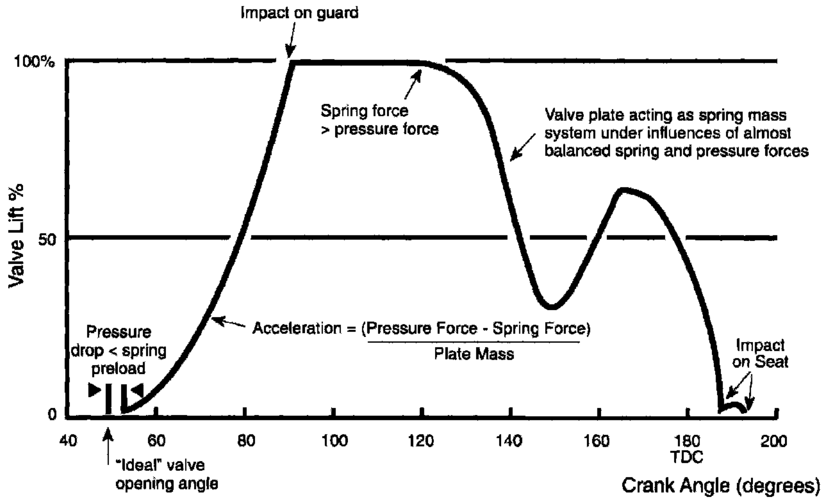


FIGURE 2.41 Basis of valve dynamics calculation. *(Dresser-Rand Company, Painted Post, N.Y.)*

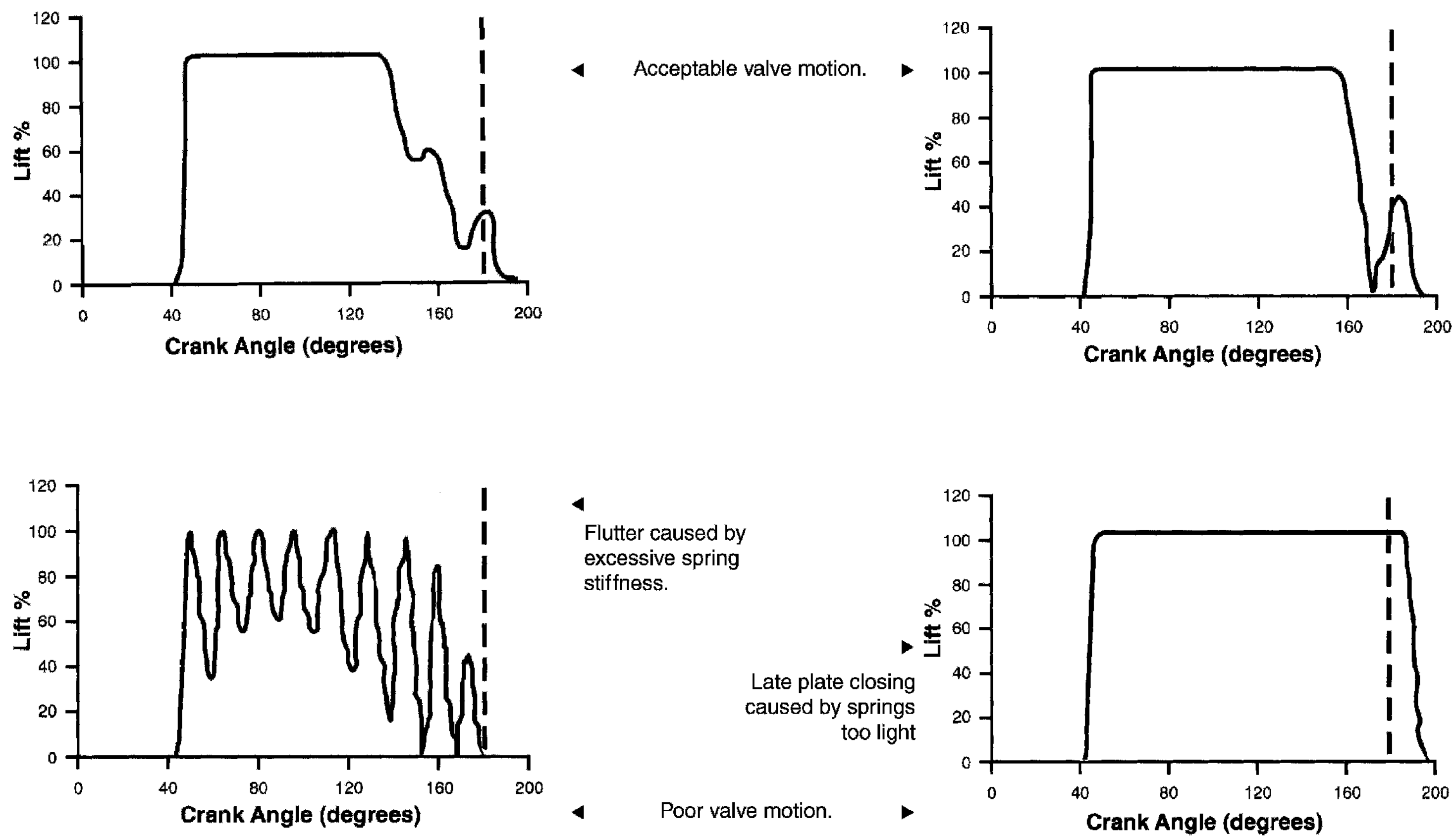


FIGURE 2.42 Acceptable and unacceptable valve motion illustrated on lift vs. crank-angle diagrams. *(Dresser-Rand Company, Painted Post, N.Y.)*

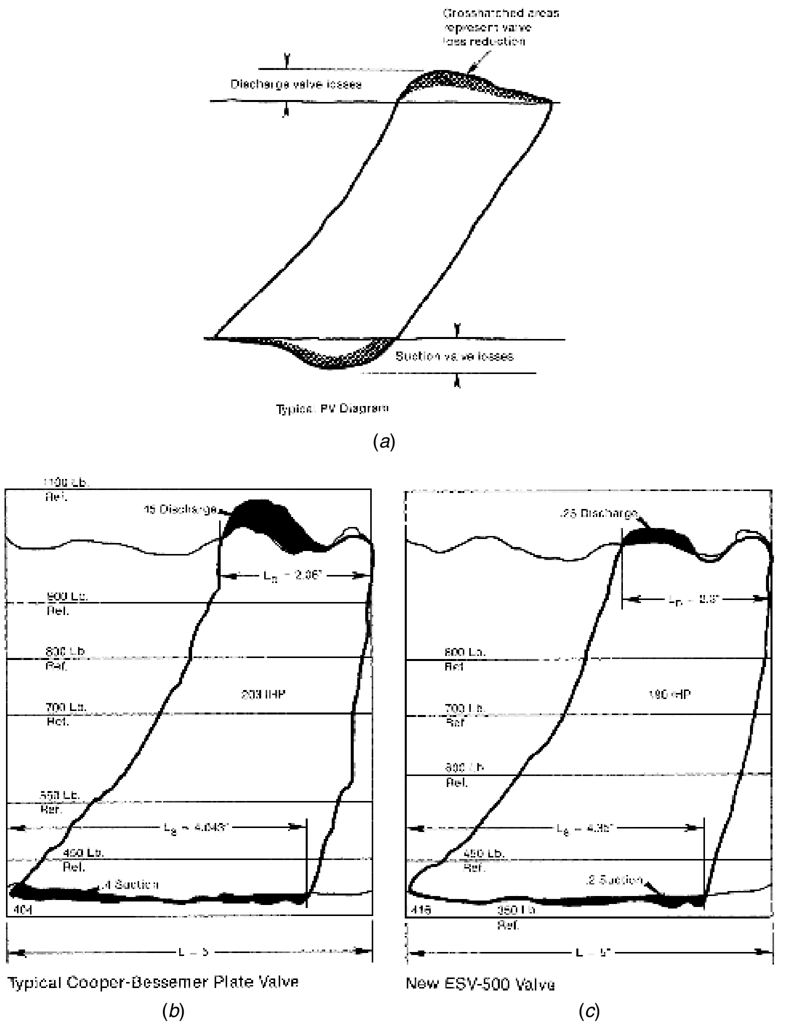


FIGURE 2.43 The *p–V* diagrams can reveal valve losses. Typical diagram (*a*) is compared to a traditional plate valve (*b*) and enhanced design (*c*). *(Cooper Cameron Corporation, Cooper-Bessemer Reciprocating Products Division, Grove City, Pa.)*

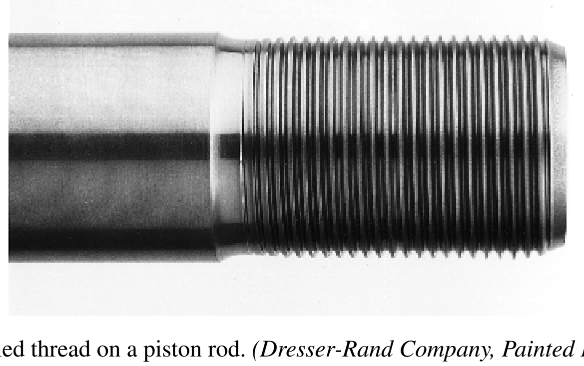


FIGURE 2.44 Rolled thread on a piston rod. *(Dresser-Rand Company, Painted Post, N.Y.)*

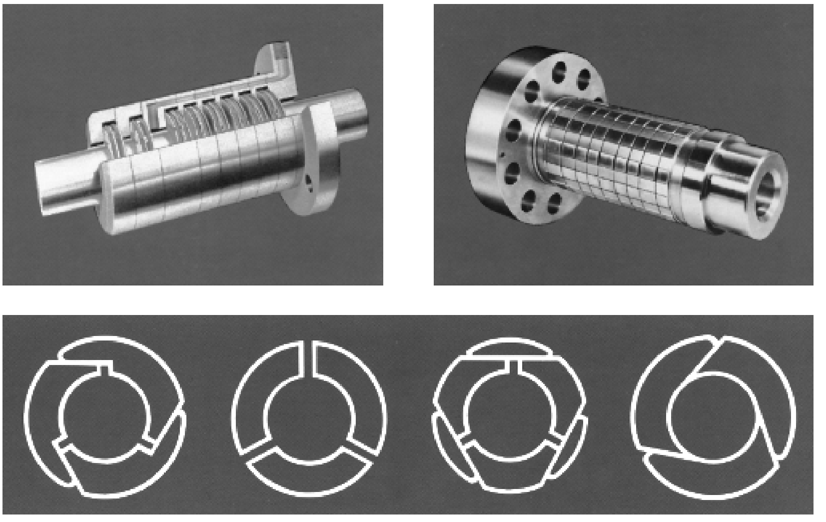


FIGURE 2.45 Packing cartridges and available arrangements. Single-, double-, radial-, or tangential-cut rings with passages for lubrication, coolant, and venting are provided, as required by the application. Surfaces are usually lapped. *(Dresser-Rand Company, Painted Post, N.Y.)*

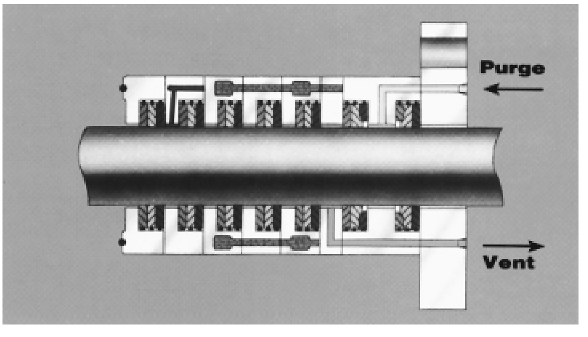


FIGURE 2.46 Lubrication and cooling passages on rod packing. *(Dresser-Rand Company, Painted Post, N.Y.)*

2.11 PACKINGS

Packings (Fig. 2.45) are required wherever piston rods protrude through compressor cylinders and distance pieces. Vented, full-floating, self-lubricating PTFE packing is standard and provides long-lasting operation with a minimum of gas leakage. One lubrication feed is common, but pressures over 150 atm absolute may have two feeds (Fig. 2.46). Many packing cases are also equipped with internal cooling passages. A typical self-contained cooling system for piston rod pressure packing is shown in Fig. 2.47.

2.12 CYLINDER LUBRICATION

Proper cylinder lubrication may greatly reduce compressor maintenance requirements. Cylinders are typically lubricated by a forced-feed lubricator system that is separate from

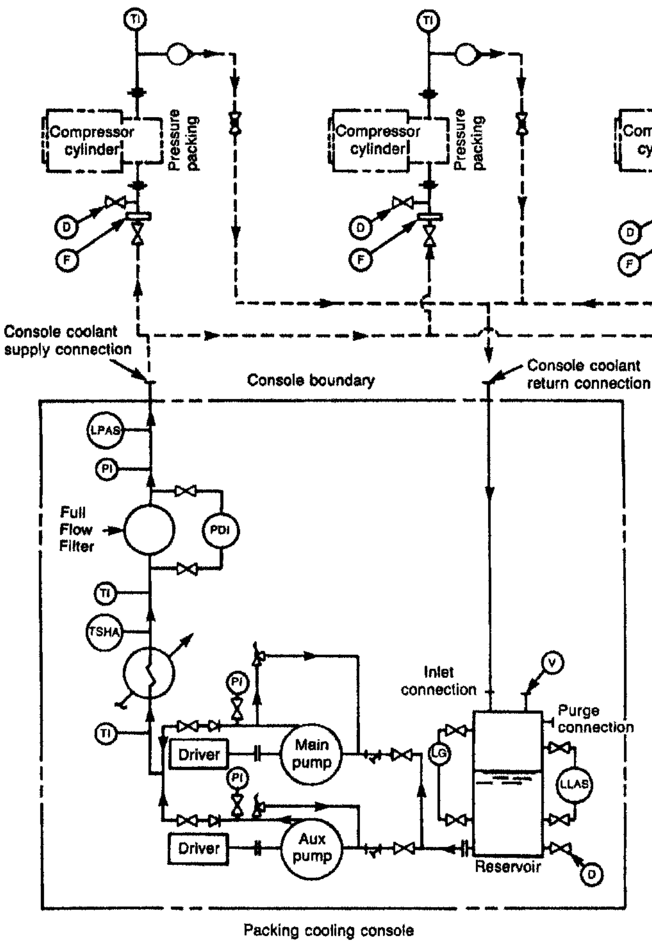


FIGURE 2.47 Typical self-contained cooling system for a piston rod pressure packing schematic, per API 618. *(American Petroleum Institute, Washington, D.C.)*

the crankcase system. The lubricator is normally crankshaft driven; however, motor drive is also available. Cylinders have at least one lubricator feed each in the top of the bore and in the packing. Large-diameter and high-pressure cylinders may have additional feeds in the bottom of the bore and packing. Each lubricator pumping unit delivers from 10 to 50 drops/min and has individual flow adjustment. The flow rate required can only be determined by experience and cylinder inspection on each application by checking that an adequate oil film exists in the cylinder.

The lubricant required for cylinders is a heavy well-refined oil, compounded with 5 to 10% animal fat if the gas is saturated. Diester synthetic lubricants are also extremely well suited for cylinder lubrication.

2.13 DISTANCE PIECES

Distance pieces are usually furnished as steel or cast iron castings or steel weldments. Distance piece geometry can vary to meet the application. The standard distance piece is a

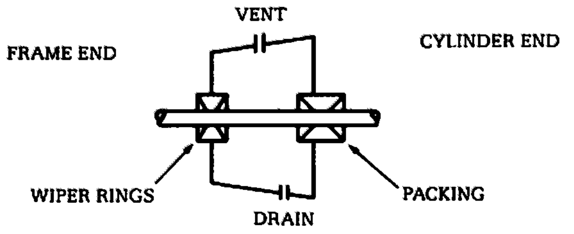


FIGURE 2.48 Single-compartment API standard distance piece for general compression applications. *(Dresser-Rand Company, Painted Post, N.Y.)*

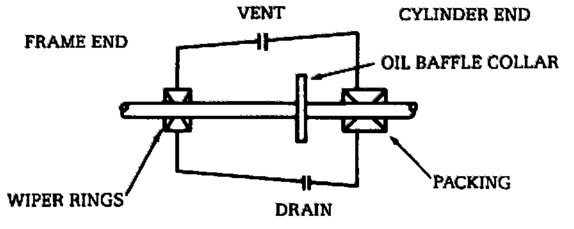


FIGURE 2.49 Extended-length single-compartment distance piece. No portion of the piston rod that enters the packing will enter the frame oil wiper rings. *(Dresser-Rand Company, Painted Post, N.Y.)*

single compartment with vent and drains (Fig. 2.48). The pressure packing is vented separately. All distance pieces typically have large openings with gasketed, gastight covers for ease of packing maintenance.

For nonlubricated or other services requiring an oil slinger, an extended-length distance piece is used so that no portion of the piston rod enters both the crankcase oil wipers and the cylinder packing (Fig. 2.49). The primary function of an oil wiper is to prevent loss of crankcase oil; it will not prevent gas from entering the crankcase.

For gases that could contaminate the crankcase oil or are hazardous, a two-compartment distance piece that has intermediate packing is recommended (Fig. 2.50). The cylinder-side compartment is vented to a safe area, and the crankcase-side compartment is normally vented to atmosphere or purged with nitrogen. An oil slinger may be located in this compartment. The packing vent and distance piece vent and drain manifolds should always be kept separate.

2.14 RECIPROCATING COMPRESSOR MODERNIZATION

Competent compressor manufacturers recognize the occasional need to modernize their proven heavy process reciprocating compressor line. These companies consider key factors such as manufacturing economics, reliability, and ease of maintenance during the design stage. The result can mean redesigned cylinders and improvements in frames and running gear, the crosshead, access opening in distance pieces, and hydraulic bolt tensioning. A modern compressor line is designed to meet the best current design practices, be easy to maintain, and be reliable and economical to manufacture.

Modern cylinder lines are analyzed using finite element analysis (FEA). Each cylinder model is strain-gauge tested to prove the FEA model, and selected cylinders are burst

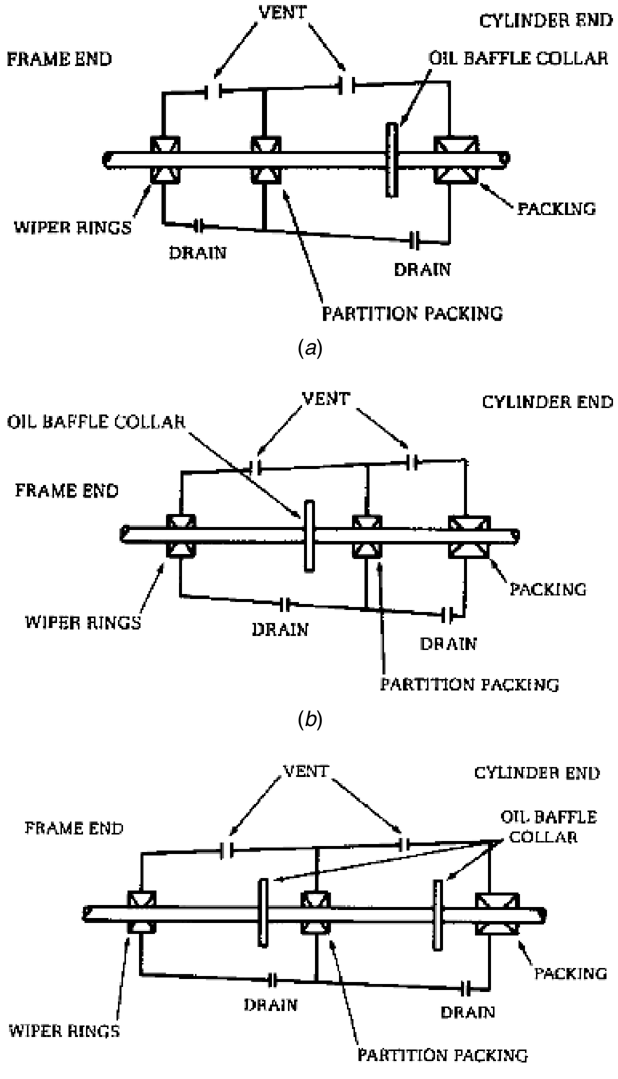


FIGURE 2.50 Two-compartment distance pieces with lubricated partition packing. Baffle collars at cylinder end (*a*), frame end (*b*), or both ends (*c*) prevent oil migration. Venting or purging of each compartment is possible. *(Dresser-Rand Company, Painted Post, N.Y.)*

tested. Standardization efforts demand that all cylinders within a rod load class have a common distance piece bolt circle. Occasionally, new distance pieces are designed, and these often have external bolting that can be tensioned easily.

Large access openings should be provided to simplify packing maintenance. Also, the distance piece should be very rigid to prevent cylinder alignment problems. The production of sound castings is of extreme importance and extensive cooperation is needed between the foundry and the manufacturing floor.

Improvements in the frame and running gear often lead to redesigned crossheads so as to eliminate the threaded connection between the piston rod and the crosshead. A flange design crosshead with hydraulically tensioned studs is used on certain piston rods, and the crosshead pin on all frame sizes is full floating for ease of maintenance. Crosshead materials should be castable and have both good ductility and excellent fatigue properties.

In general, the connecting rod pin bushing is grooved and the pin is nonrotating in the crosshead. This design provides good lubrication of the bushing and is quite tolerant of poor rod load reversal (e.g., due to a valve failure). Hydraulic tensioning should be standard on all but the smaller (1.25 in. and less) frame and cylinder bolting.

2.14.1 Cylinder Upgrades

Competent manufacturers occasionally redesign their lineup of process compressor cylinders for a number of reasons. They recognize that:

- Due to outdated design and frequently modified and worn-out wooden patterns, there occur significant casting quality problems, with high scrap rates on many patterns.
- High internal cylinder clearances will result in low volumetric efficiency.
- The older patterns and resulting castings may incur high costs.
- Older designs might be "unfriendly" to the user's maintenance crews (e.g., some internal bolting was difficult to reach and could only be tightened with "slugging" wrenches).

2.14.2 Design for Easy Maintenance

All cylinders within the same rod load class might use one API type C or type B distance piece. Not only do redesigned distance pieces have external bolting that allows for easy and accurate tightening of the bolts (designed to be tightened either by hydraulic tensioning, hydraulic torquing, or, if preferred, by Supernuts), but modern distance pieces are heavily ribbed for rigidity to minimize rod runout and cylinder vibration. Large access openings are provided for ease of packing maintenance; a fully assembled packing can be installed through the access openings. Figures 2.51 through 2.53 show a typical type C distance piece and how the same piece fits on a small cylinder (head inside the distance piece), medium-sized cylinder (sandwich head), and large cylinder (distance-piece bolts to the head and the head bolts to the cylinder).

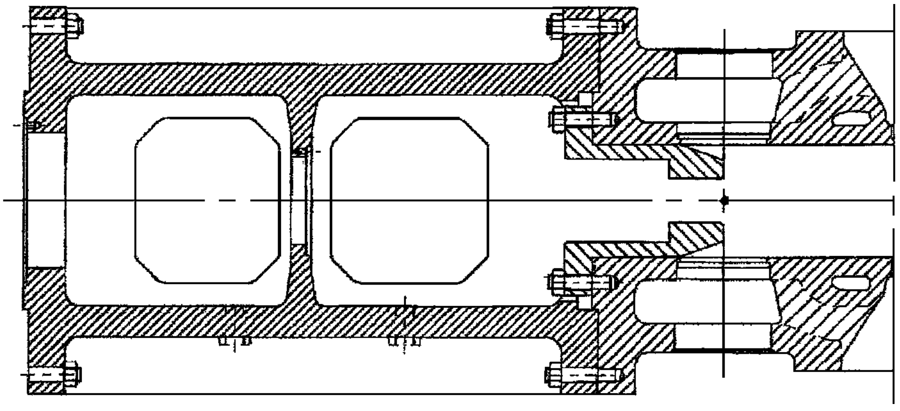


FIGURE 2.51 Distance piece with a small cylinder. *(Dresser-Rand Company, Painted Post, N.Y.)*

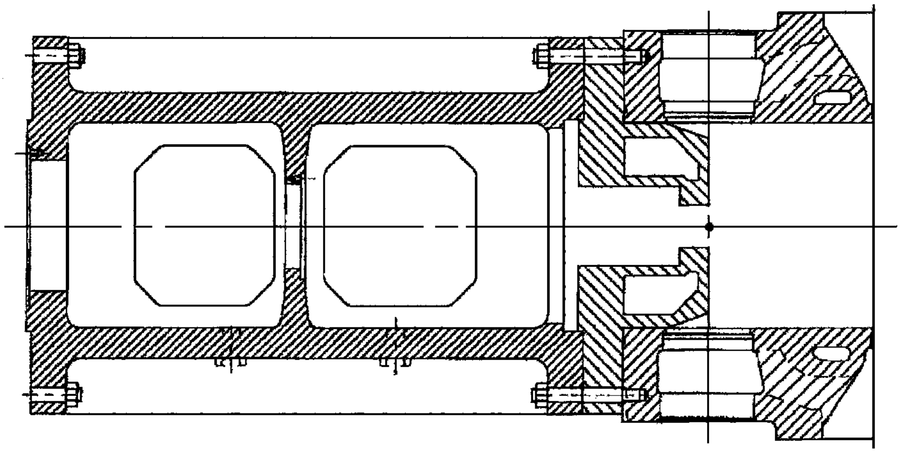


FIGURE 2.52 Distance piece with a medium-sized cylinder. (*Dresser-Rand Company, Painted Post, N.Y.*)

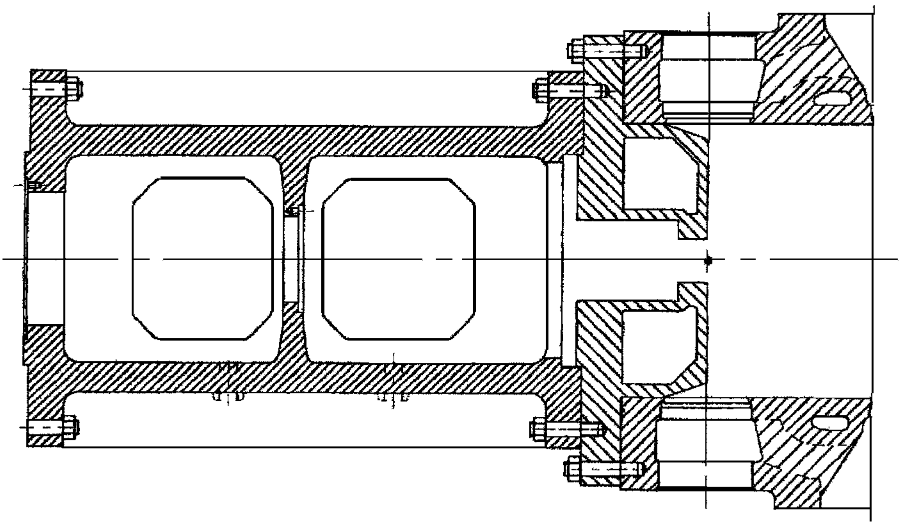
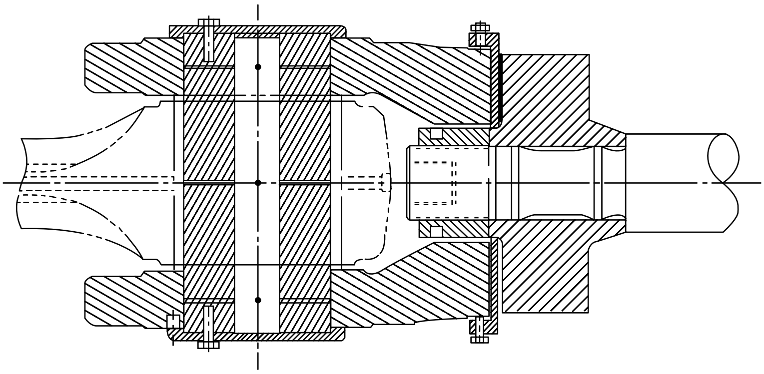


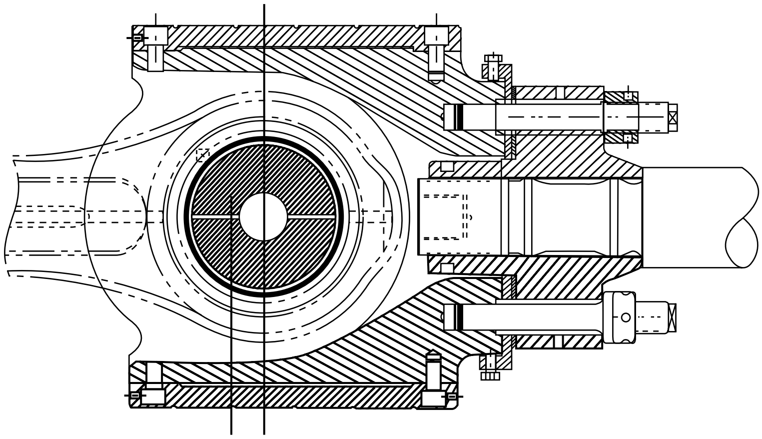
FIGURE 2.53 Distance piece with a large cylinder. (*Dresser-Rand Company, Painted Post, N.Y.*)

Cylinders are designed using normal calculation for hoop stresses and end wall stresses. Sample castings are burst-tested to hydrotest pressures 1.5 times the maximum allowable design pressure (MADP). In fact, one of the premier compressor design and manufacturing companies has verified burst pressures greater than four times MADP on many cylinders! The actual failure mode was achieved by yielding of the material, resulting in leaking at the test gasket joints.

Dresser-Rand verifies that the material properties in the critical section of their modern cylinders meet the minimum design requirements. They do this by utilizing "in mold" test bars on all sample castings and by machining tensile test bars and Charpy test bars from the critical sections on the two burst-test castings.



(*a*)



(*b*)

FIGURE 2.54 Flanged crosshead: (*a*) plan view; (*b*) front view.

2.14.3 Crosshead Designs and Attention to Reliable Lubrication

Modern machines with piston rods 4 in. or more in diameter often use a flanged crosshead design (see Fig. 2.54). The crosshead shown here has a round body with cylindrical shoes bolted to the crosshead with four cap screws. The shoes are shim-adjustable for adjusting the crosshead-to-guide clearance; modern crosshead pins are cylindrical and often full-floating for easy assembly. In general, pins are retained by caps at each end. There is an antirotation pin to ensure that it is the pin to the connecting rod bushing that acts as the bearing. The connecting rod bushing is bronze and has helical grooving to provide for lubrication under conditions of zero rod reversal (as is the case, for example, in the event of a valve failure).

Lubrication is accomplished by a “gun-drilled” oil passage through the connecting rod to the pin to lubricate the pin bushing and the pin-to-crosshead fit. Shoe-to-guide lubrication is by separate lube feed from the main oil header to the guide and by internal drilling in the guide to the shoe running surface.

Piston Rod-to-Crosshead Joint Note how the piston rod is necked down at the flange and the nut is hydraulically tensioned on the crosshead side to preload the joint. The flange is bolted to the crosshead using six hydraulically tensioned studs. There is an adjusting ring on the nose of the crosshead to allow the piston rod to be adjusted both vertically and horizontally. Piston rod runout is adjusted in this manner. A spacer is provided to adjust piston end clearance.

2.14.4 Materials

Many modern compressors use nodular iron for crossheads. Nodular iron is readily castable and sound-quality castings can be produced without resorting to the welding repairs that are typically required on cast steel. The proper grade of nodular iron (ASTM A536 60-40-18) has excellent fatigue strength for reliable operation. The carbon nodules tend to act as natural crack stoppers to prevent crack initiation and growth. Moreover, this material has good ductility. Other typical material selections include:

- *Crosshead pin:* alloy steel, surface hardened
- *Crosshead shoe:* cast iron with babbitt face
- *Connecting rod bushing:* bronze
- *Flange:* alloy steel
- *Studs:* ASTM A193 grade B7
- *Crankpin and main journal bearings:* aluminum with micro babbitt overlay

We are now ready to consider other aspects of reciprocating compressor technology in greater detail. Refer also to section 9.3, dealing with gas cleanliness issues that are applicable to all positive displacement compressors.