Introduction

Nearly all refinery-class reciprocating compressors employ capacity control devices. An external bypass valve around the compressor (Figure 1) is the simplest capacity control device. It can accurately regulate flow from 0% to 100% of compressor capacity. It is also the least efficient method and can be very costly if used over a long period of time.

SUMMARY

This paper introduces two stepless capacity control systems for reciprocating compressors: Dresser-Rand’s Infinite Step Control (ISC) system and Hydraulic Variable Volume Clearance Pocket (HVVCP). Case studies describe the relative advantages of each unloader system and how they increase compressor efficiency and reduce energy costs.

The Infinite Step Control system (ISC) is a hydraulically actuated inlet valve unloader system that is used in conjunction with Dresser-Rand’s Magnum® valve technology. The ISC features electronically controlled, high-speed precision timing of the inlet valve closing to deliver the required compressor capacity. A typical field installation is shown in Figure 2.

The Hydraulic Variable Volume Clearance Pocket (HVVCP) is an automated outer-end clearance pocket (Figure 3). The clearance volume in the pocket is precisely controlled and can be adjusted without using an externally powered pump.

Pneumatically actuated inlet valve unloaders and clearance pocket unloaders offer discrete capacity steps and are more efficient than an external bypass valve. However, these devices are often used in conjunction with the bypass to obtain the required flow and are therefore somewhat inefficient. Manually operated outer-end variable volume clearance pockets can regulate capacity throughout a wider range than pneumatic unloaders but are less safe to actuate while the compressor is running. Stepless (or infinite) capacity control systems are designed for safe, automated operation, and they minimize power consumption by delivering the required amount of gas without the need to bypass. The oil and gas industry is considering stepless capacity control systems now more than ever because of safety considerations, the ability to reduce operating costs by optimizing compressor efficiency and compliance with “green” initiatives.
Traditional Finger Unloader Concept

Inlet valve unloaders are normally installed on both the outer end and crank end of a reciprocating compressor cylinder. A common style of inlet valve unloader is the finger unloader, in which small steel rods, or “fingers,” depress the valve elements to unload a cylinder end and retract from the valve elements to load a cylinder end. A traditional finger unloader is a pneumatically actuated on-off device. In the case of a finger unloader with air-to-unload logic, it is either in the activated position to unload a cylinder end or in the deactivated position to load a cylinder end. Therefore, finger unloaders are able to provide only discrete load steps, usually 0%, 50% and 100%. A load step of 0% occurs when the outer end and crank end unloaders are simultaneously activated at compressor start-up. The 0% load step can usually be sustained for just a few minutes before excessive heat is generated, so the next discrete load step (often the 50% step) must be activated quickly. The 50% load step is achieved when the crank end finger unloader is deactivated and gas is allowed to compress on the crank end. At 50% load, the outer end finger unloader is continuously activated. Therefore, the moving elements of the outer end inlet valve are depressed by the fingers and are continuously held open in a stationary position, such that gas cannot compress on the outer end. The 100% load step is achieved when both outer end and crank end unloaders are deactivated, allowing compression to occur on both ends as a normal double-acting cylinder. An intermediate load step between 50% and 100% (often 75%) can also be achieved if a fixed volume clearance pocket is installed on the outer end of the cylinder. Regardless, the amount of capacity control that can be obtained solely with on-off unloading devices is limited to just a few discrete load steps. Stepless, or infinitely variable, capacity control requires a somewhat more complicated device.

ISC Unloader System Concept

The ISC system is a hydraulically actuated finger unloader system that is also normally installed on both the outer end and crank end of a compressor cylinder. However, instead of remaining stationary at a discrete load step, the finger unloaders on an ISC system are timed to move with each stroke of the compressor and therefore actuate at a rate equal to the compressor speed. If the compressor motor speed is 300 rev/minute, the finger unloaders also move at 300 rev/minute, or 5 cycles/second. The high-cycle demands of the ISC unloader system require more rugged moving parts than traditional finger unloaders, which are primarily static devices.

The ISC system works by delaying the closing of the inlet valve for a precisely timed portion of the discharge stroke of the compressor piston. The sequence of events is as follows. First, differential pressure opens the outer end inlet valve and allows gas to begin entering the outer end of the cylinder bore. (This is the normal intake stroke event for any inlet valve, regardless of whether it is used with an ISC system.) Then, a programmed electronic control signal is sent to the servo valve that is externally mounted on the outer end of the cylinder. The servo valve opens to allow approximately 1,800 psi of hydraulic fluid to actuate a hydraulic piston, which is located inside the actuator subassembly that is bolted to the valve cover. The hydraulic piston then pushes a rod located inside the valve cover. The rod then activates the outer end finger unloader. The finger unloader physically depresses the outer end inlet valve elements before the compressor piston reaches top dead center (TDC) and continues to hold the valve elements open after the piston reverses direction to begin the discharge stroke. With the outer end now in the unloaded condition, the piston begins to push the gas in the cylinder bore back through the outer end inlet valves, so there is deliberate leakage through the inlet valves. Then, a programmed electronic control signal is sent to the servo valve to cut the 1,800 psi hydraulic fluid.
pressure. This deactivates the finger unloaders and thus lifts the fingers off the valve elements so that the outer end inlet valves can close; this allows the outer end of the cylinder to build pressure for a precisely timed portion of the discharge stroke. The outer end discharge valves will then open, and the delivered amount of compressed gas will be exactly what is required based on the client-defined control variable. When the piston reaches bottom dead center, the sequence will be repeated on the crank end, approximately 180 degrees out of phase with the outer end sequence. Since the ISC system can be programmed to meet the exact flow demand without expending unnecessary horsepower, it is more efficient than employing an external bypass valve in conjunction with traditional finger unloaders.

When reviewing compressor horsepower consumption via pressure-volume (P-V) diagrams, the shape of the P-V diagram for an ISC system will look much different than that of typical cylinder operation. Figure 4 shows a typical P-V diagram, with the compression event of the discharge stroke beginning at 100% cylinder volume and ending at approximately 50% cylinder volume. The area of the P-V diagram represents the compressor horsepower requirement. Figure 5 shows a P-V diagram of the same cylinder when the ISC is activated. Note that the first part of the discharge stroke shows the cylinder pressure essentially staying at inlet pressure from 100% cylinder volume to approximately 55% cylinder volume, because of intentional leakage through the inlet valve. When the ISC is deactivated at 55% cylinder volume, the compression event begins and continues until approximately 15% cylinder volume. Again, since the area of the P-V card represents horsepower, Figure 5 shows a much reduced power requirement to achieve the precise flow needed by the downstream process and therefore saves energy.

ISC Subsystems
The ISC system is comprised of three distinct subsystems: the electronic subsystem, the hydraulic subsystem and the unloader subsystem. A simplified schematic of the ISC system is shown in Figure 6.

The electronic subsystem primarily consists of a programmable logic controller (PLC) that is installed in a stand-alone control panel outfitted with a human machine interface (HMI) touch-screen. The control panel is usually installed in a safe area
near the compressor and can be rated for a Class I, Division II hazardous area. The control panel contains all hardware and software to operate the other two subsystems and can be operated either directly from the panel’s HMI touch-screen or remotely from the refinery’s distributed control system (DCS). The ladder-logic-based software module is the brain of the operation. It is flexible enough to be configured for any client-specified control variable, such as suction pressure, discharge pressure, flow rate, or horsepower. Interstage pressures on multi-stage compressors can be independently controlled if necessary. The software is programmed only by Dresser-Rand and is fully integrated with the hardware in the control panel. Since the user does not program the PLC, the electronics subsystem is truly a turnkey feature of the ISC system.

The HMI interface takes the user through a series of menu screens that are easy to navigate. The two primary screens are ISC Operation and ISC System. The ISC Operation screen features a color illustration of the compressor configuration and displays the current capacity set point. Lower level screens show information about the servo valves, permissives status and hydraulic system status. The hydraulic subsystem is fully instrumented and monitored by the controller. Therefore, the hydraulic pump’s start and stop signals, the supply and return pressure signals, the oil temperature signals, and any leakage from the oil reservoir are monitored. The controller will shut down the hydraulic subsystem if there is a serious issue and the HMI will display the cause. However, and very importantly, the controller will not shut down the compressor if there is a shutdown of the hydraulic subsystem. Instead, the finger unloader will simply retract to the loaded position and remain there, so the compressor will continue to run, but at full capacity. If compressor flow must then be trimmed, the bypass valve should be programmed to open as needed until the ISC problem is resolved. If there is a true compressor shutdown that requires hydraulic lines to be opened, then another HMI screen will guide the user through a hydraulic purge cycle prior to restarting the compressor.

The ISC System screen primarily shows the status of various alarm configurations, as well as which alarms are enabled or disabled. Some alarms are fixed but some alarm set points can be modified. If an alarm occurs, the alarm status is shown so that it can be acknowledged and reset if necessary. An alarm history is also captured. Overall, the various HMI screens provide a comprehensive yet straightforward picture of the ISC controls. All relevant information about the controller, servo valves and hydraulic power unit is available with a few touches of the screen. Figure 7 shows a field installation of an ISC control panel.

Figure 7: ISC control panel with HMI.

The electronic subsystem also includes a top dead center (TDC) sensor mounted in close proximity to the flywheel so that compressor piston position is accurately known. This enables the servo valves to fire at the correct crank angles. Not only must accurate TDC be established in the field, it is vitally important that the TDC sensor be securely fixed, because the timing of the unloader subsystem depends on an accurate read of crank angle position from the TDC signals.

The hydraulic subsystem consists of the hydraulic power unit (HPU), servo valves and hydraulic manifolds to direct oil between the HPU and the finger unloaders. The HPU is a stand-alone skid that contains a highly durable, motor-driven hydraulic pump. The pump is a pressure compensated, variable displacement style, so it only uses the amount of oil necessary for the given pressure and flow conditions and therefore saves energy. The HPU is completely instrumented, with transmitters for oil pressure, temperature and tank level. The control panel reads and monitors the signals from all the HPU transmitters and initiates an HPU shutdown if any allowable parameters are exceeded. The HPU has dual oil filters outfitted with differential pressure transmitters and gauges. When it is time to replace a filter, a three-way valve can be switched to isolate it so that the filter can be removed while the HPU is running. The oil reservoir has a heater to ensure proper oil temperature for start-up, and a heat exchanger maintains proper temperature during normal operation. Figure 8
shows an HPU skid in the field.

A servo valve and hydraulic manifold are mounted on each end of the compressor cylinder. The servo valve receives a signal from the controller and uses a torque motor to send a pulse of hydraulic oil to all finger unloader actuators on one end of a compressor cylinder. Since finger unloaders are normally installed on both ends of a cylinder, there are typically two servo valves on each cylinder. The servo valves are used with intrinsically safe barriers and operate at 12 VDC and 8mA. Since the hydraulic fluid pulsates during normal ISC operation, it is important to dampen the pulsations with accumulators. Each compressor cylinder has two accumulators, one on the supply line to the servo valves and one on the return line. Despite the dampening effect of the accumulators, the hydraulic hoses tend to vibrate in operation and are securely held with specially designed brackets to minimize potential abrasion. Still, the hydraulic hoses and fittings must be frequently checked to ensure they are not leaking, wearing or abrading against any surfaces, which could shorten their operating life. (The typical service life of the hoses is three years). To ensure maximum service life of the other hydraulic components, the hydraulic oil must be tested and meet a specified ISO code rating. Hydraulic oil purchased in plastic containers tends to be the cleanest, whereas oil purchased in metallic containers is relatively dirty. If the oil is contaminated, it can be flushed with the help of the HPU, but the servo valves must be removed from the flushing loop to prevent fouling.

The unloader subsystem (Figure 9) is comprised of the hardware installed in the inlet valve pockets of the compressor cylinders. The major components of the unloader subsystem are the inlet valve, plunger plate with fingers and return springs, actuating rod with seal pack for the process gas, valve cover, and hydraulic actuator subassembly with seal pack for the hydraulic piston. The inlet valve is a special version of Dresser-Rand’s Magnum valve, which is a highly durable miniature poppet-style valve. The stainless steel fingers are particularly robust to prevent deformation of the Magnum valve’s moving elements. The plunger plate, which contains the fingers, is well-guided in its travel with a rod that receives the hydraulic actuating force. The hydraulic actuator has an uncomplicated, clean piping arrangement, with a hydraulic oil supply line and a return line. There is also a drain connection for the hydraulic oil. A very small amount of oil leakage is not unusual, but a constant drip indicates it is time to replace seals. All components of the unloader subsystem can be designed for sour gas compliance if hydrogen sulfide is present in the gas stream. If the cylinder is non-lubricated and hydraulic fluid cannot come into contact with the process gas, the valve cover’s seal pack can incorporate a special seal design to ensure that hydraulic oil stays separated from the process gas.

At the heart of the ISC’s reliability is Dresser-Rand’s Magnum valve, which was commercially launched in the year 2000. The rugged bullet-shaped poppet element is made of a special blend of polyetheretherketone (PEEK), which is a tough, high-strength thermoplastic that is inert to just about every gas and absorbs impact velocities better than almost all other non-metallic valve materials. The shape of the bullet is designed to ensure that pressure loads impart minimal tensile stress. Therefore, the stresses on the bullet element are virtually all in compression, which eliminates nearly all bending loads that will tend to deform the bullet during operation. Consequently, the Magnum valve can be applied at differential pressures up to 3,000 psi. The advanced spring design minimizes operating stresses, so the wire will not be overloaded even if the springs are inadvertently compressed to solid height. Spring materials with high fatigue strength are available for both sour and non-sour gases. The bullet elements are efficiently arranged in a square pattern to optimize valve flow area and to allow for a simple plunger plate design. Since the same PEEK bullet element is used in all stages of compression, the inventory of spare parts is easy to manage with Magnum valves. Figure 10 shows a Magnum valve and plunger assembly used in an ISC system.
Traditional Clearance Pocket Unloaders

There are two major types of traditional clearance pocket unloaders that are used for compressor capacity control: the manually operated outer end variable volume clearance pocket (VVCP) and the pneumatically operated fixed volume clearance pocket (FVCP).

The VVCP is horizontally mounted to the outer end of a compressor cylinder. The VVCP’s piston is attached to a threaded stem that protrudes through the outer end pocket and is attached to an external hand wheel. Turning the hand wheel will cause the clearance pocket piston to move. If the clearance pocket piston is moved outboard, i.e., away from the cylinder bore, then clearance volume will be added to the cylinder bore and compressor capacity will be reduced. If the pocket piston is moved inboard, then compressor capacity will be increased. The external part of the stem is generally scaled with graduated marks that represent a certain volume of gas, so the VVCP can be positioned to add a precise amount of clearance volume to achieve the desired amount of compressor capacity (usually any capacity step between 55% and 100%) depending on what the compressor operating conditions will allow. Most manual VVCP applications are found on high-speed natural gas compressors; that is, compressors that operate from 900-1,800 rev/minute. Since many high-speed natural gas compressors must operate over a wide range of pressures, temperatures and compressor speeds, they must be designed for a wide capacity range. The VVCP is the simplest and most economical way to accomplish this.

For safety purposes, it is normally recommended that the manual VVCP be moved only when the compressor is shut down, which is often an inconvenience. When a manual VVCP is moved while the compressor is running, the alternating pressure forces in the compressor cylinder introduce a vibratory load that could weaken the VVCP assembly. Over time, fatigue cracks in the VVCP assembly could propagate to the point of failure. Figure 11 shows a VVCP assembly that ejected from the outer end of a 40-year old compressor cylinder while the operator turned the hand wheel (fortunately, there were no injuries).

The pneumatic FVCP is commonly applied to the slower-speed compressors found in oil refineries and chemical plants. Since the FVCPs are remotely actuated with air pressure, they are inherently safer than manual VVCPs. However, the FVCP is an on-off device that can only add a fixed amount of clearance volume to achieve a single, discrete capacity step between 50% and 100% (often 75%). Though safe to operate, the FVCP’s ability to alter capacity is limited.
Hydraulic Variable Volume Clearance Pocket (HVVCP)

The design of the outer-end HVVCP features both safety and flexibility. The HVVCP is remotely actuated for safe operation, yet has the flexibility of accurately positioning the clearance pocket piston. Thus, any desired capacity step between 55% and 100% is achievable in a safe, energy-efficient manner. The HVVCP is a horizontally-mounted, bolt-on assembly that consists of a custom-designed hydraulic cylinder, an accumulator, a clearance pocket piston that attaches to the hydraulic cylinder piston, and hydraulic manifold blocks. Each of the two manifold blocks contains a set of solenoid valves and check valves that allow hydraulic fluid to flow in a closed circuit. A common misperception is that the HVVCP uses an external pump to move the clearance pocket piston. Instead, the HVVCP uses alternating pressure in the compressor cylinder as the force to move the clearance pocket piston. The hydraulic cylinder and circuitry act as a brake when the clearance pocket is stationary.

An air-operated solenoid valve is mounted on each of the two manifold blocks that are attached to the inner and outer ends of the hydraulic cylinder. No hydraulic fluid flows when both solenoid valves are closed, so the HVVCP stays in a fixed position. When the outer solenoid valve is opened, hydraulic fluid flows from the outer end of the hydraulic cylinder to the inner end via a check valve in the inner manifold block. However, fluid only flows during the discharge stroke of the compressor piston, which provides the pressure force to move the clearance pocket piston towards the outer end. This increases the clearance volume in the pocket and reduces compressor capacity. The check valve in the inner manifold disallows hydraulic fluid from flowing on the intake stroke of the compressor piston, so the clearance pocket piston cannot move during this portion of the compressor cycle. Therefore, when the outer solenoid valve is open, the clearance pocket piston ratchets outward during each discharge stroke until the desired clearance pocket setting is reached, at which point the outer solenoid is closed. A position transducer inside the hydraulic cylinder records the pocket position and provides feedback to the client’s control system, which keeps the outer solenoid open until enough clearance is added to obtain the required capacity turndown.

When the inner solenoid is opened the clearance pocket piston moves inward on the intake stroke because the inlet pressure force on the clearance

![Figure 12: Schematic of the HVVCP concept.](image)
pocket piston is less than the pressure force acting on the opposite side of the pocket piston during this part of the compressor cycle. The hydraulic fluid in this case moves from the inner end of the hydraulic cylinder to the outer end. This results in decreased clearance volume in the pocket, which increases compressor capacity. The check valve in the outer manifold block disallows hydraulic fluid from flowing during the discharge stroke, so the clearance pocket piston ratchets inward during each intake stroke until the desired reduction in cylinder clearance is obtained, at which point the inner solenoid valve is closed. Figure 12 shows a simplified schematic of the HVVCP system. Figure 13 shows a rendering of a manual VVCP. Figure 14 shows a rendering of an HVVCP retrofit to replace the manual VVCP depicted in Figure 13.

Since the diameter of the HVVCP piston is normally a large fraction of the compressor cylinder bore, there are no pressure or horsepower losses associated with the movement of gas in and out of the clearance pocket. The clearance pocket is wide open to the cylinder bore throughout the compressor cycle, which makes the HVVCP the most efficient capacity control device. This should be considered when calculating the overall compressor power savings that the HVVCP can provide, particularly in relation to the inherent power loss associated with an ISC during its unloading cycle.

Case Studies – Application Ranges and Relative Advantages
Compressed gas that is not delivered to the downstream process is recycled back to the compressor inlet piping via the bypass valve. The primary purpose of the ISC and HVVCP is to save money by reducing or eliminating the energy costs associated with bypassing flow around the compressor. Compressor operating conditions may require the driver (motor or engine) to use 10,000 horsepower or more. Bypassed flow represents wasted horsepower (and wasted money), which could be a significant percentage of the horsepower consumed by the compressor driver. Evaluating whether to apply an ISC or an HVVCP depends on the amount of bypassed flow to be avoided and then determining which unloader system will maximize the return on investment. Since stepless capacity control systems are more expensive than traditional inlet valve and clearance pocket unloaders, one must decide whether the horsepower savings are worth the investment. Figure 15 is a set of bar charts that shows the amount of money saved by employing an ISC or HVVCP if electricity costs $0.10 USD per kilowatt-hour. Cost savings at 10% of capacity turndown are represented by the blue bars for normal compressor power consumption levels of 500, 1,000, 5,000, and 10,000 horsepower. A capacity turndown of 10% means the downstream process only requires 90% of the flow delivered by the compressor, so 10% of the flow would normally be recycled through the bypass valve. The green and red bars represent cost savings at 15% and 20% turndown, respectively. As an example, if normal compressor power consumption is 5,000 HP and an ISC or HVVCP provides a capacity turndown of 15% for one year, then the green bar at 5,000 HP in Figure 15 shows a cost savings of nearly $500,000 USD per year. The payback period of a typical ISC system is often one year; for a typical HVVCP system, the payback
is less than six months. Actual cost savings depend on the complexity of the ISC or HVVCP and the amount of power savings in a defined time period. Figure 15 implies that if the compressor driver is relatively low-horsepower, the payback period of an ISC or HVVCP could be several years, in which case the cost of these unloader systems may not be justifiable.

In many cases, the ISC and the HVVCP system are both sufficient to meet the capacity reduction requirement, so client preference for a given system may then decide which to implement. The ISC is more complex than the HVVCP because it requires multiple subsystems. The whole cost of the ISC system, including initial cost and long-term maintenance costs, will also be higher than the HVVCP. However, since the ISC potentially offers a greater range of capacity turndown, it is sometimes a more attractive option than the HVVCP. The HVVCP offers a straightforward bolt-on addition to the outer end of an existing compressor cylinder, whereas the ISC requires dedicated additional space for the control panel, the HPU and electrical conduit and hydraulic hoses. Commissioning time for an ISC often requires several days, including flushing the hydraulic lines, testing the control panel and the HPU, and training site personnel. Commissioning of an HVVCP often requires just one day, including training. To date, the number of ISC applications is approximately equivalent to the number of HVVCP applications, so the markets for both energy-savings systems appear to be equally strong.

To assist the decision-making process, Figure 16 shows an application chart with the green HVVCP application range overlaid on the red ISC application range. The chart shows that the ISC can attain a compressor flow range of 35% to 100% for any compression ratio up to 4.00, which means the maximum turndown is 65%. At a compression ratio up to 3.00, the ISC can provide compressor flow of 30% and higher, or a maximum turndown of 70%. The HVVCP chart shows the range of compressor flow is 55% to 100% for compression ratios of 2.50 to 4.00, or a maximum turndown of 45%. We find that many clients who wish to apply the HVVCP only require compressor flow turndowns of 30%
or less. The chart shows that this is feasible for compression ratios of 1.80 and higher. Since most compressor services operate with ratios above 2.00, the HVVCP is a cost-efficient device to seamlessly adjust compressor flow between 70% and 100% of rated capacity.

In the case of a client who operates several engine-driven natural gas compressors across the eastern United States, several ISC systems are used to regulate flow in compressor pipeline stations and in natural gas storage fields. In some instances, the ISC system is used to regulate high volumes of natural gas in multiple pipelines during the busy winter season when heating needs increase. This is a time when flow to certain pipelines is very closely managed and bypassing flow is particularly wasteful. The major mechanical equipment in a natural gas transmission station is often a series of engine-drive reciprocating compressors, so any energy wasted by recycling gas directly affects profitability. In other cases, the ISC is used to strategically draw precise amounts of natural gas out of underground storage only during the winter and is therefore used only seasonally.

HVVCP and ISC systems are both being applied by clients who manage hydrogen for oil refineries. The purpose is to ensure that precise amounts of hydrogen are accessible for constantly changing oil refining requirements. In some instances, financial penalties are incurred if minimum levels of hydrogen are not available to the refineries, so the hydrogen suppliers must maintain an adequate reserve. This has traditionally been done by constantly running the compressors at full load and recycling a large percentage of hydrogen back to the compressor inlet to ensure gas is always available. These clients realized immediate savings by implementing stepless capacity control systems to provide only the amount of gas required — no more and no less. The ISC and HVVCP are “green,” environmentally friendly devices that can be of significant value when strategically employed as part of an energy management program.

Figure 16: Application chart – ISC and HVVCP.