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Improved Performance of a Pipeline Compressor Station

Adam Long
Manager of Compression & LNG Support
Piedmont Natural Gas
Author

Dwayne A. Hickman
Director of Software Development
ACI Services, Inc.
Author/Presenter,
Previous GMC Author/Presenter

Shelley D. Greenfield, P. Eng.
Vice President Design Services
Beta Machinery Analysis Ltd.
Author/Presenter
(Previous Author/Presenter)

Hemanth Satish
M. Eng. Design Analyst
Beta Machinery Analysis Ltd.
Author

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Executive Summary

Many pipeline owners have a keen interest in improving the efficiency of their existing compressor stations. Even small improvements in compressor efficiency can result in significant reductions in fuel costs and can lead to increases in throughput, thus generating higher revenues. A business case for removing bottlenecks within station piping systems is made.

This paper discusses an engineering approach to improve the operational flexibility, throughput, efficiency and reliability of a reciprocating compressor station. Ways to evaluate a compressor station piping system and to quantify the financial returns for improving the system efficiency are identified. The investigation includes evaluating a compressor station over a wide range of operating conditions required at the facility and assessing the most beneficial technical and economic solutions. The analysis is conducted with a combination of field analysis and computer simulation for an existing Piedmont facility.

Improved Performance of a Pipeline Compressor Station

Introduction

Many pipeline owners are keen to improve the efficiency and operation of their reciprocating compressor assets. Large incremental profit can be achieved by removing bottlenecks and generating additional flow (for the same power). There is a strong business case for optimizing the design of the compressor layout and associated piping within the station.

Current practices make it difficult to optimize the compressor package design. Historically, no individual or team is evaluating the entire layout to assess improvement opportunities. In addition, the industry lacks the technology to properly evaluate the performance of the overall system, identify the best way to optimize the layout, and to quantify the financial benefits. As a result, many current designs can suffer from excessive pressure drop, limited flexibility in operating across a wide operating range, and uncertainty that the final design will meet the intended specification. Often the proposed design was not the best overall solution possible.

There are new approaches that enable the owner to optimize the compressor design. This paper explores key steps in the process, including the need to assess the overall system performance. Specific examples illustrate how the optimization integrates the design of a capacity control scheme with the piping and pulsation control solution. This integration is critical to an improved layout that can potentially generate multi-million dollar financial improvements. This fresh approach allows the owner to evaluate one or more different designs, over a wide range of required operating conditions.

In today’s world of highly competitive companies, owners who opt to save a few thousand dollars on unloading equipment or pulsation control may quickly find themselves losing out on millions of dollars of lost revenue due to lower flow rates and higher fuel costs.

An existing Piedmont Natural Gas (Piedmont) facility illustrates both the design optimization process and the resulting financial improvements that can be achieved.

This paper is a collaborative effort between Piedmont, ACI Services, Inc. (ACI) and Beta Machinery Analysis (Beta).

The first section is a review of the barriers to effective compressor optimization. Section 2 outlines the key success factors that enable owners to improve the design process. An example site is used to illustrate these points in Section 3. Conclusions and recommendations are summarized in Section 4.

Figure 1.1: There is a Compelling Business Case for Compressor Design Optimization

1.0 The Problem

1.1 Compressor Performance Shortfall: Barriers to Optimized Design

There are many documented cases where overall performance of a reciprocating compressor system (e.g., compressor plus bottles, coolers, and all package and plant piping) falls short of anticipated performance. This has become a more frequent issue when high speed compressors are employed on low ratio, high flow applications; however, significant problems have also occurred on other upstream and midstream reciprocating compressor applications. [1]

Even when compressor OEMs and system designers meet their contractual obligations, owners may encounter performance shortfalls from;

- higher than predicted system pressure drops through vessels, piping, etc.,
- miscalculation of pressure drops through coolers,
- the effects of pulsations at the compressor suction and discharge valves, or
- operating outside the design points that were considered during the initial station conception.

To the casual observer it would seem that these issues should be easily solved. The common view may be that optimizing a compressor should be a straightforward task. If so, “what is the problem”?

For many organizations, the current procurement process often does not allow optimization to happen. Figure 1.2 illustrates some of the common barriers that exist.

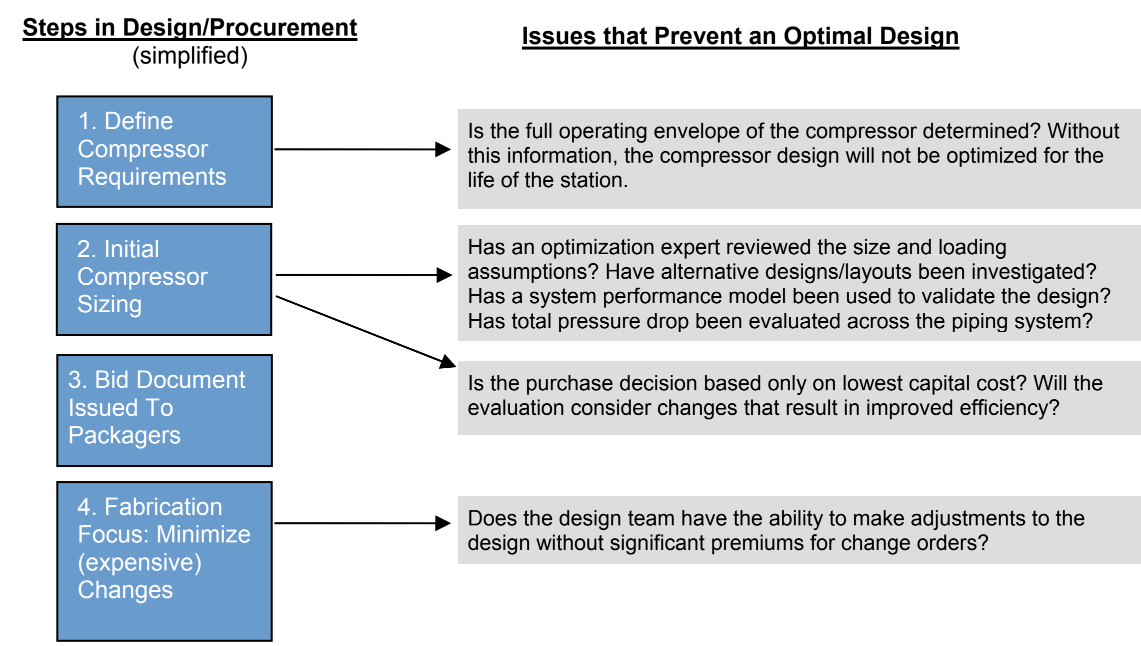

Figure 1.2: Barriers to an Optimized Compressor Design

1.2 Conflicting Design Objectives

All compressor package designs are a compromise of design objectives. Three of the common design objectives are minimizing capital costs, maximizing unit flexibility, and having the most efficient compressor possible. All these objectives are in conflict and achieving a well balanced design involves careful thought and new design methodologies and tools. The design triangle shown in Figure 1.3 illustrates this conflict and trade-offs.

For example, there is typically a conflict between operating flexibility and compressor efficiency. A compressor design based on a limited number of conditions will be quite different from one that requires a wide operating envelope. Understanding and resolving these priorities from an operational perspective is the starting point for the optimization process.

Capital cost always has a critical bearing on the final design. If the primary focus is to minimize initial capital cost, then it is unlikely that the design team will have the opportunity to optimize the performance. Incremental capital costs need to be evaluated against the improvements in efficiency and operating flexibility.

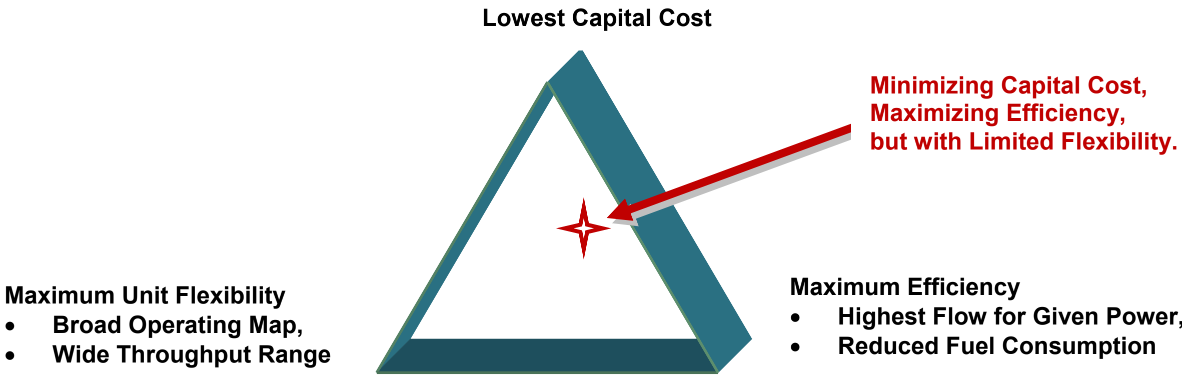

Figure 1.3: Conflicting Design Objectives

1.3 Generic Pressure Drop Assumptions Can be Costly

Conventional industry practice is for a packager to build a reciprocating compressor system using the compressor OEM components. The compressor OEM, then, only guarantees performance between the compressor flanges, which is all that the OEM has control over. The packager, or systems integrator, relies on the compressor OEM's data, and then *provides a generic assumption of pressure drop* through the rest of the package. Because of these assumptions, the supplier cannot provide a meaningful guarantee of overall system performance.

Performance based problems often only appear after the unit is installed and in production using this approach. Only then can the owner test the unit and identify if a performance shortfall occurs. Sub-optimal performance often results in a significant financial loss.

1.4 Who is Looking at the Whole Picture?

A successful design optimization needs someone who can see the whole picture and evaluate the impact that different components have on performance and operating flexibility. For example, a change in the unloading scheme can impact the effectiveness of the pulsation control.

In most cases, there is no one looking at the linkages between different components of the compressor installation. Each supplier tends to look at their own area of influence or discrete function. Some call this the "silo mindset", referring to the situation when people limit their involvement to their area of expertise.

1.5 Summary

This discussion highlights the challenges and opportunities associated with compressor designs. Various owners interviewed on this subject agreed that they would like to see improvements with their compressors.

Owners would like:

- to quickly and economically compare different design alternatives and implement an optimized design,
- to verify that a selected compressor system will meet their requirements over the full range of potential applications and needs, and
- to have more comprehensive information for operating their compressors to ensure that unsafe, unreliable, and/or inefficient areas of operation are identified before attempts are made to operate in regions of potential compromise.

2.0 Improving the Design Process

The following section outlines requirements for a successful optimization project.

One of the most important factors is to start the process early, before issuing tender documents for fabricating the unit, as it is often difficult and costly to make changes once the design has been set.

The design team would include the owner, its Engineering Consultant, and qualified experts who can assist in the process.

This section includes these topics:

- A summary of evaluation criteria used in optimization projects.
- Importance of reviewing alternative capacity control schemes. This decision has a bearing on many of the later design aspects.
- Accurate data from the overall system as needed for decision making.

2.1 Evaluation Criteria

There are a number of factors to evaluate in the process. The following criteria can be used to evaluate alternate designs:

Operating Flexibility and Reliability

- Ability to operate safely across the required operating envelope
- Pulsation forces across the system

Compressor System Efficiency

- Pressure drop (from lateral to lateral)
- Total flow at key conditions
- Overall efficiency across the required map
- Power requirements

Financial Metrics (to Compare Different Alternatives)

- Net profit potential
- Capacity
- Investment payback and discounted cash flow

Environmental and Greenhouse Gas

Other Regulatory or Site Specific Criteria

The weighting of each factor depends on the specific situation and requirements. As discussed earlier there can be design conflicts between many factors, including operating flexibility and efficiency. It may be difficult to fully satisfy each objective.

General Comments on Terms Used in the Evaluation

- Pressure Drop: Any pressure drop reduces the overall station efficiency. The goal of the design team is to optimize the layout to reduce total pressure drop. Note that total pressure drop includes static and dynamic pressure drops. [2].

  Pressure drops can be identified throughout the system (see Figure 2.1). Understanding the magnitude of these losses is essential in pinpointing opportunities for design optimization.

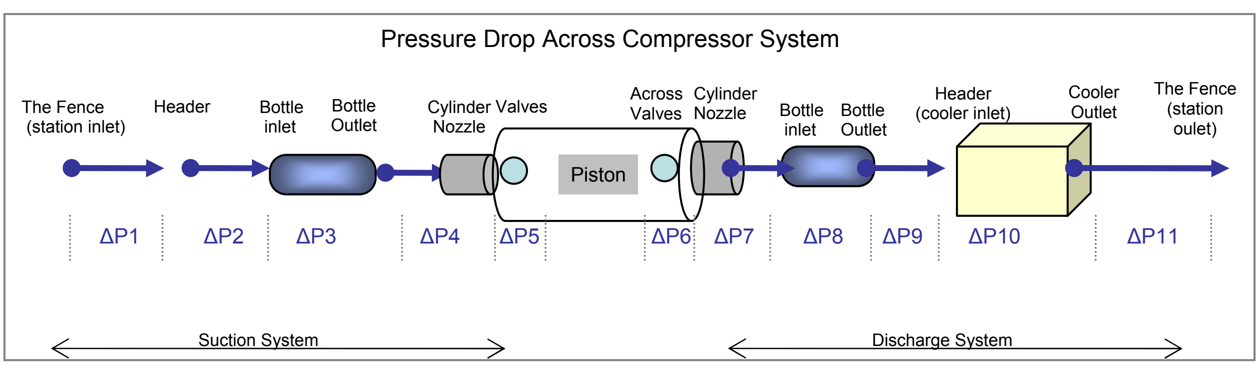

Figure 2.1: Pressure Drop Locations for a Compressor System

- Net Profit Potential: A number of efficiency and financial metrics have been published in the industry. One of the more effective metrics is to compare the Net Profit $ for a given design [3]. This simple approach is based on the net flow through the compressor less the operating costs, the bottom line performance – and takes into account all the inefficiencies in the system.

  This net profit financial indicator is used in the paper to compare and contrast the design alternatives.

2.2 Appropriate Capacity Control Strategy

One of the early steps in the design process is to define the capacity control strategy. The initial package design usually does not include evaluating the different unloading options and the impact on performance, efficiency, rod loads, and operating flexibility.

Based on the owner's specified design points, a packager can size a reciprocating compressor (frame, driver, stages, throws, cylinder bore sizes, and unloading devices) to reasonably achieve the buyer's objectives. This does not mean that it is the best or ideal solution. Thus, it becomes important that buyers review multiple hardware combinations that can meet their objectives [4].

There are many different choices (and combinations) to consider. Each has an impact on efficiency, reliability, and life cycle costs. As illustrated in the case study below, the consideration of pressure drop losses and other operating factors in the evaluation will generate large financial returns to the owner. This optimization can, and should, take place early in the design phase, before the package is tendered for fabrication.

Example:

To provide sufficient turndown (on load as well as capacity requirement), for the initial design conditions, the compressor packages were supplied with four (4) finger-type suction valve end deactivators (unloaders). While this choice may have reduced the price of the unloading devices, it led to other expenses: modified valves for ends with those devices, less efficient compression (regardless if devices used or not) more complex (and hence more costly) pulsation bottles, higher pressure drops, and potentially higher pulsation effects on compressor performance.

An alternate (and ultimately better) control strategy was subsequently identified. As illustrated in the case study, a more flexible solution also enabled better performance and much more reliability in terms of lower pulsation forces. The financial business case can easily be justified.

2.3 *Accurate Data on the System Performance*

Past attempts to optimize the compressor design often failed. The primary reason was that the engineers lacked an accurate performance model of the entire system. Without an accurate model, it was impossible to evaluate design changes.

System performance models are now available to support the optimization process. As the name implies, the performance model includes the static and dynamic pressure drops through the piping, coolers, vessels and pulsation control (per Figure 2.1).

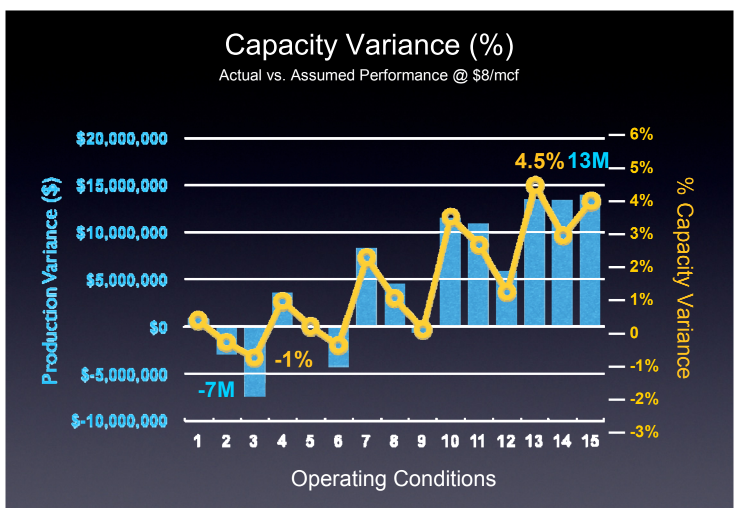

Figure 2.2: Identify Capacity Variance (Actual System vs. Initial Assumptions)

Traditionally, during the compressor package design, the compressor's OEM performance program is used to size the unit over the various conditions. As already discussed, generic assumptions are made regarding pressure drop, pulsation effects on the performance, losses through the cooler, etc. This assumed pressure drop can result in as much as +/- 15% error in performance predictions. Many customers find out that the unit will not meet the required specification once the system piping is considered. In general, customers want to avoid large variances, both positive and negative.

Figure 2.2 is an example that illustrates the variance between actual performance vs. the assumed performance (based on OEM program and generic pressure drop assumptions). This is a 6 throw, 4000 HP compressor. In this project, the variance was -2% to +4.5%. At condition 3, the production is off -2%, resulting in a $7 million reduction in assumed throughput (per year).

By evaluating the entire system, including all the dynamic losses and at all operating conditions, the variance between the assumed performance and the actual system performance can be identified. If the performance does not meet the required specification, changes can be made prior to finalizing the design.

3.0 Case Study – Piedmont Natural Gas, Cabarrus Compressor Station

This case study includes variable speed compressor packages in a pipeline booster type application. Some specifics on this unit are given below and illustrated in Figure 3.1.

The existing compressor package design was based on twelve (12) operating points (combinations of cylinder unloading and suction and discharge pressures). The initial compressor performance was based on an assumed pressure drop of 2.5% from the header to the compressor on the suction and 2.5% from the compressor to the header on the discharge.

The acoustical analysis was conducted for the design as proposed by the compressor packager. The pulsation control utilized low-pass filter type bottles as well as orifice plates recommended at key locations to reduce acoustical resonant responses.

- Sweet natural gas, 0.63 SG
- Single stage
- Six throws
- 13.625 inch bore cylinders
- 750 -1000 rpm
- 4735 HP driver (G3616 CAT Engine)
- Ps=645 to 712 psig (Initial design study)
  Ps=500 to 800 psig - Future
- Pd=745 to 780 psig (Initial design study)
  Pd=800 to 945 - Future
- Cylinder loading – no clearance pockets, four cylinders equipped with finger-type valve unloaders on the head end

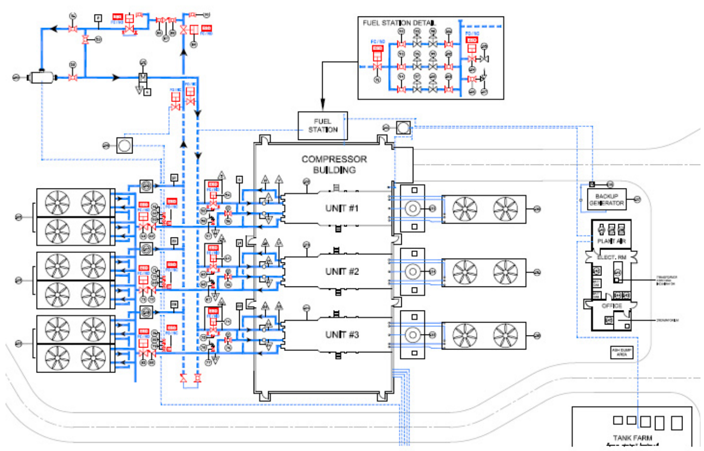

Figure 3.1: Case Study: Compressor Station

The discharge pressure for this facility is being increased to 945 psig, as well there is a requirement to increase the overall plant capacity to add new compressor packages. The plan is to add new compressors and drivers that are identical to the existing units. Review of the existing unit operation as well as review of the existing and new compressor performance revealed several areas for optimization of the compressor package in terms of lower capital cost and improved efficiency, while allowing for operation for the new, wider operating range. High rod loads were calculated for some areas of the new operating map with the existing compressors. High pressure drop was identified in the existing pulsation bottles. The pressure drop in the piping, cooler, and other components was not included the original performance calculations. There is the potential for significant improvements in many aspects of the new (and existing) compressor package design.

Note: any pricing, financial data and other sensitive information has been hidden or modified to avoid releasing company confidential information.

3.1 Methodology and Results

A number of different scenarios were evaluated for this station, both for existing and new units. This paper presents a subset of the different aspects of the project.

Base Case:

- The system performance model is used as the base case for evaluating changes and modifications to the units.
- Over 364 different conditions (pressures and load step) were evaluated across the existing operating map. For each condition, the speed was evaluated at 50 speed increments, resulting in a total of 18,200 operating points.
- Field test data was used to confirm the model accuracy.
- The compressor performance model was also compared to the initial design assumptions (based on OEM performance program, assumed pressure drop, and pulsation design).

Design Goals:

- The unit must be configured to efficiently operate at higher discharge pressures (maximum discharge pressure increased from 800 to 945 psig).
- The station must now operate over a wider range of operating conditions:
  - Suction pressures from 500 to 800 psig
  - Discharge pressures from 645 to 945 psig
- Operating flexibility is a driving goal for the optimization.
- Maximize efficiency.
- Control pulsation forces to safe levels.

Comments on Methodology

- Evaluation Process:
  - Beta/ACI utilized sophisticate modeling tools for this analysis, including System Performance Models (SPM), eRCM, and data-mining software.
  - The paper illustrates some of the available evaluation tools.
- Capacity Control:
  - Unloader control scheme was reviewed and proposed changes identified.
  - The SPM was used to validate how the recommended changes affect the reliability, efficiency and control. In addition, changes from pulsation effects are included in the analysis.
  - The SPM included 563 conditions for the expanded operating map for the new control scheme. For each condition, the speed was evaluated at 50 speed increments, resulting in a total of 28,150 points.
- Pulsation Control
  - Changing to fixed volume clearance pockets allowed for changes in the improvements in the pulsation control. Minor changes to baffle and bottle internals (choke tube) were evaluated.
  - The SPM was analyzed to determine the impact of the small changes to pulsation control.
- Other Changes
  - Other changes are being evaluated to the pulsation control and other components in the system. A number of options show merit for increasing flow. Results from this effort will be available later.
- Financial Results. An example of financial data is presented. Actual financial results remain confidential to Piedmont.

3.2 System Performance Analysis Identified Opportunities for Increased Compressor Capacity

The first step in evaluating the existing units at the station was to gain a better understanding of the system performance. The system performance includes calculation of the compressor capacity, efficiency, power, total pressure drop, pressure pulsations, and shaking forces. These characteristics are calculated for the full range of operating conditions. For the example units, the control panel utilizes pressures near each unit suction and discharge tie-ins to the common headers. In this case the “system” extends from the compressor suction header piping though the suction pulsation bottles, compressor, discharge pulsation bottles, and discharge header (see Figure 2.1).

The system performance calculations are done using a variety of customized and specialized tools. The primary analysis tools are the compressor performance software and the pulsation (acoustical) analysis software. The pulsation analysis was done using a non-linear Time Domain pulsation model of the suction and discharge systems. The non-linear Time Domain model allows for accurately calculating the dynamic pressure drop, which is not possible with most other models.

The model accuracy was verified by comparing actual performance measurements using a Compressor Analyzer and through comparisons to actual SCADA operating data.

The original performance calculations for the existing compressors are based on an assumed pressure drop of 2.5%. This assumption can have a significant impact on the compressor capacity. The actual pressure drop (static plus dynamic) can be calculated with the pulsation model. This pressure is the used in the System Performance Model to more accurately determine the compressor capacity. The variance between the original performance (based on the assumed 2.5% pressure drop values) and the performance using the accurately calculated system pressure drop (from the pulsation models) is shown in Figure 3.2.

Note:

- positive variance = compressor can deliver more gas than expected
- negative variance = compressor does not meet the specified requirement
- original design estimate calculated using OEM performance program plus generic pressure drop assumptions

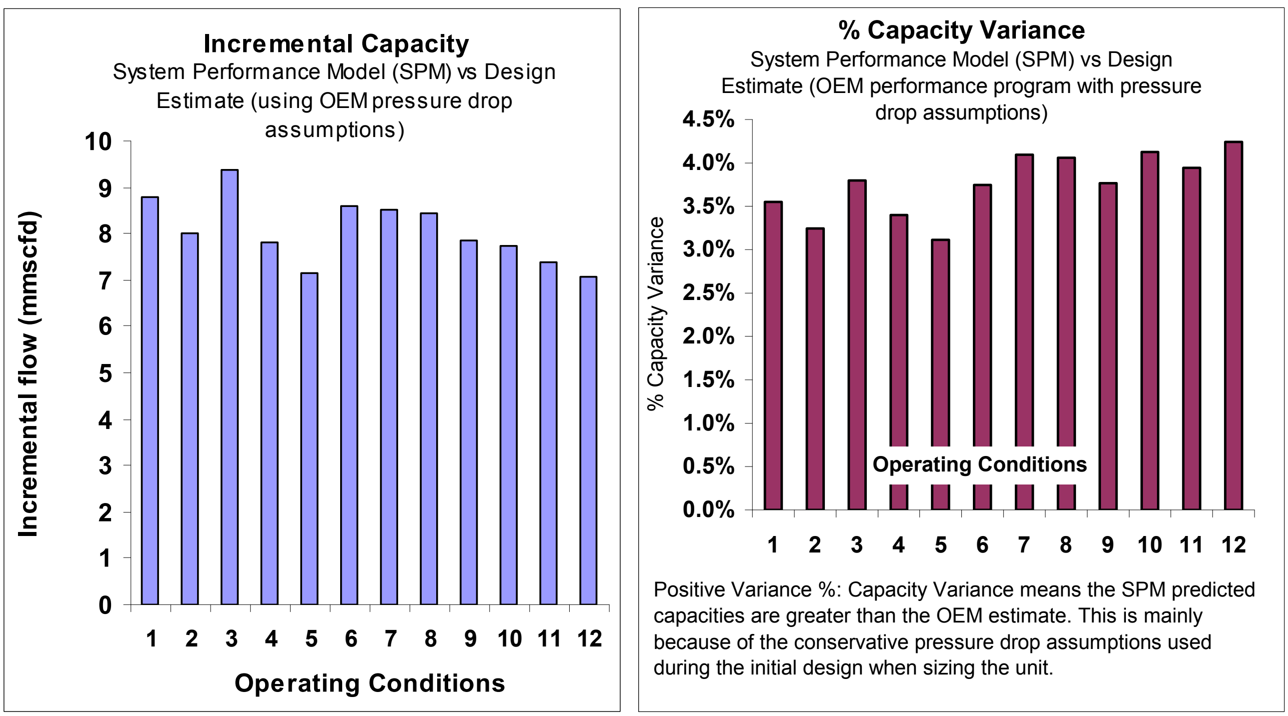

Figure 3.2: Capacity Variance Between System Performance Model and Original Design Estimate

The difference in the pressure drop assumed by the packager performance runs and total (static plus dynamic) system pressure drop calculated by the pulsation simulation was significant. The total pressure drop calculated was consistently less than 1% on both the suction and discharge sides. This difference in the pressure drop has been shown to have a significant effect on the calculated compressor performance. The comparison of the different performance calculations indicate that the initial pressure drop assumptions, which were used to program the PLC, were conservative and the capacity difference ranges from 3% to 5%. This corresponds to 7 MMscfd to 9 MMscfd difference in the assumed versus calculated capacity in absolute terms – a significant impact on the compressor throughput. Furthermore, a better pressure drop review helped to better clarify some issue with rod loads in certain areas of the operating map.

The operator was able to make some adjustments to the PLC based on collected compressor performance data, which validates the findings of the performance calculation comparison.

3.3 Optimized Compressor Loading (Pockets vs. Unloaders)

As often happens, the operating pressures for the station ended up being substantially different from what was initially anticipated. Furthermore, as the station expands, its site conditions will likely change as well. With the changing conditions, the potential of high rod loads becomes a concern. Alternate loading scenarios for the existing (and future) units were investigated to address the rod load concerns and look at optimizing loading over the anticipated wider range of operating conditions.

For this application, one solution to improve compressor loading is to replace the finger type valve unloaders (currently on four of the six cylinders) with fixed volume pockets on all six cylinders.

<u>Comparison: Increased Flow Across Map</u>

A good technique for evaluating the different loading schemes is to compare the calculated compressor capacity (flow) for the operating map. In Figure 3.3, the darker green areas are when the pockets-only option provides more flow, whereas the lighter green areas with data reflect areas where the unloaders-only option provides more flow. The numbers in the cells indicate the difference in flow for the pocket and unloader schemes. A positive value (**dark green**) means the pockets generate x% increased flow compared to the unloaders. A negative value (light green) means the unloaders have superior flow (% increase over pockets).

Here are some conclusions from this analysis:

- The light green area has an average of 0.8% improvement over pockets indicating very little difference between compressor loading schemes.
- The dark green areas show significantly higher flow with an average of 5% for all dark green areas. Note that many areas have substantial improvement in flow with more than a 10% increase for the higher discharge pressures. This is an important result as the station discharge pressure is increasing.
- Over the complete operating map, the pockets yield about a 2% increase in flow compared to finger unloaders.
- In summary, the pockets allow the unit to be run efficiently across the entire map. There are considerable performance gains as the station moves to the high discharge pressure condition.

Ps / Pd	600.0	617.3	634.5	651.8	669.0	686.3	703.5	720.8	738.0	755.3	772.5	789.8	807.0	824.3	841.5	858.8	876.0	893.3	910.5	927.8	945.0
500.0		-1%	-1%	-1%	-1%	-1%	-1%	-1%	4%	0%	5%	3%	0%	5%	3%	2%	5%				
515.0		-1%	-1%	0%	0%	-1%	-1%	-1%	-1%	3%	5%	5%	-1%	9%	7%	4%	2%	10%			
530.0			-1%	0%	0%	-1%	-1%	-1%	-1%	5%	1%	7%	1%	4%	9%	1%	-1%	0%	10%		
545.0				-1%	-1%	-1%	-1%	-1%	-1%	-1%	5%	2%	7%	2%	9%	4%	2%	4%	7%		
560.0					-1%	-1%	-1%	-1%	-1%	-1%	-1%	2%	7%	4%	4%	7%	5%	4%	7%	20%	
575.0					10%	-1%	-1%	-1%	0%	0%	-1%	3%	3%	7%	4%	7%	8%	2%	5%	9%	18%
590.0						-1%	-1%	-1%	0%	0%	-1%	-1%	5%	3%	6%	1%	10%	5%	4%	11%	11%
605.0							-1%	-1%	-1%	-1%	-1%	-1%	0%	4%	8%	3%	5%	7%	5%	8%	6%
620.0								-1%	-1%	-1%	-1%	-1%	-1%	2%	1%	8%	3%	10%	8%	0%	-3%
635.0									-1%	-1%	-1%	-1%	0%	0%	4%	3%	5%	3%	11%	1%	-4%
650.0									10%	-1%	-1%	-1%	0%	0%	0%	4%	6%	5%	7%	4%	-6%
665.0										-1%	-1%	-1%	-1%	-1%	0%	0%	1%	7%	3%	8%	-1%
680.0											-1%	-1%	-1%	-1%	0%	0%	3%	2%	7%	5%	3%
695.0												-1%	-1%	-1%	-1%	0%	0%	4%	6%	4%	5%
710.0													-1%	-1%	-1%	0%	0%	-1%	2%	8%	5%
725.0													10%	-1%	-1%	-1%	-1%	-1%	-1%	1%	8%
740.0														1%	-1%	-1%	-1%	-1%	-1%	2%	4%
755.0															0%	-1%	-1%	-1%	-1%	-1%	2%
770.0																-1%	-1%	-1%	-1%	-2%	-3%
785.0																	-1%	-1%	-1%	-2%	-2%
800.0																	10%	-1%	-1%	0%	-1%

Dark Green: % flow increase due to pockets (vs. unloaders). Average of 5% improvement in this area, a large gain.

Light Green: % flow increase due to unloader (vs. pockets). Average of 0.8 % improvement in this area – indicating solutions are essential the same.

Figure 3.3: Difference in Maximum Flow: Finger-type Unloaders (light green) vs. Fixed Volume Pockets (dark green)

Another way to view the differences in the options is to plot their maximum flow rates as a surface map, as shown in Figure 3.4. The plot shows the calculated maximum flow for the full range of suction and discharge pressures. The red areas indicate the calculated flow with the unloaders and the green areas show the flow for the pocket configuration.

Why does each option sometimes outshine the other? The reason for this is that when the pockets are configured with the unit, there is more fixed clearance on the compressor cylinders as compared to the finger-type unloaders. This added clearance effectively reduces the maximum unit loading while subsequently maximizing the unit flow rate when all pockets are used at the higher discharge pressures.

The finger-type unloaders have several disadvantages. The fingers used to deactivate the compressor valves impede gas flowing through the valves whether the unloaders are being used or not. This impedance or flow resistance requires a bit more work to get the gas through the head end suction valves. Also, when the unloaders are used, the power required to pull and push the gas into and out of the head ends is wasted power. Additionally, the unloaders-only option provided for only five (5) distinct load steps, while the pockets-only option provided for seven (7) distinct load steps

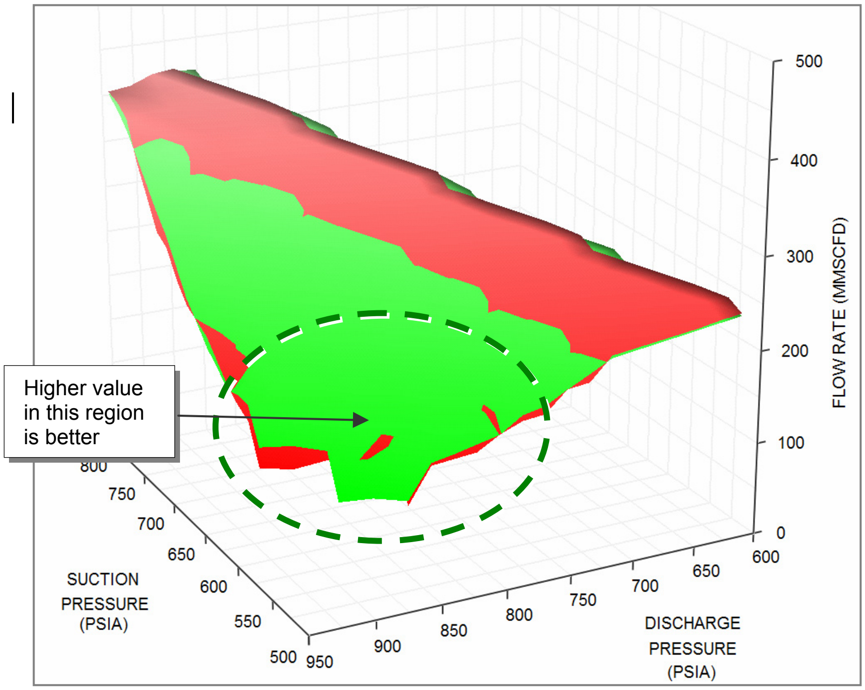

Figure 3.4: Flow Map (Pocket vs. Unloader)

For these two arrangements, the current configuration benefits from having minimum fixed clearance, but suffers from requiring additional power at all times, and results in wasted power when ends are deactivated. The pocket-only proposal suffers from requiring additional fixed clearance per head end, but benefits from maximizing the amount of power available to compress gas.

Thus, there are times when each arrangement has an advantage over the other. However, across the entire operating map used in this study, the pocket-only proposal yields the best long term results. When the unloaders-only option is better, it provides only a small amount of improvement; when the pockets-only option is better, it provides a noticeable improvement. Also, the improved performance of the pockets is at the higher discharge pressures, which are more likely the operating pressures for the station's foreseeable future.

Ultimately, the decision as to which compressor control scheme is better resides with the owner. That is, on what portion of the defined operating map will the unit most often operate? If the owners knows this information, and can weight various sections accordingly, then they may elect for a different option, as compared to assuming equal weighting across the entire operating map. In the case of Piedmont, more preference was given to areas of higher discharge pressure, the areas where the pockets-only option excelled.

Another common plot that helps when comparing alternative solutions is a **Full Map Safety Check**. In this

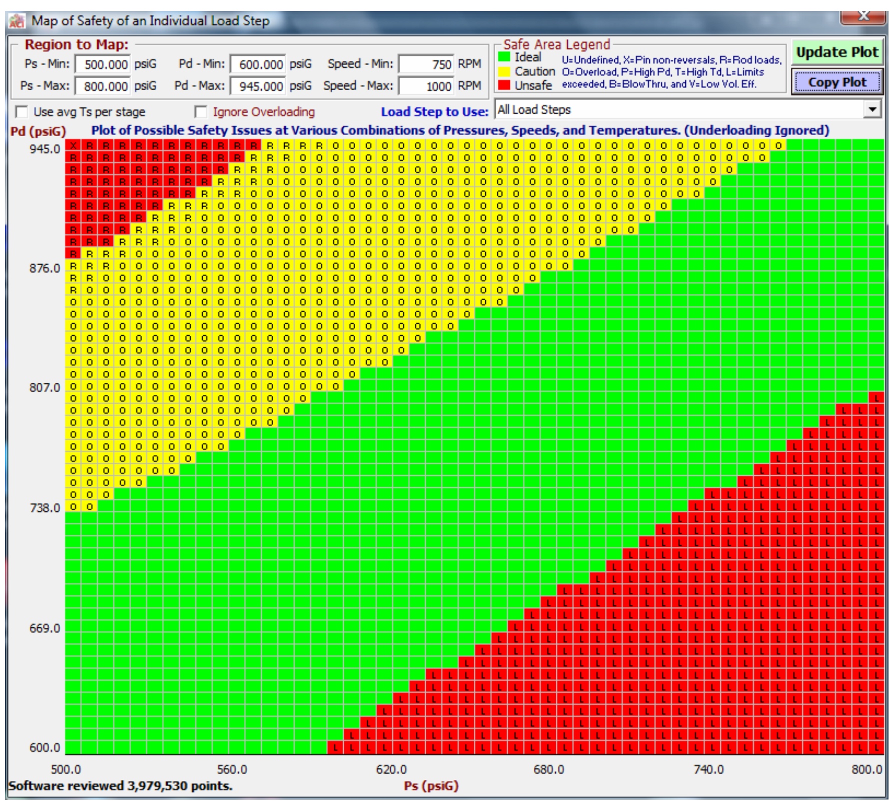

Figure 3.5a: Safety Map for Unloader Configuration

plot, “safe” means reliable compressor operation such as adequate rod load, allowable discharge temperatures, within pin reversal limits, with volumetric efficiency limits, etc., but does not include excessive pulsation forces. For these maps, green areas are safe for all load steps regardless of speed, pressures, or suction gas temperatures. Red areas are unsafe for all load steps at any speed and any suction temperature. Yellow areas identify areas where unit safety is a function of load step, speed, and gas temperatures requiring special attention to the control to operate safely. Thus, when maps show a lot of yellow area, then a properly programmed PLC is prudent for optimal unit control.

In the case of Piedmont, both options result in about the same safety operating map (see Figures 3.5a and 3.5b. For the Piedmont case, the basis for the unloading hardware selection resided more with increasing potential flow rates rather than increasing operating map potential. For other customers, expanding the operating map may be of more importance

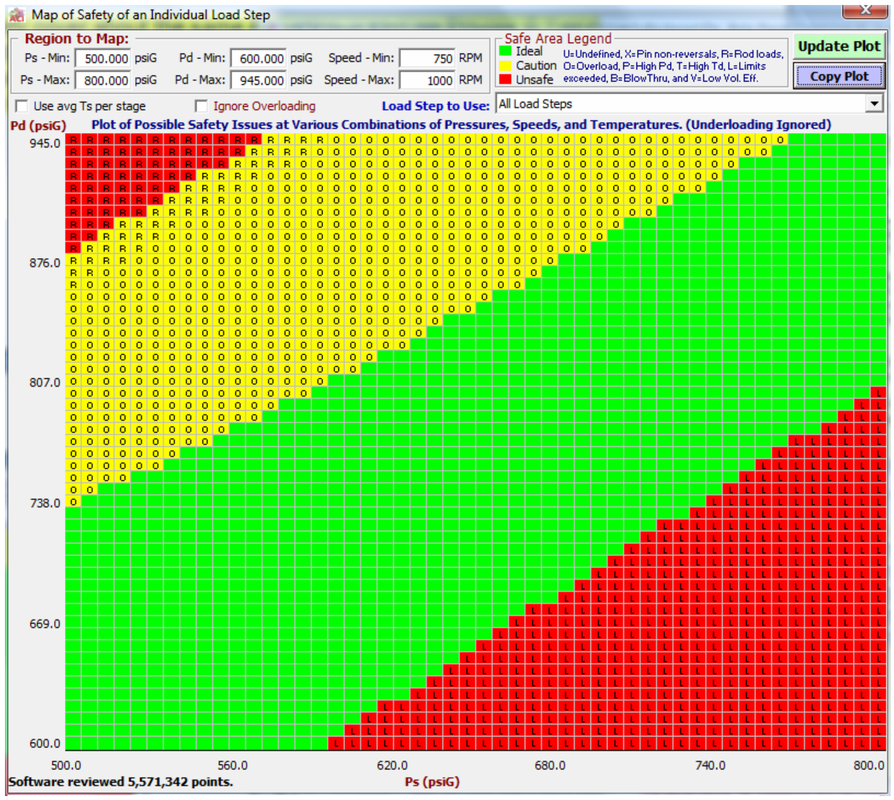

Figure 3.5b: Safety Map for Pocket Configuration

While this paper only covers one alternative solution to meet Piedmont’s goals, others were proposed. In particular, reducing the cylinder bore from the current size of 13.625-inches to the next smaller bore in the same cylinder class, 13.125-inches. The advantage of this proposal was that it helped to reduce rod load concerns at some of the higher compression ratios (i.e., expanded operating map); however, its disadvantage was that it reduced maximum flow rates (increasing flow rates was the primary goal of the study).

Pulsation Effects

The SPM model highlights the variances between the OEM performance program (with generic assumptions) and actual system performance. This variance is due to effects calculated by the pulsation model. The pulsation model calculates the static and dynamic pressure drop through all components of the system. This pressure drop is then used in the performance calculation resulting in capacity variance as demonstrated in section 3.2. Also, pressure pulsations at the compressor valves will impact the compressor performance. This effect can be quantified by the pulsation model.

Figure 3.6 is a chart illustrating the differences in the compressor performance for the full operating map when the pulsation effects are included. This example chart shows the percent (%) change in power or load. In many conditions, the adjustment is minor at 0% - 2%; however, other conditions shows a more significant change in the order of 3% - 10%. As a minimum, this more accurate compressor performance analysis can be used to make adjustments to the PLC control system so the compressor operation can be better controlled. A more powerful use for this information is to compare the compressor performance for different station or compressor package configurations. Higher capital costs for some designs may be justified given the improvements in compressor performance that could be realized.

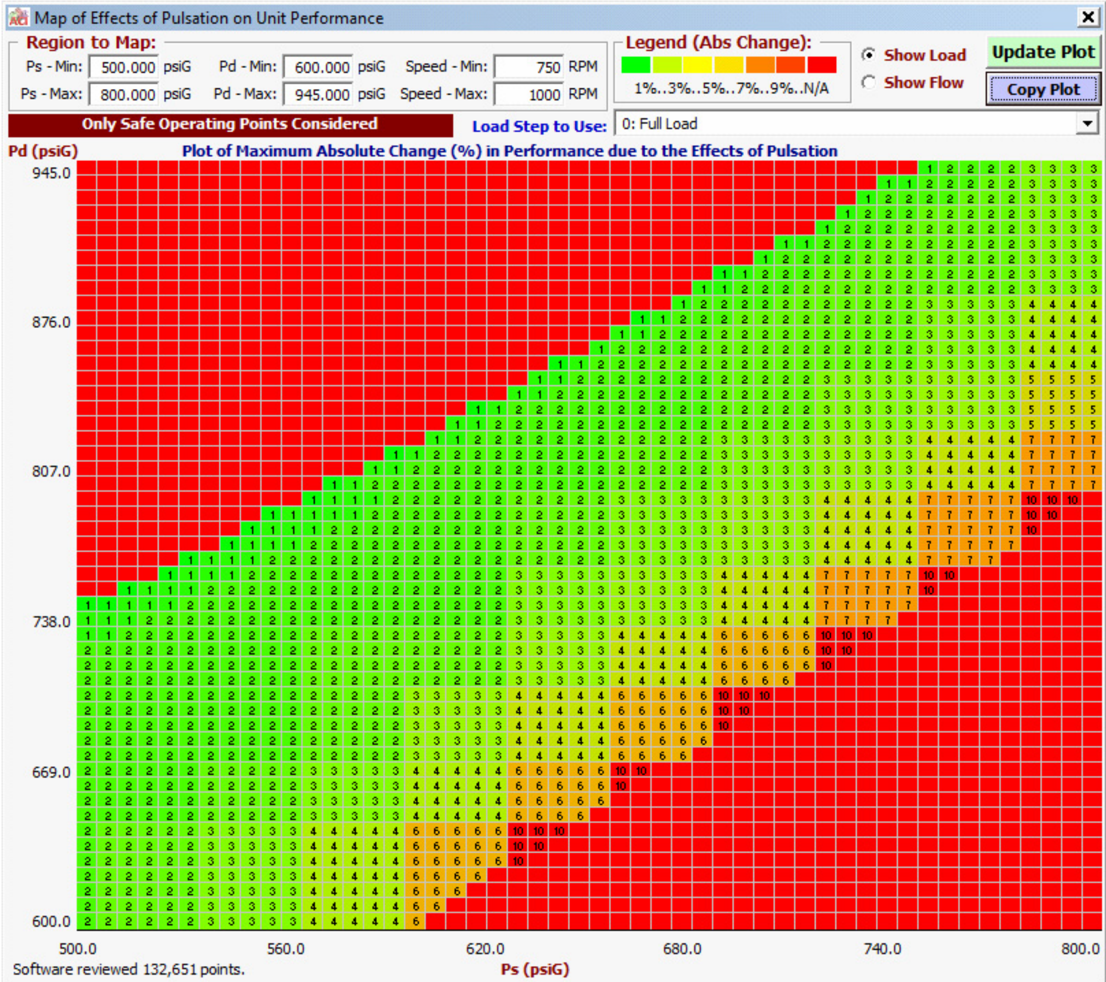

Figure 3.6: Adjustments to OEM Performance Program to Account for Pulsation Effects

3.5 Optimized Pulsation Control

3.5.1 Initial Design

An API 618 pulsation study was conducted on the existing units when they were fabricated in 2006. A review of this earlier work showed that although it was well done, there are several areas for improvement and optimization.

The initial pulsation control was based on 12 operating conditions. These conditions may have been sufficient for the initial design but do not reflect the current and future operating conditions. Also, the response of the system over the full operating map is not known. The pulsation bottle design was focused on minimizing pulsation forces in the bottles and minimizing pulsations leaving the bottles. The result was that large pulsation bottles were designed using a low-pass filter type. The static pressure drop from the bottle internals was calculated to be 15% over the API 618 guideline.

Recognizing these limitations, a pulsation model of the existing compressor installation was developed to create a base case for comparison of design options and evaluating specific system characteristics.

3.5.2 System Pressure Drop (Base Case)

This analysis of the total system pressure drop (static plus dynamic losses) for a single unit helps to direct efforts to areas that can be optimized. Table 3.1 and Figure 3.7 outline the total pressure drop between different locations in the system (refer to Figure 2.1). The pressure drop from the pulsation controls is shown to be significant for both the suction and discharge systems. The discharge piping loss and cooler loss are also significant.

Valve losses were not investigated in this phase of the project. An estimate of these losses is shown for completeness.

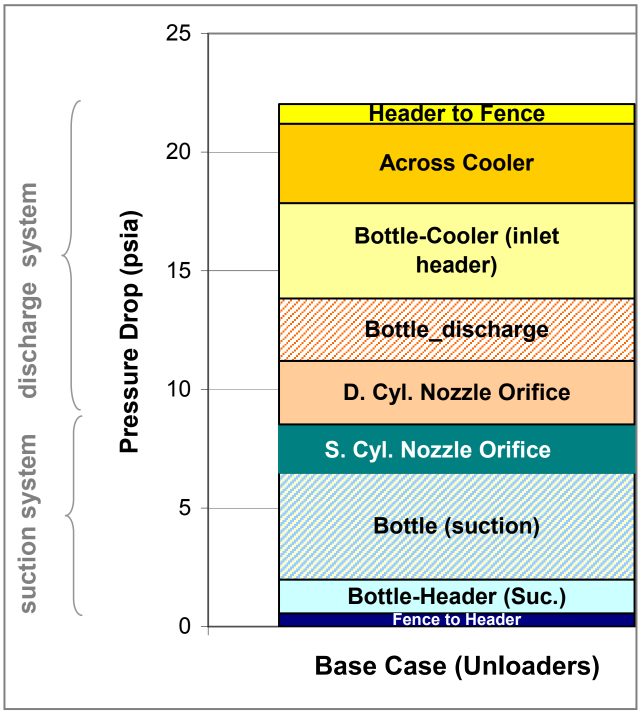

Figure 3.7: Pressure Drop Across the Compressor System (Base Case)

Base Case: With unloaders - no changes to system

Presure Drop Location	Pressure Drop	
Suction System	**(psia)**	**% of total**
S. Cyl. Nozzle Orifice	2.03	9.2%
Bottle (suction)	**4.51**	**20.5%**
Bottle-Header (Suc.)	1.42	6.4%
Fence to Header	0.56	2.5%
Total Suction	8.52	38.7%
Discharge Sysem		
D. Cyl. Nozzle Orifice	2.69	12.2%
Bottle_discharge	**2.63**	***11.9%***
Bottle-Cooler (inlet header)	4.01	18.2%
Across Cooler	3.35	15.2%
Header to Fence	0.83	3.8%
Total Discharge	13.51	61.3%
Total (psia)	**22.03**	**100.0%**

Table 3.1: Summary of System Pressure Drop (Fence to Fence)

3.5.3 Change To Pulsation Bottle Design

Changes to the pulsation bottles to minimize pressure drop were investigated as these were identified as high pressure drop components. Also the proposed change in the compressor capacity control from finger-type unloaders to pocket unloaders will tend to reduce the pulsation energy that the compressor cylinders generate. This reduction in pulsation energy means that the pulsation bottle design can be relaxed.

The first step of the project involved evaluating minor modifications to the pulsation control. The changes included maintaining the existing pulsation bottle size and simply changing the internal baffles and choke

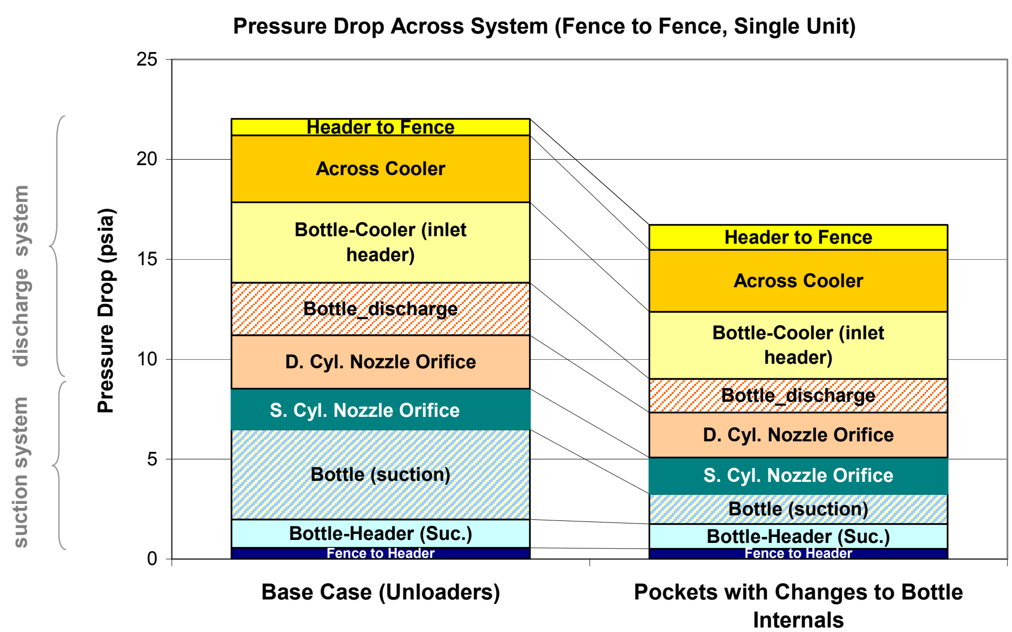

Figure 3.8: Comparison of System Pressure Drop (Fence to Fence) for the Base Case and Revised Bottle Internals with Pockets

tubes. This design modification results in a new bottle that can be easily installed in the existing installation.

The pulsation models were rerun to evaluate these bottle internal changes. These modifications resulted in significant improvements in reducing total pressure drop while still maintaining acceptable control of pressure pulsations and shaking forces. It was determined that the suction and discharge bottle pressure drop could be reduced by 66% and 37% respectively. This relatively simple change in the bottle internal results in an overall reduction in the system total pressure drop of 20%. Figure 3.8 and Table 3.2 show these results in more detail.

Presure Drop Location	Base Case: With Unloaders	Install Pockets; Modify Internals	Reduced Pressure Drop (psia)	
Suction System	(psia)	(psia)	(psia)	%
S. Cyl. Nozzle Orifice	2.03	1.81	-0.22	-10.8%
Bottle (suction)	**4.51**	**1.52**	**-2.99**	**-66.3%**
Bottle-Header (Suc.)	1.42	1.24	-0.18	-12.7%
Fence to Header	0.56	0.51	-0.05	-8.9%
Total Suction	8.52	5.08	-3.44	-40.4%
Discharge Sysem			0	
D. Cyl. Nozzle Orifice	2.69	2.26	-0.43	-16.0%
Bottle_discharge	**2.63**	**1.67**	**-0.96**	**-36.5%**
Bottle-Cooler (inlet header)	4.01	3.36	-0.65	-16.2%
Across Cooler	3.35	3.1	-0.25	-7.5%
Header to Fence	0.83	1.26	0.43	51.8%
Total Discharge	13.51	11.65	-1.86	-13.8%
Total (psia)	**22.03**	**16.73**	**-5.3**	**-24.1%**

Table 3.2: Comparison of System Pressure Drop for the Base Case and Revised Bottle Internals with Pockets

The system total pressure drop has a direct impact on the compressor flow as demonstrated earlier in this paper. The reduced pressure drop with the revised pulsation bottle internal design was evaluated for a few discrete operating points which included:

- Condition 1: Low compression ratio (1.16)
- Condition 2: High compression ratio (1.52)
- Condition 3: Higher Suction/Discharge pressures

A comparison of the calculated flow for the base case (Case A), that is, the existing system, with the compressor modified with the pockets and the new pulsation bottle internals (Case B). As shown below in Figure 3.9a and 3.9b, there is no incremental benefit to Condition 1. For the other conditions, there is a significant increase in flow varying between 8.5% and 11.5%.

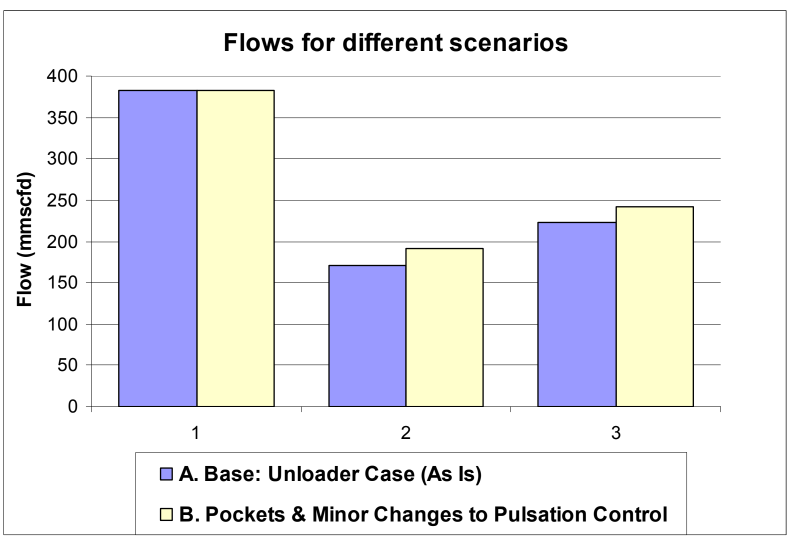

Figure 3.9a: Flow Comparison of Base Case (A) and Modified Case (B) over 3 common conditions

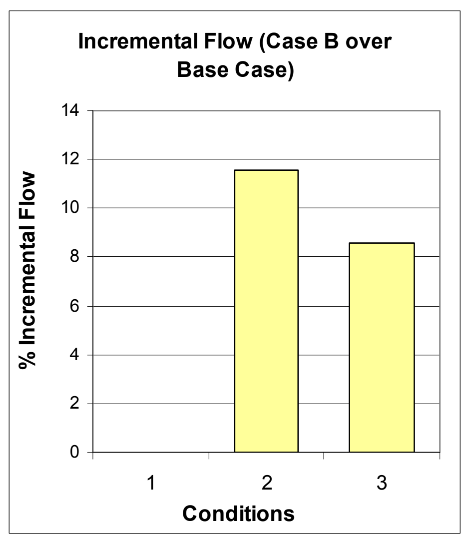

Figure 3.9b: Incremental Flow (Case B vs. Base Case in %)

The optimization process must also evaluate the new pulsation forces as a result of the modified bottle internals. Compared to the existing design, it was observed that the pulsation forces could be reduced by 45-70 % in most cases by adopting the modified design. Some representative examples of pulsation plots are presented below (Figure 3.10). The red line shows the existing system, the green line is the modified solution (changes to bottle internals), and the black is Beta's unbalanced force guideline.

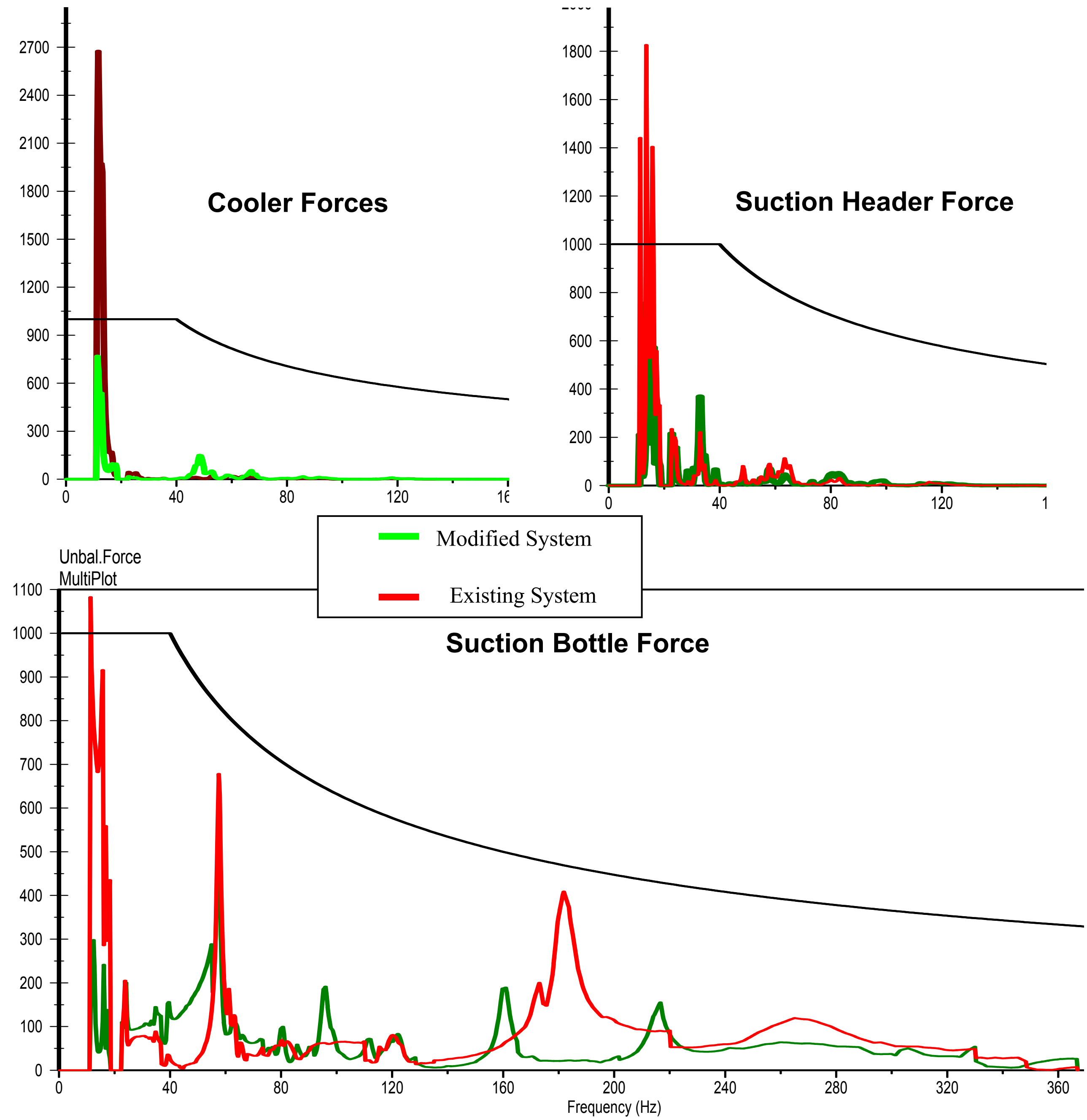

Figure 3.10: Reduction in Pulsation Forces

3.5.4 Other Opportunities

The scope of the system changes presented in this paper are relatively minor in terms of design changes but represent significant improvements in efficiency and increased station capacity. There are other opportunities for changing the systems design to optimize the overall design. The pressure drop in the discharge piping and through the cooler was identified as significant and a potential area for further investigation. It is also possible to determine alternative pulsation bottle designs and pulsation control devices which may result in further improvements in flow. Results from these activities are beyond the scope of this paper.

3.6 Financial Comparison

The Gross and Net Profit financial metrics [3] are an effective way to compare different design alternatives. The calculation is based on the following:

Gross Profit = Flow X Transportation Value

Net Profit = Gross Profit – Expenses (maintenance and fuel costs)

For each of the three conditions evaluated in Section 3.5, the financial analysis examines the INCREMENTAL net profit ($/year). The key assumptions include:

- A range of transportation fees were evaluated. The chart below illustrates the financial metrics for two prices: $0.06 and $0.18 per Dekatherm.
- $5.00/MMscf is applied for fuel gas cost.
- This is an average estimate used within the industry.
- Based on a review of the conditions, there was no incremental maintenance fee associated with the different conditions.

The financial impact of the base case (existing system) versus the compressor modified with the pockets and the new pulsation bottle internals (Case B) is shown in Figures 3.11 and 3.12.

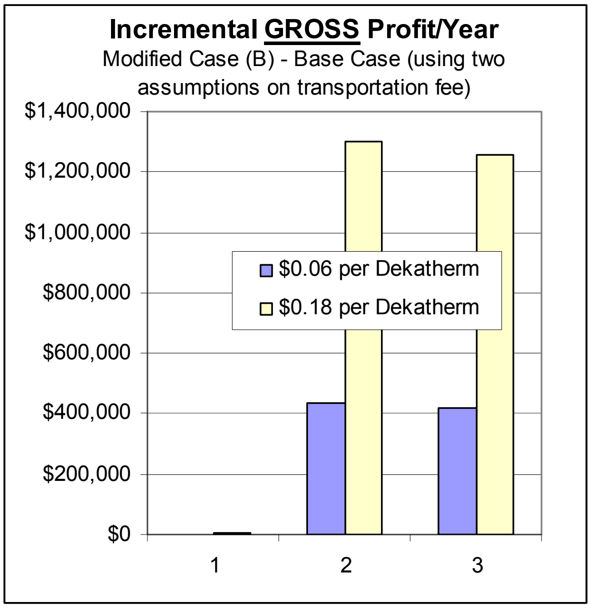

Figure 3.11 Gross Incremental Profit per Year (Modified - Base Case). Gross Profit = Flow x Transportation Fee

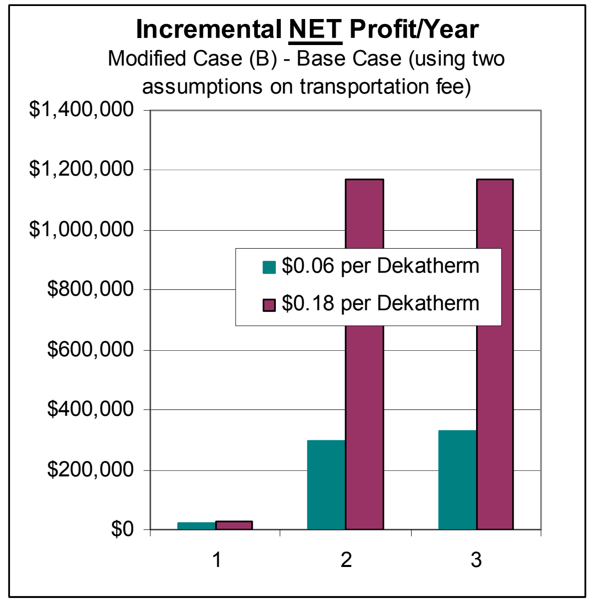

Figure 3.12 Net Incremental Profit per Year (Modified - Base Case). Net Profit = Gross Profit – (Fuel + Maintenance)

Overall improvement across entire map

The net changes resulted in increased flow rate (average across all conditions).

A common metric is Q/HP-hr to evaluate the improved capacity. The average increase was 2% for the minor changes in pulsation internals and modified control scheme. Additional improvements are available in different areas of the system.

3.7 Compressor Control

Very often, the compressor's performance characteristics (for the entire operating envelope) must be imported into a PLC or compressor control system. A fully automated compressor enables the unit to run more efficiently and generate higher throughput (e.g., reducing fuel, compressing more gas, lowering emissions and total carbon footprint, reducing wasted energy, avoiding areas of high rod load, etc.).

Tuning compressors towards real-world performance, to reflect the effects of dynamic and static pressure drops, and to reflect the effects of pulsation, are great concepts. However, ultimately the compressor is controlled by operators and/or a control panel. Thus, if the benefits of tuning and integrating pulsation data into the compressor model are not available to the station operators and/or for programming into the PLC/Control Panel, then most (if not all) of those benefits will be lost or diminished.

For operators, printed manual curves cannot properly indicate unit performance if that unit experiences significant areas where dynamic pressure drops or pulsation effects noticeably affect the unit's performance. Therefore, operators need software with dynamic performance to properly control their station's compressors. Embedding the results from an acoustical study that affect unit performance into a

Windows® based software package is trivial. Therefore, operators should expect the same level of unit performance prediction at their control end as the engineers and Gas Control have at their ends.

For units controlled via control panels, the situation becomes a bit more complicated. Standard PLCs do not often have the raw computing power to handle complex algorithms and intense database accessing involving Megabytes of potential data. As such, it becomes important that the results from the acoustic study can be rendered in such a way that the significant effects to unit performance can be reasonably integrated into standard controllers used in our industry (e.g., Allan-Bradley, GE Fanux, Siemens, etc.). Therefore, one key part of this endeavor was to be able to reduce the amount of data to a level that could be effectively used in a commercial PLC, while simultaneously maintaining the relevant data needed to accurately predict unit performance based on the results of the acoustical study.

In the case of the Piedmont units, the collective size of the databases generated from the full-map acoustic review was about 8.5 Mb of data. Initial consolidation reduced this down to about 6.7 Mb. Then, the data was further filtered, merged, and simplified to about 675 Kb. The final pass resulted in a compact, byte-oriented lookup table (ideal for PLCs) of only 130 Kb. Thus, the data went from 8,500,000 bytes to about 130,000, or about a 98.5% reduction in size.

3.8 Summary of Case Study

There are significant benefits using this optimized design approach:

- ability to operate across a much wider operating envelope
- improved flow in the key conditions (mid to higher discharge pressure) and equivalent efficiency in other conditions
- improved pulsation control (lower forces, less losses)
- more accurate control of PLC system (discussed below)
- significant financial improvement with relatively minor changes

This new control strategy will be implemented for new units, as well as existing units

4.0 <u>Conclusion and Recommendations</u>

Pipeline operators continue to focus on ways to improve the profitability and reliability of their stations. Achieving this goal requires an optimized design of new or existing compressor packages. Reducing pressure drop through the piping system represents a significant economic advantage for the industry.

There are many barriers that prevent optimization, such as:

- Lack of accurate information to evaluate the merits of different layouts or operating strategies;
- Conflicting design objectives; and
- Limited involvement early in the design process to evaluate the entire package and alternatives.

Based on the authors' experience, the following suggestions have proven to be effective at overcoming these barriers:

- The design team responsible for optimization includes the owner, its designated Engineering Consultant and optimization experts.
- Early in the design process, the team can assess different capacity control schemes, pulsation solutions, cooler designs, and other factors that influence the system performance.
- Problems occur when only a few operating points are evaluated. It is recommended that the performance and operating factors are evaluated over the entire operating envelope. This allows the owner to ensure the system will meet the intended requirements.
- Address the conflicting design goals and balance the need for lowest capital cost with operating flexibility and system efficiency.

The paper presented a case study that illustrates how the recommended process can be applied in practice. As a result of this work, a number of modifications are being implemented for the procurement of the new units and for modifying existing units.

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