Technology Status Assessment

ADVANCED RECIPROCATING COMPRESSION TECHNOLOGY (ARCT)

A Joint DOE and GMRC Sponsored Program

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Prepared by:
Danny M. Deffenbaugh
Anthony J. Smalley
Ralph E. Harris
Klaus Brun
Robert J. McKee

Prepared for:

U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940, MS 921-107
Pittsburgh, PA 15236-0940

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SOUTHWEST RESEARCH INSTITUTE®
6220 Culebra Road, P.O. Drawer 28510
San Antonio, Texas 78228-0510

1. OVERVIEW

The objective of the Advanced Reciprocating Compression Technology (ARCT) program is to create the next generation of reciprocating compressor technology to enhance the flexibility, efficiency, reliability, and integrity of pipeline operations. The suite of technologies developed by this program will not only provide pipeline operators with improved, affordable choices for new compression, but will also provide innovative products that can be retrofitted to existing machines to substantially improve the current infrastructure.

The current subsystem state of the art is passive and generally fixed configurations for a specific operating design point. However, compressors infrequently operate at their design point, resulting in an overall reduction in reliability and efficiency. The intelligent compression technology to be provided by this program will be comprised of many active and adaptive subsystems that can automatically be tuned to off-design operating conditions. The ARCT program will advance the technology in five specific areas: pulsation control, capacity control, valves, sensors and automation, and systems integration.

2. PIPELINE COMPRESSION EVOLUTION

Advances in compression technology helped the U.S. gas industry expand after World War II. The original first generation compression infrastructure (Figure 1) consisted of many small slow-speed (180 rpm) compressors to move gas from producing regions to markets. To provide the necessary expansion, a developmental second generation of “larger, higher-speed” machines promised a significant reduction in installed cost. As industry installed the first machines, they experienced many reliability and operational problems. These problems involved flow pulsations and mechanical vibrations that resulted in piping failures. It was imperative that the industry solve this vexing set of problems.

To address this challenge, the pipeline industry formed what is now the Gas Machinery Research Council (GMRC), which contracted with Southwest Research Institute® (SwRI®). SwRI developed pulsation control systems that combined acoustic filters and dampers with effective mechanical restraints. The Analog Simulator, an ASME engineering landmark, was developed by SwRI to optimize the design of pulsation filter bottles and predict pulsation performance. SwRI has continuously operated the GMRC pulsation design service for the last 50 years, generating royalties that have funded GMRC research since 1955.

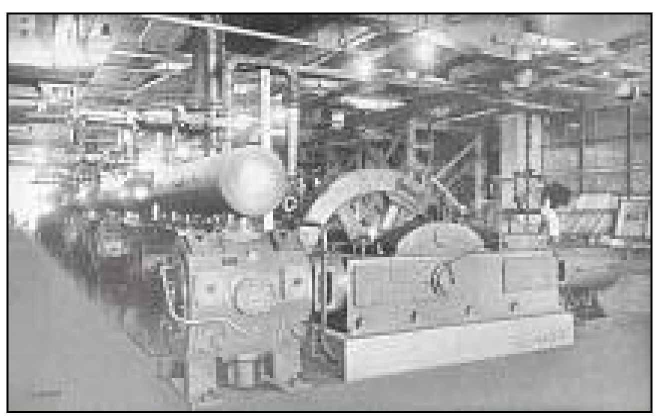

Figure 1. Early Slow-Speed Compressors Running at Less Than 180 rpm in the 500 to 750 hp Range Without Pulsation Control

This second generation of compression technology (Figure 2) has now become known as “slow-speed integral” compression. A single crankshaft drives power and compression cylinders mounted in a single block. This equipment is nominally three times the horsepower running at twice the speed of the equipment it replaced. The slow-speed integral machines have been the U.S. pipeline industry’s compression workhorse for the past 50 years. With pulsation problems under control, this compressor technology has built a long record of reliability, ruggedness, long life, and high efficiency. Compressor stations consist of many individual machines, and the primary method of capacity control is to activate a different number of machines.

Figure 2. Slow-Speed Integral Compression Running at Less Than 300 rpm in the 1,500 to 2,500 hp Range With Pulsation Control Systems

3. MODERN PIPELINE COMPRESSION

The promise of dramatic cost reductions has driven the industry towards even higher-speed, larger-horsepower reciprocating compression powered by efficient separate modern gas engines or large electric motors. Within the last few years, the first vintage of this new class of machines has been installed. This third generation of equipment (Figure 3) is four to five times the power of the prior generation and is now running at two to three times the speed. With this technology came new vibration and pulsation problems. The pipeline industry faces a technology transition similar to 50 years ago. As a few large machines replace many small machines, each machine must provide a wider capacity range and increased reliability. Varying speed more widely complicates pulsation control, and higher speeds have resulted in significant losses in compressor-efficiency, contributed in part by both pulsation control and conventional valve technology.

Figure 3. Modern Large High-Speed Separable Compressors Running in the 500 to 1,000 rpm Range in the 8,000 to 10,000 hp Range

The last generation of slow-speed integral machines is no longer commercially available because it was perceived as unaffordable. While affordable, the current generation of high-horsepower, high-speed compression requires advancements in technology to meet their full potential to address the pipeline industry's compression needs.

4. STATE-OF-THE-ART COMPRESSION TECHNOLOGY

4.1 PIPELINE OPERATIONS

The U.S. natural gas transmission industry operates pipelines throughout key corridors of the country, with compressor stations at regular intervals (30 to 100 miles) to compensate for pressure drop and gas consumption. Within a pipeline, a central "gas control" facility monitors operation and establishes targets for flow or pressure, based on current contracts, or anticipated near-term needs. Much of the recent and anticipated growth is driven by the increased use of natural gas-fueled power plants. Some power plants are operated in a peaking mode, while others support base load. However, all power plants are required to follow variable load profiles, thereby increasing pipeline flexibility demand.

4.2 SYSTEM INTEGRATION AND STATION OPERATION

At the individual compressor station level, flow flexibility requirements translate into an increasing need for automation (remote start-up), reliability, and broader capacity control. Short-term contracts, combined with large price swings, have led to less use of "line pack" to store gas in the pipeline. Volume flow requirements are up to meet the increased demand, while less "line pack" results in lower pressure ratio requirements. Pipelines earn revenue only by transporting "other people's" gas. Increased efficiency directly affects fuel consumption, operating cost, emissions, and capacity, but contractual arrangements do not always motivate the most efficient compression solution. As part of the pipeline system, a successful reciprocating compressor system must manage these interacting factors: capacity control, pulsation control, and valves. System efficiency, smooth operation, and the resulting reliability are maximized at the system design point. Small departures from this design point have modest impacts on efficiency, smooth operations, and reliability. Major departures have significant adverse effects, but reciprocating compressors must increasingly operate over a wide range of conditions.

4.3 PIPELINE CAPACITY CONTROL

Capacity control is the method to vary the flow rate and engine load in response to end-user demand and pipeline required pressure ratio. Historically, pipelines installed many small compressors and adjusted flow rate by changing the number of machines activated. This capacity and load could be fine-tuned by speed or by a number of small adjustments (load steps) made in the cylinder clearance of a single unit. As compressors have grown, the burden for capacity control has shifted to the individual compressors. The following equation for volume flow rate (suction conditions) helps illustrate available options.

$$\textit{Flow} = \textit{Swept Area} \times \textit{Stroke} \times \textit{Speed} \times \textit{Volumetric Efficiency}$$
$$\textit{Volumetric Efficiency} = f\ (\textit{Pressure Ratio, \% Clearance})$$

The common methods of changing flow rate are to change speed, change clearance, or deactivate a cylinder-end (hold the suction valve open). Another method is an "infinite-step" unloader, which delays suction valve closure to reduce volumetric efficiency. As Table 1 shows, each method has advantages and disadvantages.

Table 1. Capacity Control Methods

Capacity Control Method	Advantages	Disadvantages
RPM	Simple Control	Adverse Pulsation
Clearance Volume	Efficient	Limited Range
Valve Unloader	Effective Control	Adverse Pulsation and Low Efficiency
Deactivate Cylinder	Effective Large Step	Adverse Pulsation and Low Efficiency

4.4 PULSATION CONTROL

The critical development that allowed widespread use of slow-speed integral compressors was the pulsation control filter bottles and associated design tools. These bottles functioned as low-pass acoustic filters using a "volume-choke-volume" technique. Figure 4 shows idealized response of a low-pass filter bottle, superimposed on the pulsation spectrum for a 300-rpm double-acting compressor. For a fixed operating speed, the Helmholtz frequency and cut-off frequency of the filter are located between the fundamental operating speed and second order. The first pass band is located between the seventh and eighth order. This method is extremely effective for fixed speeds. However, even with small speed variations, the effectiveness of this method is complicated and certain speeds must be locked out to avoid response at the pass band frequency.

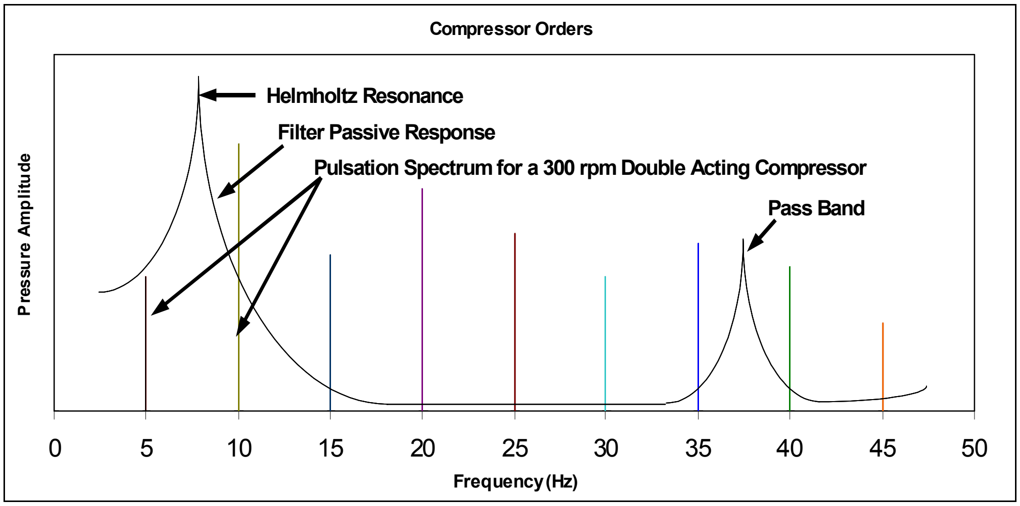

Figure 4. Filter Bottle Helmholtz Response

Acoustic filter bottles can be implemented as two bottle or single bottle designs that have advantages in terms of vibration control, but disadvantages in terms of space and weight. Nozzle orifices and side branch resonators are other pulsation control methods, and each method has its advantages and disadvantages as shown in Table 2.

Table 2. Pulsation Control Methods

Pulsation Control Method	Advantages	Disadvantages
Filter Bottle	Effective Pulsation Control at Fixed Speed	Cost, Size, and Weight
Orifices	Damper Nozzle Pulsation	Pressure Drop
Side Branch Resonator	Fixed Frequency Control	Fixed Speed Only

4.5 VALVES

Simple passive check valves have generally served pipeline slow-speed compression needs. The valve-sealing element opens when pressure overcomes the spring force. Ideally, the differential pressure due to flow creates a force, and the difference between pressure and spring forces accelerates the sealing element until it hits a guard, which limits travel ("lift"). In a simple model, sealing elements stay against the guard until the spring force exceeds the pressure force, then the spring closes the valve and holds it closed. Suction valves open when cylinder pressure drops below suction line pressure and closes near bottom dead center. Discharge valves open when cylinder pressure exceeds discharge line pressure and closes near top dead center. The sequence repeats in each cylinder, each revolution. Desirable attributes include perfect sealing when closed, rapid opening, sustained high flow area when open, rapid timely closing, tolerable impact with no bounce, tolerance to maximum temperature, and low-flow resistance of entire flow path. Proper parameter choices (material, mass, spring constant, spring preload, lift, flow area) maximize the chance of success. However, these simple, passive valves do not tolerate wide operating ranges well. Operational problems include "flutter," late/early closure, imperfect sealing, excessive impact force, and excessive compression temperature. Achieving long life with low losses and acceptable operation while minimizing leak potential is very challenging. Valve manufacturers have made great advances (materials and configuration). Yet, design trade-offs are often mismanaged. The push for low-flow resistance leads to excessive impact forces, or the drive for long life leads to flow resistance so high the driver cannot provide needed capacity. The increased number of impacts and higher impact velocities with high-speed compression exacerbate the problems. Valves are the single most significant maintenance item in pipeline compression. The advantages and disadvantages of each of the common passive valves are shown in Table 3.

Table 3. Compressor Valve Types

Valve Type	Advantages	Disadvantages
Plate	Low Cost/Simple	Relatively Short Life
Ring	Low Pressure Drop	Shortest Life
Poppet	Longer Life and Rugged	Highest Pressure Drop

4.6 SENSORS AND AUTOMATION

Slow-speed integral machines operate with minimal unit instrumentation. Pressure ratio and temperatures are measured at the station level, but unit flow rate is not typically measured. Meter stations are located at pipeline custody transfer points, which in most cases are not collocated with the compressor station. Flow measured at the meter station is available to central gas control, but not compressor station operators. Current high-speed units have sophisticated engine instrumentation and controls, but very little instrumentation on the compressor side. Load steps are programmed with various pocket and unloader settings to give prescribed capacity and load control without a closed-loop feedback control system. Remote operation from central gas control can start and stop units and can select speed and load steps through the unit control panel to provide the required capacity and loads. Since reciprocating compressors are positive displacement devices prescribed settings give a reasonable approximation of the resulting capacity. However, sufficient margin is provided in recognition of this approximation.

5. TECHNOLOGY BEING DEVELOPED

Advanced concepts for ARCT include intelligent compression technology that monitors operational conditions and automatically adjusts internal geometry to tune performance over the full-extended operational range, thereby optimizing performance and minimize life-shortening machine vibration. No such technology currently exists for reciprocating compression.