MACHINERY MONITORING UPDATE

by

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ABSTRACT

This paper describes and economically justifies one major oil company’s utilization of a total integrated mechanical inspection program as an alternative to high maintenance costs and reduced plant productivity.

INTRODUCTION

An all-out war on excessive maintenance cost incurred on major turbomachinery can result in a dollar saving of up to 30% using a total integrated machinery inspection program. The exact savings in a given plant will depend on how much of the total program is already being effectively utilized. Chevron reduced the mechanical dollars by approximately 1/2 in one of its newer refinery and petrochemical plants after initiating this program. The major areas of the integrated machinery inspection (IMI) program include:

A. Machinery Protection — Shut machine down automatically before catastrophic failure, utilizing vibration, thrust position, low lube oil pressure, etc., instrumentation (run the machine the last mile, but don’t demolish it).

B. Machinery Surveillance and Diagnostics — Routine surveillance to continuously track machine’s on-line condition. Vibration diagnostics, performance testing, torque or horsepower readout, etc. (machines are only profitable when running, and when running efficiently).

C. Record Keeping — Maintenance history and cost, performance records, vibration history, (the best doctor’s diagnosis is only a best guess without his patient’s complete medical history).

D. Design Review — Excessive maintenance and down time may indicate a design fault. (Solve the problem; don’t continue to fight it.)

E. Quality Control — Detailed maintenance checklist, 100% inspection by non-maintenance personnel, on-the-job technical advisor, etc. (The very best design cannot truly be evaluated if not followed to the letter.)

F. Attention, Care, and Dedication — The above can be best accomplished if one dedicated individual is responsible for the total IMI Program. (Love is never having to say I’m sorry — it wrecked.)

A. MACHINERY PROTECTION

Protection instrumentation on turbomachinery is not new to the petrochemical industry. Single-channel shutdown instrumentation (low lube oil pressure, low seal oil pressure, high temperature, etc.) has been standard for years. However, as designers continue to press the “state-of-the-arts” technology, the need for additional protection is evident. Sophisticated vibration and axial position instrumentation is rapidly becoming standard equipment on most major turbomachines. In order to realize the maximum protection for the dollars invested, these protection instruments must also be connected to the machine’s shutdown system.

At Chevron, we have advocated activating all machine shutdown devices from the beginning. We have adopted the philosophy that it is better to take an occasional quick shutdown than to create a major machine, jeopardize plant operations and suffer prolonged shutdowns. Originally, our vibration and position monitoring systems were single-channel units with one probe, lead, and driver per monitor. A malfunction of any one component could (and did) result in false plant shutdowns. Nine false shutdowns in one year encouraged the development of a redundant system. Our current vibration and axial position instrumentation consists of a two-channel, voting logic, redundant system as outlined in API Standard 670, “Noncontacting Vibration and Axial Position Monitoring System.” To the author’s knowledge, no major machine equipped with the API 670 redundant vibration and axial position monitoring system has experienced a false shutdown or catastrophic failure to date. We have experienced several component failures in one-channel only, resulting in an anticipatory alarm and circuit fault indication. The API 570 Vibration Protection System consists of: (1) two noncontacting proximity probes at each radial bearing, measuring shaft vibration displacement in mils peak to peak; and (2) two noncontacting proximity probes for each shaft, measuring axial position (Figure 1).

Radial Vibration Monitors

The redundant—voting logic radial vibration monitor requires the vibration levels to exceed the shutdown limit in both the X and Y direction (45 degrees each side of top dead center) for shutdown. If the shutdown limit is exceeded in one direction (either X or Y), only the anticipatory alarm occurs. This arrangement offers maximum machinery protection from catastrophic failures (blade or wheel failure, foreign object damage, etc.) with minimum risk of an unnecessary shutdown. The au-
that's experience indicates that in all cases of catastrophic failure, the vibration orbit always blossoms, exceeding the shutdown limit in both the X and Y directions. In most cases, the distressed machine is shut down before major damage occurs. In all cases, the damage is greatly reduced. Normally the machine can be restarted and operated at a minimum condition long enough to get the plant down safely. On the other hand, we have experienced potentially damaging vibration levels in one direction only (misalignment, internal rubs, bearing preloads, etc.) that would eventually result in a machine failure if not corrected or reduced. In these cases, an anticipatory alarm is preferred to shutdown. It offers the opportunity to reduce the vibration by changing operating conditions, reducing the speed, etc., or to plan an orderly plant shutdown.

**Thrust Bearings**

The redundant-voting logic thrust monitor consists of two probes measuring the shaft’s axial position. Both probes must indicate axial movement in excess of the predetermined shutdown limit to initiate a trip. As with the radial vibration monitors, if only one probe exceeds the shutdown limit, only the anticipatory alarm occurs.

The majority of thrust bearing failures that occur are instantaneous, allowing only seconds from first indication to metal-to-metal contact of the rotating and stationary parts. There is simply not enough time to allow the operational personnel to make human decisions and prevent major mechanical damage. Therefore, if the axial position monitor is to achieve full potential, it should be connected to the machine’s shutdown system (Figure 2). One of the most common arguments against arming a machine’s thrust protection devices is that it is better to sacrifice the machine in some cases than the process catalyst or the operating plant. However, we have operating experience that indicates the opposite may occur. One of the cases in point was a thrust bearing failure on a high speed centrifugal compressor caused by excessive balance piston labyrinth clearance. About five seconds after the excessive thrust load overcame the lube oil film between the thrust shoes and disc, the machine was automatically shut down. As the overload dissipated, the lube oil film was re-established between the slightly wiped thrust shoes and disc. The compressor was restarted and operated at minimum condition until the plant could be safely shut down. The plant catalyst was saved and the machinery damage limited to replacement of a thrust disc and shoes. Undetected, this condition could have resulted in major damage to the rotating machinery and plant catalyst. In most cases, once the machine craters, it cannot be restarted.

**B. MACHINERY SURVEILLANCE AND DIAGNOSTICS**

The machinery protection instrumentation (radial vibration and axial position monitors) offers a bonus for the dollars invested; it is an excellent surveillance and diagnostics tool.
Connected to today's sophisticated analytical equipment, the transducer signal is an excellent indicator of a machine's mechanical condition. The installation of this instrumentation permits expanding the Surveillance Programs to include radial and axial shaft vibration and radial and axial position measurements, in addition to the bearing cap and case measurements obtained with accelerometer type transducers. The Program can be expanded to include:

1. Photographed oscilloscope displays of phase-related shaft orbits and time base vibration sine wave signals.
2. Frequency base spectrum (displacement and frequency X-Y Plot) for each probe.
3. Shaft's geometrical position within the bearing.
4. Axial shaft position relative to thrust limits.

To realize the full potential of the vibration data available from the noncontacting probes and case acceleration transducers, some sophisticated analytical equipment is mandatory. The most commonly used instrumentation package for total machine surveillance consists of:

1. Oscilloscope and oscilloscope camera.
2. Real time analyzer.
3. Digital readout phase, amplitude and speed instrument.
4. X, Y1, and Y2 hard copy plotter.
5. Tape recorder.

To obtain maximum benefits from the Major Machinery Diagnostics and Surveillance part of the program, base machine data is essential. The best places to establish the personality profile of the machine are: (1) on the manufacturer's test stand; (2) during the new machine startup, at the plant site; and (3) after each major overhaul. The minimum data obtained should include:

1. Oscilloscope pictures of orbits and time base wave form of each probe at slow roll, minimum governor, operating conditions, and maximum continuous speed (Figure 3).
2. Spectrum plots of amplitude vs. frequency for each probe at slow roll, minimum governor, operating condition, and maximum continuous speed.
3. Raster plots of amplitude, frequency, and speed for each probe at 500 rpm intervals (Figure 4).
4. Tracking plots of speed, and amplitude, and phase for each probe from slow roll to trip speed (Figure 5).
5. Case and bearing cap accelerometer measurements at minimum governor, operating conditions and maximum continuous speed.
6. The machine's speed, probe gap, filtered vibration, unfiltered vibration, and phase angle should be handlogged at 500 rpm intervals for each probe. The tape recorded footage should also be recorded at each interval.

A more detailed data presentation may be required if a problem is suspected.

After the acceptable base data profile of the machine is established, it should be surveyed at least once a month. A complete set of oscilloscope pictures and spectrum plots should be obtained for each probe and compared with the previously obtained data for trends that could signal any potential area of concern. Case and bearing cap acceleration should also be measured and compared with previous plots for frequency and amplitude changes. The running coupling alignment of the machine should also be monitored each month.

Economic Caution

In today's energy-conscious world, a means of accurately measuring the efficiency of the machinery train becomes a very important part of any conscientious program. Utilizing the state-of-the-art techniques (both mechanical and instrumenta-
tion) it is possible to safely operate a machine from a mechanical standpoint longer than it may be economically sound from a production or an energy viewpoint. Adopting base and periodic performance testing has proven to be a very helpful tool for defining on-the-line operational and mechanical problems. However, even our best effort only produces an accuracy of about ± 5%. The ability to analyze operational and mechanical conditions has been greatly improved by recent introduction of direct shaft torque and horsepower measurements, with accuracies up to ± 1%. With this information, logical economic decisions can be made relating the important parameters of production, energy consumption, and overhaul dollars (Figure 6).

C. RECORD KEEPING

Reliable inspection, maintenance and financial records are a necessary part of the IMI Program. The goal of this Program should be to increase profit by improving reliability and throughput and at the same time reducing the cost to maintain the machinery. The success of the Program can be ascertained only if accurate maintenance and financial records are maintained.

History of the Machine

All the significant events should be documented in simple history form for easy reference. The minimum requirements should be:

- Routine maintenance
- Repeat maintenance
- Excessive maintenance
- Catastrophic failure
- Design improvements
- Operational difficulties
- Performance history
- Torque or horsepower measurements
- Vibration history

There are a number of reliable record keeping systems capable of highlighting significant changes in cost and maintenance. Entries for any of these systems should be brief but clear enough so anyone could obtain a clear and accurate description of what occurred. One simple but effective system utilizes the PICO method, indicating the Problem, what the Inspection data revealed, the Corrective action taken, and the Outcome of the job.

A good record system should also include a maintenance overhaul checklist. This checklist details critical part sizes, clearances, arrangements, torque value, and all other items essential for sound mechanical overhaul (see Appendix A). The base and periodic performance data of the machine is also an important part of the Program. Shaft torque and horsepower measurements are also gaining in popularity and proving very useful. A complete vibration history is required.

In addition to justifying the need, and measuring the results of the Program, these records are also valuable for: (1) forecasting equipment life; (2) planning inspection intervals; (3) predicting overhaul cycles; and (4) making judgment decisions of the scope of maintenance required during a scheduled plant shutdown.

D. DESIGN REVIEW

Often excessive maintenance, poor performance, and/or extended down time of major machines result from design faults. Too often, we just accept the idea that a machine requires maintenance at certain time intervals. By carefully scrutinizing the machine's history, and reviewing its design, often the overhaul intervals can be greatly extended by including design changes or upgrading with the IMI Program. However, machine designs are continuously improving, and by incorporating the latest technology in design, protection, and monitoring techniques, machine runs can be extended, thereby increasing the earnings from your IMI Program.

E. QUALITY CONTROL

The very best machinery design can be seriously compromised if the machine is not accurately assembled. Machinery design improvements cannot be adequately evaluated unless
the recommended changes are followed to the letter, and specified quality maintained. In some cases, a good design improvement has been ineffective due to startup failures caused from improper installation. Detailed maintenance overhaul checklists completed and signed by the maintenance personnel, 100% inspection by non-maintenance inspectors and on-the-job technical advisors are all an essential part of the Quality Control portion of the IMI Program. Having detailed, accurate, assembly records is a valuable tool in making judgment decisions if complications should arise during plant operation.

F. ECONOMIC JUSTIFICATIONS

Since the establishment of the Integrated Machinery Inspection Program in one of the major petrochemical plants, the average maintenance cost for all turbomachinery has been reduced 30% from $6.60 to $4.60 per horsepower per year (Figure 7). The dollar earnings resulting from extended plant runs are significant. The total earnings from the IMI Program can be broken down into components for individual evaluations. Our experience indicates that the Machinery Protection amounts to 30% of total earnings; Machinery Surveillance, 20%; Record Keeping, 15%; Quality Control, 15%; and Design Review and Improvement, 10%. In order to realize the full financial potential of a total IMI Program it must be carried out in its entirety.

Financial return from the Program include the following:

1. Early detection of an impending mechanical problem can divert the expensive and potentially catastrophic-type failure into routine scheduled repairs. Plant downtime, material, and labor are substantially reduced.

2. On-stream inspection of major turbomachinery eliminates the need to perform the insurance type open inspection at regular intervals. Maintenance can be restricted to "only when absolutely necessary" basis. Too many times, perfectly good machines have been overhauled on a preventive maintenance basis and then suffered startup problems, ranging from improper installation of bearings to rags left in the lube oil lines.

3. Extended runs have been experienced with turbomachines having moderate to high levels of vibration by utilizing the sophisticated diagnostic and machinery protection instruments. By determining the cause and severity of a problem, distressed machines can be operated at minimum risk until the plant is shut down for other reasons. In today's market, unscheduled plant shutdowns can result in considerable financial losses.

4. Continuous review and implementation where applicable of the latest advancements in turbomachinery technology, can also increase reliability and extend overhaul intervals.

ESTABLISHING A PROGRAM

Recently, we applied the knowledge and experience gained over the last seven years developing an IMI Program for rotating equipment to a similar program for reciprocating equipment. The reciprocating program has been even more financially rewarding than the rotating program; utilizing the previously developed techniques, the reciprocating program reached maturity in only two years. At the onset of the reciprocating program, the maintenance cost was averaging $15.75 per horsepower per year. At the end of two years the maintenance cost had been reduced to $6.25 per horsepower per year. The computed annual energy savings alone more than offset the cost of the overhaul and upgrading of the compressors. Pre-program manpower requirements were 30 man-days per cylinder per year, 34% of which was unscheduled overtime. Post-program manpower is averaging 7.6 man-days per cylinder per year. No overtime has been required through the first quarter of 1977.

The steps used for that program will serve as a guideline for establishing an IMI Program for all types of mechanical equipment. There are nine steps that are necessary if maximum financial benefits are to be derived from the IMI Program:

1. Establish scope of desired long-range program.
2. Determine factual pre-program costs to maintain the equipment chosen for the test program.
3. Determine pre-program maintenance and reliability factors.
4. Investigate the latest turbomachinery and instrumentation technology.
5. Establish detailed overhaul and surveillance checklists incorporating all technology gained in step four.
6. Select and train dedicated, full-time, qualified, investigators.
7. Obtain instrumentation and hardware to implement the program; schedule, installation and upgrading.
8. Officially initiate your IMI Program D-Day.
9. Review the results of the original objectives. Explore the degree and rate of program expansion.

Initially, formulate a long-range plan for any IMI Program. This plan should include realistic estimations of initial cost and manpower to implement the program, a reasonable timetable for achieving each step (see Figure 8), and the expected return on investment and long-range earnings. Three main points to keep in mind: Most business managers realize the fact that you must invest money to make money. Most managers have enough problems and don't need to be presented with another one; however, most will consider a well thought-out solution to a problem. Always deal with only the facts. Original estimates may be low, but final returns are usually rewardingly high.
INITIAL PROGRAM OBJECTIVES AND TIME TABLE
A. DETERMINE PRESENT COST TO MAIN EQUIPMENT (OBTAIN CONTROL CHARGE NUMBER & REVIEW PAST RECORDS).
B. DETERMINE PRESENT MAINTENANCE & PERFORMANCE HISTORY (ESTABLISH RECORD SCHEDULE).
C. INVESTIGATE ADVANCE TURBOMACHINERY TECHNOLOGY.
D. DEVELOP MACHINERY OVER HAUL CHECK LIST (FOR EACH MAJOR MACHINE IN PROGRAM).
E. DETERMINE PRESENT CONDITION OF MACHINERY, ESTABLISH PARTS, & MAN POWER TO UP DATE STATE OF THE ARTS.
F. TRAIN PERSONNEL, PURCHASE MACHINERY PROTECTION, & DIAGNOSTIC EQUIPMENT.
G. INSTALL EQUIPMENT - UP GRADE MACHINERY.
H. INITIATE THE INTERROGATED MACHINERY INSPECTION PROGRAMS.
I. REVIEW RESULTS. (PRESS FORWARD)

<table>
<thead>
<tr>
<th>YEAR 1</th>
<th>YEAR 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Qt. 2nd Qt. 3rd Qt. 4th Qt.</td>
<td>1st Qt. 2nd Qt. 3rd Qt. 4th Qt.</td>
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</tbody>
</table>
A.                                |        |
B.                                |        |
C.                                |        |
D.                                |        |
E.                                |        |
F.                                |        |
G.                                |        |
H.                                |        |
I.                                |        |

Figure 8. Interrogated Machinery Inspection Program.

Top management's active support is essential. Without it, the Program will not be totally successful.

The establishment of factual pre-IMI Program conditions, cost and reliability, to which all progress can be related, is essential. If accurate accounting records are not available, it is advisable to establish a means of monitoring all maintenance and related cost for a reasonable period; preferably one year.

The machinery reliability and performance history is equally important. If started early, this phase of the Program can be performed concurrent with other preliminary steps.

Before committing to a set program, it is advisable to thoroughly explore the latest technology in turbomachinery designs, monitoring and diagnostic instrumentation. Many recent advancements have proven successful in improving reliability and efficiency. This information can be obtained by researching the technical libraries and by contacting noted specialists in the area of concern.

After compiling sufficient amounts of technical data and machine history, you can easily establish a personalized overhaul checklist for each major machine in the Program.

The selection of personnel to manage the program is all important. Diagnostic instruments (Black Boxes) are not the total answer; they are only tools to be used by skilled, dedicated, investigators. A successful investigator should be knowledgeable of the equipment, both technically and practically. Alternately you may choose to use a close-knit team of technical and practical talent. Procurement of the right people may be one of the most important phases of your program. It is unwise to invest in instrumentation or upgrade hardware until potentially qualified personnel have been dedicated to the Program.

After completing the above steps, the IMI Program should be commissioned. The all-out war on known-documented mechanical problems can be effectively launched. The true picture of the Program usually takes about one year to fully develop. A continuous in-house review of the progress is advisable, but the official review should be at one-year intervals. If you can achieve all the goals on your planned objective chart, continued success of the Program is almost guaranteed.

CONCLUSION

The achievements to be expected from an Integrated Machinery Inspection Program will be relative to the quality and extent of the existing inspection practices. Essentially any process plant could benefit from at least some of these procedures. If a new integrated program is being considered, the following suggestions may be useful: (a) do not over-extend your resources initially; start with one troublesome process plant, unit, or area. The limited site chosen for testing the program should be the "toughest" problem area available. If you can conquer the "bully," then remaining areas should be easy, and (b) based on that experience (and the resulting predictable payout), extend the program on an orderly basis to additional facilities where appropriate.
## CENTRIFUGAL COMPRESSOR OVERHAUL CHECK LIST

**REASON FOR OVERHAUL**


<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>SPECIFICATIONS</th>
<th>MEASUREMENTS &amp; REMARKS</th>
<th>MECH.</th>
<th>FOREMAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor</td>
<td>INSPECT FOR WEAR, DAMAGE, &amp; FOREIGN MATTER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaft Runout</td>
<td>Maximum .001&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust Runout</td>
<td>Maximum .0005&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust Collar Fit</td>
<td>&lt;.001&quot;</td>
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<td></td>
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</tr>
<tr>
<td>Balance</td>
<td>Kin - .2 oz./in. Dyn - .2 oz./in.</td>
<td>Kin oz./in. Dyn oz./in.</td>
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<tr>
<td>Bearings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearance</td>
<td></td>
<td></td>
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<tr>
<td>N.P. Radial</td>
<td>.005&quot; To .008&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crush</td>
<td>.0005&quot; To .002&quot;</td>
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<td></td>
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</tr>
<tr>
<td>L.P. Radial</td>
<td>.005&quot; To .008&quot;</td>
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<tr>
<td>Crush</td>
<td>.0005&quot; To .002&quot;</td>
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<td></td>
</tr>
<tr>
<td>Thrust</td>
<td>.012&quot; To .014&quot;</td>
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</tr>
</tbody>
</table>

**AXIAL MOVEMENT**

**LIMITED MOVEMENT**

(B) Should 5/12 of Total Movement

(D) To Allow For Thermal Expansion.

**RECORD MEASUREMENTS**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thrust Clearance</td>
<td>5/12 Of Total Axial Movement</td>
<td>7/12 Of Total</td>
<td>Total Axial Movement</td>
</tr>
</tbody>
</table>

**COUPLING**

Continuous Oil Lubricated

Check Teeth For Wear, Damage, Sludge, Etc. Thoroughly Clean

Align Match Marks, Hub, Bell & Spool.

Check Distance Between Shafts 6 Inches

Coupling Box Torque 37 Ft./Lbs.

Visually Observe Oil Flow To Coupling With Oil Pump

Check Axial Movement Of Coupling Min. 3/32"
### LUBRICATION
- **Description**: Engine Oil Pressure Feed
  - **Specifications**: 0.0-9 Pressure Fed
  - **Measurements & Remarks**: Drain, Clean & Refill

- **Main Oil Press.**
  - **Specifications**: 85 To 100 PSIG
  - **Measurements & Remarks**: 80 PSIG

- **Alarm And A.P.S.**
  - **Specifications**: 15 To 20 PSIG

- **Bearing Press**
  - **Specifications**: 10 PSIG
  - **Measurements & Remarks**: 8 PSIG

- **Filter:**
  - **Specifications**: Change Filters Before Starting Machine

### PRE-START UP CHECK OUT
- **Blinds Pulled**
- **Make Final Inspection Of Machine**
- **Check For Foreign Material**
- **Leak Test**
- **Remove All Tools, Parts, Etc.**

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The above portion of check list must be completed and returned to the mechanical equipment inspector before machine is started.

### INSPECTION

#### Pre-Run-in Check
- **Check That All Items On The Above Check List Are Completed**
- **Check That All Mechanical Work Is Completed And Machine Is Ready To Start**
- **Check That Lube Temperature Is 80°F — 120°F**
- **Check That All Probes And Monitors Are Working**
- **Make Sure All Cases Have Been Blown Down**

#### Run-in Check
- **Obtain Slow Roll Data**
- **Check All Oil Flows And Temperatures**
- **Check All Bearing Temperature**
- **Check For Unusual Noise**
- **Take Full Set Of Base Vibration Data**
- **Check Hot Alignment**

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Inspector Sign For Each Step