Optimizing Compressor Design for Complex Reciprocating Compressor Installations
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Beta Machinery Analysis
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Abstract

Compressors in applications such as mainline transmission and gas storage are required to operate across a wide range of suction pressures, discharge pressures, and capacities. These applications require multiple compressor units, which create different operating scenarios and pulsation effects in the system.

An optimum design for these applications poses several challenges for the pulsation study:

- Designing pulsation and vibration control for all operating conditions
- Minimizing pressure drop
- Ensuring that capacity requirements are met while observing horsepower limits
- Identifying conditions that represent the limiting cases for each attribute

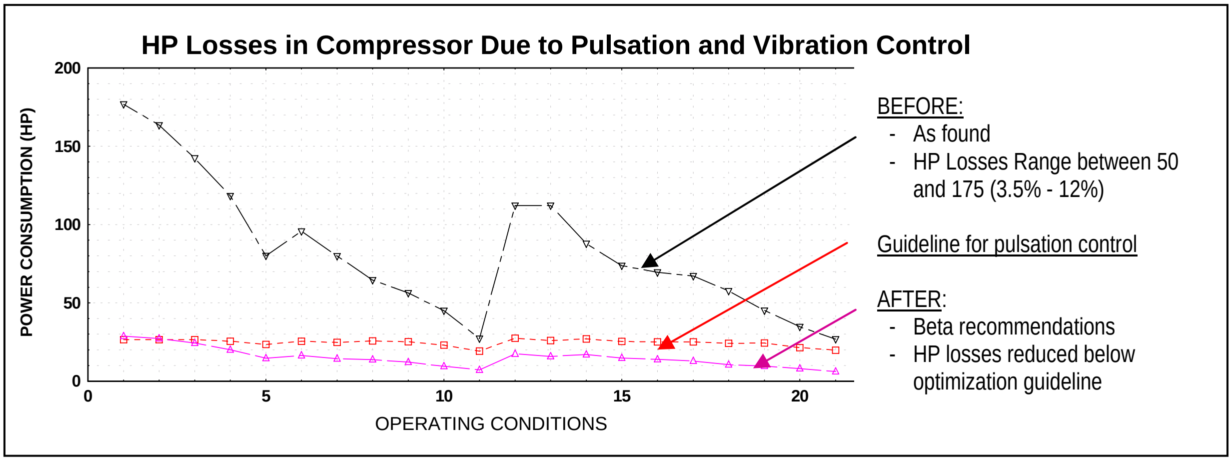
The last point poses a major challenge. Because of the complexity of these systems it is difficult to know what operating condition will govern. The limiting operating conditions for pulsation, unbalanced forces, pressure drop, and total horsepower will generally be different.

The designer is faced with the challenge of comparing various attributes:

- Across many operating conditions
- For multiple units
- For alternative designs

Traditionally, conservative assumptions are made during the design of the pulsation and vibration control devices to address the complexity of these systems. We suggest that this approach is incorrect and results in a serious compromise. Extreme operating conditions do not necessarily correlate to worst-case acoustical forces or pulsation levels. Furthermore, the compromise incurred with this approach does not get communicated appropriately to all involved parties. Ultimately, the end user has limited means, if any, to determine whether the actual operating scenarios have been considered in the analysis. In recent examples, the author has seen losses of over 150 horsepower (HP) on one unit due to this simplistic approach.

With new tools, designers can now simulate and compare results for many units and operating conditions. This allows for optimized designs that reduce losses significantly, as shown in the figure below. By freeing up horsepower, customers achieve higher capacity, lower operating costs, or both. In the case shown, an additional 2 MMSCFD was achieved **resulting in over 1.75 million of incremental profit per year.**



This paper describes methods of condensing the results in the form of a series of "profile" graphical presentations. These simple, but effective, presentations make the situation clear for the designer, supporting rapid and, even more importantly, accurate design decisions. The graphs provide practical tools to explain the tradeoffs clearly to the end user, enabling the end user to become part of the decision on design tradeoffs.

Introduction

Optimizing the compressor design to minimize vibration and operating costs is an important issue for the owner, packager, and machinery consultant. An effective study will save significant operating cost, and will maximize production capacity and reliability. Significant savings can be realized through optimizing pulsation control even for relatively straightforward installations.

Compressor packages often have many different operating conditions to analyze. In some cases the unit configuration is complex. In other cases, there are multiple packages at one site and they have many operating combinations. Compressors in applications such as mainline transmission and gas storage are required to operate across a wide range of suction pressures, discharge pressures, and capacities. These applications require multiple compressor units, which create different operating scenarios and pulsation effects in the system.

An optimum design for these applications poses several challenges for the pulsation study:

- Designing pulsation and vibration control for all operating conditions
- Minimizing pressure drop
- Ensuring that capacity requirements are met while observing horsepower limits
- Identifying conditions that represent the limiting cases for each attribute

The last point poses a major challenge, especially for complex systems, as it is difficult to know what operating condition will govern. The limiting operating conditions for pulsation, unbalanced forces, pressure drop, and total horsepower will generally be different.

The pulsation study designer is faced with the challenge of comparing various attributes often across many operating conditions, for multiple units, and for alternative designs. Once the designer has evaluated the various attributes, he or she must still succinctly present the findings to the various parties involved.

With new tools, designers can now simulate and compare results for many units and operating conditions. This allows for optimized designs that can reduce losses significantly. Condensing the results in the form of a series of "profile" graphical presentations makes the situation clear for the designer, supporting rapid and, even more importantly, accurate design decisions. The graphs provide practical tools to explain the tradeoffs clearly to the end user, packager, or machinery consultant, enabling interested parties to become part of the decision on design tradeoffs.

Case Study 1

This case study illustrates optimization ideas for improving reciprocating compressor throughput and operating efficiency. The optimization techniques can be applied during the initial design, reconfiguration, or revamp of a compressor package.

Situation:
A 1400 HP reciprocating compressor in a gas gathering application was designed for a variety of operating conditions including flow rates between 7 and 19 MMSCFD.

During an equipment review it was found that the unit was experiencing high horsepower losses. The analysis further indicated that the losses would prevent the unit from achieving the maximum capacity – a key requirement for the owner.

Table 1 outlines the characteristics of this common compressor package.

Table 1:

Compressor Details
- Flow: 7-19 MMSCFD
- 4 throw; 2 Stage; 1200 RPM
- Calculated BHP: 1415 HP
- Ariel compressor/Waukesha engine package
- Suction Pressure: 100-420 psig
- Discharge 1200-1400 psig

Operating Conditions
- 21 different operating conditions
- Different suction pressures
- Different compressor settings (double acting, single acting)

As found situation
- High HP losses due to pressure drop
- Not able to achieve its desired capacity

Optimized compressor design resulted in improved capacity and significant reduction in operating cost.

Pulsation Control Requirements:
The owner did not invest in a pulsation design study during the initial compressor design. As a result, the unit was delivered with many orifice plates to reduce pressure pulsations.

Pulsations are pressure waves created when the compressor valves open in the suction or discharge lines. Like a ripple on a pond, the pressure waves travel throughout the system. The pulsation pressure waves create high forces and vibration on piping and vessels. Figure 1 illustrates the forces (red vectors) that act on the piping. Every reciprocating compressor will generate pulsations; however the magnitude will vary due to geometry and other characteristics of the package.

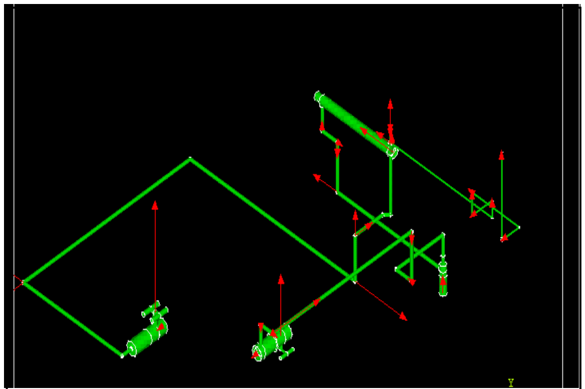


Figure 1: Compressor interstage piping. Pulsation related forces are shown as red vectors. Forces alternate throughout each revolution

Typically, compressors have pulsation control devices to reduce the forces and prevent failures. Various solutions are available to control pulsations; however, each solution has two types of costs: (1) the initial cost to install orifice plates, different piping, bottles, etc. and (2) the ongoing operating costs associated with these devices (power loss due to pressure drop). A pulsation and mechanical study (API 618 Design Study) evaluates the range of solutions and identifies the optimal approach.

Optimization Analysis:
During a pulsation analysis of the installation the performance, pressure drop, pulsation, unbalanced forces, and efficiency were evaluated throughout the 21 different operating conditions, over the full speed range of the engine.

In Figure 2, the <u>required brake horsepower (BHP)</u> for the package is compared to the <u>available BHP</u> from the engine. When this ratio exceeds 100% the unit will not achieve the required operating condition – at least, not reliably. The red stars on the chart illustrate key conditions where the capacity is being constrained.

The chart also illustrates the power used to control pulsations. Note the pulsation control requires over 10% of total BHP for some conditions.

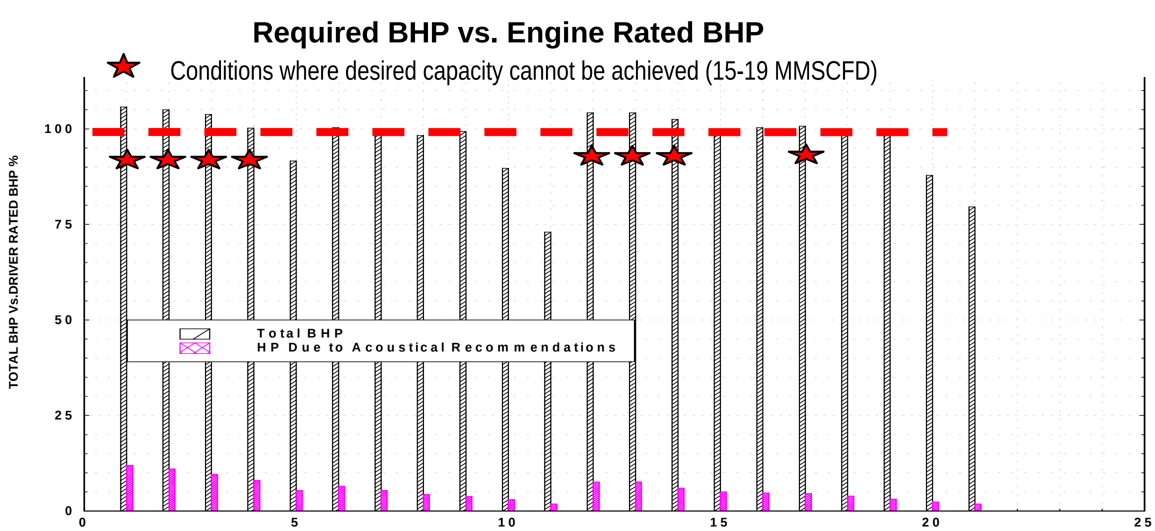


Figure 2: Total Required BHP vs. Available BHP from Driver (%)

Figure 3 presents the total HP losses in the "as found" case for each condition. Notice that losses can exceed 170 HP – a significant operating cost.

Rather than using only orifice plates, modifications were made to bottles to include baffles and a choke tube. With these changes, the losses were reduced significantly - from 90 up to 150 HP for the key operating conditions.

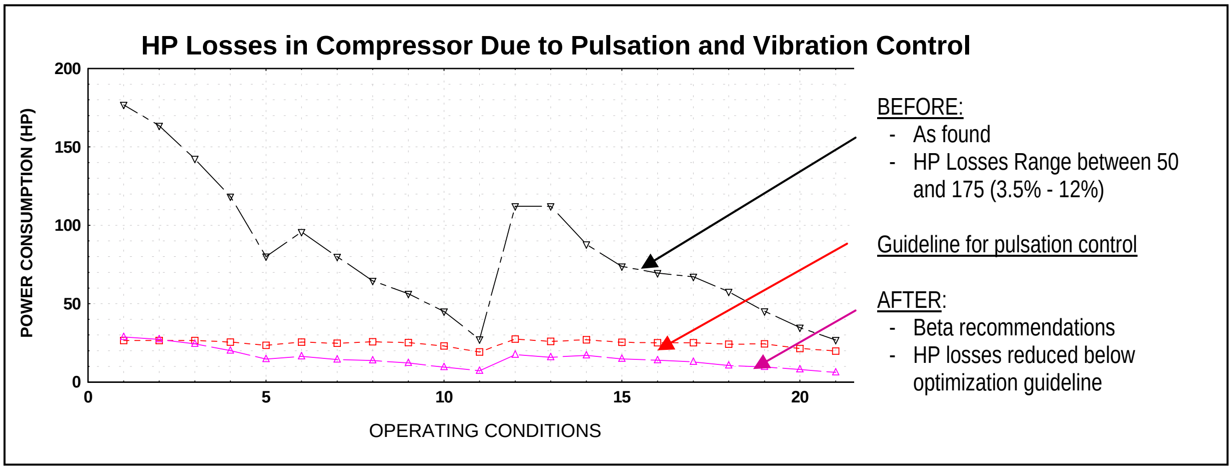


Figure 3: HP Losses Per Condition (Before and After)

Results of Optimization

By reconfiguring the piping and vessels, the owner was able to gain significant power. Table 2 outlines the HP savings for the key operating conditions.

The annual savings in fuel gas through the improvement is estimated at $75,000 per year – a reasonable gain.

The more interesting result is that the unit can deliver an additional 1.0 to 2.0 MMSCFD of throughput. Based on the customer's pricing situation, this translates to over $3.0 million of incremental production.

Operating Condition #	1	2	3	4	12	13
HP Savings	150	137	118	100	95	100
HP/Q Ratio	72	75	83	92	92	92
Incremental Q (Capacity in MMSCFD)	2.08	1.83	1.42	1.09	1.03	1.09
Incremental Revenue (Annual)	$6.1 million	$5.3 million	$4.2 million	$3.2 million	$3.0 million	$3.2 million

Table 2 – HP Savings for Key Operating Conditions

The cost of the pulsation study and changes to bottle internals and piping were under $80K, generating a payback in less than a month (based on capacity increase). The project paid out in about a year when based on fuel gas savings alone.

Case Study 2

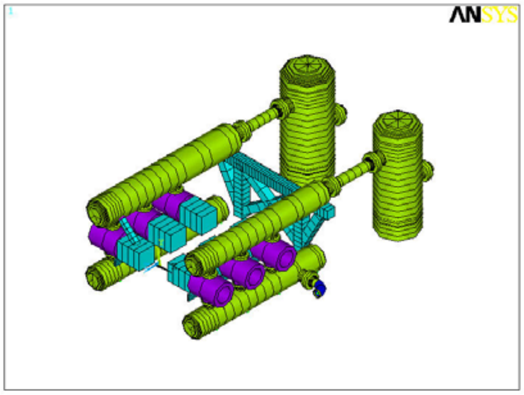
This case study illustrates how new tools can be used to optimize the design for a complex installation.

Situation:
Two new compressor packages were purchased for a storage facility. Due to the complexity of the unit an API 618 Design Approach 3, (Studies M.2 –M.8) plus a thermal analysis, was specified for the units. Ideally, for an installation of this type the station piping should be included in the acoustical models used to design the pulsation control devices. However, in this case the project schedule dictated that prior to the station piping layout being available for analysis, the pulsation bottles had to be designed.

Table 3 outlines the characteristics of this typical storage facility compressor package.

<u>Table 3:</u>

Compressor Details
- Flow: 63 – 337 MMSCFD
- 6 throw; 1 or 2 Stage
- Rate BHP: 4735 HP at 1000 RPM
- Ariel compressor/Cat engine package
- Suction pressure: 400-900 psig
- Discharge 600-1850 psig



Operating Conditions
- 97 different operating conditions
- Different suction and discharge pressures
- Different compressor settings (one or two stage, double acting, single acting, inactive cylinders)

Pulsation Vibration Requirements:

Operating Conditions
One of the first tasks in designing pulsation control for a complex storage facility is to gain a thorough understanding of not just the range of operating conditions for the compressor, but also the range of conditions each cylinder (or pulsation bottle) will experience. Figures 4 and 5 graphically represent critical operating parameters and critical performance parameters of all operating conditions for overall compressor operation for one and two stage operation. Data is also available for individual cylinders.

- X-axis of all plots are operating condition numbers
- Operating condition numbers were determined by using performance requirements from the owner

The critical operating parameters shown in Figures 4 and 5 are:

- Pressures (first suction and final discharge)
- Unit compression ratios
- Number of single acting (unloaded one end) and inactive (blow through) cylinders

The critical performance parameters in Figures 4 and 5 are:

- Capacity (mass flow rate) Q
- Volumetric Efficiency
- Power consumption BHP
- BHP/Q (the lower the ratio, the better the performance) to find good operating conditions
- Rod loading

Typically, low compression ratios, high horsepower, and single acting or inactive cylinders tend to be the worst pulsation conditions. The high flow conditions tend to be the worst pressure drop conditions. A simplified approach to this analysis would be to try to pick a few conditions that represent the extremes of the variables.

Based on an analysis of the operating conditions, and some preliminary acoustical modeling, conditions 30, 33, 37, and 67 were flagged to be the worst pulsation cases for one stage operation and conditions 7, 16, 24, and 31 as the worst pressure drop cases. For two stage operation the analysis flagged conditions 14, 19, and 21 to be the worst pulsation cases and conditions 10, 15, and 19 as the worst pressure drop cases. Many of the conditions that ended up dictating the final acoustical design did not correlate to the extremes of the operating range. Thus, using a simplified approach and only analyzing a few operating conditions would have resulted in a design that would not represent an optimum balance of pulsation control, pressure drop, and capital cost.

Figure 4: UNIT SUMMARY (By Operating Condition) – One Stage Operation

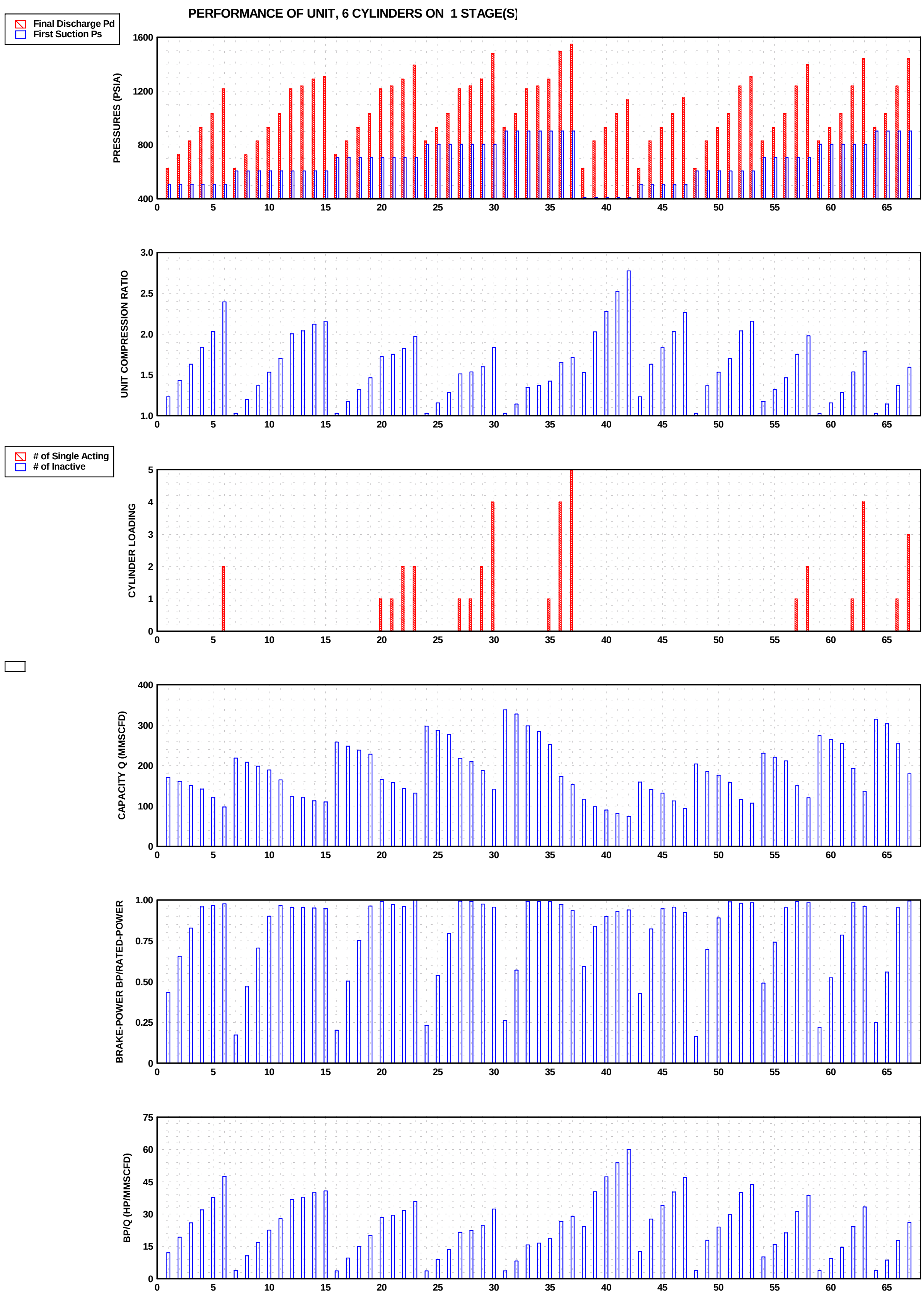
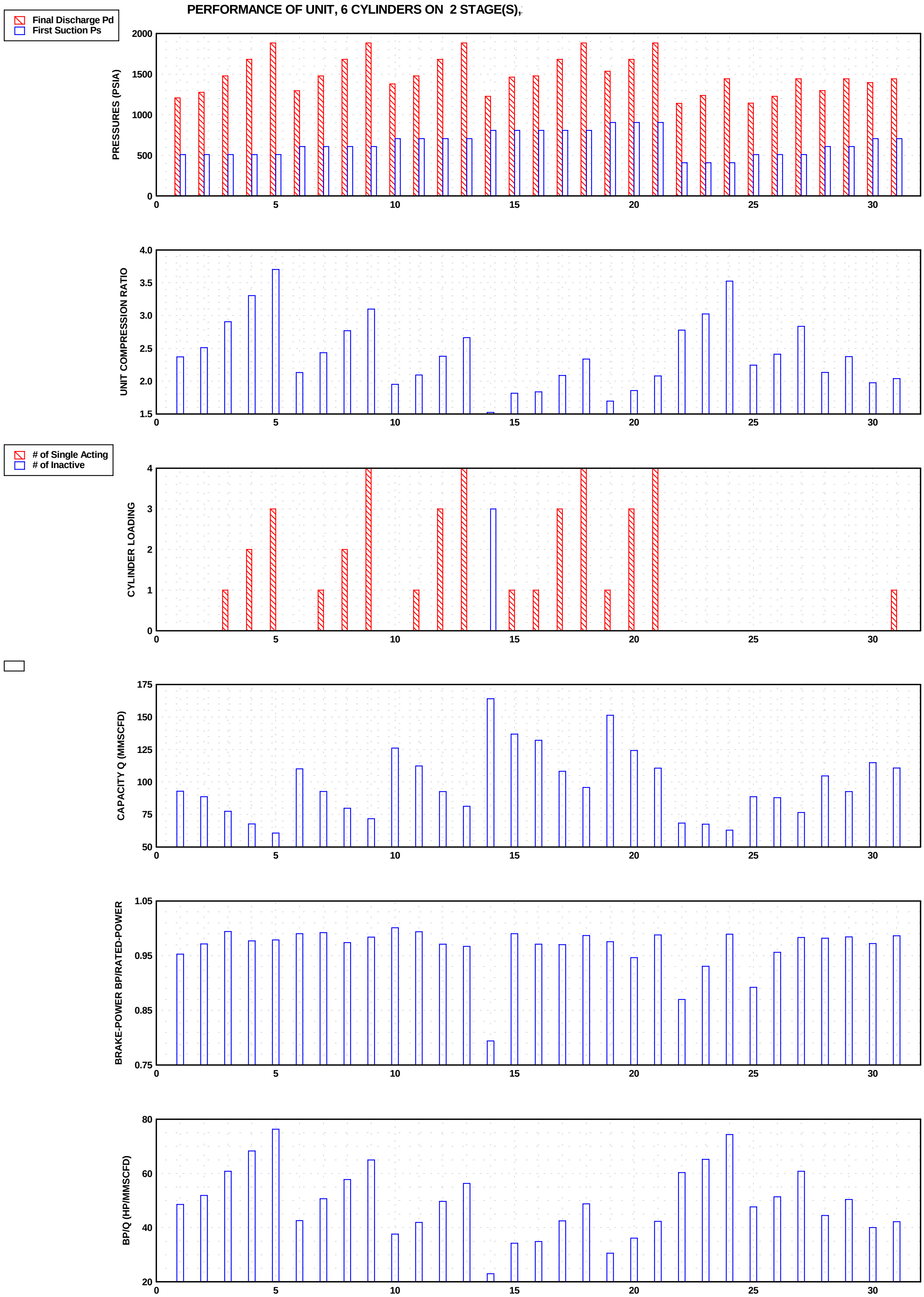


Figure 5: UNIT SUMMARY (By Operating Condition) – Two Stage Operation



Acoustical Analysis

In optimizing pulsation control devices the designer will need to balance a variety of parameters:

- Compressor side pulsation (pulsation levels at the compressor valves)
- Pulsation in the piping
- Pulsation induced unbalanced forces in vessels and piping
- Static and dynamic pressure drop (and flow velocities) across pulsation control devices
- Meter error
- Mechanical response characteristics of pulsation bottles
- Physical constraints of the compressor skid package or installation
- Capital cost versus operating cost

Typically, this type of compressor and installation would require four chamber, low pass filter design pulsation bottles. For this particular installation larger scrubbers are mounted about 6' away from the back of the compressor. Preliminary bottle sizing calculations for the suction bottles indicated that a shorter, three chamber bottle design utilizing the scrubbers as the "fourth" chamber may have been an effective layout for balancing the design parameters. The proposed layout would have allowed for much simplified, and hence more cost effective, support structures for the suction bottles. Tentative solutions were developed for both the three and four chamber bottle designs; see Figure 6 for a sketch of the two bottle designs.

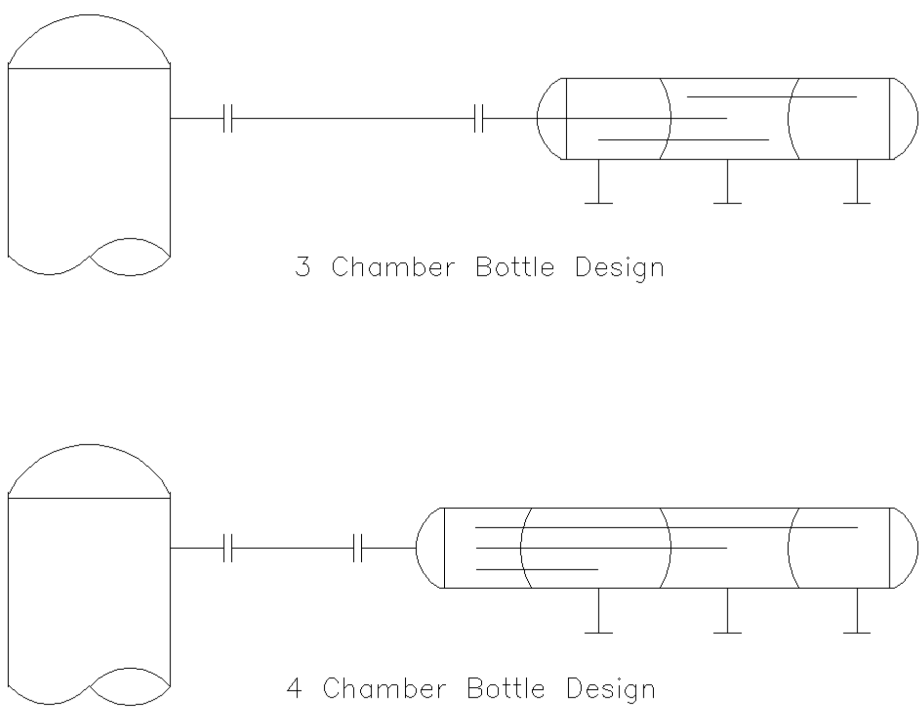


FIGURE 6: Sketch of Bottle Designs

Three key parameters for One Stage Operation were compared for the two solutions over the full range of conditions; suction bottle unbalanced forces (Figure 7), pulsation levels upstream of the scrubbers (Figure 8), HP losses (pressure drop) through the pulsation control devices (Figure 9).

Unbalanced forces across the bottle (except for a few conditions that could likely be lowered by fine tuning choke tube locations) and pulsation levels upstream of the scrubber were similar in magnitude. To achieve similar pulsation control results, significantly more pressure drop and HP losses were introduced into the system with the three change design; thus it became obvious that the four chamber bottle design provided the best solution, even though a support structure would be required for the overhung end of the suction bottles.

In order to minimize pressure drop and, hence, long term operating cost, bell mouth entrances and diffuser exits were recommended for all the choke tubes in the suction and discharge bottles (3 choke tubes per bottle x 4 bottles x 2 units = 24 choke tubes). The compressor packager who will be building the bottles typically uses a forged bell mouth entrance and a straight cut exit.

The packager questioned whether the cost of tapering the choke tube exits, or purchasing forged diffusers (24 x ≈$1,900 = $45,600 USD) would be worth the investment for their customer. Figures 10 and 11 illustrate the Power Consumption versus Operating Conditions (One Stage Operation) for the scenario where straight cut exits are used on the choke tubes and where diffuser exits are used on the choke tubes. For all plots the cylinder nozzle orifice plates and all choke tubes (using bell mouth entrances) are included for both suction bottles and both discharge bottles. The top plot on the figures illustrates the pressure drop through the pulsation control devices converted to equivalent HP. The guideline shown in the plot is the API 618 guideline pressure drop converted to HP. The second plot shows the HP as a percent of guideline. The last plot on each figure represents the total HP consumption (compression HP + auxiliary HP + HP consumed by pulsation control devices) for each condition.

The plots demonstrate a few points.

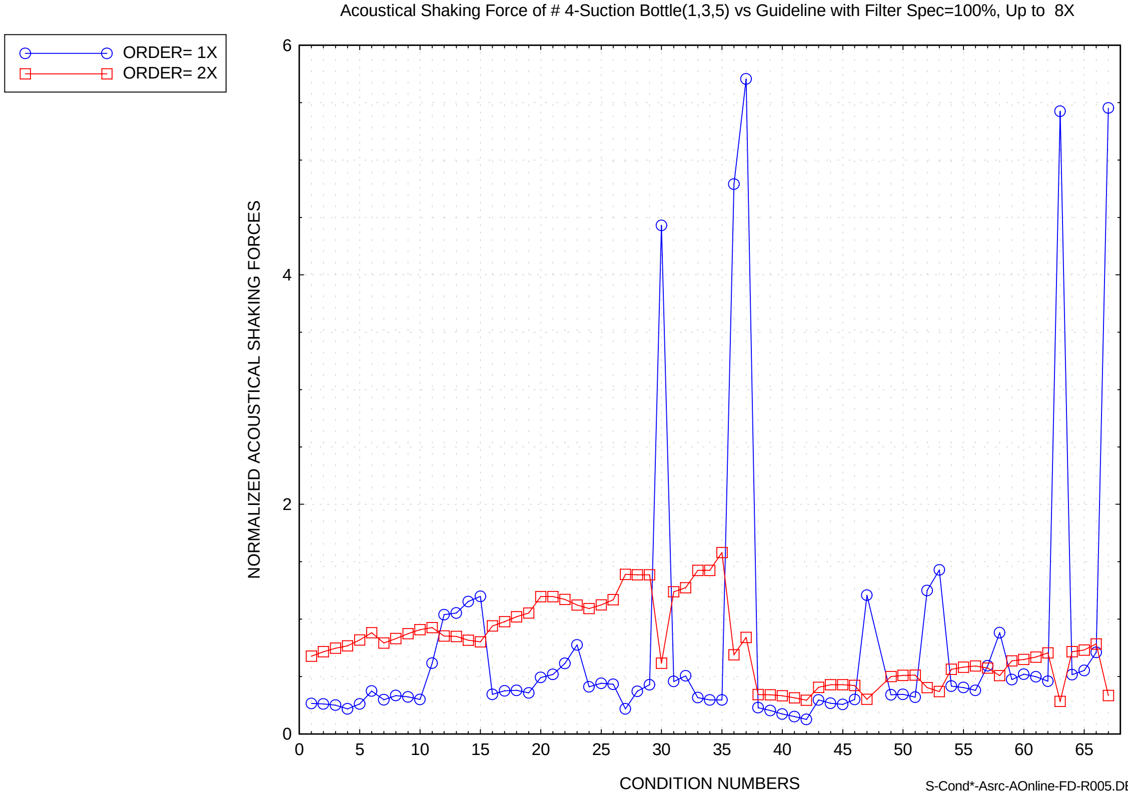
- The worst pressure drop conditions (7, 16, 24, and 31) are conditions where there compression HP is low; therefore, unit capacity would not be adversely affected by high pressure drop.
- For several conditions (23, 27, 33, 34, 35, and 67) compression HP (plus auxiliary) is consuming almost all of the available HP, therefore, any additional HP consumption may adversely affect unit capacity.
- In the worst case the choke tubes with straight cut exits consume about 30 HP more that the choke tubes with diffuser exits.

Pressure drop and HP losses were significant enough to consider choke tube end treatments of some sort. A third alternative of trimming down a standard reducer was considered. The modified reducer solution lowered the pressure drop and HP losses almost as much as the diffuser exit approach (see Figure 12), but provided a much more cost effective solution for the packager.

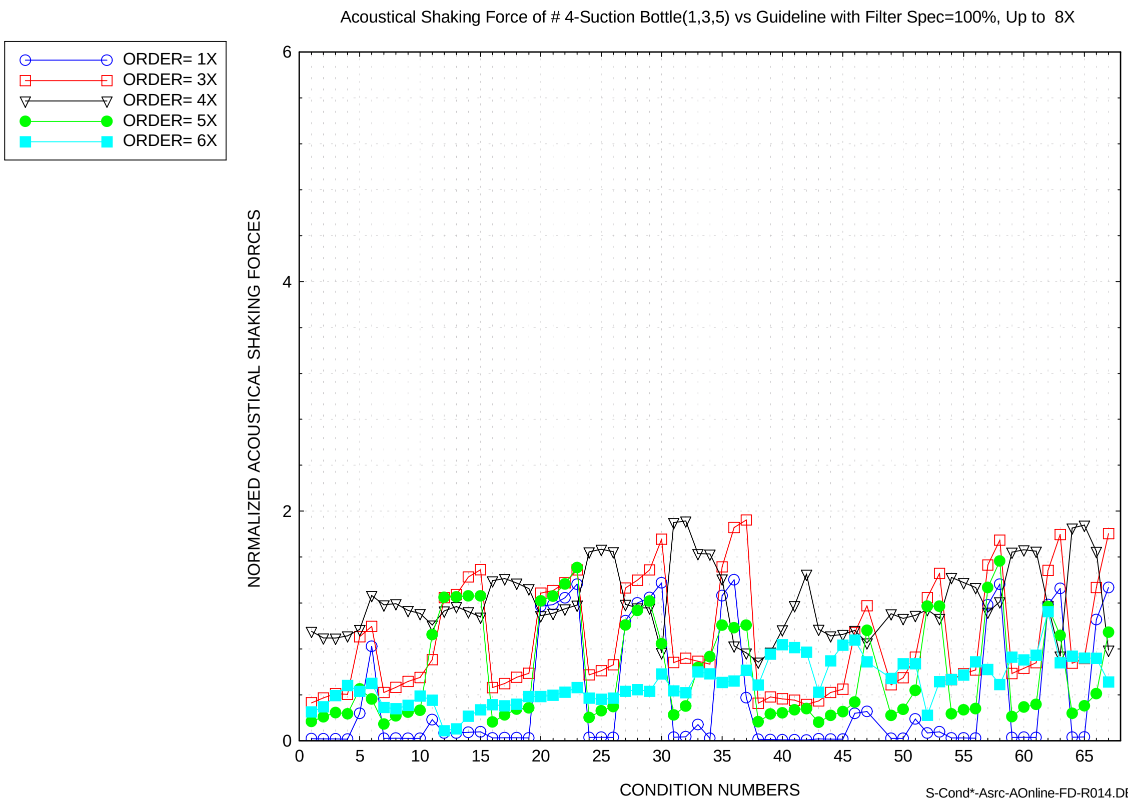
For facilities operating over a wide range of conditions, such as storage facilities, it is not practical to meet typical industry guidelines for all parameters for all conditions. Thus, it becomes the designer’s job to understand the various tradeoffs and ultimately communicate the various options with the parties involved. For example, there was a reluctance to install end treatments on the choke tubes due to capital cost of the modification. A graphical representation of the compromise in pressure drop helped the client make the decision to proceed with choke tube end treatments.

Figure 7: SUCTION BOTTLE UNBALANCED FORCES – One Stage Operation

3 Chamber Bottle Configuration



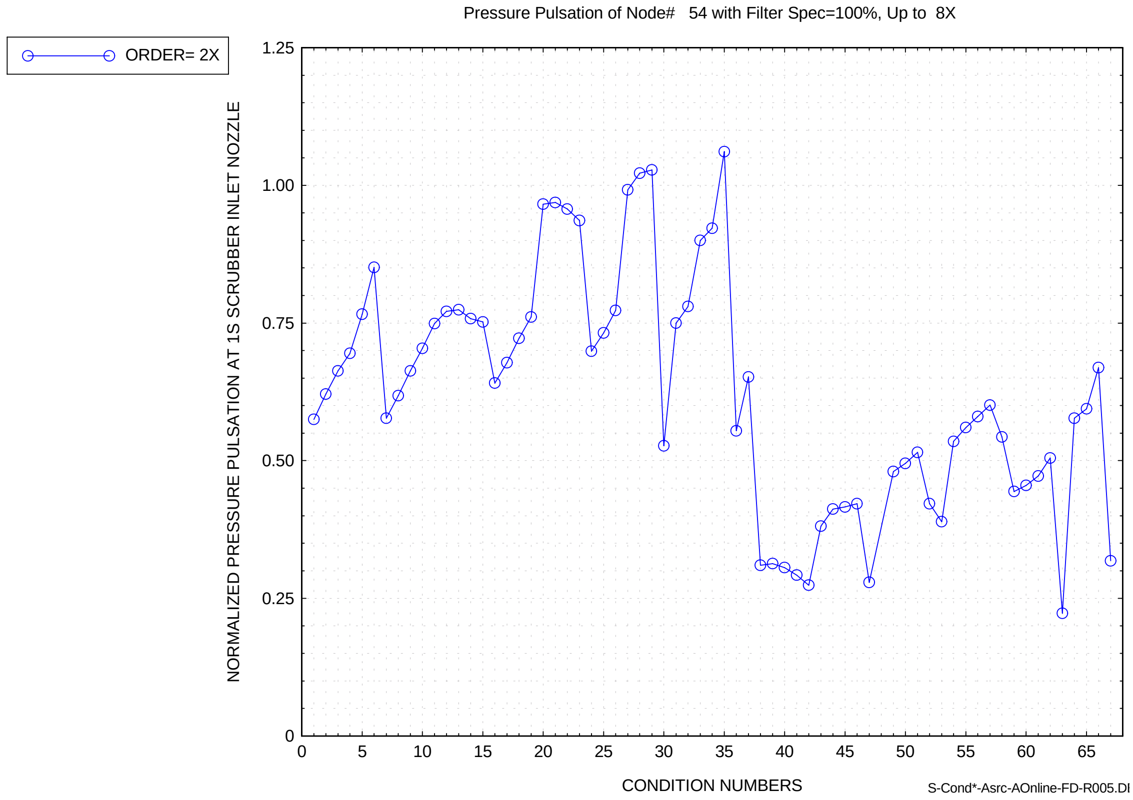
4 Chamber Bottle Configuration



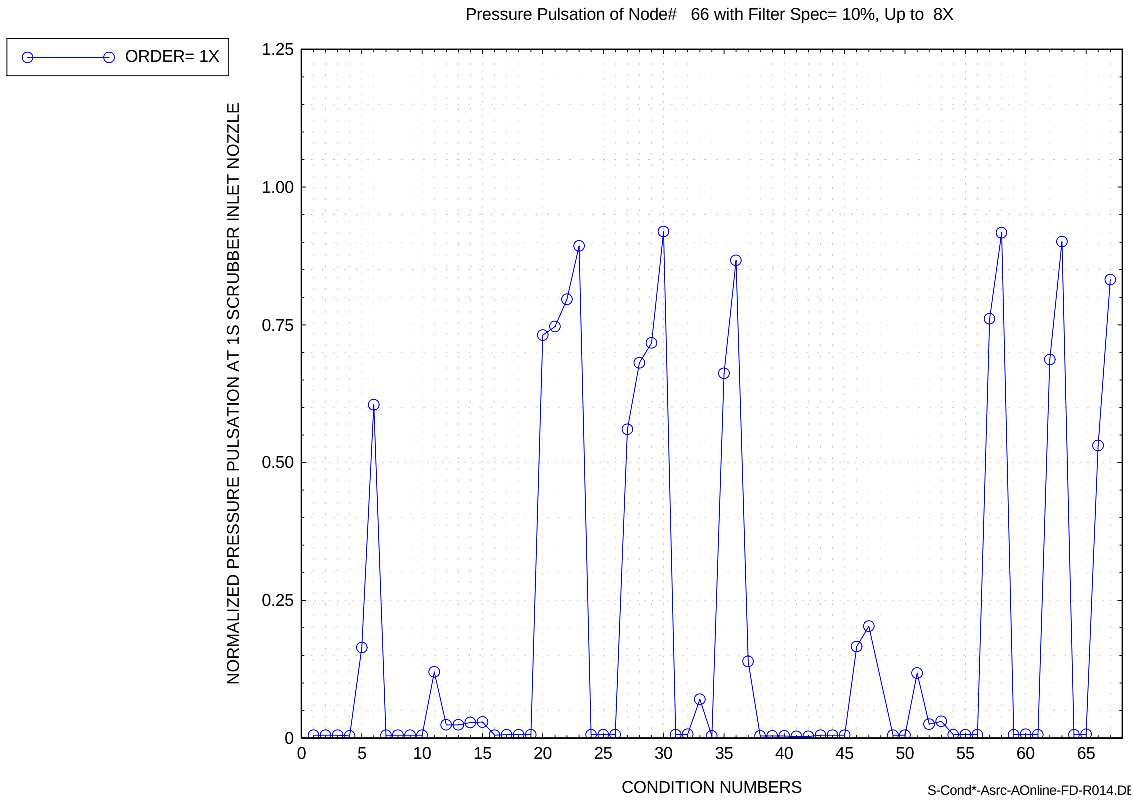
(Note: Unbalanced Acoustical Shaking Forces Normalized to 1000 lbf pk-pk)

Figure 8: PULSATION LEVELS UPSTREAM OF SCRUBBER – One Stage Operation

3 Chamber Bottle Configuration



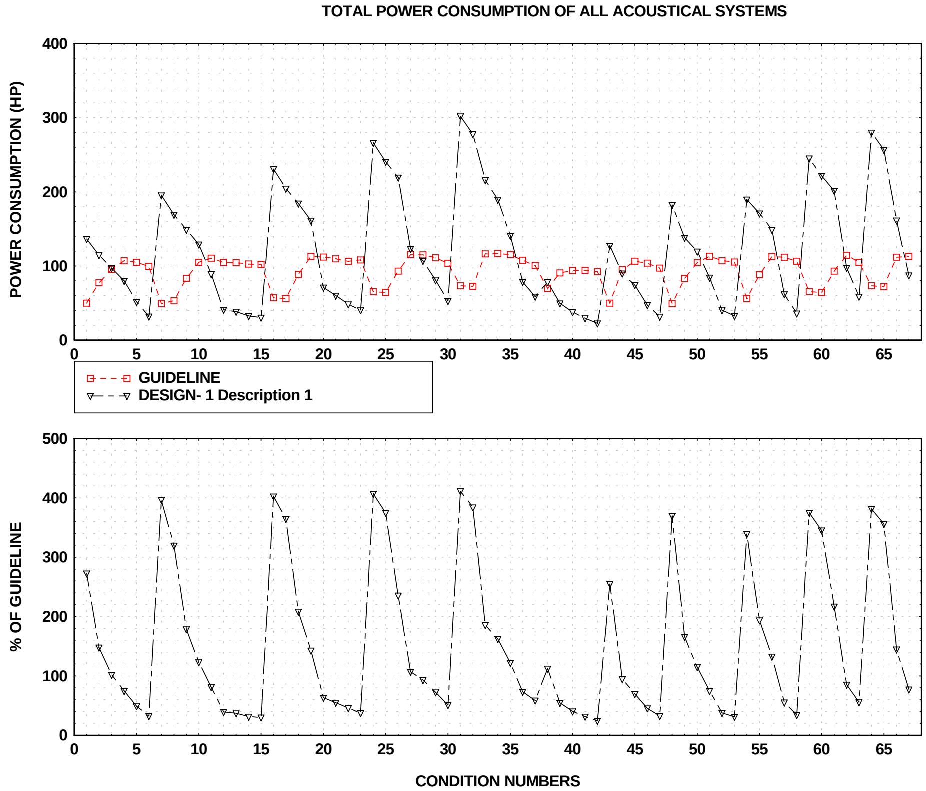
4 Chamber Bottle Configuration



(Note: Pulsations Normalized to API 618 Line Side Pulsation Guideline)

Figure 9: POWER CONSUMPTION – One Stage Operation

3 Chamber Bottle Configuration



4 Chamber Bottle Configuration

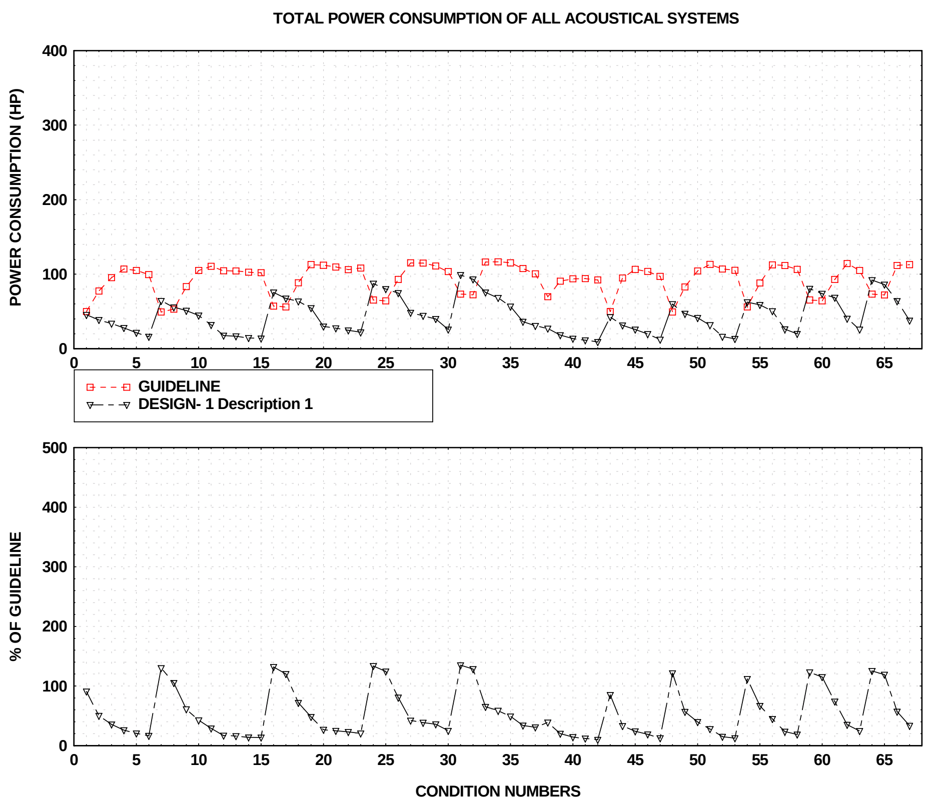
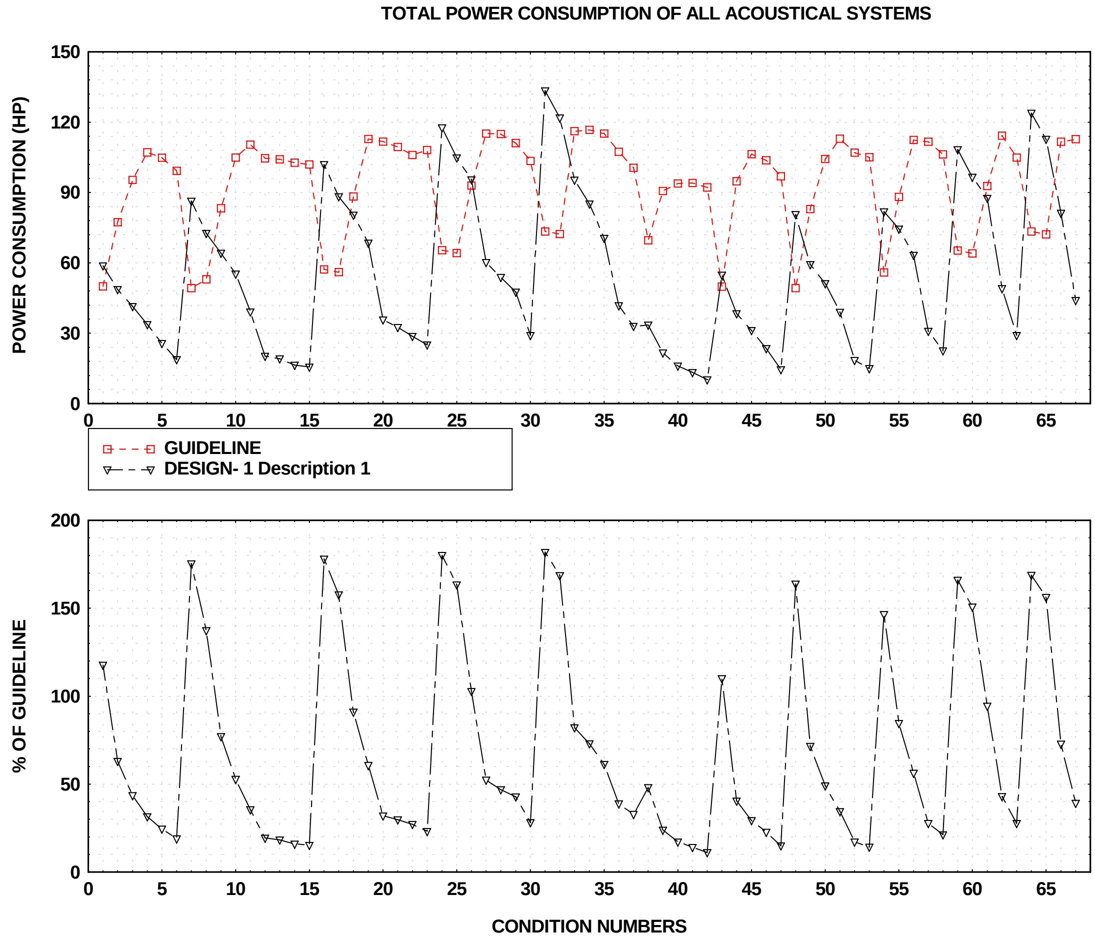


Figure 10: POWER CONSUMPTION – Choke Tubes with Straight-Cut Exit (One Stage)



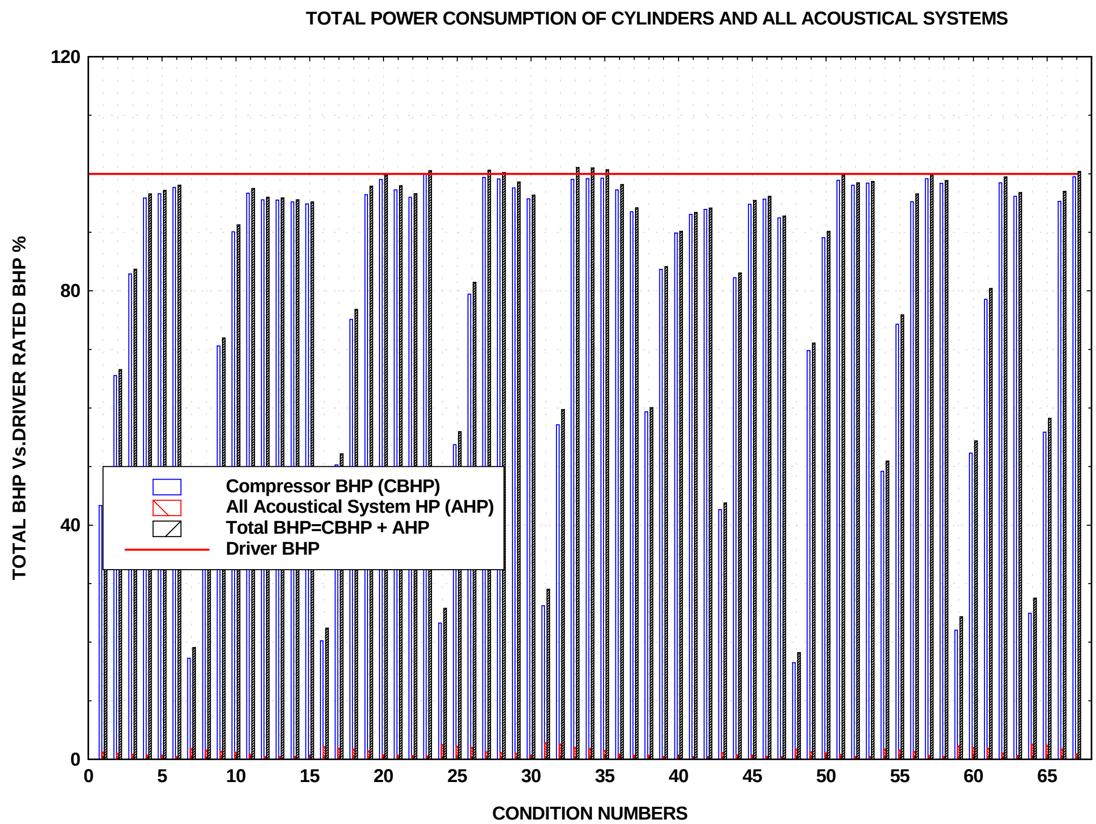


Figure 11: <u>POWER CONSUMPTION – Choke Tubes with Diffuser Exit (One Stage)</u>

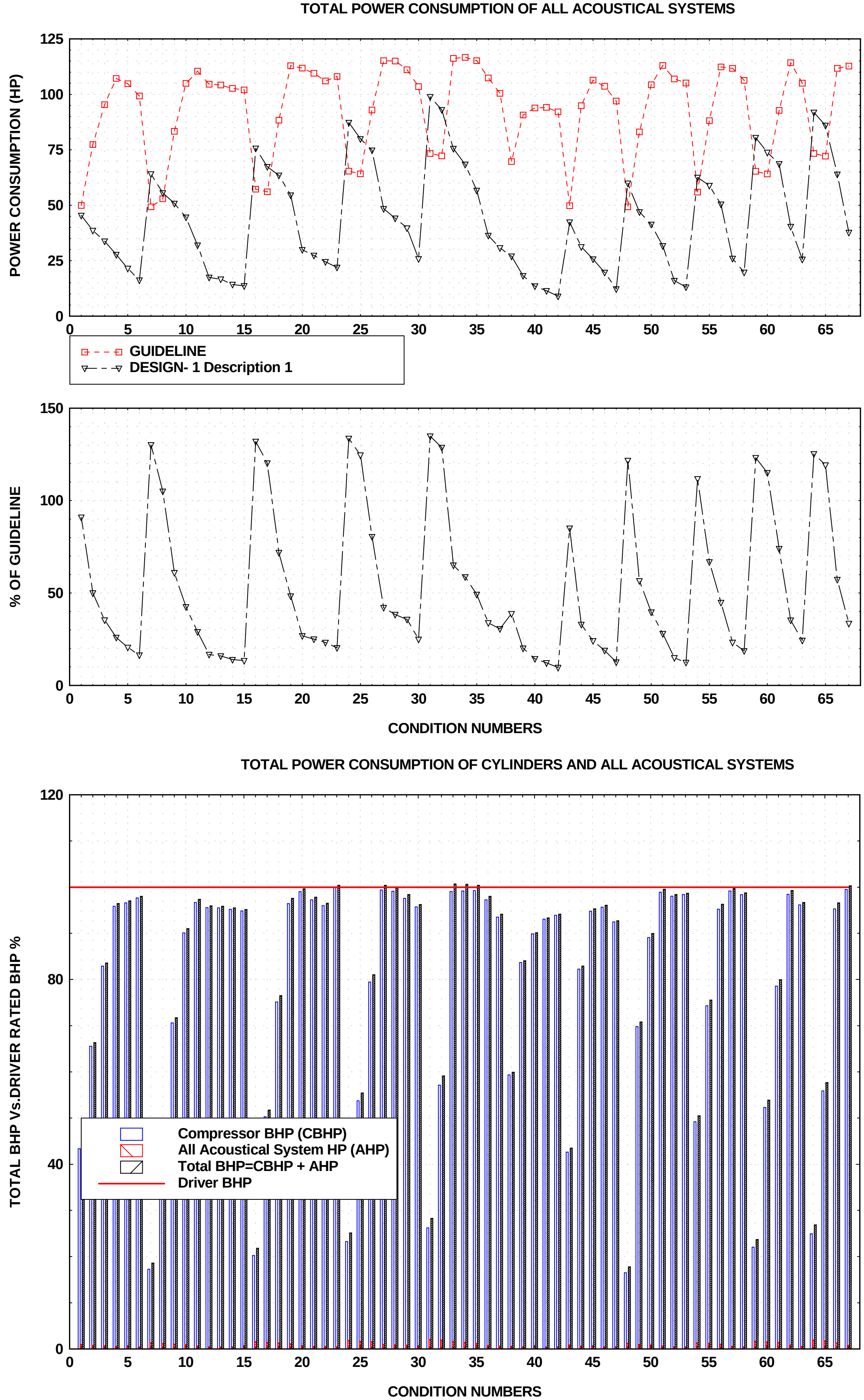
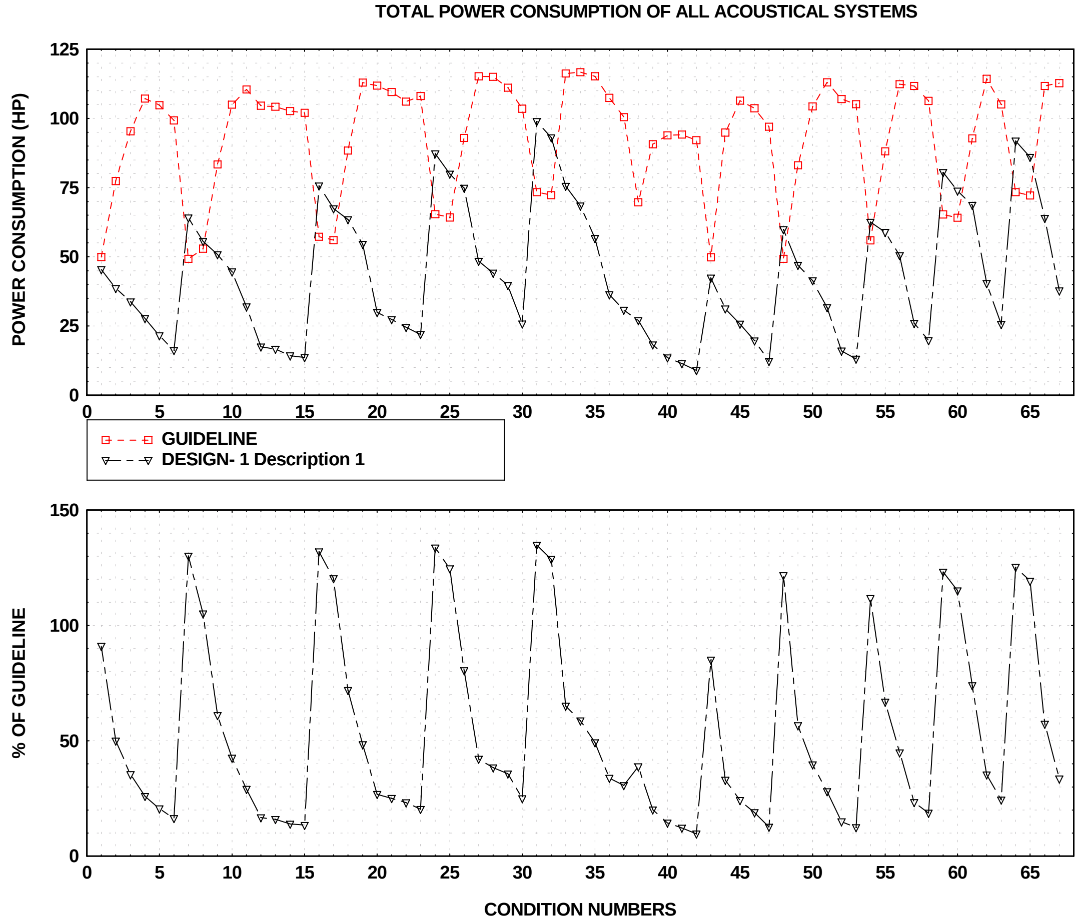
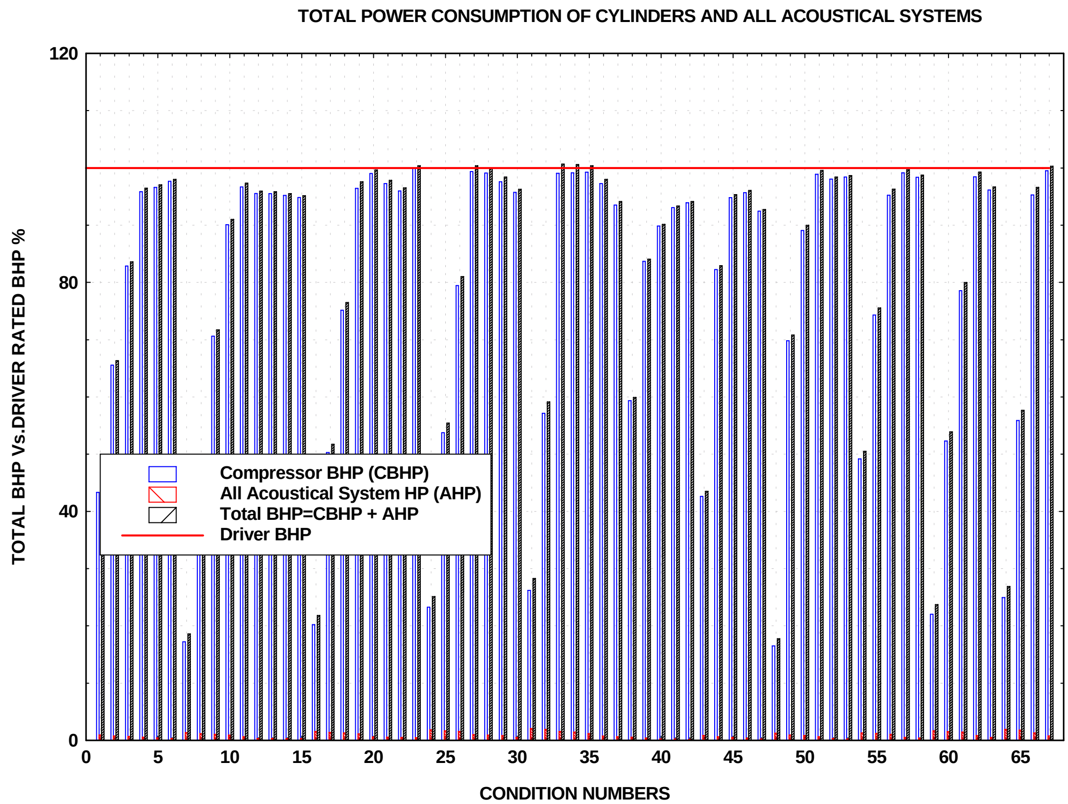


Figure 12: POWER CONSUMPTION – Choke Tubes with Modified Reducer Exit (One Stage)





Summary

Traditionally, conservative assumptions are made during the design of the pulsation and vibration control devices to address the complexity of these systems. We suggest that this approach results in a less than optimum design that will compromise performance. Extreme operating conditions do not necessarily correlate to worst-case acoustical forces or pulsation levels. Furthermore, the consequences of using this simplistic approach do not get communicated to all involved parties. Ultimately, the end user has no way to determine whether the actual operating scenarios have been considered in the analysis. In recent examples, the authors have seen unnecessary losses of over 150 HP on one unit due to this simplified approach.

The pulsation study analyst is faced with the challenge of comparing various attributes, often across many operating conditions, for multiple units, and for alternative designs. Once the designer has determined an optimized design, it still remains a challenge to clearly communicate the findings to the various stakeholders. The profile graphs are a useful tool for this purpose, as non-specialist and non-technical personnel can readily understand the reasons for certain design decisions. Also, these presentations can be used to illustrate the merits of alternative designs in easily understood terms.