RECIPROCATING COMPRESSOR VALVE DESIGN: OPTIMIZING VALVE LIFE AND RELIABILITY

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The Compressor cylinder intake and discharge valves are the "heart" of a reciprocating compressor. They are the primary consideration in designing a compressor that will operate 25,000 hours between scheduled maintenance shutdowns. Continuing advancement in compressor valve design, particularly valve materials, is critical to achieving this 25,000 hour operating target. This paper presents our current understanding, describes recent design advancements, and discusses the work remaining to optimize valve life and reliability.

INTRODUCTION

Reciprocating compressor intake and discharge valves are typically the controlling factor for scheduling compressor maintenance downtime. A goal of three years (25,000 hours) is an achievable, but difficult, target because of the harsh service conditions these valves are subjected to. To achieve the three-year goal, the moving valve parts must operate without failure a half billion times and be subjected to seating impact during each operating cycle.

Advances in valve design and materials, and increased understanding of the effect of the gas being compressed on valve service life, are providing positive signs that the three-year operating target is a realistic goal; and is in fact being achieved on representative compressors.

This paper presents our current understanding of valve life and reliability. It also discusses the work remaining to extend the service life of compressor valves even further.

THE PROBLEM

There are four or five main components in a typical valve (Figure 1). These are the seat, the guard or stop plate, the moving/sealing elements, the springs and, in some valves, the spring buttons or nubs. (Bolts, guide pieces etc. may also be used, but will not usually be a problem.) Each of these can fail by wear, by overstress, by fatigue, by corrosion, or by any combination of these factors.

Seats. If properly designed and applied, a valve seat will not fail by fatigue under normal operating conditions. A seat may fail from overstress if the compressor is slugged with liquid. Actually it may be preferable that the valve fail in this case rather than the cylinder head, piston rod, crosshead or other more expensive part. The only question related to valve reliability here is to determine what overpressure the valve should be designed for. A valve designed for a higher pressure will reduce efficiency, have more clearance (thus reducing compressor capacity), and be more expensive.

A valve seat will always wear where the moving element seals on it. However, with modern non-metallic plates, a life well in excess of three years should be obtained. With metallic plates, especially if the gas is dirty or the cylinder non-lubricated, seat maintenance may be required in less than three years. Correct choice of material can maximize the seat life.

Valve seats are usually made of nodular iron or carbon steel and these materials give good service in the majority of cases. For extremely corrosive environments a stainless steel chosen with regard to the actual corrosives present in the gas should be used.

In general, valve seat life is not a major consideration in improving valve reliability and extending service life.

Guards or Stop Plates. The above discussion on valve seats applies in general to guards. On a guard, the potential wear areas are where the moving element is guided and where the springs contact the guard. The guard must be sufficiently hard to resist wear from the spring.

Guards are seldom a valve service life issue.

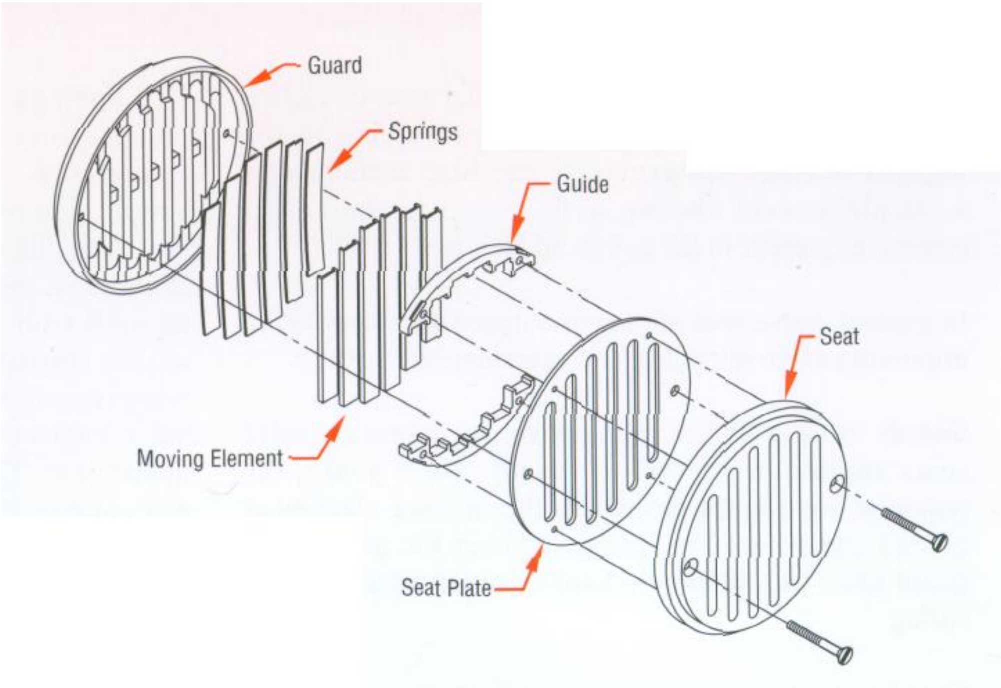


Figure 1A. Channel Valve

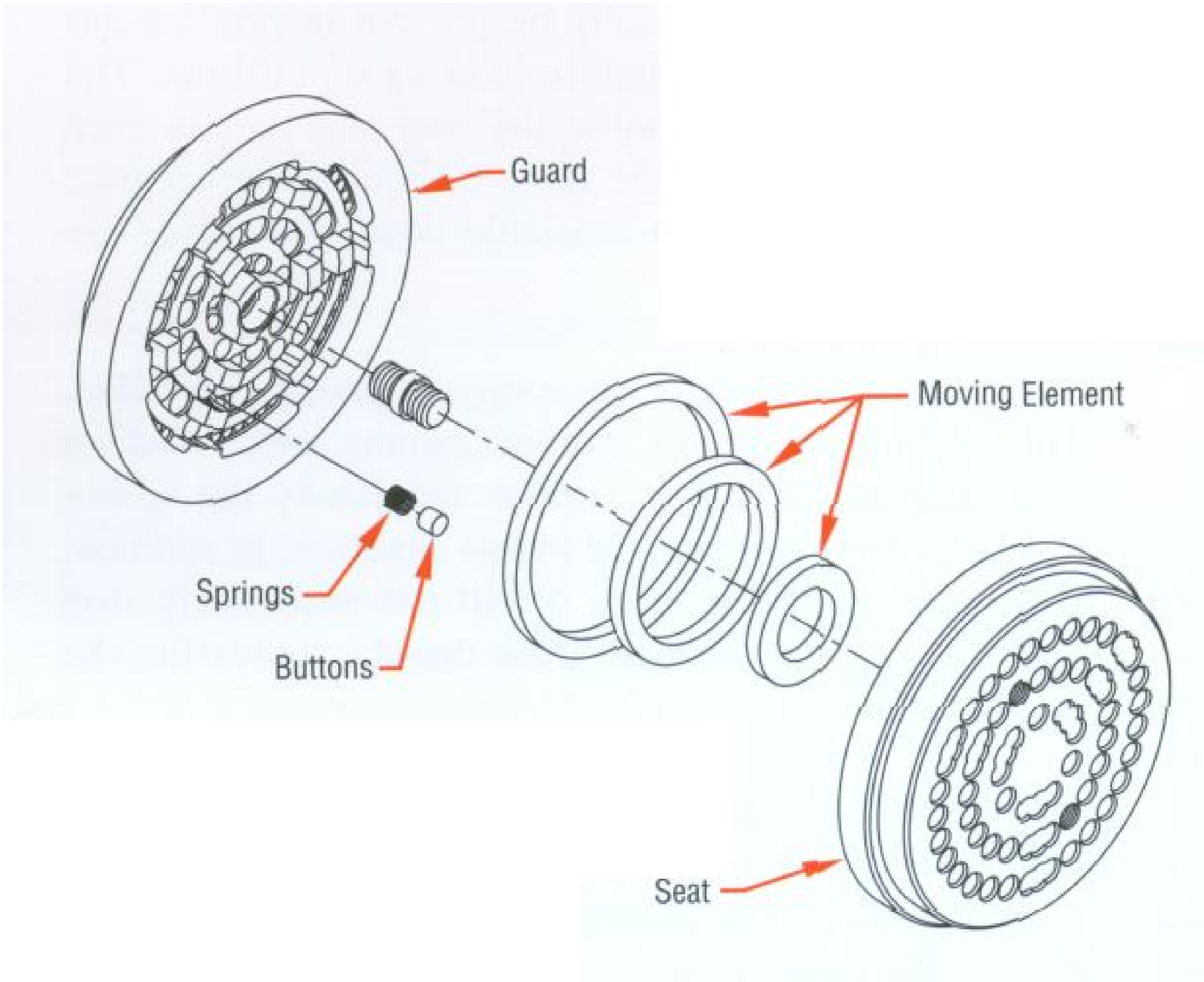


Figure IB. Concentric Ring Valve

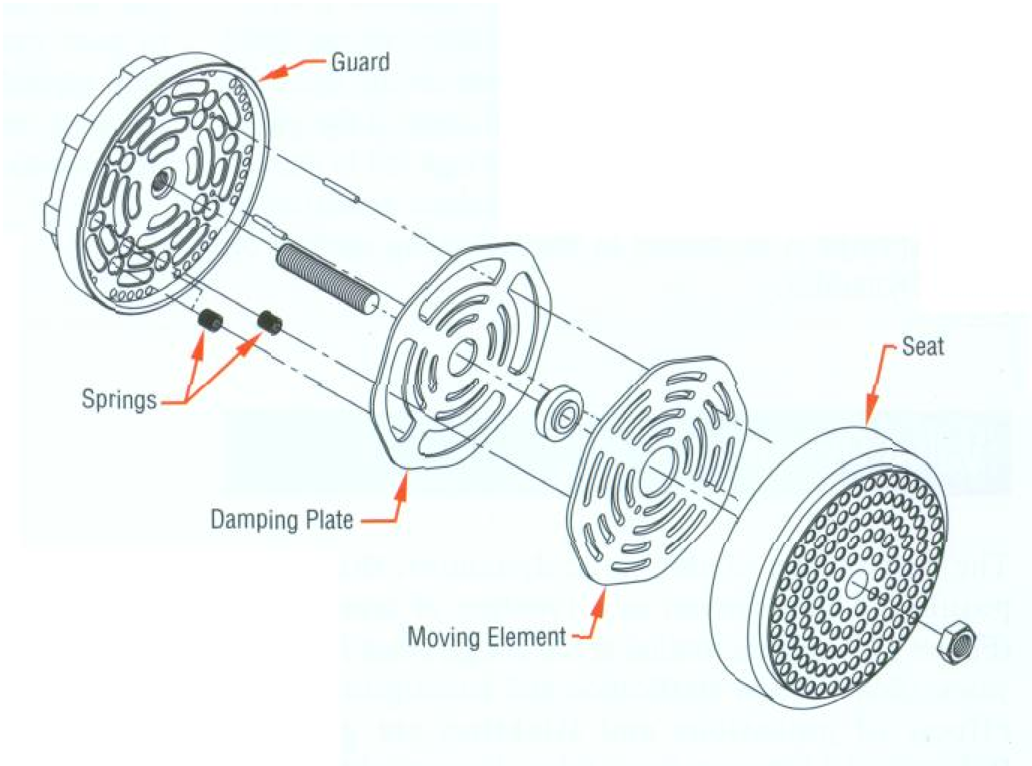


Figure IC. Ported Plate Valve

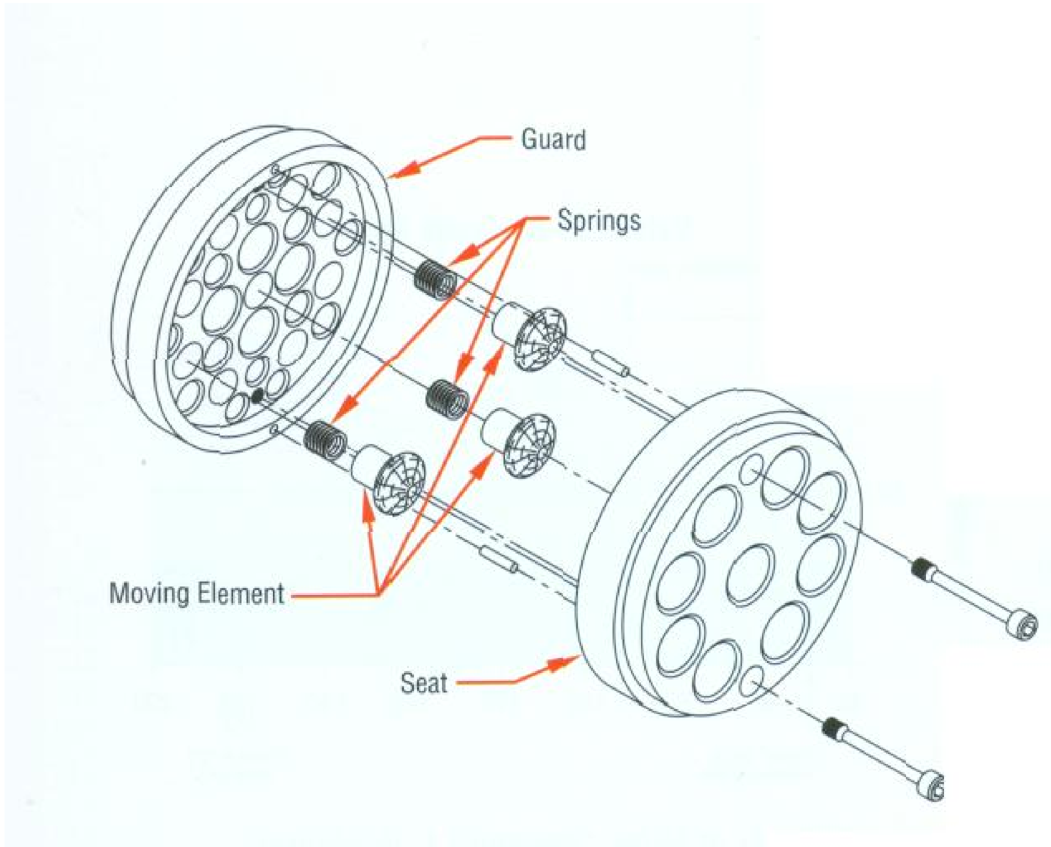


Figure ID. Poppet Valve

Figure 1. DR Valve Types

The Moving/Sealing Element. The moving element may be a ring, a plate, a poppet or a channel. In any case, the primary failure modes are impact fatigue caused by the repeated impact on the guard and seat, fatigue caused by the varying differential pressure resisted by the element, and corrosion. Simple wear is usually not a problem. Today, rings, plates and poppets are made of engineered plastics if the differential pressure is less than about 2000 psi. If top quality PolyEtherEtherKetone (PEEK) based materials are used, and if the valves are designed and applied correctly, life of these parts should meet the three-year requirement. Problems will occur if the gas is dirty or liquids are present or if the springs fail to control the element motion correctly. The correct selection of valve springs is discussed in the following section on Valve Dynamics.

The Springs. Most valve types used in stationary compressors use cylindrical coil springs loaded in compression. We might think that the reliability of this simple component would be excellent. In practice, however, the springs are the most frequent cause of failures in modern valves. It is impossible to find a material with good spring properties that is resistant to all the corrosives that may be present in process gas compressors under dynamic loading conditions. The valve engineer must choose the best material for each application. This is made more difficult if an accurate gas composition is not available when the valves are designed.

The operating motion of the springs is poorly controlled. This motion consists of a rapid opening with a sudden stop, and the closing is similar. Obviously the spring dynamics are far from ideal in this situation. In addition, if a spring button is used, it will not necessarily stop when the moving element does thereby increasing the spring deflection.

Spring Buttons. Buttons are often used between the spring and the moving element for three reasons: They reduce wear of the plate caused by the spring; they prevent the spring from catching on the edge of its hole; and they reduce the side force that can cause the spring to wear against the side of the hole. They are usually only needed if high aspect ratio (i.e. long, thin) springs are used, or if the moving element material is very soft (e.g. nylon).

VALVE DYNAMICS

The calculation of the valve dynamics, that is the position of the element as a function of crank angle (Figure 2), has been routine at the design stage for many years. (Some recent verification and investigation of the effects of pulsations and sticktion are given in Reference 1.) Interpretation of this diagram and relating it to valve life is not easy.

It is widely accepted, and clearly demonstrated for steel elements, that the velocity with which the element impacts on the guard or seat is important. For steel [Reference 2], it is known that there is an impact velocity below which failures will never occur due to impact fatigue. This velocity depends on the element and the seat or guard materials and on the valve design. For steel elements and guards, a value of 25 ft/sec is typical. For crystalline plastics such as carefully manufactured nylon or PEEK, the allowable impact velocities are much higher, but less well defined.

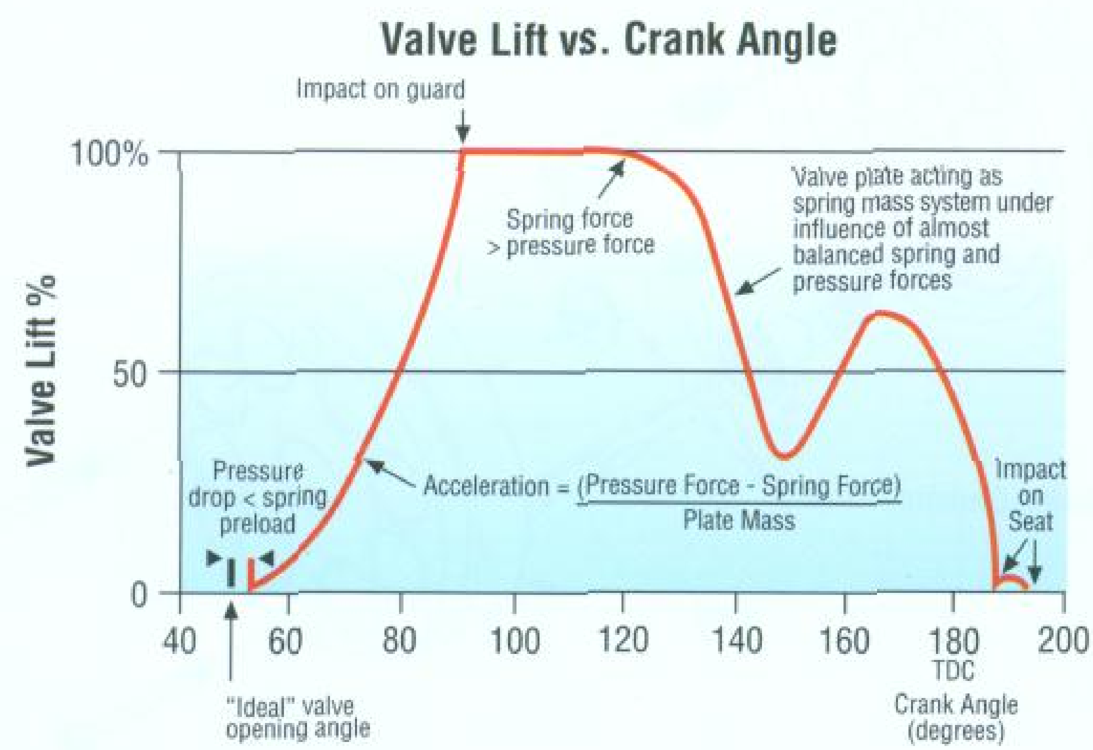


Figure 2. Basis of Valve Dynamics Calculation

The tests on a compressor running on methane in the Laboratory described in Reference 1 showed that sticktion on the seat is unimportant although it is significant on the guard. Indirect evidence from the field suggests strongly that this is not always true. An oil is usually selected for use in a compressor cylinder based on the gas, the operating conditions and the cylinder design. Very heavy oils, frequently compounded with animal fats, are sometimes specified. These are valuable for break-in in those cases when metallic piston rings are used, but are not needed for this purpose when nonmetallic rings are used. They are also specified when the gas contains liquids that could wash the oil from the cylinder bore or when the gas is a hydrocarbon at a high enough pressure to dissolve in the oil and reduce its viscosity. We have examples where a compounded oil was specified unnecessarily and caused very rapid valve spring failures. Changing to a non-compounded oil greatly increased the valve life. The failure mechanism is that the oil causes the valve element to stick to the seat. At the time the valve should open, the pressure drop tending to open the valve becomes positive and increases very rapidly. Once the force is enough to release the element from the seat, it is high enough to accelerate the element very rapidly, causing a very high impact velocity on the guard.

The effects of sticktion on the seat are difficult to measure in the field, but can be estimated from pressurevolume cards. A pressure-volume card from a compressor in a refinery running on a fairly viscous, but not compounded oil, is shown as Figure 3. The suction valves removed from this compressor had a heavy coating of oil, but no sign that the oil was thickened by temperature, dirt contamination or any other cause. The calculated diagram from our valve dynamics program without seat sticktion is shown as Figure 4. It will be noted that the overshoot of pressure at valve opening is larger on the measured diagram. By increasing the sticktion factor in the calculation, the diagram shown as Figure 5 was obtained. We assume that the sticktion is correctly modeled when the calculated pressure overshoot agrees with that measured in the field. In this case, the calculations showed that sticktion increased the impact velocity on the guard by a factor of three.

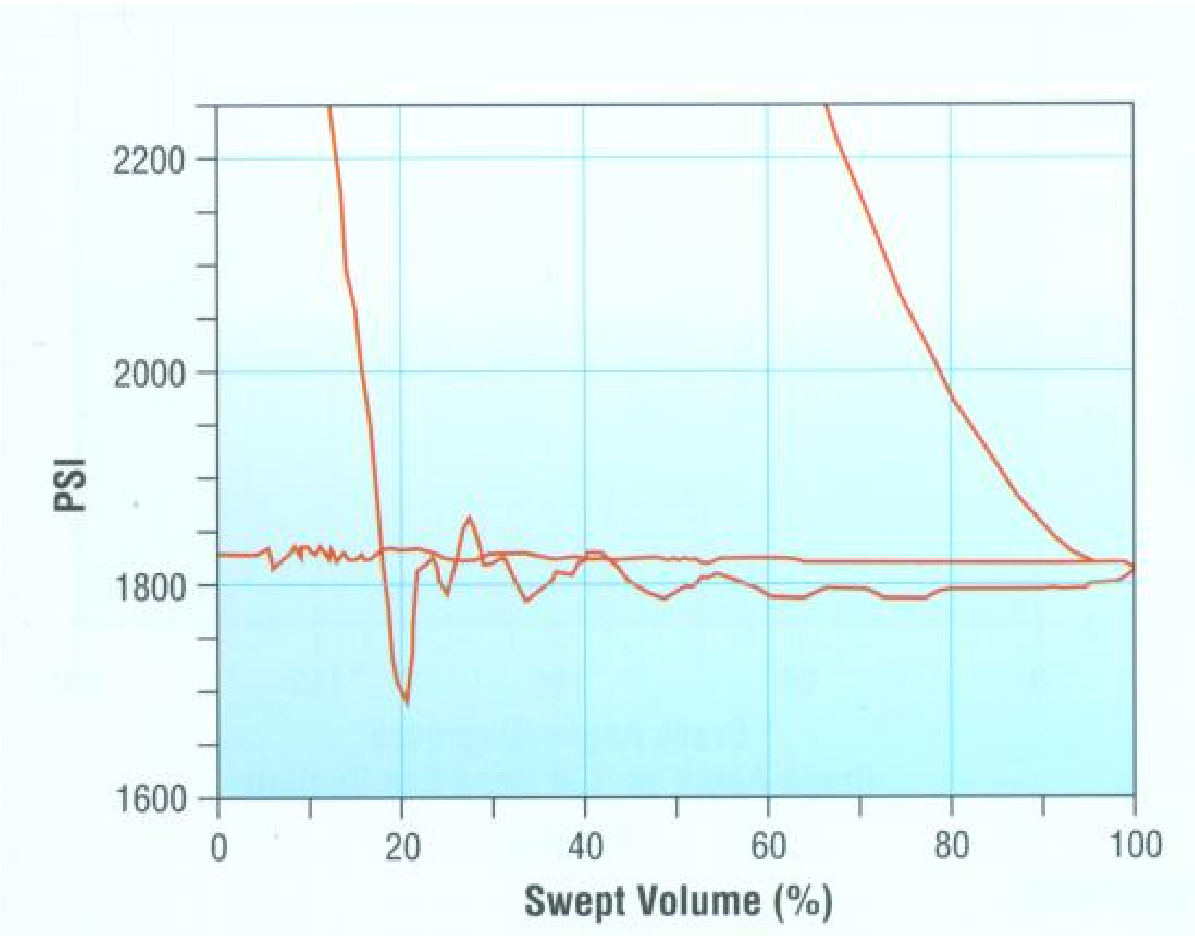


Figure 3. Measured Pressure Volume Diagram

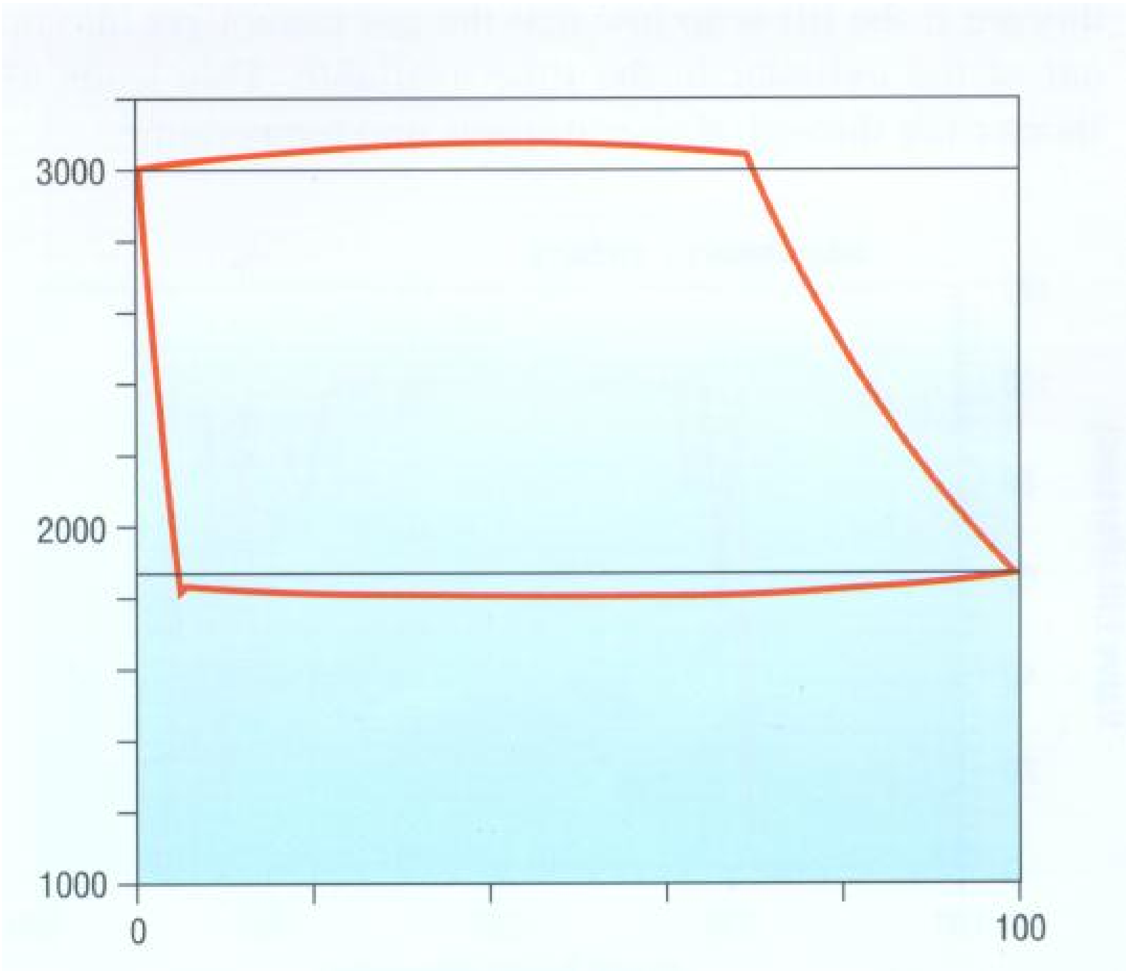


Figure 4. Calculated P-V Diagram with Normal Sticktion

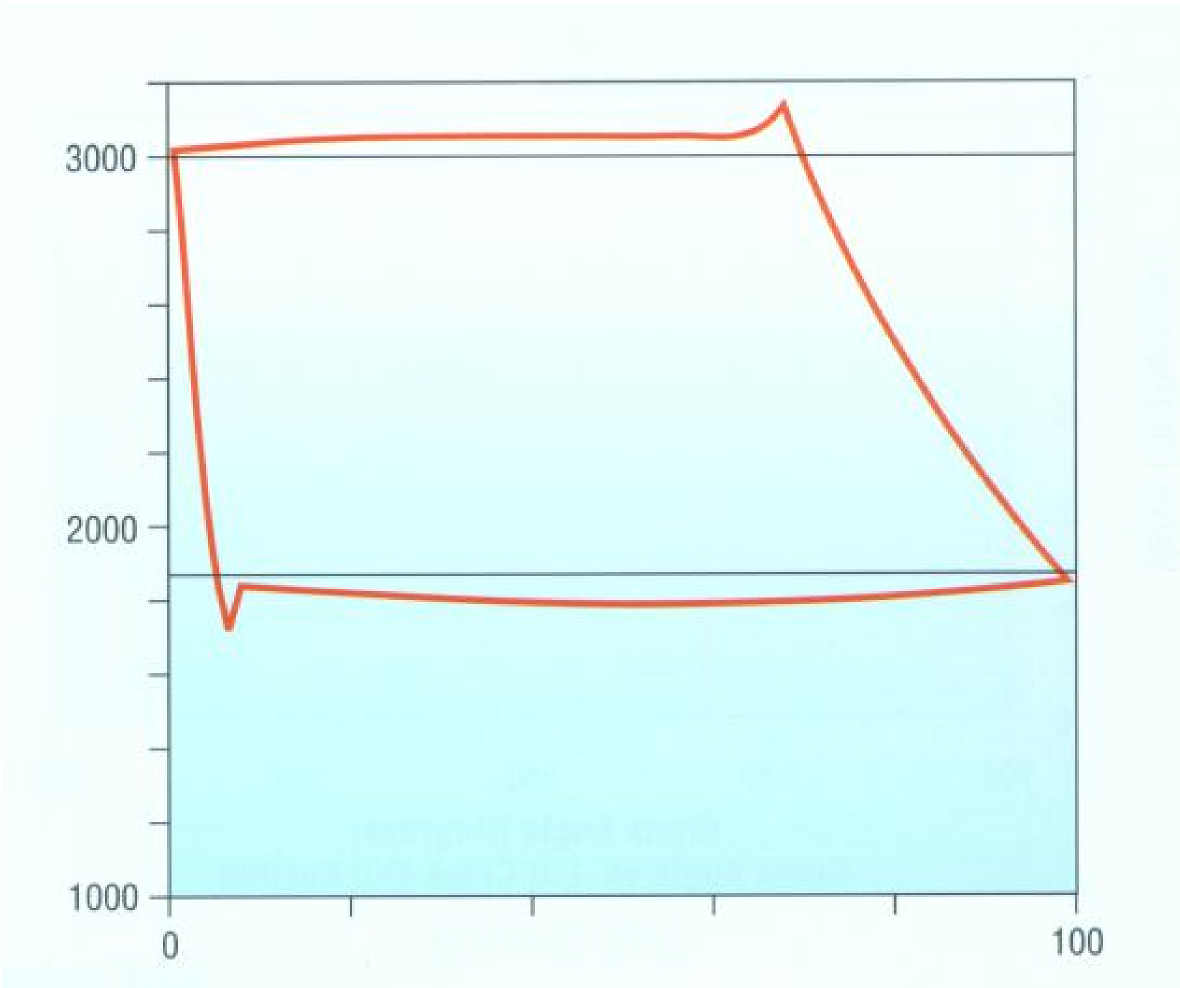
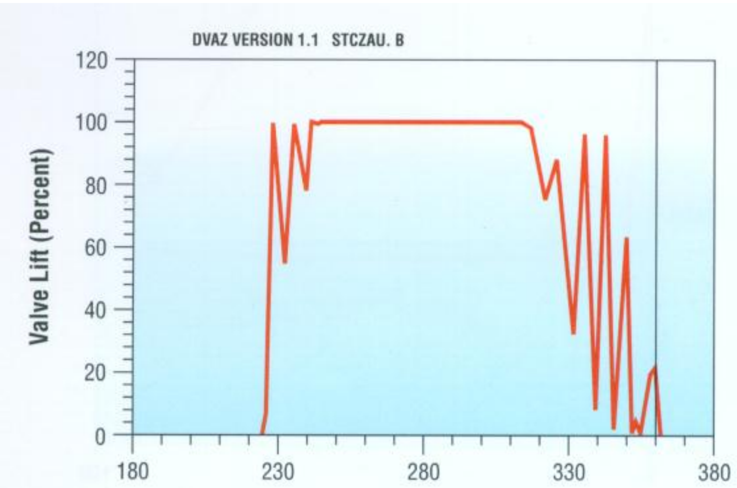
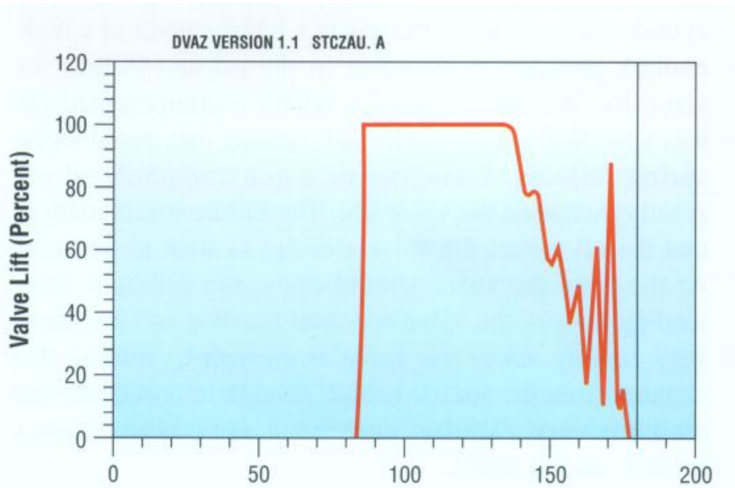


Figure 5. Calculated P-V Diagram with Increased Sticktion

The valve dynamics program results are used to help select the valve lift and springing for a compressor. The information obtained from the program include the valve lift (Figure 2) and pressure-volume (Figure 4) diagrams, as well as the impact velocities on the guard and seat, the average valve lift (which is a measure of the flutter), the valve closing angle, and the loss of power and capacity caused by the valves. The valve lift must be chosen low enough that the opening impact velocity is within the acceptable range and the pressure drop high enough to ensure proper valve action, but the lift must be high enough that the loss in power and capacity are acceptable. Within reason, a lower lift will give longer valve life but lower compressor efficiency. Exceptions to this are if the lift is so low that the gas cannot get into or out of the cylinder in the time available. This leads to shorter life through higher impacts and temperature.

The valve spring is used to close the valve in time. That is, before the dead center (when the piston reverses direction). If the spring is too light, the valve will close late and will then be slammed shut by the reverse gas flow. This is a common cause of premature valve failure. It is found that the spring has little effect on the opening of the valve. It must be chosen by considering the closing only. Sticktion is also a concern here. Results from laboratory testing [Reference 1] gave us a typical value to use for guard sticktion, but it is unlikely that this value applies to all compressors under field conditions. It is best to err on the side of using too heavy a spring to avoid any possibility that the sticktion will cause late closing. The negative effect this has on compressor efficiency is usually negligible. Calculated valve lift diagrams that show good and bad selection of lift and springing are shown in Figure 6.

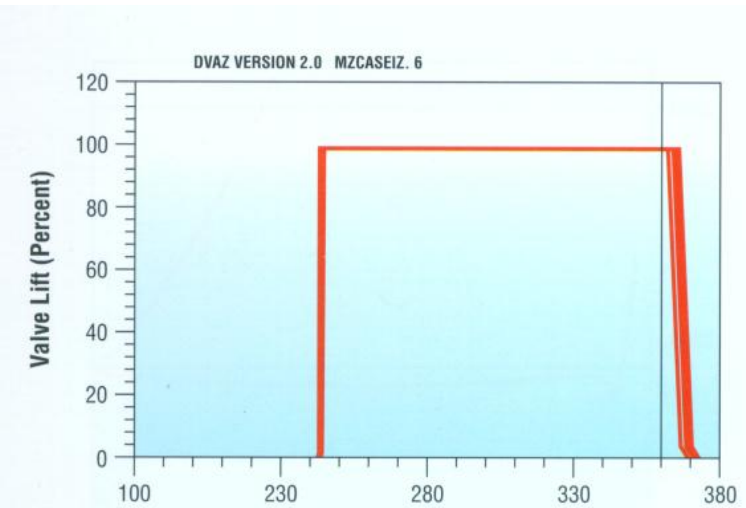


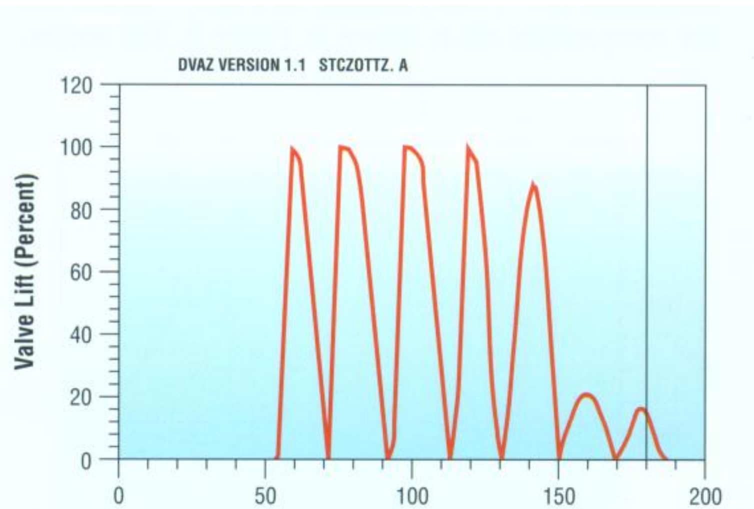


Crank Angle (Degrees)
Crank Angle vs. Lift Crank End Suction

Crank Angle (Degrees)
Crank Angle vs. Lift Crank End Discharge

Good Valve Dynamics





Crank Angle (Degrees)
Crank Angle vs. Lift Crank End Suction
Late Closing

Crank Angle (Degrees)
Crank Angle vs. Lift Head End Suction
Flutter

Bad Valve Dynamics

Figure 6. Examples of Good and Bad Valve Dynamics

It is known that pulsations can affect the valve dynamics and cause valve failures. We have found that if a careful, preferably digital, pulsation study is done and the pulsations at the valves are considered, and if the valves are chosen to give a reasonable pressure drop, then the effect of the pulsations on the valve dynamics will not be harmful. If there is concern during the pulsation study, we calculate and evaluate the effect on the valves (Figure 7).

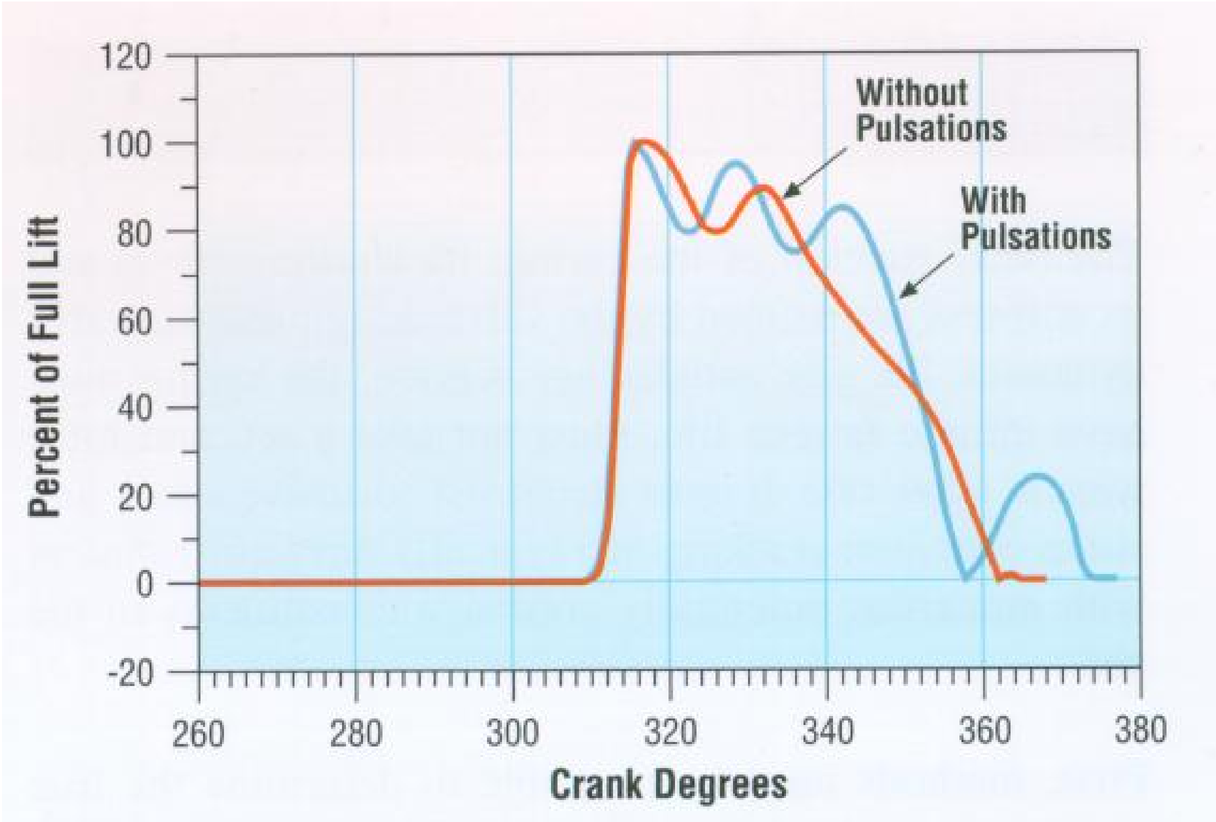


Figure 7. Valve Lift Diagram Showing Calculated Effect of Pulsations

MOVING ELEMENT DESIGN

The geometric design of the moving element is usually straightforward. The part must be thick enough to withstand the bending stress that will result from the highest differential pressure it will be exposed to, and the sealing surface must be wide enough that the compressive stress is not excessive. Care must be taken that the maximum differential pressure is known. This frequently occurs before start up when the valve is exposed to the full discharge pressure while the cylinder pressure is atmospheric.

MOVING ELEMENT MATERIAL

For some time now, valve elements for all but the highest pressures have been made of plastics. After considerable testing, the industry has settled on PolyEtherEtherKetone (PEEK) as the material of choice. The PEEK is usually reinforced with glass or other fibers and frequently contains other additives. Unfortunately, compressor valves are a unique application for this material and formulations and manufacturing methods that work well in other applications are not optimum for compressor valves. Great care must be taken when molding compressor valve plates that the correct crystallinity is obtained, that the material is not overheated during manufacture, and that there is good fibre orientation with no knit lines or other molding imperfections. Getting good PEEK plates is at least as difficult as getting good iron castings and involves many of the same considerations: Correct composition of the raw material, correct temperature and cooling rates, correct flow in the molds with correct gating, and correct heat treatment. Achieving this required much experimentation and close process control. Some details are given in Reference 3.

With correct manufacturing procedures in place and quality carefully controlled, moving element failure is uncommon if the valve is applied correctly and not abused by the service conditions. The plastic parts are more expensive than metal parts, but a bargain when the costs of a valve failure or short service life are considered.

SPRING DESIGN

The outer envelop of the spring, its working travel and its stiffness are defined by the valve design and the valve dynamics. To give satisfactory service, the spring must have infinite fatigue life, must not take a set, and must wear at a low rate. It must also resist corrosive attack and stress corrosion cracking in a typically dirty environment with numerous potentially corrosive constituents in the gas.

First, methods must be available to determine the true maximum and minimum stresses in the spring. The nominal stresses with the valve open and closed are easily calculated. If the impact velocities are known, corrections for button overshoot, if any, and for the high spring acceleration can be determined using known techniques. Calculation of the complete spring dynamics under the repeated operation and impacts is less certain and usually not attempted.

Next a material for the spring must be chosen. Temperatures seldom go much above 300°F and so Chrome Silicon Steel gives good spring properties (fatigue strength and modulus) and good resistance to taking a set. However it is not very corrosion resistant. In a lubricated compressor, the oil film is frequently enough protection from corrosion, but this can be unreliable. There are several materials (e.g. Inconnel X750, Hastelloy C276) that give better corrosion resistance at the expense of poor fatigue resistance. However, these are not all resistant to all probable corrosives. (e.g. Inconnel X750 does not do well in the presence of chlorides, although it is good for use in sulfides.) There are also high strength materials with corrosion resistance. Examples are Elgiloy and MP35N. These have also given good results in some applications. It is essential that the wire the springs are made from is specified carefully. Many alloys are sensitive to the amount of cold working, and to details of the heat treatment; most require careful quality control to ensure that the wire is free from inclusions, tears and scratches. Experience with springs and a knowledge of the process the valve will be used in usually allows an adequate spring material to be chosen. A spring can then be designed within the limits imposed by the material.

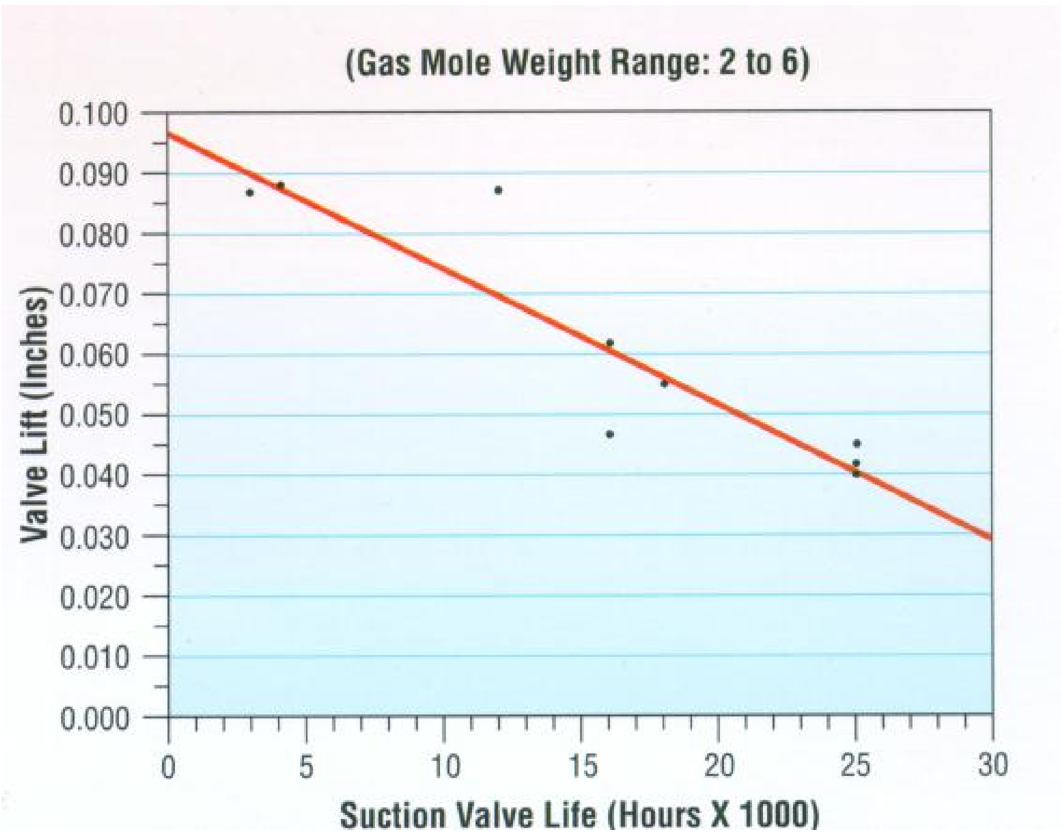
RELIABILITY IN THE FIELD

We learn from applications where valves fail prematurely and also from those where they run well. We have recently completed an initial survey of compressors on hydrogen service in refineries and chemical plants that give good run times between overhauls.

We find that these good compressor installations have two things in common: First, the compressors and auxiliary equipment were selected conservatively with more emphasis placed on reliability than efficiency or first cost; and second, the maintenance staff responsible for the compressors have a commitment to, and take pride in, getting good service life. Also, of course, the valves had been designed well, applied correctly and manufactured to high quality standards. None of these sites was new and start up problems with the process and compressor operating procedures had been resolved.

Survey results were collected from 12 sites and 32 compressors. The gas molecular weight varied from 2 to 32, the discharge pressures from 67 to 3600 psi., the speed from 277 to 327 rpm, the compressor horsepower from 650 to 13,000 and the cylinder bores from 6.75 to 40.5 inches. The survey is continuing and the results given here are preliminary.

A correlation of valve life against valve lift in those surveyed compressors running in refinery service on gases with molecular weights from 2 to 6 is given as Figure 8. The correlation is striking. For those low molecular weight applications where everything is done to make sure the compressors run well, a valve lift of 0.090 inch gives a valve life of one year and lift of 0.040 inch gives a life of three years. Most, but not all, of the valves were manufactured by Dresser-Rand or the companies that joined to form Dresser-Rand, but the variety of valve designs is interesting. The list includes ported plate valves and ring valves. Plate materials include 410 stainless steel, 17-7PH steel, Nylon and PEEK. Valve springs are made of 17-7PH steel, Nimonic 90 and chrome silicon steel. Different valve designs and materials can perform very well in this service if applied, maintained and operated correctly. However, experience with applications where the valves gave trouble has shown clearly that in less ideal situations, the valve design and materials can make the difference between success or failure. For example, we have jobs where changing from steel to PEEK plates eliminated premature failures and other jobs where channel valves were unreliable, but plate and/or poppet valves have proven more reliable.



Curve Basis 36 Cylinders on Hydrogen Service (Final Discharge Pressure Range: 435 to 2400 psig)
Figure 8. Suction Valve Life on Hydrogen Service

Care must be taken not to read too much into these results. For example, other processes may have higher levels of corrosives and different materials will be needed. Also, this applies only to low molecular weight service; higher lifts are needed for higher molecular weights. However, the results do show what can be achieved under real refinery conditions if care is taken with the application and maintenance.

CONCLUSIONS

The design and operating environment considerations required to achieve good compressor valve reliability are understood. Obtaining good reliability is difficult in highly corrosive applications or those where dirt or liquids are not removed from the gas stream. It may also be difficult to apply valves if the operating conditions, (for example the pressures or gas molecular weight) vary over a wide range, or if there are frequent process upsets. The use of finger type unloaders does not preclude long valve life, but often makes it more difficult to achieve.

If the compressor manufacturer and the user work together to achieve good valve reliability, a life of three years can be achieved consistently in refinery service.

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Refer questions to:
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