



# ASSESSMENT OF TECHNOLOGY AND ECONOMIC BENEFITS OF RECIPROCATING MACHINE CONDITION MONITORING AND DIAGNOSTIC SYSTEMS

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## ABSTRACT

The ongoing trend toward automation of the oil, gas, and chemical industry has significantly changed the entire industry. Digital control systems utilizing advanced computer technologies are installed to manage integrated production units. Corporate consolidations and globalization movements have forced reductions in operations staff and maintenance personnel. These changes require plant managers to implement more effective and efficient means to maintain or even increase productivity while protecting critical equipment with fewer resources.

Rapid development in sensor and computer technology has led to “smart” monitoring and diagnostic systems to effectively evaluate the condition of the critical production equipment continuously in real-time. Condition monitoring systems for rotating (centrifugal and reciprocating) equipment, in particular, have become much more sophisticated in recent years affording users an intelligent means of extending maintenance cycles, increasing performance, and improving plant safety. But, during the evaluation process of the investment decision, it is far easier to calculate the capital cost associated with installing any given system than it is to derive a realistic rate of return analysis. With a variety of proven systems now available, it is up to design and facility engineers to be able to understand and effectively present the clear benefits and advantages that affect the bottom line of the business.

This paper describes specific methods to calculate and clarify the costs and benefits of condition-based online diagnostic system’s rotating equipment. It delivers practical ways to estimate results and relate them to economic figures upon which to base sound investment decisions.

## INTRODUCTION

Over the years, electronic measurement devices and analyzers have increasingly been used for condition monitoring in the maintenance of machines in industrial installations. The piezoelectric accelerometer and the digital fast Fourier transform (FFT) analyzer replaced the screwdriver behind the operator’s ear.

For economic reasons, the providers of condition monitoring and diagnostic systems focused initially on the large market for rotary machinery, e.g., turbines and centrifugal compressors. For

condition assessment and monitoring of oscillating machines, such as reciprocating compressors, special segmented analyses were developed in order to meet the special requirements in terms of the characteristics of reciprocating machines.

The ever-increasing demands made on the availability of machines resulted in a change from periodic (offline) to continuous (online) condition monitoring. With the major expansion in digital process control systems and large area networks (LANs), integrated analysis systems are needed today. The electronically measured data of the entire compressor are presented to the group of maintenance engineers via a central visualization monitor.

Those responsible for maintenance can use their workplace computers to access the monitoring system via a network. Modern possibilities in telecommunications and the increasing automation of business mean that remote monitoring is fast becoming the standard in condition monitoring.

With the proven advantages of continuous condition monitoring and diagnostics for reciprocating compressors now well known and accepted, a firm place for itself has been established in modern maintenance engineering.

## INDUSTRY TRENDS

Today, petrochemical as well as chemical plants try to adapt their overhaul intervals to the inspection intervals regulated by local authorities like Technischer Ueberwachungsverein (TUV), American Petroleum Institute (API), and others. Depending on local regulations, there can be up to five years between mandatory outages, which means five years stream time for the equipment.

Coupled to this maintenance strategy, several challenges have to be addressed to plant management, maintenance departments, and operators.

- Safety of personnel, plant, and environment
- Avoidance of production loss
- Reduction of downtime
- Reduction of maintenance cost
- Increase of productivity
- Optimal use of wear potential of all wear parts
- Increase of performance

To increase stream time, plant management has to be informed about the economical impact of different operating conditions of the plant, maintenance departments need online information about the stress loads of the machines, and operators need feedback from maintenance to learn how to reduce these loads while optimizing production.

The tool to meet these challenges is the use of advanced technologies in the field of condition-based monitoring and diagnostics. Moreover, it is important to manage the information flow created by modern condition monitoring systems, i.e., provide useful diagnostic information in plain text to the responsible people. Based on this, informed decisions can be made.

### RECIPROCATING COMPRESSORS

Condition monitoring system requirements for reciprocating machines are unique. Figure 1 shows, that only a few components cause more than 90 percent of unscheduled shutdowns of reciprocating compressors. Condition monitoring systems have to take this fact into account. They must be designed specifically for this type of machinery and their historical malfunction modes.

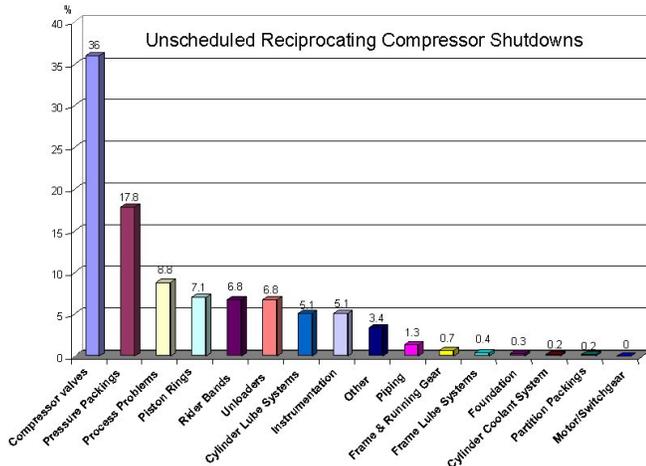


Figure 1. Reasons for Unscheduled Reciprocating Compressor Shutdowns. (Courtesy Leonard, 1997)

First, the parameters to be monitored must be defined, and it has to be evaluated whether additional sensors have to be mounted on the machine or if the required data can be provided via a digital link from other systems. Measurement points have to be designed into the machine and sensors have to be chosen with respect to required measuring range, frequency range, and accuracy.

Second, the data transfer medium between sensor and data acquisition unit must be evaluated, i.e., 4:20 mA cabling, field bus systems. In the next step, the data acquisition hardware has to be designed with respect to filtering, data sampling rate, and signal conditioning.

Third, data processing and data compression algorithms need to be adapted to meet the specific requirements, such as crank angle related and event triggered data sampling.

In general one can distinguish between static (low-speed) data like temperatures, static pressures, etc., and dynamic (high-speed) data, e.g., dynamic pressure or vibration.

A general function diagram of a condition monitoring system for reciprocating compressors can be found in Figure 2.

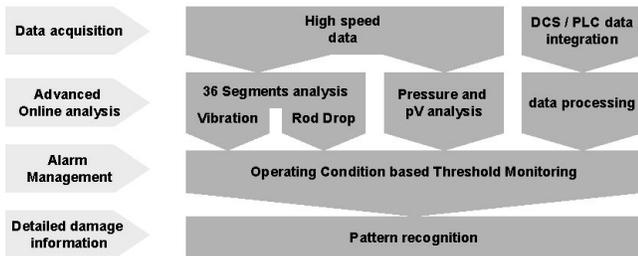


Figure 2. Typical Layout of a Condition Monitoring System for Reciprocating Compressors.

The application of measurement points for high-speed dynamic data on a reciprocating compressor can be seen in Figure 3. The most important dynamic data points are: crosshead vibration, cylinder vibration, rod position, dynamic cylinder pressure on crank end and head end, as well as a trigger signal, which also indicates the speed of the crank shaft.

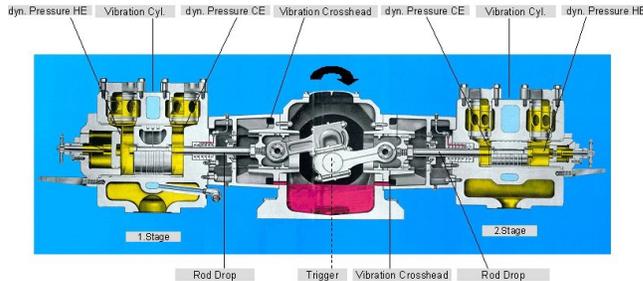


Figure 3. Sensor Positions for High-Speed Data.

Low-speed data values include: stage pressures, mass flow, gas temperatures, valve temperatures, leak gas temperatures, leak gas volume, bearing temperatures, motor current, oil temperature, oil quality, etc. Those parameters can be integrated into the data acquisition system through digital links from programmable logic controllers (PLC) or distributed control systems (DCS) systems.

### THREE STAGES OF CONDITION-BASED MONITORING AND DIAGNOSTICS

As seen above, several challenges have to be fulfilled in the day-to-day business of a plant. The most important ones are to ensure the health of the employees, to avoid pollution of the environment, and to prevent damage of plant assets.

#### Safety

To prevent catastrophic failures of machinery, causing damage to equipment, and endangering the health of employees, automatic shutdown systems are well known in the industry. These systems must alarm dangerous conditions below the trip level, providing an early warning signal and trip the machine reliably when higher limits are violated. Furthermore, false trips as well as missed trips must be avoided.

Unlike rotating machines, oscillating machines cannot efficiently be protected from severe damage by monitoring overall vibration levels only. Reciprocating machines often have to be shut down within three rotations of the crank shaft to prevent damage on the cylinder frame, piston, piston rod or plunger, crosshead, connecting rod crankshaft, and crankshaft bearings. The measured crosshead vibration signals must therefore be analyzed for different excitation sources to reliably protect the machine. This analysis is preferably done by relating the vibration signal to the crank angle as shown in Figure 4. By doing so, only important events in key areas of the operation cycle of the machine, e.g., rod reversal or events near top-dead-center (TDC) or bottom-dead-center (BDC), will be alarmed and further processed to trip the machine. Figure 5 shows the principal flow diagram of a safety system for reciprocating machines. In case of an event, high resolution data must be captured to allow the root cause analysis.

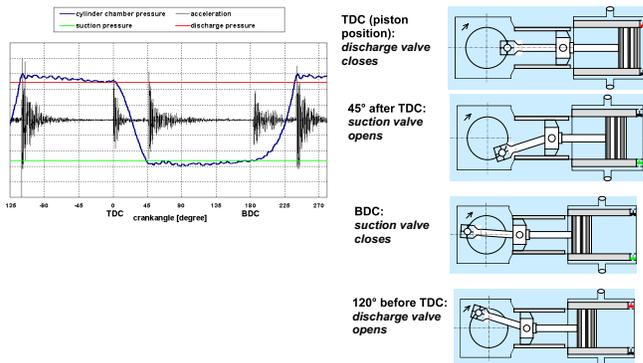


Figure 4. Crank Angle Related Vibration Signal.

Ensure safety

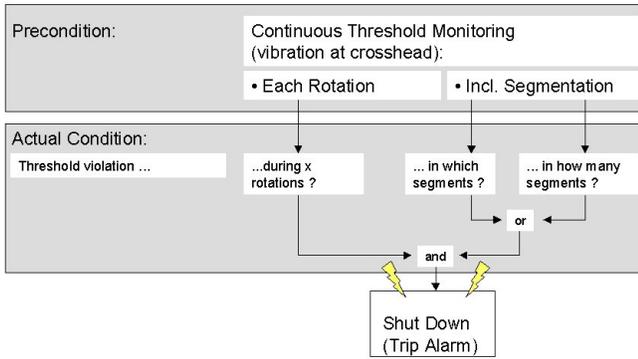


Figure 5. Principle Flow Diagram of a Safety System.

Condition Monitoring

In general, condition monitoring can be divided into three major tasks:

- Early failure detection
- Wear monitoring
- Integration and analysis of process data

Early Failure Detection

The early detection of impending damages is important to operators as well as maintenance departments to increase the reliability and availability of the plant.

Crank angle related vibration analysis of the cylinder vibration signal, correlated with other parameters like rod position measurements or valve temperatures, provide an early warning system for failures of valves, bearings, loose connections, or rod and piston cracks. This enables maintenance to plan the unplanned shutdown of the machine and minimizes downtime.

Figure 6 shows crosshead vibration, dynamic pressure crank end, dynamic pressure head end, and rod position during one cycle of the machine. The machine is in good condition.

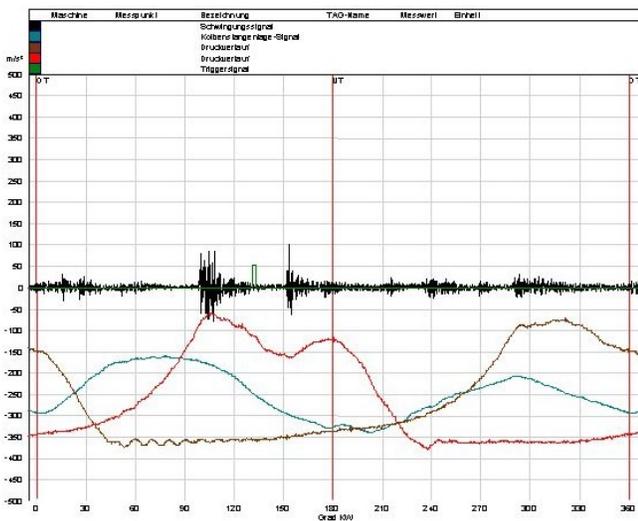


Figure 6. Loose Crosshead Connection (1).

The vibration signal in Figure 7 shows a drastic change near top-dead-center; the rod position signal is affected over the entire cycle. Analysis of both signals combined indicate a movement of the piston relative to the crosshead. Maintenance decided to take the machine out of service after the spare was started up and found a loose screw connection at the crosshead pin.

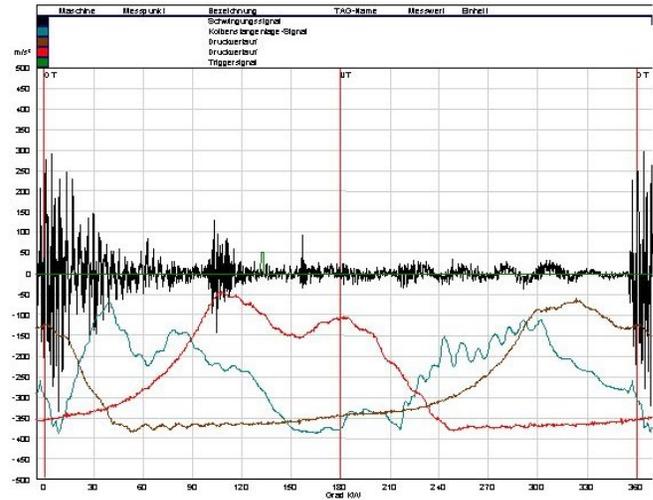


Figure 7. Loose Crosshead Connection (2).

Being able to locate the problem early and plan appropriate actions avoided more severe damage at the machine and saved about \$8000 in production loss due to the early start of the spare machine.

Wear Monitoring

The permanent monitoring of typical wear parameters like temperatures, seal gas pressure, rod position, etc., enables maintenance to replace parts, based on their condition. Furthermore, gathered data and experience can be utilized to reduce wear by optimizing materials of wear parts. The trend in Figure 8 indicates rider band wear. When the alarm level was reached, maintenance planned for a shutdown of the machine and the rider rings were renewed.

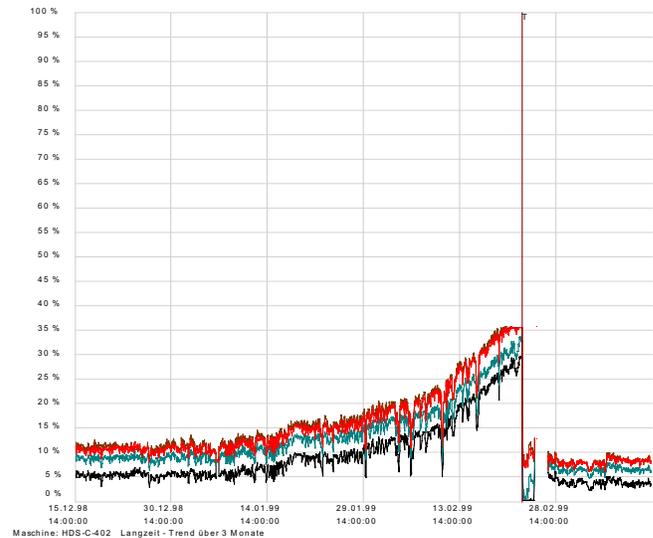


Figure 8. Rider Band Wear.

Integration and Analysis of Process Data

Integration and correlation of process parameters from other data acquisition systems like DCS or PLC are important elements defining discrete operating states of the machine. Each individual operating state (e.g., full load, part load, or speed band related) can in return be used to set alarm specific threshold levels for each operating state of the machine, thereby providing a greater degree of protection and increasing availability of the machine by avoiding false alarms. Thus it is important to set alarm thresholds

in an intelligent way, as there can be thousands of parameters to be monitored. An algorithm must be provided to set limits for different parameters automatically based on the “good” or reference condition of the machine.

*Efficiency Optimization*

One major goal in operating a plant is to optimize the efficiency and maximize the output. Therefore, the whole process as well as every individual machine should be monitored for efficiency losses. For reciprocating compressors the monitoring of valve function and losses, clearance volumes, flow balance, compression ratio, indicated power, and, most important, the analysis of the gas dynamics using the p-V diagram are the critical parameters to reduce direct operation cost of the machine. Shown in Figure 9 are parameters, such as polytropic exponents of expansion and compression phase, intersection of the expansion, and compression line, which indicate reduced efficiency.

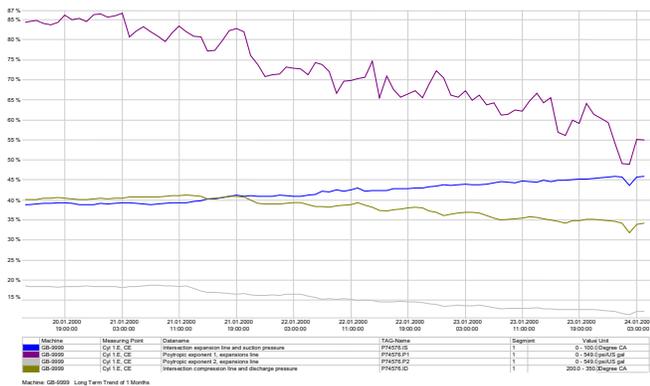


Figure 9. Reduced Efficiency.

In addition, direct stress measurements like rod load and rod reversal indicate whether the operation of the machine is still in safe limits or if the overall plant output can be increased by adjusting compressor capacity. High vibrations around the rod reversal positions point to a dangerous situation (Figure 10).

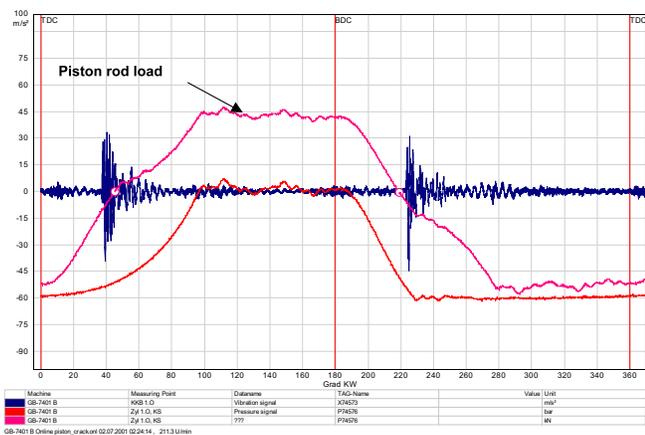


Figure 10. Rod Load, Cylinder Pressure, and Crosshead Vibration.

*Intelligent Reporting*

Intelligent reporting is based on knowledge gathered during years of operation of reciprocating machines and fed into the condition monitoring system as a knowledge database. Self learning capabilities like pattern recognition and manual input from the user allow the database to expand in a fast and effective way.

All messages from the system must be created in plain text to avoid time-consuming analysis of captured data to determine the

fundamental cause of an event. Modern communication systems like e-mail, short message service (SMS), voice mail, the Internet, or fax are used to transport the information to the responsible people in time, no matter where they are when the event occurs.

Remote access to all data via LAN, wide area network (WAN), or Internet allows specialists with advanced diagnostic knowledge to become involved in problem solving and decision making. Data export functions are provided to enable convenient report generation in standard word processing software.

**THE PAYOUT**

Before the benefits of a condition-based monitoring and diagnostic system can be earned, an investment has to be made. The investment comprises hardware, software, implementation cost, and, last but not least, the training of the people who operate the system when it is installed. Further investments could be considered in remote service contracts.

As budgets for such expenditures have to be approved by management, it is of vital importance to provide an accurate payout analysis. The payout period for a system should be less than a year. Following are some examples that have been gathered from customers with actual systems installed.

*Payout Based on Avoided Production Loss*

In this example, the authors look at a two-throw reciprocating compressor located in the hydrocracker unit of a refinery. The reformer, desulphurization, and hydrogen (H<sub>2</sub>) unit are downstream of the hydrocracker and directly dependent on the output of the compressor. A standby unit is in place. In case of an unscheduled shutdown of the machine, the startup of the other machine takes between several minutes and several hours. Figure 11 shows the calculation of the payout based solely on the production loss due to unplanned shutdown of the machine. A shutdown of only two hours per year costs the production an equivalent of \$64,000. This is more than 50 percent of the—here calculated—price for an online monitoring system including wiring, mechanical work, and installation at site (refer to Figure 14). There are even more influences that are described in the following examples.

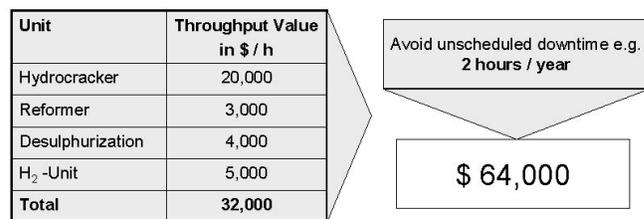


Figure 11. Payout Based on Production Loss in a Refinery.

*Payout Based on Increased Efficiency*

As total energy cost for compressors is quite high, even small efficiency losses have a large impact on the direct cost of operation. Figure 12 shows how the improvement in the efficiency of the same machine can save quite a lot of money.

In this case study the springs of the outlet valves have been optimized. The gain in performance was only 6 percent. The saved energy cost after one year totaled up to \$65,700.

*Payout Based on Condition-Based Maintenance*

The knowledge about the condition of the machine enables maintenance departments to avoid preventive maintenance work. This calculation refers again to the double-throw H<sub>2</sub>-compressor in a refinery considering preventive work on valves, packings, and piston rings only. Due to the avoidance of preventive work in one year, an amount of \$76,000 had been saved (Figure 13).

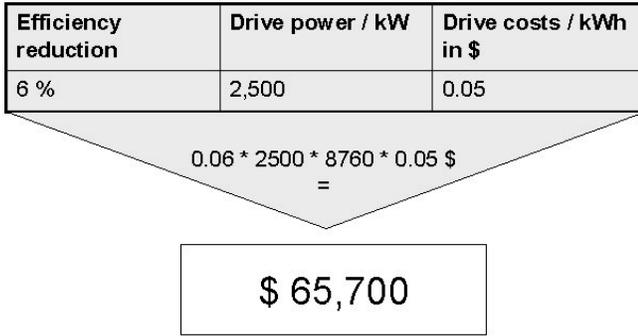


Figure 12. Avoided Efficiency Losses per Year.

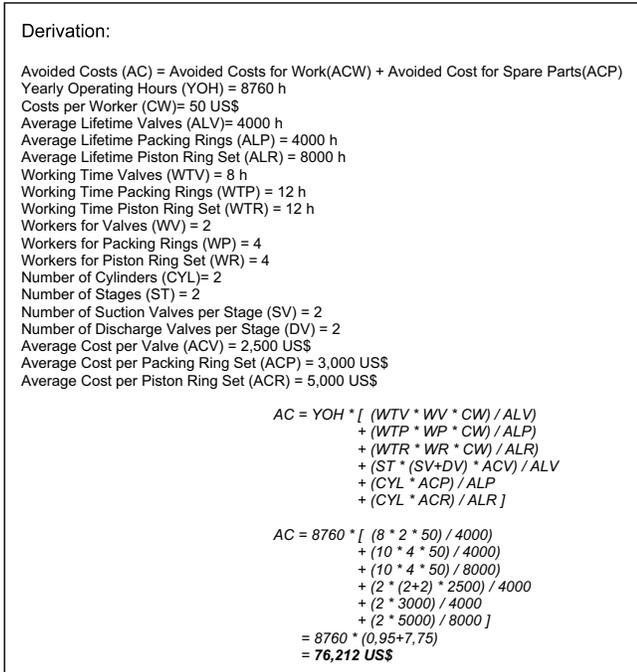


Figure 13. Avoided Cost for Preventive Work per Year.

**Payout**

Return of investment of less than one year is mandatory today. Adding up the three cases above and considering that the condition monitoring and diagnostic system for this hydrocracker cost approximately \$100,000, the system paid for itself in less than six months. Figure 14 gives an overview of the return on investment of the hydrocracker plant.

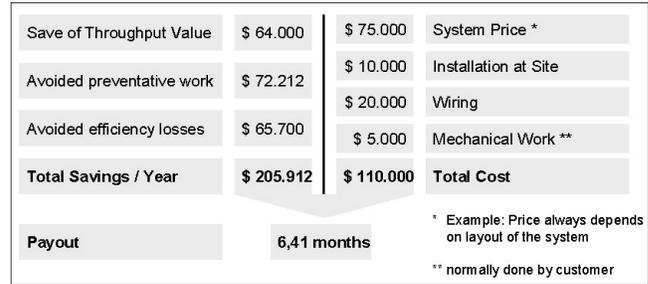


Figure 14. Payout Calculation for a Monitoring and Diagnostic System in a Hydrocracker Plant.

**CONCLUSION**

Intelligent condition monitoring systems are able to detect the real health condition of rotating equipment and ultimately improve their economic efficiency. Many compelling cases can be demonstrated as a proof for the return on investment. The payback period can be easily calculated and effectively communicated to plant management.

Experience gained by the study of reciprocating compressor operations has reinforced the focus on maintenance procedures. The methods and calculations for condition analysis have been known and tested for many years. Of particular importance are the seal related components (valves, packings, piston rings) and the critical drive elements of the machine. All of them can be monitored and protected to varying degrees by today's condition monitoring systems.

Certain analysis methods, such as p-V diagram or vibration analysis, make it possible to evaluate several components with one recorded signal. But in order to get a high level assessment of the condition, different measurements are applied. Here, rapidly changing condition values, such as vibrations and slowly varying values, such as temperatures, supplement each other. These values are monitored and automatically adjusted according to changing operating conditions. Both kinds of condition values have to be integrated into a modern monitoring system. They offer the entire maintenance team a single analysis and diagnostic interface via a network.

The described system has been in use commercially for more than 12 years and installed by many maintenance teams in the refining, chemical, petrochemical, and natural gas industry. In the future, mathematical models will increasingly be used to display the mechanical and physical processes of the reciprocating compressors. This will help the operating plant achieve revenue objectives, while at the same time assist operations and maintenance staff with managing their responsibilities and tasks more effectively.

**REFERENCES**

Leonard, S. M., 1997, "Increasing the Reliability of Reciprocating Compressors on Hydrogen Services," Presented at the NPRA Maintenance Conference, New Orleans, Louisiana.

