# Economics of Engine and Compressor Analysis

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# 43rd Annual Gas Compressor Short Course
# The University of Oklahoma
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# Course Overview

The use of engine and compressor analysis data to justify and prioritize maintenance and repairs will include discussion of data collection and analysis, methodologies/results. The lab session will include examples of economic analysis for engine and compressor faults.

Many companies strive to determine the mechanical condition of the equipment utilized within the business. This is done with many different programs at various levels of the organization. In today's environment, maintenance must be prioritized and justified for completion.

# Corporate Culture

The environment that the company has towards change and optimization will determine the success of the program. The organization has to evaluate the data that is being collected and determine the potential to convert the data into information. The focus must be on improving the bottom line. Many of today's companies are data rich and information poor. They have been collecting data forever but have trouble converting it into information that can directly affect the bottom line.

## Dollars vs. Technical Terminology

Today, many companies still utilize technical terminology to determine the performance of engines and compressors. Typical examples of these include horsepower per million standard feet of gas moved (HP/MMSCFD) and brake specific fuel consumption (BTU/BHP-HR). While these values have significance as technical indicators, managers and corporate accountants do not understand the impact of changes in these values. However, everyone understands the importance of dollars and time. These two values will allow communication across the entire organization. In fact, most good technical terms can be directly converted to dollars and time.

## Management Ready Information

Most managers, foremen, and supervisors have a very limited amount of time. While they might want to understand the individual traces collected and at a previous point might have collected the data, it is your job as an analyst to filter this information for them. The two most important values to provide a supervisor with are an estimate of the consequences and the probability of the consequences. This should be done as quickly and with as little additional information as possible.

## Compensation Issues

The organization rewards and penalizes actions based on a perceived value to the company. Here are some extreme examples that I have seen:

### Minimize Fuel Cost

A manager gets rewarded for an excellent fuel rate consistently. His equipment regularly operates 2000 BTU/BHP-HR below the manufacturer's curve and similar units on this system. The orifice plate size was either entered incorrectly or the plates have been modified.

### Minimize Overtime

After collecting data on a unit in obvious distress, the supervisor sent the analyst home to avoid overtime charges for completing the analysis. Gas control did not want to shut the unit down until the repairs could begin. The unit had a catastrophic failure that night.

### Minimize Maintenance Costs

For three years a supervisor was rewarded for the lowest maintenance cost on the system. He received a promotion and the new supervisor had the highest costs on the system for the next two years.

**Maximize Availability**
A unit catastrophically fails at a location with spare units. The availability at the location was not affected by the failure due to the spare units. A similar unit has a minor failure at a different station with no spare units. This location is penalized for availability during the repair.

These are extreme cases of perceived value to the company. While the general measure was correct, the implementation was poor. The organization rewards personnel for meeting the perceived values of the company.

### Prerequisites for Economic Analysis

The amount of additional information that must be collected to complete an in depth economic analysis depends on the accounting practices that are in place. The fuel, maintenance and operations, and capital costs should be applied at a unit level. It is not possible for 10 units at the same location to use the same amount of fuel for a year. Every location has a "bad unit" that costs additional money for maintenance. These costs need to be captured to develop a good baseline and to track improvements over time. It has been said that you can't improve what you don't measure. Making these measures frequently confirms perceptions of personnel in the field.

### Return on Machinery Investment

The goal of economic analysis is to provide the maximum return on the machinery investment. This concept includes determination of both costs and benefits for completion of maintenance. In addition, the costs and benefits must be considered at the same point in time. Many times there are several alternatives that must be compared to each other using this methodology.

## Basic Economic Decisions

Decisions based upon economics can range from simple to complex based on the amount and accuracy of the information utilized in the decision making process. A minimum of two different parameters must be considered in the analysis. These two basic parameters directly affect personnel, property, and profit for the organization.

### Consequences

What are the consequences of a failure? Does it cause the unit to shutdown? Is there any secondary damage that could occur prior to or during the shutdown? Another word for consequences is impact. What is the impact to personnel, property, and profit if the unit fails?

**Example**
Rank the following items from one to four with one being the highest priority given the information shown.

| **Case Description** | **Rank** |
|---|---|
| Discharge valve leak on second stage of a three stage field compressor | |
| Crosshead knock in unspared plant compressor | |
| High vibration in a pump, where we have spare units | |
| High flow past an exhaust valve during low pressure flow testing of power cylinders on engine driving a field compressor | |

Complete the ranking a second time. Include the knowledge that the crosshead knock has been present for two years.

| Case Description | Rank |
|---|---|
| Discharge valve leak on second stage of a three stage field compressor | |
| Crosshead knock in unspared plant compressor has been present for two years | |
| High vibration in a pump, where we have spare units | |
| High flow past an exhaust valve during low pressure flow testing of power cylinders on engine driving a field compressor | |

Complete the ranking a third time. Include that the field compressor is at the rod load limit and has a history of failures.

| Case Description | Rank |
|---|---|
| Discharge valve leak on second stage of a three stage field compressor that has a history of rod failures and is at rod load limit | |
| Crosshead knock in unspared plant compressor has been present for two years | |
| High vibration in a pump, where we have spare units | |
| High flow past an exhaust valve during low pressure flow testing of power cylinders on engine driving a field compressor | |

Most people change their rankings when the additional information is available. Typically, the first ranking places the crosshead knock first and the spared pump vibration last due to consequences. However, once you know the crosshead knock has been present for two years, its likelihood of immediate failure is much less, so other needs take priority. Similarly, when you know that the field compressor has a history of rod failures, a valve leak, which could change the rod loading on the compressor, becomes much more important.

## Probability

There are very few sure things in this world. The consequences might be catastrophic only one out of one hundred times. There might be several possible alternate possibilities that could occur. It is important to include the probability of a failure in the decision.

**Example of Decisions Involving Uncertainty**

During a regular predictive maintenance check, evidence of a significant mechanical knock is discovered in one power cylinder of a 10W330 engine. It is strongly suspected that excessive wrist pin clearance has developed. The engine is used during the summer to compress gas into underground storage. Any shutdown at this time has production and revenue consequences. At the start of the heating season, in about two months, the unit can be shutdown without revenue loss. How would you proceed to a decision? What do you think your decision would be?

It is certain that if we shut down now to perform maintenance, we will incur revenue loss. But is the maintenance necessary. We need information that will help us understand the probability that the unit will experience a failure prior to the heating season. If we had information about the consequences of such a failure, then we could determine the risk to the organization posed by the equipment.

## Risk Matrix

The combination of consequences and probability in one parameter can be accomplished in a number of different ways. The methodology utilized by BMA is shown below. It results in a matrix that consists of four possible consequences and probabilities. The ranking from one to five provides guidance on the need for maintenance.

| Probability of Failure | Consequences of Failure: Catastrophic | Serious | Marginal | Insignificant |
|---|---|---|---|---|
| **Certain** | **1** (C,C) | **1** (C,S) | **2** (C,M) | **3** (C,I) |
| **Likely** | **1** (L,C) | **2** (L,S) | **3** (L,M) | **4** (L,I) |
| **Possible** | **2** (P,C) | **3** (P,S) | **4** (P,M) | **5** **(P,I)** |
| **Unlikely** | **3** (U,C) | **4** (U,S) | **5** **(U,M)** | **5** **(U,I)** |

***Maintenance Priorities:***

**1.** Take **immediate** action
**2.** Perform action as soon as possible
**3.** Take action at next available opportunity
**4.** Monitor Only
**5.** No action required

This matrix is used to assess the risk of component failure and the consequence of such failure based on its "as found" condition (performance) at the time of the inspection. The assessed risk level code is then shown with each specific report recommendation. If you do not agree with Beta's risk assessment, you may do your own using the same matrix.

Example: A burnt exhaust valve has a high risk of breaking off at the stem and possibly causing a complete engine failure. Therefore, a replacement of this valve, (or the cylinder head), would be required immediately. The assessed risk code would be then: "(L,C)" or "Likely-Catastrophic". Each box in the Matrix has a number from 1-5 in it. These numbers should be used to aid in scheduling of the report recommendations into your regular maintenance program. The component condition, the possibility of the failure and the consequence of such failure should be the factors when determining the risk level i.e. a need for action.

**Example of a typical decision making situation**
As part of a routine predictive maintenance program, you detect signs of a failing bearing in a cooling tower fan. The fan is essential for production. What would you do?

There is a tendency to call for the immediate replacement of the bearing. Under what circumstances would this be a poor decision? Because we might incur unnecessary lost production which would lead to reduced revenue and profit.

On the other hand, if we ignore the problem and let the unit run, we risk a catastrophic failure with secondary damage and lost production. We would see lost revenue, reduced profit and increased maintenance costs.

A third alternative would be to increase the monitoring frequency of the bearing. This would permit trending of the fault to determine the degradation of the bearing over time. All decisions, including non-decisions, have economic consequences. These must be weighed to provide the optimum return on the machinery investment.

## Cost Benefit Analysis

The costs of a project must be compared with the benefits possible due to the modification. This means that the costs for a project must be determined. Next, the improved performance or decrease in risk must be determined. These costs and revenues do not occur at the same point in time, so an accounting method must be used to bring the dollars to the same time for comparison. This is called the net present value of a project. Finally, the actual costs and benefits should be tracked with the estimations. This will assure the economic impact of the modification is meeting expectations.

### Costs

The costs associated with a project should be estimated. Initially, orders of magnitude can be used complete a quick estimate. Comparing the estimate with actual costs after completion will permit a better future estimate.

#### Lost Production due to shutdown

If the project requires a shutdown that can not be scheduled with other projects then the cost for lost production should be included in the cost to complete the project. This should include gas lost to purge the system and revenues lost due to the shutdown. In some cases this will be simple to calculate, such as for production units. In other cases it will be more difficult, such as for mainline transmission units with spare capacity available.

##### Example

A writer in the April 1997 issue of plant services magazine describing the application of pumps under intermittent operation said that turning pumps on and off on a regular basis will prove fatal to any pump. His view is that the design should be modified (perhaps with a recirculation loop) to run the pump continuously. Is this a good decision?

Even if the writer is correct by describing on and off service as fatal to a pump, his solution is not the guaranteed to be the best. His recommendation will presumably reduce maintenance costs. There could be a benefit of increased throughput and revenue if these pumps are critical to production.

On the other hand, making the recirculation loop would increase energy cost. In most cases energy costs are the largest expense over the life of the machinery. Another cost is the capital cost of making the necessary changes. The best alternative will increase revenues and decrease costs to provide the highest return on machinery investment.

### Labor Charges
The cost of labor including both contract and internal must be included in the estimate. Be sure to include the appropriate loading factors for the internal costs. These might include such items as administrative loading, benefits loading, and engineering loading. The labor costs vary tremendously depending on the organization.

### Parts Cost
One of the simplest costs to calculate is the parts cost. It consists of determining the parts that require replacement, the consumable used, and the new parts that are installed to complete a project. The difficulty in parts costs is in determination of severity of the project and probable replacement required for project completion. Probabilities associated with severity can be utilized to approximate a cost for all possible scenarios.

## Benefits
The benefits associated with a project should be estimated. Initially, orders of magnitude can be used complete a quick estimate. Comparing the estimate with actual benefits after completion permits a better future estimate.

### Increased Production
A production increase is possible by either reduced downtime or modified unit operation. Examples of modified operations include changing load and speed.

#### Example
A gas production operation has three large integral units, factory rated at 330 RPM. The owner is now operating these units at 350 RPM. Was this a good decision?

The major considerations are:
Potential to increase throughput and revenue by approximately 6%.
Possible decrease in availability
Possible increase in maintenance cost
Project cost to allow the units to operate at the increased speed

If the actual increase in revenue exceeds the increase in costs providing an appropriate return on machinery investment, then this was a good decision.

### Decreased Operating and Maintenance Costs
Completing the scheduled tasks in a shorter period of time and optimizing the schedule interval can reduce maintenance costs. In addition, maintenance induced maintenance should be identified and tracked to improve maintenance practices. Operating costs can be reduced with improvements in performance.

### Reduced Risk
If a unit's or system's potential for failure is decreased this could be used as a benefit. The percentage reduction should be multiplied by the cost of failure to determine the impact to be used as a benefit.

#### Example
A location has multiple crankcase explosions in one year after over 20 years of operation without a single such failure. The system consists of multiple locations with similar historical operation but only a few are exhibiting the

increase in explosions. Should the increase in explosions be included in the budgeting for next year's maintenance costs at the remaining locations? Can the reduced potential for explosion be used as a benefit of the appropriate maintenance or operational changes to resolve the problem?

### Net Present Value Calculation

The benefits and costs will occur at different points in time. This must be taken into account. One methodology used to complete economic analysis brings the costs and benefits back to today's dollars. This is known as a net present value analysis. It will determine the amount of funds that must be set aside today to complete the project in the future. Many other economic methods can be used for analysis besides the net present value calculation just as easily. Utilize the appropriate method for your organization.

## Individual Unit Examples

Initially, all analysis techniques must be applied on individual units. This analysis will provide information about the health of the unit without comparison with multiple units on the system. However, it might include comparisons with standards for the unit type and comparison with one other unit on the system. An example of this is the manufacturer's fuel consumption curve or comparison with a similar unit at the location.

### Bypass Valves

The bypass valves and recycle valves used on units can leak even when closed allowing gas to recirculate in the unit piping. If a leak is present then the capacity expected on the pipeline will not be correct and additional fuel will be consumed to move the recirculated gas. The temperature prior to the bypass line on the suction should match the temperature after the bypass line. If there is a difference then a leak is present. The ratio of the difference in suction temperatures over the difference in temperature between the suction and discharge will calculate a leak percentage. This percentage can be used to calculate the economic impact of the leak.

#### Example

A unit was found to be leaking 17.6% through the bypass using the calculation above. After greasing the valve the leakage dropped to 12.5%. When the valve was replaced with a new valve the leak dropped to zero. This leak caused an additional $18,300 in fuel to be consumed by the unit per year to move the gas.

### Operational Differences

Subtle differences in operation affect the performance of the engine and compressor. These are frequently not just one difference but several combining to create an overall effect on engine performance. Resolving the combination takes time, experience, and patience. One of the most common operational differences is the ignition timing. This will be changed due to a variety of reasons to mask mechanical problems and overcome shortcomings in performance. These changes directly affect the amount of fuel that the engine must consume to deliver the horsepower required by the compressor. Frequently similar units running at different locations have different ignition setpoints due to the operating experience of the crews. One four-stroke unit on a system had ignition timing that varied by 20 degrees depending on where it was operated.

#### Example

There are two units sitting side by side at a location. Both units are in good mechanical condition, but unit 1 consumes 2.5% less fuel than unit 2. Using a tool called the first derivative of the pressure time pattern; subtle differences in the PT patterns were noticed. The air manifold pressure was lowered on unit 2 dropping the fuel consumption by 2%. Then, the ignition timing was advanced by one degree reducing the fuel consumption by 0.5%. The estimated cost saving due to modifying these operational parameters was $113.00 per day.

### Pulsation Control

Pressure pulsations are an inherent part of reciprocating compressors. Depending on the size and mode of operation of a compressor the inherent pulsations will be more or less likely to cause problems such as high vibration, excessive meter error or premature compressor valve failure, if left uncontrolled. Proper pulsation control represents a balance of resulting pulsation levels, capital cost (eg. cost of building pulsation bottles) and operating cost (ie. added pressure drop) for the range of operating conditions expected over the life of the unit.

**Example**

A pipeline company was planning on revamping an existing 2 stage 4000 HP 310 RPM integral compressor. Both its vibration levels and economic performance had been satisfactory. The plan was to significantly increase the flow, and restage the compressor so that it could operate either as single stage or two stage unit. The revamped unit compressed about 205 mmscfd in single stage mode through 7 cylinders. In 2 stage mode, in compressed about the same amount through 4 cylinders. Most of the gas was diverted elsewhere, and the 3 cylinders on second stage compressed only about 28 mmscfd. The Project Manager was aware that if no modifications were made to the existing pulsation suppression devices that pressure drop, and hence operating costs, could be significantly increased. He was also concerned that vibration levels could increase once the modifications were made. Beta Machinery Analysis was contracted to perform an acoustical analysis of the revamped mode of operation. As a result of the acoustical analysis several modifications were presented that would reduce pressure drop while not impacting the existing vibration levels. The modifications presented offered a range of options where the greatest pressure drop savings came at the expense of the highest capital cost. The options implemented represented a balance of long term fuel cost savings and installation costs. Assuming the unit operated half the year in one stage mode and half in two stage mode the fuel cost savings are $57,000/year. The payback period for implementing the modifications was 15 months.

## System Wide Examples

The individual contributions similar to those described above will lead to savings in operations. The following will require application throughout the organization to optimize the use of existing capital and maximize the return on the machinery investment.

### Load Curves

Performance testing the compressors across a system allows for many possibilities that could only previously be assumed. Each unit has a set of equations that describe its performance to within 2.5% on horsepower and capacity. The equations were used for the following purposes:

Daily station operations to determine the first unit on and last unit on
Gas control to determine the best possible method to move gas across the system
System planning to complete increases in capacity utilizing existing horsepower effectively
Targeting the best and worst units on the system to improve individual performance
Deviation from the tested baseline to alarm for performance problems

**Example**
There are two units on the system having high HP/MMSCFD equations when compared with multiple similar units on the system. The plant personnel are satisfied with the performance but it is costing additional horsepower and therefore revenue to move gas with these units amounting to approximately $5,000 per month. New compressor valves were budgeted for this location with local personnel objection. The units now are operating similar to the remainder of the units on the system.

**Example**
There is not enough unloading capacity on a unit at a location. They have requested additional unloaders be purchased in the budget. Using the load curves for similar units on the system, it is determined that there are other locations on the system with excess unloading capacity identical to that required. Instead of purchasing new equipment the existing equipment was redistributed.

**Example**
100 units on a pipeline system were measured for excess fuel consumption due to recirculating gas within the compressors during analysis, on average the deviation in fuel consumption over the baseline was $3 per day. This amounted to $300 per day in excess fuel consumed to move gas on the system. Assuming the units run on average 200 days out of the year, this would mean that the potential saving across the system is $60,000. These units are only consuming approximately 0.5% above the baseline for the unit.

## Fuel Consumption Deviation

A measure of the performance on the engine is brake specific fuel consumption. The units for BSFC are typically given in BTU per BHP – HR. There are several possible baselines that can be used for comparison including manufacturer curves, generic unit type curves, and individual unit tested curves. The difference between the baseline curve and the actual operation can be used as a measure of improvement. If the unit is operating above the baseline then there are possible improvements that can be made in the performance of the unit. If the unit is operating below the baseline then the unit should be used to develop a new baseline for comparison.

Subtle differences in operation and mechanical condition can be noticed utilizing this measure. It must be converted into economic terms to determine the significance of the deviation. Larger horsepower units or units that operate for longer periods will generate higher economic returns.

**Example**
100 units on a pipeline system were measured for fuel consumption during analysis, on average the deviation in fuel consumption over the baseline was $50 this amounted to $5,000 per day in excess fuel consumed to move gas. Assuming the units run on average 200 days out of the year, this would mean that the potential saving across the system is $1 million. These units are only consuming approximately 7.5% above the baseline for the unit. From the above example in operational differences, we can potentially recover 2.5% for ignition timing and air/fuel ratio corrections. This would amount to approximately $300,000 for this system just by adjusting the timing and air manifold pressure on the units.

## Dynamic Pressure Drop and Instantaneous Flow

As the pressure fluctuates in a reciprocating compressor installation, due to pulsation, the flow velocity of the gas also fluctuates. If the volume velocity fluctuations are significant the pressure drop through system components such as choke tubes, orifice plates and coolers can be significantly higher than what would be caused by the mean or steady state flow alone. As well, the opening and closing of the compressor valves results in a lumped flow – no flow pattern, especially between the compressor valves and the pulsation bottle. Orifice plates are often added at the bottle to cylinder flange connection to control pulsation. Depending on the volumetric efficiency of the cylinder, the lumped, or instantaneous, flow will result in the pressure drop through the cylinder nozzle orifice plate being significantly higher than what would be caused by the mean alone. These dynamic flow effects can not only increase the system pressure drop, and hence operating cost, in extreme cases can limit the performance of the compressor.

**Example**
Two 2 stage 13000 HP 327 RPM separable compressors operating in hydrogen services were experiencing rod loads above the allowable rod loads on first stage under certain operating conditions, thus limiting operation. The excessive rod loads were due to a large pressure drop in the interstage. The pressure drop was occurring for two reasons. First, the cylinder nozzle orifices were causing large amounts of pressure drop. This was due to the large instantaneous flow through the orifice during the valve opening event. The second reason was large volume velocities occurring at the entrance and exit of the choke tube in the first stage discharge bottles. The pressure drop through the cylinder nozzle orifice based on mean flow was calculated to be 1.2 psi. The pressure drop through the orifice including the instantaneous flow effects was calculated to be 23 psi. The pressure drop through the choke tube due to mean flow was calculated to be 7.1 psi. The total pressure drop through the choke tube, including the effects of the high volume velocities at the entrance to the choke tube, was calculated to be in the range of 25 psi, which agreed with the pressure drop measured in the field. The horsepower lost due to mean flow is 83.4 HP and the horsepower lost due to total flow is 482.4 HP. Assuming $200/HP-YR, the savings possible due to minimizing the dynamic loss is $79,800 per year. Increasing the size of the cylinder nozzle orifice and moving the choke tube reduced the interstage pressure drop. Once the pressure drop was lowered, the compressors could be run at maximum load with reduced operating costs and without excessive rod loads.

## Conclusion

Immense progress has been made recently in the capabilities of analysis equipment to provide meaningful technical measures of performance. These measures can be utilized as a foundation to complete an economic justification for maintenance or performance improvements. This will include a conversion of the technical terms to dollar savings per unit time. The future developments that must be completed include integration of this information into the corporate culture of the organization, development of accounting methodologies to determine impact and provide feedback, and systemwide integration of the economic analysis methods. These developments will provide organizations with techniques to determine the best return on the machinery investment with relative ease and document successful project implementation.