

# ROOT CAUSE ANALYSIS OF A LONG TERM RELIABILITY PROBLEM WITH RECIPROCATING COMPRESSORS IN H<sub>2</sub> SERVICE

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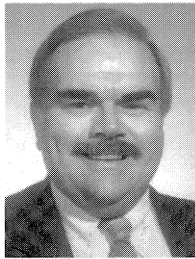
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## ABSTRACT

Three large reciprocating compressors in H<sub>2</sub> makeup service had been a chronic reliability problem for 30 years. Unit revisions greatly compounded this issue by eliminating builtin spare capacity. A Root Cause Analysis Team was chartered to address the reliability problem. Results achieved by this study essentially eliminated production losses (which had peaked at over three million dollars), improved valve life from three to six months to two to four years, and decreased maintenance costs by factors of three to five (several hundred thousand dollars per year).

This paper describes the overall root cause analysis study of these compressors and presents the conclusions and recommendations. It also details one phase of the analysis, evaluation of a specific valve failure, in order to permit the reader to follow the rigor utilized in the application of this type of analysis process.

## INTRODUCTION

In 1994, a Root Cause Analysis (RCA) Team was chartered by process unit management at Shell's Norco Refinery, to investigate the causes and provide solutions for the poor historical reliability of its three reciprocating hydrogen makeup compressors, K-1926, K-1927, and K-2179.

Prior to 1994, poor compressor reliability had manifested itself in terms of higher than desired maintenance costs, as only two of the three compressors were required to meet production rates. In 1993, compressor availability was:

- K-1926 = 87 percent
- K-1927 = 66 percent (impacted significantly by a main bearing failure)
- K-2179 = 96 percent

Following a unit upgrade in early 1994, the reliability problems began to cause significant production losses in addition to maintenance costs. The production losses peaked at over three million dollars in 1994. Maintenance costs peaked at over six hundred thousand dollars in 1994.

The "prevailing mindset" was that these machines had "typical" poor reciprocating compressor reliability and probably had to be replaced or augmented by additional machines to improve this reliability. There had been unnumbered hardware changes made to these machines in efforts to improve the reliability. It was obvious that the standard problem solving approach had not worked.

In order to address this complex, long lived problem; a root cause analysis study was performed. A multidiscipline team was assembled and proceeded to analyze the performance problems. The process chosen was to select several specific incidents (in late 1993 and early 1994) for which solid data were available and which appeared to cover the spectra of problems. The incidents selected for detailed analysis were:

- K-1926 main bearing failure—March 5, 1994
- K-1927 first stage valve failure—April 15, 1994
- K-2179 first and fourth stage valve failure—May 16, 1994
- K-1927 third stage rider band/ring failure—March 26, 1994
- K-1926 first stage crosshead failure—October 6, 1993
- K-1926 third stage packing case leak—June 6, 1994

The set of reports generated by this analysis process is quite comprehensive and detailed. As an example of the rigor and detail used in the analysis procedure, more detail of the second incident (K-1927 first stage valve failure—April 15, 1994) is included as the APPENDIX of this paper.

Causes were identified for each incident and then compared and correlated to determine common causes. Solutions were defined and evaluated using a rating criterion, and final recommendations were presented to site management. Many of the recommendations were implemented with rather spectacular results (when compared with past performance). The study required a sum of approximately one man-year from the participants spread over an eight-month calendar period.

This paper describes root cause analysis application to this reciprocating compressor reliability problem.

## COMPRESSOR SYSTEM DESCRIPTION

### *Process Unit Overview*

The processing unit in which these compressors were located converts gas oils from the three major process units into fuel oils, such as jet fuel and unleaded gasoline. Separated hydrogen from the two conversion stages is continuously recycled to the reactor feed furnaces by recycle compressors K-1928 and K-1929.

Compressors K-1926, K-1927, and K-2179 provide makeup hydrogen for both stages to replace the hydrogen not recoverable from the product. High purity hydrogen (88 percent to 96 percent) from the makeup compressors is supplied to each stage at 1950 psi and 250°F. Any reduction in hydrogen flow from the makeup compressors negatively impacts both stages of the unit and limits total production capability.

The makeup compressors draw hydrogen primarily from a hydrogen plant, which purifies the low purity hydrogen (80 percent to 85 percent) to a final purity of approximately 96 percent. When the hydrogen plant is down, the compressors draw all their feed directly from the off-gas header. Throughout the history of the unit, the hydrogen plant has been up and down for long periods for various financial reasons.

### *Compressor System Overview*

The three reciprocating compressors in hydrogen makeup service are Dresser-Rand (Worthington) Model BDCs identified as K-1926, K-1927, and K-2179. K-1926 and K-1927 are identical three stage machines that were installed during the initial plant construction in 1967 as primary and spare. Unit capacity increases in 1981 led to the parallel installation of K-2179, a four-stage compressor. From 1981, full capacity operation of the unit was possible with two of the three compressors in service. A debottleneck of the unit in February 1994, now requires all three machines in service for full capacity operation.

K-1926 and K-1927 are parallel, four cylinder compressors (size 17½ / 17½ / 15½ / 11 × 18) with three stages of compression and a capacity of 36 mm scfd. The compressors have two first stage cylinders, one second stage cylinder, and one third stage cylinder. 6000 hp, 277 rpm synchronous motors drive the compressors. Since the original design intended the compressors to operate as primary and spare, they share common systems such as knockout pots and intercoolers. These common systems were designed for one compressor operation, i.e., either K-1926 or K-1927 in operation separately.

K-2179 is a four cylinder compressor (size 24 / 17½ / 13 / 11 × 18) with four stages of compression and a capacity of 37.4 mm scfd. A 6000 hp, 277 rpm synchronous motor drives it. Unlike K-1926/27, the compressor has one cylinder for each compression stage and has its own independent knockout pot and intercooler system. The compressor running gear lubrication, cylinder lubrication, and jacket cooling water system are the same as the other two compressors. The third and fourth stage packing has a thermosyphon antifreeze cooling system.

Because the three makeup compressors share common suction and discharge piping, the compressor inlet and outlet pressures are the same, and many varying control combinations are possible between the three to meet unit hydrogen demands.

## PROBLEM DESCRIPTION

### *Compressor Performance History*

The three hydrogen makeup compressors, K-1926, K-1927, and K-2179 have experienced high historical failure rates when compared to other company and industry reciprocating compressors in similar services (Leonard, 1996). Failures have occurred on most of the compressor components at various times throughout their history, including valves, unloaders, piston rods and packing, piston rings and rider bands, crosshead assemblies, connecting rods, and main bearings. Table 1 lists the number of outages for each compressor from 1989 through 1993 (based on mechanical equipment data tracking that began in 1989).

Historically, K-1926 has been the worst performer and K-2179 the best performer, though still below best performing industry comparisons. By comparison, the eight reciprocating compressors in hydrogen service at a sister refinery average 2.2 outages per machine per year.

Table 1. Makeup Compressor Outage Data from 1989 to 1992.

Year	K-1926 Outages	K-1927 Outages	K-2179 Outages	Total
1989	6	5	2	13
1990	3	3	2	11
1991	5	4	4	13
1992	6	4	6	16

The RCA team attempted to compile historical data back to the original installation of the machines. Some records were incomplete or missing during certain periods, so the data are not a complete representation of compressor performance. However, it is clear that the machines have performed poorly from the very beginning. In fact, there have been two fires due to second stage cylinder wrecks on K-1927. As a result of the fires and other significant events (cracks in the frame, fracture of cylinder anchor bolts, movement of the foundation), the third stage cylinders for K-1926 and K-1927 were redesigned in June 1982 to reduce the rod loading on the second stage. No cylinder failures have occurred since the redesign, though poor overall reliability continued.

Table 2 indicates the type of component failures that have been experienced over the last five years. These data are fairly consistent with historical performance. Valve failures have been the most predominant type of failure on all three machines.

Table 2. Compressor Outages Per Machine by Component Type from 1989 to 1993.

Component Type	Average Repair Time	K-1926 Repairs	K-1927 Repairs	K-2179 Repairs	Total
Valves	1½-2 days	52	19	24	95
Connecting rods	1-3 weeks	10	7	0	17
Crossheads	7 days	10	0	1	11
Piston rods	3-5 days	15	6	3	24
Main bearings	5 weeks	0	1	0	1
Packing	4 days	12	1	4	17
PM	3 days	11	14	18	43
Other	-	11	12	20	43
<b>Total</b>	-	<b>121</b>	<b>60</b>	<b>70</b>	<b>251</b>

Several attempts were made in the last few years to make improvements to the compressors. Some of the changes were premised on the theory that liquid slugs were causing most of the component failures. Other changes were made to return the machines to vendor recommended tolerances (historical damage led to out of tolerance components). Changes include:

- Conversion from plate to poppet valves.
- Installation of low point liquid traps on the suction lines of K-1926/27.
- Replacement of cylinder/packing lube systems.
- Installation of standard dimension crosshead components.
- Line boring of K-1927 main bearing saddles.
- Installation of pilot operated valves on K-2179 unloaders to replace Schrader shuttle valves.
- Heat tracing and insulating the suction lines of K-1926/27.
- Installing a tempered cooling water circulation system on all compressor cylinders.

The reliability of the compressors did not improve following the work performed during the February 1994 turnaround. K-1926 performed particularly poorly, with multiple valve failures and two significant events to repair a main bearing failure and a packing case leak. K-2179 performed worse than prior history with multiple valve failures. K-1927's performance did not change much, with the fewest valve failures among the three machines. However, it did experience damage to its third stage piston rings and rider bands.

#### Performance Demands

Based on operating unit requirements, the H<sub>2</sub> makeup compressors are expected to operate with an overall availability of 95 percent, including preventative maintenance downtime. This equates to an average availability of 98.3 percent per compressor and comparable to the eight hydrogen reciprocating compressors at a sister refinery, which average approximately 2.2 outages per machine per year. It is also expected that compressor system maintenance costs will not exceed \$300,000 per year or \$100,000 per compressor.

#### Problem Impact

The performance gap between expected and actual performance for the three makeup compressors is significant. Historically, the largest impact has been high maintenance costs due to frequent compressor outages and repairs. In 1993, compressor maintenance costs totaled \$565,000, and \$460,000 in 1994. High compressor repair costs also constrained maintenance spending in other areas of the unit, limiting overall reliability improvement opportunities. Historically, compressor downtime had minimal effect on production, since only two of the three compressors were needed for full capacity operation of the unit. In 1994, though, operating requirements for the compressors changed significantly. As a result of a debottleneck project completed in 1994, unit production capability increased, requiring additional hydrogen. Operation of all three compressors (at full or part load) was required to meet this additional hydrogen demand.

During the peak of the 1994 gasoline season, lost opportunity costs for compressor downtime exceeded \$10,000 per day per compressor. The production costs with two compressors down was estimated at \$100,000 per day. A five-week outage to repair a main bearing failure on K-1926 in March 1994 resulted in \$420,000 in lost production. A three-week outage to repair valves and a subsequent packing case leak on K-1926 in June 1994, cost about \$200,000 dollars in lost production. There were several other outages of two to three days in length since the 1994 turnaround, and at times, the unit was down to one compressor operation.

As a significant, secondary impact, the poor reliability of these compressors has negatively impacted the morale of personnel in the department, including operators, craftsmen, day staff, and support personnel. Due to the significant attention required by the makeup compressors, other opportunity areas have also suffered. In summary, the poor reliability of these compressors had a significant negative impact on unit operations and profitability since the startup of the unit.

#### ROOT CAUSE ANALYSIS TEAM CHARTER

The charter of the study team was to address the poor reliability of the three hydrogen makeup compressors using the root cause analysis process. Specifically, the team was chartered to:

- Determine the root causes contributing to the poor compressor reliability.
- Develop solutions to eliminate the causes affecting reliability.
- Develop a long-term preventative maintenance and repair strategy to maximize compressor availability and minimize maintenance costs.

The RCA team was an eight member team composed of representatives from different backgrounds with expertise in specific fields, including a facilitator knowledgeable in the RCA process. Team members included an operations foreman, process engineer, reliability engineer, mechanical equipment specialist, and mechanical equipment engineers. Two members were brought in from the corporate technology center and one from another refinery.

### ANALYSIS STRATEGY

The reciprocating compressor problem presented a difficult analysis with a variety of component failures (valves, piston rings, bearings, crossheads, etc.) over a 30 year period. There were many firmly held beliefs as to why the compressor reliability was so poor, yet there had been no significant performance improvements accomplished over a 30 year period.

Due to the complexity of the problem, the team developed a strategy of separating the overall problem into "subanalyses" of very specific component failures and compressor incidents. This approach permitted the analysis team to execute rigorous investigations of several specific failures to ensure the identification of all of the underlying causes impacting compressor performance.

Several failure events were selected and analyzed as representatives of the whole to identify event root cause. Event root causes from the event analyses were compared to determine whether systemic or common causes existed. Identifying and addressing causes at the systemic level has the greatest impact on long term performance improvement. The individual events selected for analysis were:

- K-1926 main bearing failure—March 5, 1994
- K-1927 first stage valve failure—April 15, 1994
- K-2179 first and fourth stage valve failure—May 16, 1994
- K-1927 third stage rider band/ring failure—March 26, 1994
- K-1926 first stage crosshead failure—October 6, 1993
- K-1926 third stage packing case leak—June 6, 1994

These six events were selected as representative of typical compressor failures. Selection criteria included frequency of occurrence, impact of failure, and independence of the events.

As may be imagined with a problem of this duration and complexity, the completed results of the RCA are involved and voluminous. Only a very small percentage of the complete analysis detail may be incorporated in this paper. In order to provide a "flavor" of the analysis rigor, details of the K-1927 first stage valve failure analysis (April 15, 1994) are included as the APPENDIX.

### COMMON CAUSE ANALYSIS

Upon completion of the specific event analyses, the RCA study team reviewed the findings for common causes (commonalties that are present in many or all of the incidents studied). Common cause analysis is perhaps the most important segment of the reliability study, because it identifies the underlying causes common to several distinct failure events and represents strategic findings for the unit area and plant. It is within the boundaries of these common causes that the various failure events and their magnitudes, which negatively impacted compressor performance, are explained. It is also possible that these causes are indicative of systemic problems that exist in other areas of the unit unrelated to the compressors. Elimination of common causes can have the greatest effect to improve makeup compressor reliability. The study team identified the following common causes responsible for the overall poor reliability of the compressors:

- Poor valve reliability (negatively impacted other machine components)

- Inadequate procurement process (allowed use of lesser quality component designs)
- Inadequate repair practices/procedures (introduced errors that increased downtime)
- Lack of experience with low frequency maintenance events (inadequate repairs)
- Inadequate problem solving methods (problems not eliminated and downtime extended)
- Poor communications between operations, engineering, and maintenance
- Lack of long term focus (no overall compressor maintenance strategy, only reactive)
- Lack of engineering design reviews (strict reliance on non-OEM vendor capability)
- Inadequate performance monitoring (problems not detected early)

### RECOMMENDATIONS

The RCA team utilized the solution development process to develop and evaluate alternative solutions to eliminate the identified causes for poor compressor reliability. This process tests solutions based on a set of weighted criteria. Listed below is a compilation of the team's recommendations. The recommendations are categorized as either short term or long term. Under each category, the items are listed in general order of priority based on likely contribution to improve compressor reliability.

#### *Short Term Recommendations*

- Establish an operations/engineering/maintenance (O/E/M) surveillance team to monitor compressor performance, analyze compressor failures, review repair plans and proposed changes, address and communicate important issues—in general, to provide overall O/E/M guidance on machine operation and reliability.
- Develop/update all repair and PM procedures for the three reciprocating compressors.
- Establish and maintain an ongoing relationship with equipment manufacturers, central engineering, and other locations for consultation on repair practices—particularly during low frequency maintenance events.
- Install redesigned (designated Type 2) low-lift poppet valves in all three compressors.
- Install pulsation suppression orifice plates in the suction and discharge nozzles of all three compressors.
- Install continuous valve temperature monitoring equipment that will allow trending capabilities for troubleshooting valve problems.
- Install permanent high temperature shutdown switches on all three compressors.
- Reduce cylinder lubrication to optimum levels to reduce excessive oil impact on the valves.
- Redesign unloader valves to minimize leakage.
- Maintain detailed reliability tracking database for long term troubleshooting.

#### *Long Term Recommendations*

- Eliminate unloader valves by installing piping and controls between stages that will provide recycle control and allow the compressors to run fully loaded.
- Install cylinder pressure valves in the cylinders of all three machines for permanent compressor performance monitoring (consider contracting Beta analysis monthly).

- Install permanent, welded-in orifice plates in the suction and discharge nozzles of all three compressors.
- Upgrade compressor shutdown and monitoring instrumentation to provide additional protection to the compressors and improve troubleshooting capabilities.

**ASSESSMENT OF RCA PROCESS RESULTS**

*Results Achieved*

A number of the recommendations have been implemented. A particularly successful implementation was the design and installation of Type 2 poppet valves. In addition, a pulsation issue was addressed through installation of orifices in the discharge of the compressors. Valve life ratcheted up to one year, then to two years, and there is one machine with valves that have been in operation over two years with no plans to change valves before four years of operation.

Production losses during the first year of implementation were essentially zero, as compared with over three million dollars in 1994. Compressor maintenance is now performed in periods of time with lessened production demands (when there is no production loss due to the shutdown of one compressor).

Figure 1 shows the availabilities of these compressors for 1993 through 1997. Figure 2 shows the maintenance spending for 1995 through 1997. As shown, the improvement has been considerable, more than paying for the cost of the RCA study and the implementation of its recommendations.

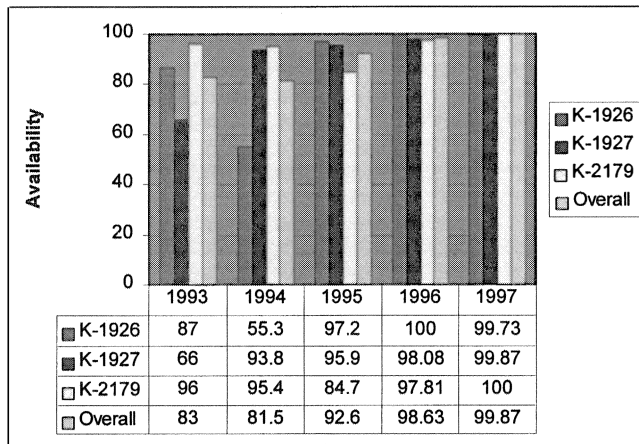


Figure 1. Availabilities of Makeup Compressors from 1993 to 1997.

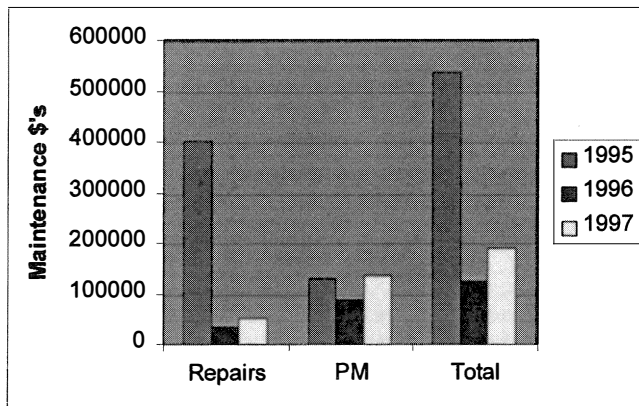


Figure 2. Maintenance Costs of Makeup Compressors from 1995 to 1997.

There are still some of the longer lived hardware issues to address, particularly those that require components to be brought back to a design standard. As an example, the crosshead pins had been modified to work with oversize bores as a “fix” during past repairs. Return to standard dimensions required new connecting rods without overbore.

An ongoing concern is that there may be “slacking off” of the attention paid to these machines. Due to the performance improvement, they are no longer at the top of the list of unit problems. This has not been an issue to date, but will require concentrated attention.

*RCA Difficulties*

Execution of a successful RCA is not easy. In this case, there were a number of barriers to overcome. Before the study was completed, the prevailing theory was that liquid carryover from the compressor knockout pots was the cause for the poor machine reliability. This “problem” had been addressed by several projects without success. With the liquid theory so well entrenched, it was suggested by some that the RCA study was not necessary, and would only validate liquids as the culprit for poor compressor reliability. Some team members and sponsors had difficulty leaving this perception of the problem.

There was considerable time pressure on the participants. Just as the RCA effort was kicked off, two compressors shutdown, one requiring significant repairs. Lost production began to significantly impact unit profits and sponsors of the effort became impatient asking for immediate answers. Due to the complexity of the problem, this was an impossible request and impacted team performance and morale.

These compressors were not equipped with cylinder pressure taps that would enable the team to capture online diagnostic information. With high quality data being the cornerstone of the RCA process, this presented a great challenge for the team to overcome.

Component quality problems also threatened the analysis. During the cause verification stage, the team received an out of specification shipment of valve springs from a manufacturer. A series of failures confused the results until the quality problems were resolved.

*Reasons for Success*

In the end, the effort was a resounding success with compressor reliability dramatically improved. There were several reasons the RCA team was able to overcome the barriers and resolve the compressor reliability problems. A significant factor was the team’s unwavering discipline and commitment to the RCA process. Although individuals and teams had made numerous attempts over the years, this was the first time a structured, rigorous analytical process like RCA had ever been applied to the problem. The analysis required a problem solving paradigm shift and the RCA process provided the framework for that shift. Ironically, the team found no evidence of liquid carryover affecting compressor performance. Applying the principles of RCA, the team was able to break through this paradigm and uncover the real underlying causes impacting the compressors.

Incorporating individuals from outside the Norco plant on the RCA team was a critical factor in the success of the effort. These “outsiders” provided new ideas and a fresh perspective to a problem so familiar to the local team members. One of these ideas was the installation of a pressure port through the valves and valve covers, permitting the collection of critical diagnostic data. The diversity of the participants, from operations to engineering, also contributed greatly to the effort. For example, the operations representative on the team helped offset the “pro-liquid” members and designed some field tests to eliminate it as a possible cause.

Although much pressure was placed on the team to find answers, the steering team came to the realization the problem was

difficult to resolve and afforded the team the time and resources to see it through. In total, the study lasted eight months and represented nearly one man-year of resource time. This unwavering support of time and resources gave the team the opportunity to be successful.

Another factor that contributed to success was the cooperative relationship that the team created with the compressor manufacturer. Several workshops were held with the manufacturer's technical personnel participating with the RCA team members. This relationship strengthened the analysis process and allowed the team to quickly work through component quality problems. The manufacturer benefitted as well, as it improved its own internal processes and strengthened an important relationship.

The analysis strategy also proved to be important. Investigating several independent component failures allowed the team to uncover numerous contributing causes that might have been missed if such a strategy had not been adopted. Not only did the team find mechanical design deficiencies, but numerous human system deficiencies were identified as well (i.e., procedures, practices, knowledge, communications, etc.). Correcting system deficiencies has greatest long-term potential as the learnings can be applied to other systems and equipment.

## CLOSURE

In summary, the results of the RCA have been very profitable with a significant reduction in production losses (peak of over three million dollars to essentially zero) and maintenance costs (peak of over \$600,000 in a year to less than \$200,000). Problems with valves that had been in existence almost 30 years have been successfully eliminated. Poor performance that had been widely accepted as the "norm" has been corrected and a new performance paradigm established. The operating unit now "expects" these machines to perform whenever that performance is demanded. The expectation has gone from "not too many shutdowns" to "no shutdowns" outside of turnarounds.

The application of RCA processes not only eliminated the immediate problem, but has been used to spread the learnings to improve other systems as well (Kepner and Tregoe, 1981; Stockholm, 1994; Perez, 1994).

## APPENDIX

### DETAILS OF ANALYSIS OF K-1927

#### FIRST STAGE VALVE FAILURE (APRIL 15, 1994)

### INTRODUCTION

This section presents details of the RCA analysis of one of the six compressor failure events analyzed by the RCA team. The intent is to demonstrate the level of detail and rigor used in the RCA process to address this type of problem.

### SUMMARY

On April 15, 1994, compressor K-1927 failed first stage west valves. Upon disassembly, two of the six head end valves were found with missing poppets. Failed poppet parts and excessive amounts of cylinder lubrication were also found.

Root cause analysis techniques found the causes of this valve failure to be due to pressure pulsation and inadequate valve design. Pressure pulsation in excess of API recommendations and of proper frequency was measured at valve covers. An acoustical study conducted by a consultant found deficiencies in the original 1965 acoustical design on K-1926 and K-1927 that permitted these pulsations to exist. Orifices were installed on K-1926 and pulsation levels dropped to acceptable levels.

Cylinder pressure monitoring and a computerized dynamic valve analysis determined excessive valve lift and spring stiffness. Dynamic valve analysis was used to redesign poppet valves for K-

1926 and K-1927 with optimized springs and valve lift. Cylinder pressure monitoring verified proper valve movement on K-1926.

Human system problems were noted that allowed poor valve performance to continue on the makeup compressors for 29 years. Problems such as lack of design reviews, lack of procurement specifications, lack of rigorous cause analysis, and inadequate use of technical consultation were the key systemic problems.

## PROBLEM STATEMENT

### *Expected Valve Performance*

Compressor valves in hydrogen service should have a one to three year life (time between replacement). Valve replacements should be able to be planned. Valve life should be predictable using cylinder pressure monitoring. This performance has been demonstrated in a similar company service, which had a 399 day mean time between failure (MTBF).

### *Actual Valve Performance*

Valve repairs consist of the actual number of valves that were fixed. Table A-1 lists the number of valve repairs for the makeup compressors from 1989 to 1993. The total numbers of outages per cylinder may consist of one or more valve failures per cylinder. Table A-2 lists repairs per cylinder attributed to valve failures for the makeup compressors from 1989 to 1993. Actual compressor shutdowns may have multiple cylinders involved. Table A-3 lists makeup compressor shutdowns attributed to valve failures from 1989 to 1993.

*Table A-1. Number of Valve Repairs for Makeup Compressors from 1989 to 1993.*

Compressor	1989	1990	1991	1992	1993	Total
<b>K-1926</b>						
1st stage East	18	9	22	18	29	<b>96</b>
1st stage West	14	14	18	17	31	<b>94</b>
2nd stage	2	13	12	0	14	<b>41</b>
3rd stage	8	4	18	28	25	<b>83</b>
<b>K-1927</b>						
1st stage East	0	12	4	6	9	<b>31</b>
1st stage West	0	3	1	11	5	<b>20</b>
2nd stage	0	0	0	0	0	<b>0</b>
3rd stage	0	8	4	12	17	<b>41</b>
<b>K-2179</b>						
1st stage	0	15	7	8	3	<b>33</b>
2nd stage	0	5	3	9	6	<b>23</b>
3rd stage	0	1	0	8	1	<b>10</b>
4th stage	0	2	5	3	0	<b>10</b>
<b>Total</b>	<b>42</b>	<b>86</b>	<b>94</b>	<b>120</b>	<b>140</b>	<b>482</b>

### *Impact*

The maintenance cost for a typical valve change is approximately \$1000. Since 1994, unit production loss due to one compressor being down is estimated at \$10,000/day. Since it takes approximately 1.5 days to get a compressor back from a valve

Table A-2. Repairs Per Cylinder Attributed to Valve Failures for the Makeup Compressors from 1989 to 1993.

Compressor	1989	1990	1991	1992	1993	Total
<b>K-1926</b>						
1st stage East	4	2	3	4	5	18
1st stage West	2	2	3	4	3	14
2nd stage	1	2	1	0	2	6
3rd stage	1	1	4	5	4	15
<b>K-1927</b>						
1st stage East	0	1	2	1	3	7
1st stage West	0	2	1	3	1	7
2nd stage	0	0	0	0	0	0
3rd stage	0	1	1	4	3	9
<b>K-2179</b>						
1st stage	0	1	1	2	2	6
2nd stage	0	2	1	4	4	11
3rd stage	0	1	0	1	1	3
4th stage	0	1	2	2	0	5
<b>Total</b>	<b>8</b>	<b>16</b>	<b>19</b>	<b>30</b>	<b>28</b>	<b>101</b>

Table A-3. Makeup Compressor Shutdowns Attributed to Valve Failure from 1989 to 1993.

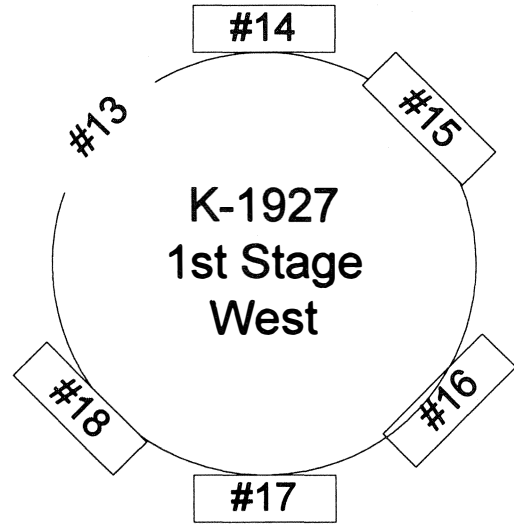
Compressor	1989	1990	1991	1992	1993	Total
<b>K-1926</b>	6	2	9	8	7	32
<b>K-1927</b>	3	3	3	6	6	21
<b>K-2179</b>	1	3	4	5	7	20
<b>Total</b>	<b>10</b>	<b>8</b>	<b>16</b>	<b>19</b>	<b>20</b>	<b>73</b>

failure, impact is estimated at \$16,000 per outage. From 1989 to 1993, the makeup compressors averaged 14.6 compressor shutdowns due to valve failures per year (25 day MTBF). With the 1994 economic value, valve failures will result in several hundred thousand dollars of nonconformance per year.

**EVENT DESCRIPTION**

At 11:15 a.m., Friday, April 15, 1994, compressor K-1927 experienced a significant reduction in hydrogen flow. The compressor had been operating without problems for approximately three weeks. The suction pressures on both the second and third stages fell. Three first stage head end valves were noted as running hot. The first stage west discharge temperature had elevated from 270°F to 350°F. The machine was stopped and a valve repair was scheduled for the first stage west cylinder. Figure A-1 identifies the valve locations on the cylinder. Upon disassembly of the first stage west head end valves, the following observations were made:

- Valve #13: Relatively oily. Leak checked OK.  
 Temperature before: 105°F  
 Temperature after: 115°F



**Valve Locations Looking North**

Figure A-1. Location of Valve on K-1927 First Stage West Cylinder.

- Valve #14: Same as #13. A piece of a broken poppet from another valve is lodged on the cylinder side of this valve.  
 Temperature before: 99°F  
 Temperature after: 114°F
- Valve #15: Unloader valve. Oily, but all poppets in place. Two out of the 12 poppets leaked slowly.  
 Temperature before: 172°F  
 Temperature after: 251°F
- Valve #16: Some black residue found around center poppets. Three outside poppets initially leaked slowly, but sealed after being solvent washed.  
 Temperature before: 244°F  
 Temperature after: 314°F
- Valve #17: One poppet and spring found missing on outside ring. Found one piece of a broken poppet stuck on the cylinder side. One complete spring was found stuck between the top of the poppet and the seat, and a piece of another spring was found stuck in the same position on another poppet. Seven of the 17 poppets had grooves cut around the outside of the poppets, probably from pumping against springs. This valve was not leak checked, because it would have leaked.  
 Temperature before: 254°F  
 Temperature after: 332°F
- Valve #18: One poppet and spring missing. Valve was oily, but had no debris. No foreign object damage to poppets.  
 Temperature before: 106°F  
 Temperature after: 107°F  
 Note: Thermocouple was assumed not accurate on valve #18.

From this information, the following failure scenario was derived:

- A discharge spring fails in valve #18.
- Due to the spring failure, the poppet fractures and comes out of the valve holder.
- The broken spring pieces fall into #17.
- The pieces cause a poppet to fail in valve #17.
- In addition to the failed poppet on #17, seven other poppets are damaged.

Figures A-2 and A-3 show the type of damage experienced on the valves.



Figure A-2. Poppet Valve with Failed Poppets. (Note the poppets at locations 5:00, 6:00, and 7:00. You can see where springs have "rolled over" the head of the poppets, causing indentations. Poppet at location 11:00 is missing.)



Figure A-3. Poppet Valve Cover Showing Damaged Springs. (Springs had extended and gotten under the heads of the poppets.)

### PROBABLE CAUSES

The two primary component level causes that led to the valve failure on K-1927 are pressure pulsation and inadequate valve design. Numerous other human system problems led to these component level causes. It should be noted that various tests were run on K-1926 instead of K-1927. Information derived from K-1926 is assumed to be representative of K-1927, since the compressors are identical and have common inlet and discharge systems. Either the poppet pushed through the seat or the poppet broke apart causing the poppet failure in valves #17 and #18. The detailed assessment leading to these conclusions can be summarized in the failure tree:

- I. Excessive loading
  - IA. Pulsation
  - IB. Normal impact force
  - IC. Spring failure
  - ID. Late poppet liftoff
  - IE. Valve flutter
- II. Inadequate strength of poppet material
- III. High temperature
  - IIIA. High base design temperature
  - IIIB. Internal gas recycling from leaking poppets
  - IIIC. Internal gas recycling from leaking unloaders

Details of these components follow:

#### IA. Pulsation

Normal valve action can be upset by pressure pulsation. Pulsation is caused by flow through various piping geometries.

Factors such as relative speed of sound, gas velocity, and compressor speed determine the level of pulsation present. Pulsation can cause late valve closing and valve slamming into seats. Piping changes and orifice plates can eliminate pulsation. Figure A-4 gives an illustration of pulsation on discharge valves. Figure A-5 shows evidence of pulsation on K-1926 third stage.

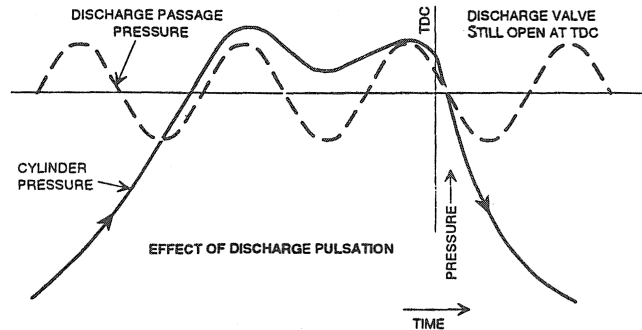


Figure A-4. Effect of Discharge Pulsation.

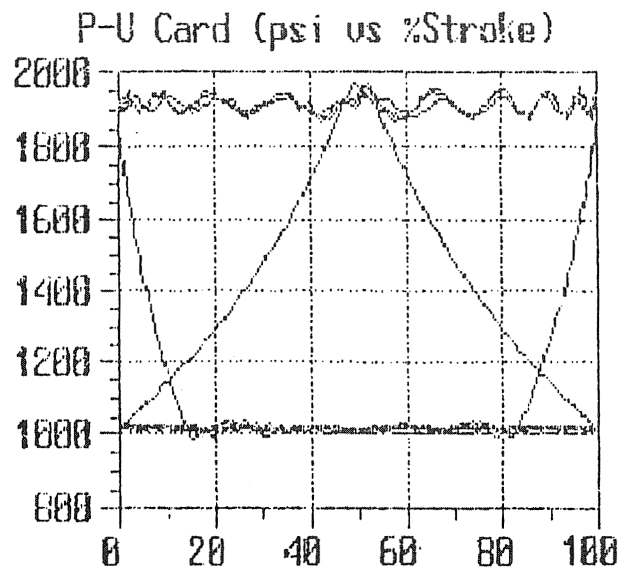


Figure A-5. K-1926 Third Stage PV Card (July 1, 1994).

Pulsation contributed to excessive loading. These pulsations were measured at the valve covers on K-1926 on July 1, 1994. Cylinder pressure monitoring found that valve movement was in phase with pressure pulsation (Figure A-5). A pulsation study verified that the pulsation at the valves was of correct frequency and sufficient amplitude to effect valve performance (Figure A-6).

This pulsation was the result of the combination of physical dimensions, running speed of K-1927, and the acoustical properties of hydrogen at the pressures and temperatures in K-1927. Classical pulsation problems normally occur in downstream piping where they cause the piping system to vibrate excessively. Pulsation bottles address these. This pulsation occurred between the valve and nozzle. Prior to the root cause analysis, pulsation was not considered as a cause, since there were no known piping system problems.

A pulsation study had been conducted on K-1926 and K-1927, prior to installation. In the time at which the study was done (1960s), hardware limitations on the system used to model the system had the potential to overestimate the damping in nozzle resonances, thus underestimating the problems that may be caused. A second pulsation study conducted in August 1994 confirmed this and clearly identified the problem.



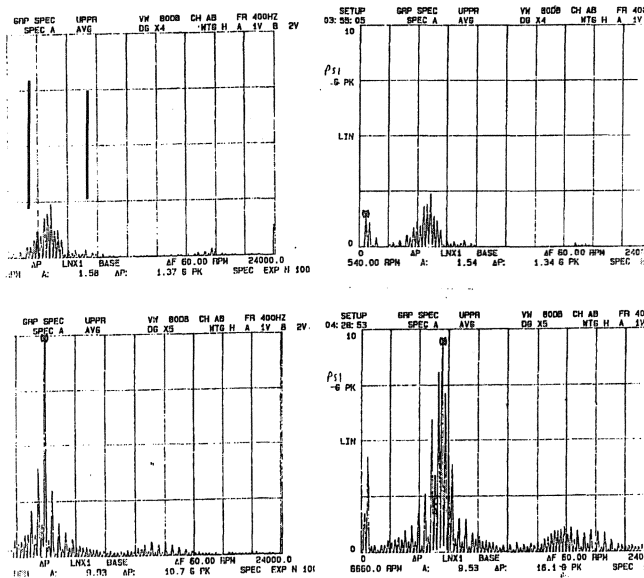


Figure A-6. K-1926 Discharge Pulsation Amplitudes Measured July 13, 1994. (From top left, first stage east, first stage west, second stage, third stage.)

**IB. Normal Impact Force**

Normal impact force contributed to excessive poppet loading. The impact force is related to the valve lift, which is a basic valve design parameter. Greater lift requires the poppet to achieve greater acceleration than lower lifts. This greater acceleration generates larger impact forces when the poppet hits the valve seat. Common valve lifts in hydrogen service range from 0.040 inch to 0.070 inch. The failed poppets had a lift of 0.220 inch. The poppet valve lift was too large for hydrogen service.

**IC. Spring Failure**

Excessive poppet results from spring failure. Springs provide a dampening force when the poppet is opening, and aids in closing the poppet. If the spring fails, poppet movement is controlled only by differential pressure. Loss of the spring will increase the normal forces imposed on the poppet. As noted above, the normal spring force is already high due to the high valve lift. Additionally, after poppet failure, springs will become lodged in other poppets attempting to seat and cause them to fail.

K-1927 springs were fatigued from too many cycles and resonance. The springs were made of Inconel, which has lower fatigue strength compared with other spring materials such as chrome silicon and Hastelloy C-276. The poppets fluttering caused additional cycles. Fluttering is caused by spring being too strong and/or valve lift being too high. Fluttering was proven on the sister compressor K-1926 by cylinder pressure monitoring.

**ID. Late Lutoff**

The poppets on K-1927 were opening late. The poppets opening late caused excessive loading, due to the additional acceleration needed to open the valve in a shortened period of time. The added acceleration results in an increased impact on the valve seat, similar to high valve lift.

Late opening is caused from excessive spring stiffness and stiction. Stiction occurs when the poppet must break the suction force from excess cylinder lubrication. At the time of the failure, the cylinders were being overlubricated, due to the optimization of a new cylinder lubrication system. Due to a new cylinder lubrication system that was installed during the 1994 unit turnaround, cylinder lubrication had not been optimized. This was apparent from the inspection of the failed valves on K-1927. In

determining optimal lubrication rates, overlubrication is preferred over underlubrication. No iterations had been made in optimizing the cylinder lubrication rates between the turnaround and the valve failure.

**IE. Valve Flutter**

Cylinder pressure monitoring identified excessive valve flutter that was an indication of inadequate valve design. The poppet valves that failed in K-1927, which exhibited this flutter, had improper spring stiffness and excessive valve lift. Both of these led to the poppets moving many times during a crank rotation, or fluttering. It was also seen that many of the valves did not fully open. The design that failed appeared to have been designed for efficiency, not reliability.

**II. Inadequate Strength of Poppet Material**

The poppets are made from a plastic material called polyetheretherketone, or PEEK. In production, the poppets were injection molded. The poppets that failed on K-1927 were fabricated from a low grade PEEK with poor molding process.

The failed poppets were manufactured by injecting resin and glass fibers at the corner of the poppet seat, as shown in Figure A-7. By injecting the resin and fibers at this point and in this direction, the glass fibers must turn a corner to fill the mold.

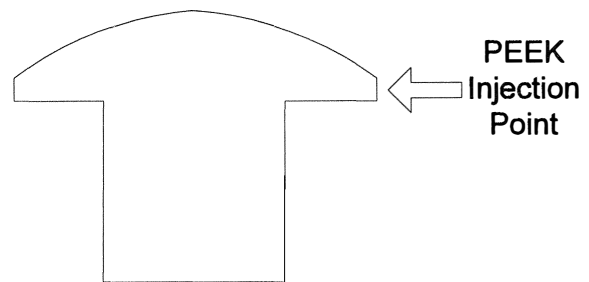


Figure A-7. Type 1 Poppet Injection Point.

To prove that the failed poppets had a lower strength than other poppets, a test was conducted at the plant central shop. At 200°F, the Type 1 poppets had 65 percent of the strength of the Type 2 poppets.

**III. High Temperature**

The poppet press test showed that Type 1 poppets had a half strength at 172°F. Type 2 poppets had a half strength at 250°F. These strengths reduce exponentially as temperatures elevate to 300°F and higher. In K-1927, there are several factors that cause temperatures approaching 300°F in the first stage:

**IIIA. High Base Design Temperature**

K-1927 is a three-stage compressor. Three stage compressors have a lower initial cost. Three stage compressors were also common in the 1960s. However, a three-stage compressor has higher design discharge temperatures due to greater required compression ratio per cylinder. By comparison, K-1927 (three-stage) has a base first-stage discharge temperature of 290°F compared with K-2179 (four-stage) base temperature of 204°F. Table A-4 displays the base design temperature by stage for the makeup compressors.

**IIIB. Internal Gas Recycling from Leaking Poppets**

During compression, gas is heated. In compressors, this heat is dissipated in heat exchangers mounted between the various stages. If the suction poppets do not seat properly, discharge gas can escape through the suction valve and reenter the cylinder without being cooled. Likewise, discharge valves not seating properly will

Table A-4. Base Design Temperature by Stage for the Makeup Compressors.

	K-1926/27	K-2179
1st stage	290°F	204°F
2nd stage	241°F	202°F
3rd stage	210°F	186°F
4th stage	N/A	187°F

admit heated discharge gases back into the cylinder. If either valve has gas leaking past, the cylinder will begin to heat up.

Solid particles will cause the poppets not to seat properly. Gas contaminants such as chlorides or rust, scale, and grease can cause poppets to not seat properly.

### IIIC. Internal Gas Recycling from Leaking Unloaders

To control total compressor flow, a controlled leak path is built into compressors. These are called unloaders. Unloaders are mounted on each end of a cylinder. Unloaders consist of a large plug that can either be held into a seat or rest some distance away from the seat. If the plug is seated, the cylinder is pumping gas and is "loaded." If the plug is not seated, gas is free to pass back and forth through the unloader port and no compression takes place.

When unloaders do not seat properly, heated gases will leak past the plug and be recycled. This is very similar to leaking suction valves. Makeup compressor unloaders have suffered from port alignment problems and inadequate guide ring clearances. Both of these problems occur commonly due to no preventative maintenance schedule for the unloaders.

## HUMAN SYSTEM ISSUES

Valve failures have plagued the makeup compressors since original installation in 1965. It was not until recently that a large economic impact was seen from the failures. It is uncommon for a problem to exist for 29 years without remedy. Numerous human system issues allowed the long existence of the valve problems.

- *Design review of replacement valves not comprehensive or detailed enough*—The design review conducted on the poppet valves prior to compete installation in K-1927 was neither comprehensive nor complete enough. The reputation of the poppet valve design benefitted from both acceptable run lengths in smaller compressors (with a history of valve problems) and a lower repair cost compared with plate valves. A more comprehensive design review should have surfaced issues found in the root cause analysis, such as excessive valve lift, high spring stiffness, and pulsation.

Poppets operated successfully for approximately six weeks in the third stage of K-1927 in late 1993. However, no measurement criteria were established that would permit positive identification of the poppet performance as successful for improving compressor reliability. It was impossible to determine if the Type 1 poppet valves were successful based on six weeks operation. However, the decision was made to change all stages of K-1927 to poppet valves at the 1994 unit turnaround.

Skill in valve design is not an expectation of company machinery engineers. It is common to rely on vendors for selection and design of valves. However, design reviews should be conducted to establish the criteria utilized by a vendor in recommending a design and to establish criteria to identify whether the design is successful.

- *Lack of proper cause analysis*—Through the history of valve failures that began in the 1960s, the problem has never been addressed by a rigorous cause analysis. There was limited data gathering to detail the failure history of the valves. There was also a limited incentive to address the poor valve performance. This was due to the idea that there was always a "spare" machine, and unit operations was accustomed to spending large maintenance dollars to keep two of the three machines running.

Proper cause analysis takes training and resources. Due to the lack of economic incentive, the resources were never dedicated to address the problem. Additionally, training to learn the problem solving skills was required. It was common to manage the problem rather than fix it. Thus, the opportunity to develop skills in problem solving techniques was limited.

Lack of proper cause analysis permitted a bias that liquids were the cause of valve problems to exist. This theory was widely accepted, limiting the perceived need for a more comprehensive analysis.

- *Procurement process inadequate*—Major, critical machinery components should be procured from a predetermined acceptable list of parts and suppliers. These parts should be supplied to a design and/or performance criteria established by the original equipment manufacturer (OEM) or a supplier with the design and quality capabilities comparable or superior to the OEM. Over the life of the makeup compressors, replacement parts from a variety of sources made their way into the machine. An example of this is the failed poppet valves provided by Type 1 products. Investigation into Type 1 products revealed that they have most of their valve design experience in gas pipeline applications, with limited design skill in hydrogen services. An acceptable supplier list should not have included them for this service.

Further investigation revealed that there were no valve acceptance criteria. Procurement processes must be in place to force careful scrutiny of aftermarket part vendors, and acceptable vendor databases for components should be created and maintained.

## RECOMMENDATIONS

*Decision Statement:* Achieve a mean time between repair (MTBR) on K-1926 and K-1927 of one year minimum.

Structured solution development and subsequent risk analysis was done to determine the importance of various recommendations. From this structured solution development, the following items were recommended (in rank order):

1. Establish a unit reciprocating compressor surveillance team. The team should have operations, engineering, and maintenance input. They should provide daily surveillance, monitor performance, and provide input into repair work.

2. Install Type 2 redesigned valves in all stages of K-1926 with followup cylinder pressure monitoring. The redesigned valves will meet specific success criteria that address a one year MTBR. The valves will also correct the design deficiencies, such as excessive valve lift and spring stiffness. Cylinder pressure monitoring will be used to trend valve performance for three months. If, after three months, cylinder monitoring shows valve performance similar to the original installation, pursue installing redesigned Type 2 valves on K-1927.

Redesigned Type 2 valves were installed in K-1926 on November 4, 1994, except for the first stage discharge. Cylinder pressure monitoring taken one week later revealed improvements in valve motion. An example of this is shown in Figure A-8 that shows a reduced noise trace following the installation of the new valves.

3. Valve pulsation elimination. Install orifice plates to eliminate valve pulsation. These orifices were recommended from an August 1994 acoustic study of K-1926 and K-1927 done by an engineering consultant.

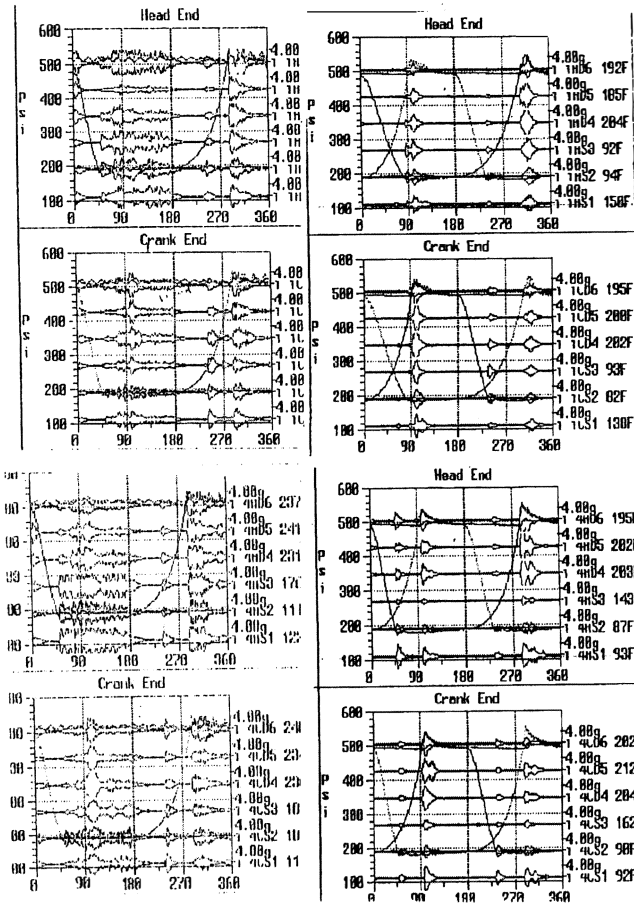


Figure A-8. Cylinder Noise Trace of K-1926 First Stage East and West. Before and After Type 2 Installation.

These orifices were installed on K-1926 in October 1994. Noticeable decreases in pulsation levels were recorded. See Figure A-6 for preorifice pulsation levels and Figure A-9 for postorifice pulsation levels.

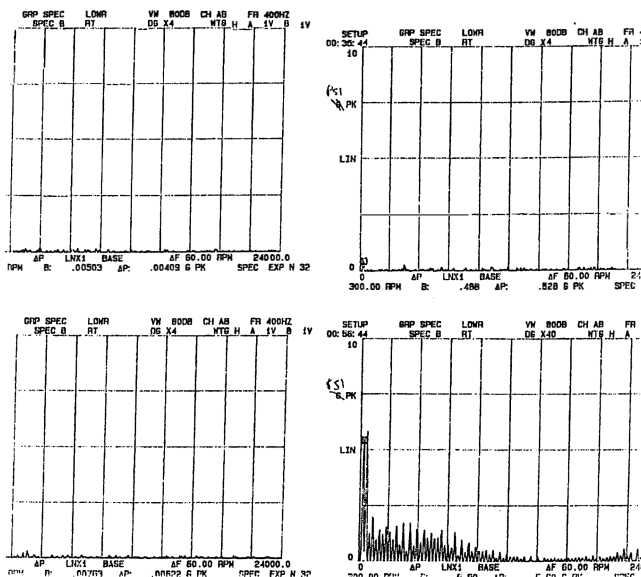


Figure A-9. K-1926 Discharge Pulsation Amplitudes Measured October 28, 1994. (From top left, first stage east, first stage west, second stage, third stage.)

4. Install continuous valve temperature monitoring equipment. This equipment will capture and record valve cover temperatures every minute. This will aid in troubleshooting valve problems.
5. Consider designating a complex reciprocating compressor inspector. This inspector should have specialized training for reciprocating compressors, and provide technical assurance to repair and preventative maintenance programs.
6. Review and revise valve repair procedure.
7. Redesign or purchase new loader valves. These unloaders should minimize gas leakage.
8. Review and optimize cylinder lubrication. This reduction will help eliminate stiction.
9. Consider designating a complex reciprocating compressor repair crew. They would require specialized training and additional tools. Their purpose would be to reduce repair induced failures.
10. Establish an ideal loading strategy. Running cylinders unloaded for long periods of time causes cylinder lubrication to collect. This collected oil can damage the valves. The machines should remain as fully loaded as possible.
11. Continue with root cause analysis efforts. Although valve failures consist of approximately 80 percent of compressor downtime, other component failures should be analyzed. Valve failures cause added loads on other compressor components, so life of these components is expected to increase as valve life increases. Also, K-2179 is a four-stage machine and may have separate causes from K-1926 and K-1927.

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Finally, we must acknowledge the management steering team that had the patience and foresight to permit this analysis to be completed, even though it took considerable time and effort.

