FAULT DETECTION AND DIAGNOSIS IN RECIPROCATING MACHINERY

Bryan R. Long, Ph.D., P. Eng. And David N. Schuh, P. Eng.

1. The Need for Analysis

Reciprocating machinery in industry is found in the following forms:

- Diesel engines
- Spark ignited engines
- Reciprocating compressors
- Plunger pumps

Machines of these types perform important roles in a number of industries, including transportation, pipelines, petrochemical and gas gathering.

Faults in reciprocating equipment fall into two general areas: Deterioration in performance and deterioration in mechanical condition. Improvements in either area generate significant benefits, including increased machine availability, reduced energy costs and optimum utilization of maintenance resources.

This paper will explore current developments which help achieve these benefits. We will concentrate on spark ignited engines, but the principles are applicable to other reciprocating machines.

2. Analysis Techniques

Analysis of reciprocating equipment is more complex than analysis of rotating equipment. Useful signals are:

- conditioned vibration versus crankshaft position
- cylinder pressures as a function of crankshaft position
- ultrasonic energy versus crankshaft position
- ignition voltages versus crankshaft position
- process type data: pressures, temperatures, flow rates

2.1 Vibration Patterns

Conventional broad-band vibration waveforms and spectra are of little value. Normal vibration in a reciprocating machine tends to obscure information associated with faults. Instead, appropriately conditioned vibration signals, presented against crankshaft position, can be used to detect and diagnose a variety of problems.

The vibrational energy associated with faults in cylinders arises from:

- mechanical impacts such as valve closure or chattering rings
- gas leakage such as cylinder blowby and leaking valves

These energies tend to be relatively broad band in frequency content. By filtering out low frequencies, the normal vibration will be excluded, leaving only the energy associated with the events in which we are interested. We then have a signal like that illustrated in Figure 1.

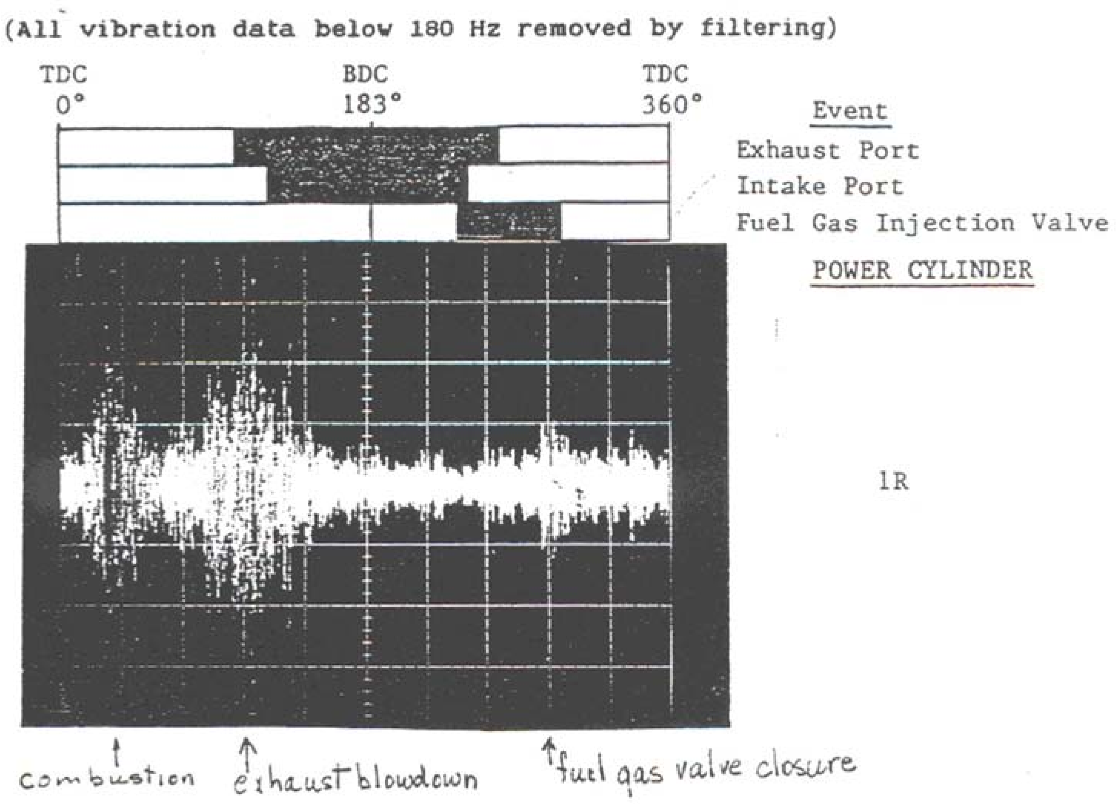


Figure 1 – This filtered vibration signal is a normal patterns representing the events happening in the cylinder of a two cycle engine

We are dealing with patterns in which some energy content is normal; the challenge is to be able to determine what is normal, what is abnormal, and the nature of any abnormality. Figure 2 presents some abnormal signals.

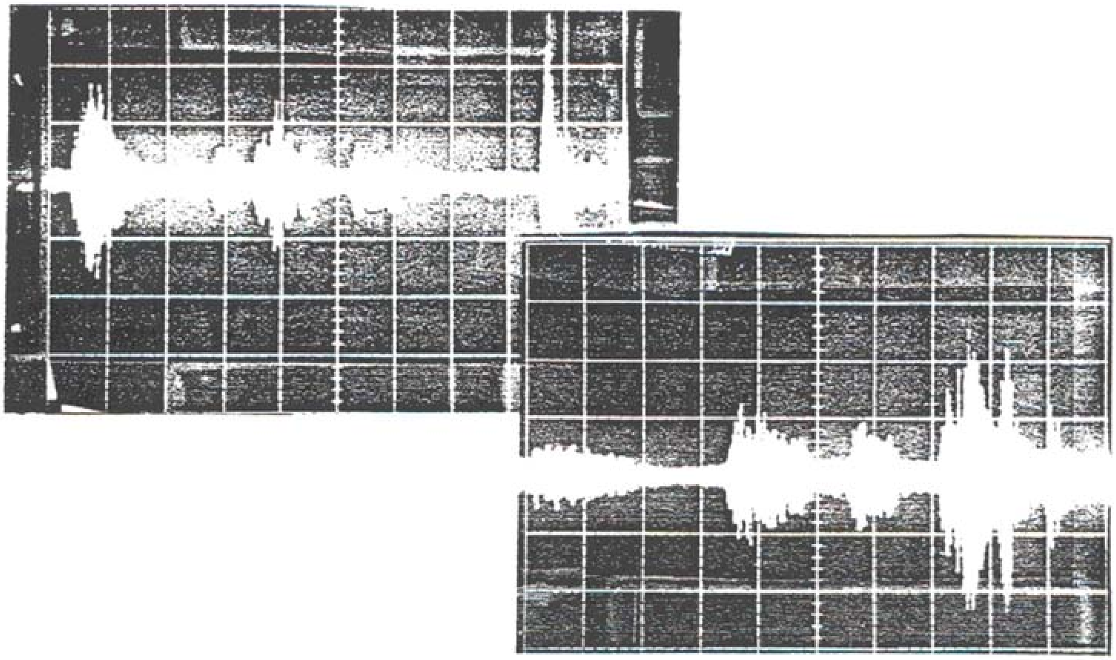


Figure 2 – The analyst must evaluate vibration patters to determine which are normal, and which are abnormal.

The patterns are complex. Even more problematic, they vary with operating conditions. Considerable art is involved, and experience is critical, but an expert can get a reasonable indication of the condition of the cylinder and valves.

2.2 Ultrasonic Patterns

Ultrasonic energy patterns can be used to enhance the information in the vibration patterns. Ultrasonic energy is collected from higher frequencies than vibration; usually in the range of 20 kHz to 100 kHz.

These patterns will be more sensitive to gas leakage and less sensitive to mechanical impact events. If we take both ultrasonic and vibration signals on a cylinder, problem detection becomes more sensitive and reliable, and diagnosis is also more reliable.

Figure 3 shows an ultrasonic pattern along with the corresponding vibration signal.

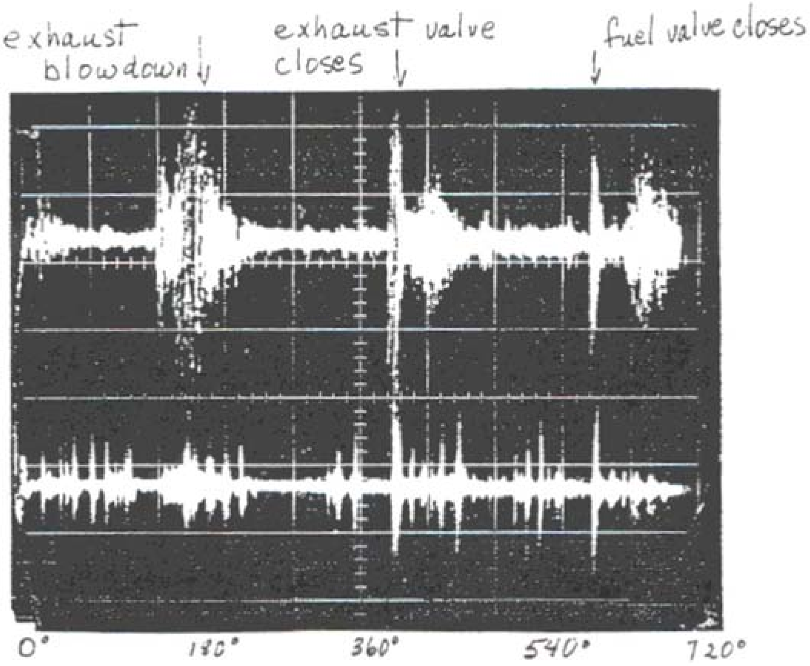


Figure 3 – Mechanical impacts tend to dominate vibration traces, while gas leakage shows up more clearly in ultrasonic traces

2.3 Cylinder Pressure

Knowledge of the pressure in the cylinder as a function of crank angle allows:

- detection of performance problems, such as poor air/fuel ratio and excessive firing pressures
- detection of mechanical problems such as low compression pressure and carbon build-up in ports
- interpretation of anomalies through correlation with vibration and ultrasonic signals

Examples of power cylinder pressure-time curves are shown in Figure 4, where traces for several cylinders are superimposed on the same picture. Several cycles were recorded for each cylinder, to illustrate the variation in peak firing pressures.

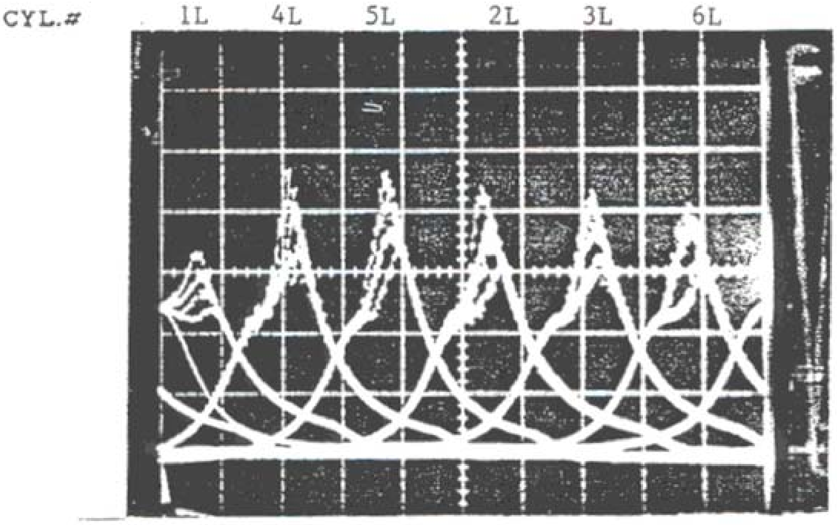


Figure 4 – Power cylinder pressure-time curves photographed from an oscilloscope display

2.4 Ignition Voltages

In spark ignited engines, the ignition system is a source of many of the problems which arise. It is common practice, therefore, to measure the ignition primary waveform and/or the ignition secondary waveform. An example is shown in Figure 5.

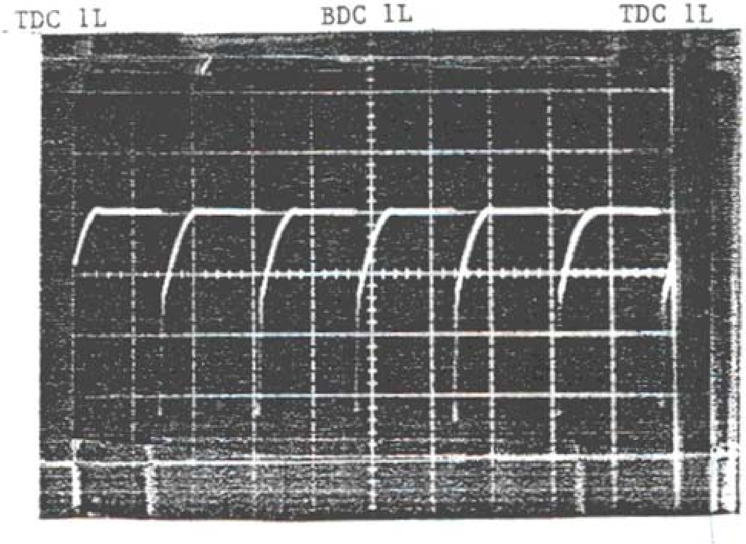


Figure 5 – Ignition primary voltage patters

3. Historical Perspective

About twenty years ago, special purpose electronic instruments called “engine analyzers” were developed. These devices provided the sensors and signal conditioning to produce the “displays present in Section 2.

The original versions were simply data acquisition and display devices, with no analysis function. More recent versions have some analytical capabilities, such as the ability to calculate and display power.

Current engine analyzers have inherent limitations:

- they are complex instruments, requiring considerable expertise to collect data
- data collection is labour intensive
- there is no systematic methodology for dealing with signals which are inherently variable
- anomaly detection is a purely manual process
- problem diagnosis is more art than science, based on the training and experience of the analyst
- there is no mechanism for retaining the expertise which an analyst develops; you have to start from zero with every new analyst and, by consensus, allow two years for his development

These problems have made true engine and compressor analysis very difficult. In practice, the analysis effort is often concentrated on machines which have been identified as suspect, because it is too time-consuming to analyze all machines regularly.

4. Meeting the Need

A new analyzer system called RECIP-TRAP has been developed. This system uses a micro-processor based portable data collector (Figure 6) and a permanent data-base on a personal computer. The major advances are:

- Data collection has been de-skilled
- Data collection is much faster
- Anomaly detection has been automated
- Decision-making has been formalized
- Expertise is built into the system

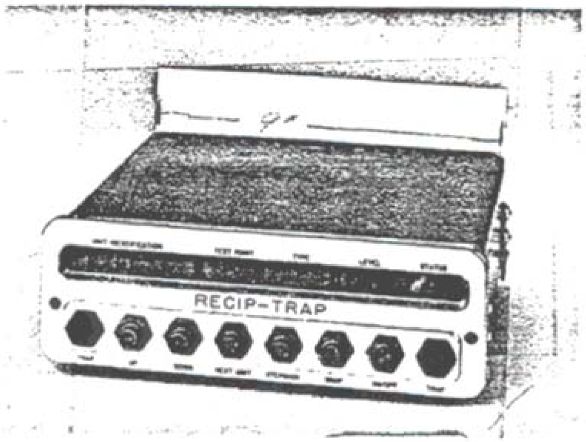


Figure 6 – The RECIP-TRAP Instrument is small and simple to use

About twenty RECIP-TRAP systems are now in use, with an average age of about one year. Experience to date indicates the following:

- tradesmen can be trained to collect data in hours
- data collection requires approximately ¼ the time
- computerized detection of anomalies is reliable when there is enough data on file; analyst time for anomaly detection is reduced to zero
- the formal decision-making process and convenient information access enhance the likelihood that good decisions will be made and some appropriate action taken
- personnel can become effective with the system in about six months, starting with no analysis expertise and no computer literacy
- the time saved during data collection and anomaly detection is used in the critical areas of decision-making and feedback, where real benefits can be achieved
- it is cost-effective to monitor machines not previously analyzed because of reduced time requirement
- it is feasible to monitor machines more often, and therefore failures between visits are much less likely

5. Improved Fault Detection and Diagnosis

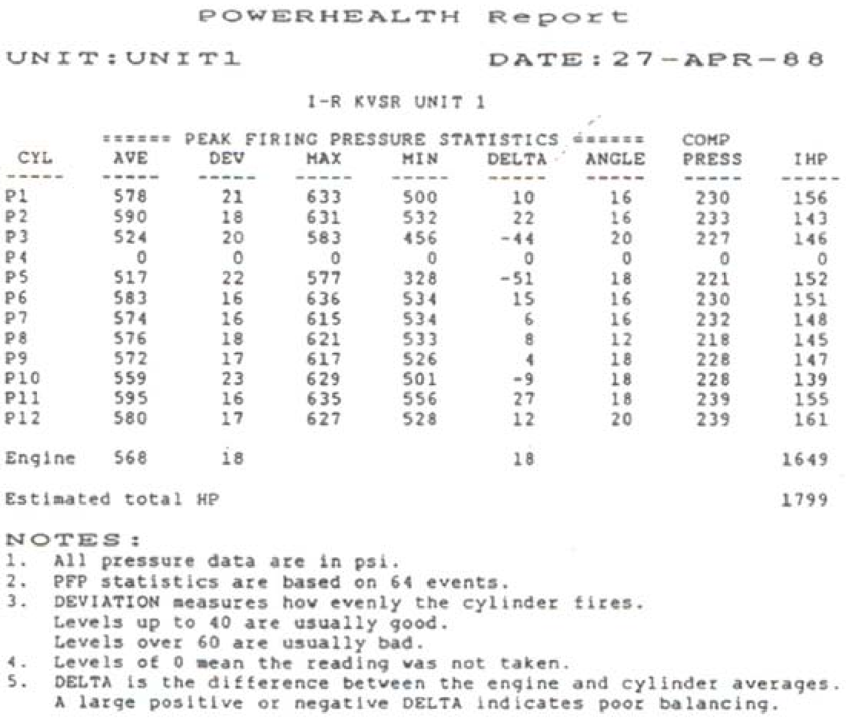
This section shows you how the difficulties in reciprocating equipment analysis described above can be reduced with modern technology. The principle is to depend on the computer for data organization, recall, and anomaly detection, and to use the person for detailed analysis and decision-making.

5.1 Detailed Illustration

A sample study is presented here for an Ingersoll Rand KVSR-12.

5.1.1 Engine Combustion Statistics

Figure 7 shows the peak firing pressure statistics, which give the analyst an overall picture of the performance of the engine. Combustion statistics indicate power cylinder balance, how evenly each cylinder fires, and the presence of misfires or detonation.



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                    POWERHEALTH Report

UNIT:UNIT1                         DATE:27-APR-88

                         I-R KVSR UNIT 1

        ====== PEAK FIRING PRESSURE STATISTICS ======    COMP
 CYL     AVE     DEV     MAX     MIN    DELTA   ANGLE   PRESS    IHP
-----   -----   -----   -----   -----   -----   -----   -----   -----
P1       578      21     633     500      10      16     230     156
P2       590      18     631     532      22      16     233     143
P3       524      20     583     456     -44      20     227     146
P4         0       0       0       0       0       0       0       0
P5       517      22     577     328     -51      18     221     152
P6       583      16     636     534      15      16     230     151
P7       574      16     615     534       6      16     232     148
P8       576      18     621     533       8      12     218     145
P9       572      17     617     526       4      18     228     147
P10      559      23     629     501      -9      18     228     139
P11      595      16     635     556      27      18     239     155
P12      580      17     627     528      12      20     239     161

Engine   568      18                      18                     1649

Estimated total HP                                               1799

NOTES:
1.  All pressure data are in psi.
2.  PFP statistics are based on 64 events.
3.  DEVIATION measures how evenly the cylinder fires.
    Levels up to 40 are usually good.
    Levels over 60 are usually bad.
4.  Levels of 0 mean the reading was not taken.
5.  DELTA is the difference between the engine and cylinder averages.
    A large positive or negative DELTA indicates poor balancing.
```

Figure 7 – Part 1 of the POWERHEALTH Report presents the results of a statistical analysis of 64 cycles in the cylinder

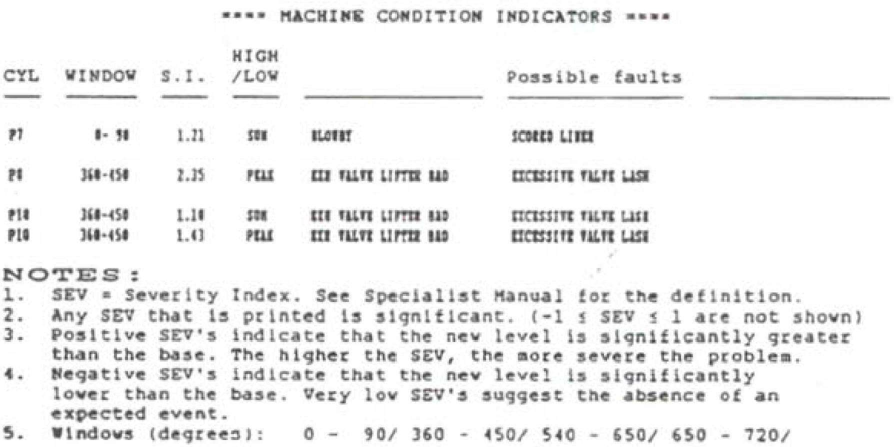
Engine balance is indicated by the cylinder DELTA readings. A cylinder which has a large positive or negative DELTA value is considered to be in poor balance.

ANGLE is the angle after top dead centre at which the peak firing pressure occurs. ANGLE is affected by air/fuel ratio, mechanical condition, and ignition timing.

Compression pressure is used to provide an indication of the mechanical health of the cylinder and IHP (indicated horsepower) tells how the load is distributed to each cylinder.

5.1.2 Mechanical Condition Indicators

One of the techniques that is used for automatic anomaly detection in the RECIP-TRAP System is the comparison of the most recent data to the baseline data. The baseline data is assumed to represent the unit in a healthy condition. Any deviation from the baseline is considered to be a result of deterioration in health. Figure 8 gives a summary of this information for the KVSR-12.



```
                    **** MACHINE CONDITION INDICATORS ****

                        HIGH
CYL   WINDOW    S.I.    /LOW                           Possible faults
---   -------   ----    ----   -------------------     ----------------    ----------------

P7       0- 90  1.21    SUM    BLOWBY                  SCORED LINER

P8     360-450  2.35    PEAK   EXH VALVE LIFTER BAD    EXCESSIVE VALVE LASH

P10    360-450  1.10    SUM    EXH VALVE LIFTER BAD    EXCESSIVE VALVE LASH
P10    360-450  1.43    PEAK   EXH VALVE LIFTER BAD    EXCESSIVE VALVE LASH

NOTES:
1.   SEV = Severity Index. See Specialist Manual for the definition.
2.   Any SEV that is printed is significant. (-1 ≤ SEV ≤ 1 are not shown)
3.   Positive SEV's indicate that the new level is significantly greater
     than the base. The higher the SEV, the more severe the problem.
4.   Negative SEV's indicate that the new level is significantly
     lower than the base. Very low SEV's suggest the absence of an
     expected event.
5.   Windows (degrees):    0 -  90/ 360 - 450/ 540 - 650/ 650 - 720/
```

Figure 8 – The POWERHEALTH Report, Part 2 picks out cylinders in which significant changes in mechanical condition have occurred

A severity index, SEV, is used to indicate the magnitude of the deviation between new and baseline vibration data. Any SEV that is between – 1.0 and 1.0 is not considered to be anomalous and is not presented in the POWERHEALTH Report.

The POWERHEALTH Report gives you:

- the names of the cylinders for which the newest data is significantly different from the baseline data
- the angular window in which the difference is found
- the Severity Index of the anomaly
- an indication that the anomaly is based on a comparison of peaks (PEAK) or area under the curves (SUM)
- a list of possible faults associated with each anomaly

A review of this report shows that power cylinder P8 has a severity index of 2.35 in the window 360 – 450 degrees based on a comparison of the new and baseline peaks. Possible faults in this region are bad exhaust valve lifters and excessive valve lash. (P7 and P10 are also significantly different than on previous occasions and require further analysis.)

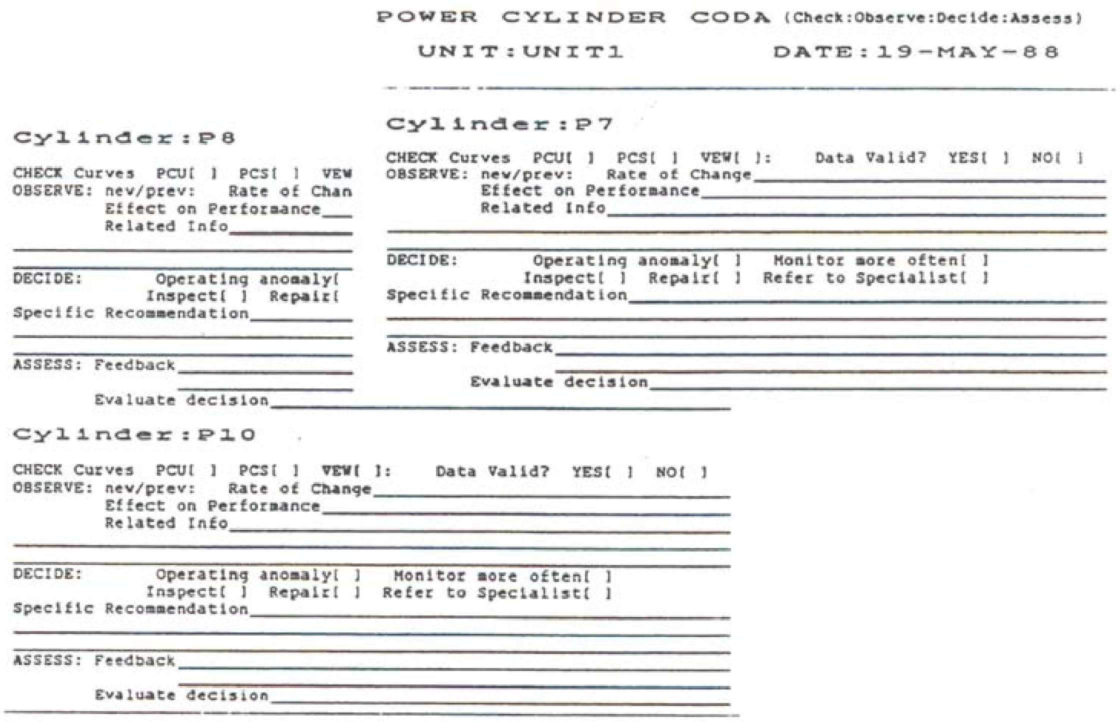
The analyst uses the CODA Decision-Making Model, which follows, to evaluate each of the cylinders identified.

5.1.3 The CODA Decision-Making Model

Experience has shown that good decision-making is the most difficult part of an analysis program. Analysts may become overwhelmed with the amount of data available to review, and find it difficult to actually decide what should be done.

The RECIP-TRAP system overcomes this difficulty, first by having the computer detect which signals are anomalous, and second, by providing CODA, for the analysis of those signals.

CODA begins with the CODA form, as shown in Figure 9. This is printed automatically for all the anomalies so that they are not overlooked. Thereafter, the system provides several analytical displays, described on the following pages, to aid the analyst in making his decision.



POWER CYLINDER CODA (Check:Observe:Decide:Assess)
UNIT:UNIT1 DATE:19-MAY-88

Cylinder:P8

CHECK Curves PCU[ ] PCS[ ] VEW
OBSERVE: new/prev: Rate of Chan
Effect on Performance___
Related Info___
DECIDE: Operating anomaly[
Inspect[ ] Repair[
Specific Recommendation___
ASSESS: Feedback___
Evaluate decision___

Cylinder:P7

CHECK Curves PCU[ ] PCS[ ] VEW[ ]: Data Valid? YES[ ] NO[ ]
OBSERVE: new/prev: Rate of Change___
Effect on Performance___
Related Info___
DECIDE: Operating anomaly[ ] Monitor more often[ ]
Inspect[ ] Repair[ ] Refer to Specialist[ ]
Specific Recommendation___
ASSESS: Feedback___
Evaluate decision___

Cylinder:P10

CHECK Curves PCU[ ] PCS[ ] VEW[ ]: Data Valid? YES[ ] NO[ ]
OBSERVE: new/prev: Rate of Change___
Effect on Performance___
Related Info___
DECIDE: Operating anomaly[ ] Monitor more often[ ]
Inspect[ ] Repair[ ] Refer to Specialist[ ]
Specific Recommendation___
ASSESS: Feedback___
Evaluate decision___

Figure 9 – The CODA Form is produced automatically for each anomaly

CODA stands for Check, Observe, Decide, Assess. It is a step by step process developed to ensure that analysts consider all the relevant information and commit themselves to a decision.

Everyone who is involved can be trained to understand CODA, so that when a recommendation is made, they understand it significance and urgency. CODA becomes a shortcut for communication, because the CODA Report reminds everyone of the detailed analysis that has gone into this recommendation.

5.1.4 The Engine P-T Parade

The first analytical display used is often the pressure-time Parade, shown in Figure 10.

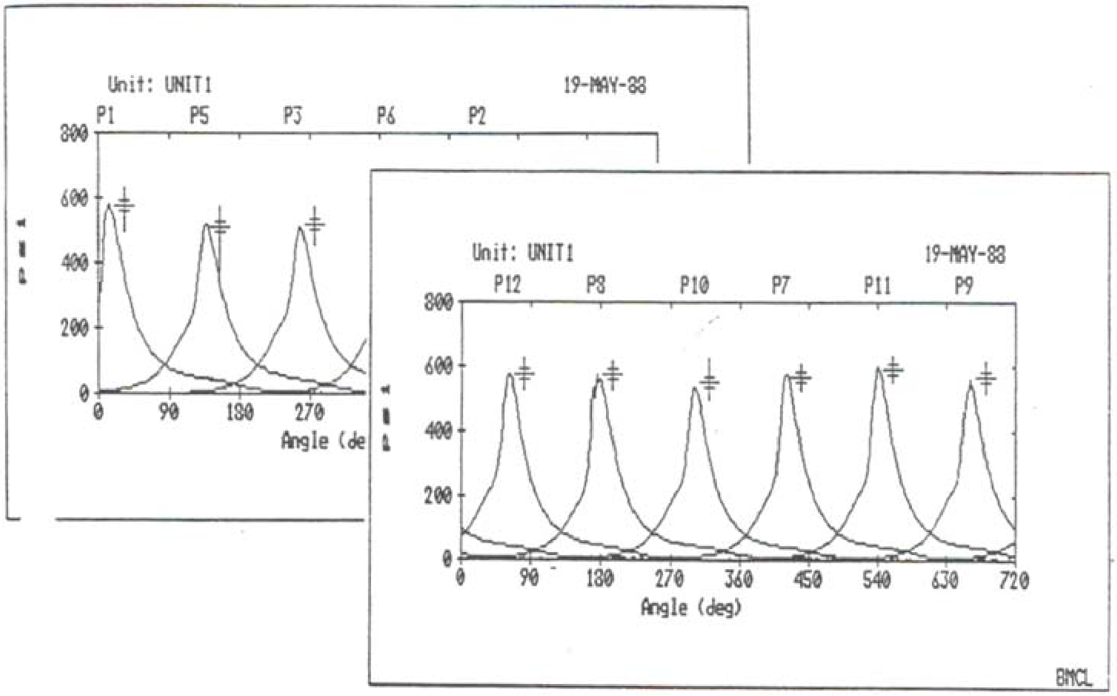


Figure 10 – The Parade presents one representative pressure-time curve, plus combustion statistics, for each cylinder. Compare this with the conventional display (Figure 4)

The pressure-time data is displayed along with the combustion statistics. Note that the combustion statistics icon shows the average (long horizontal bar), average deviation (small horizontal bars) and the maximum and minimum (extreme points of the vertical bar) peak firing pressures. At a glance we can determine whether the cylinders are out of balance, detonating, misfiring or having late combustion.

5.1.5 Power Cylinder Vibration Patterns

The power cylinder vibration display (Figure 11) shows up to eight vibration-time patterns. The patterns should be generally the same, this display makes it easy to identify differences.

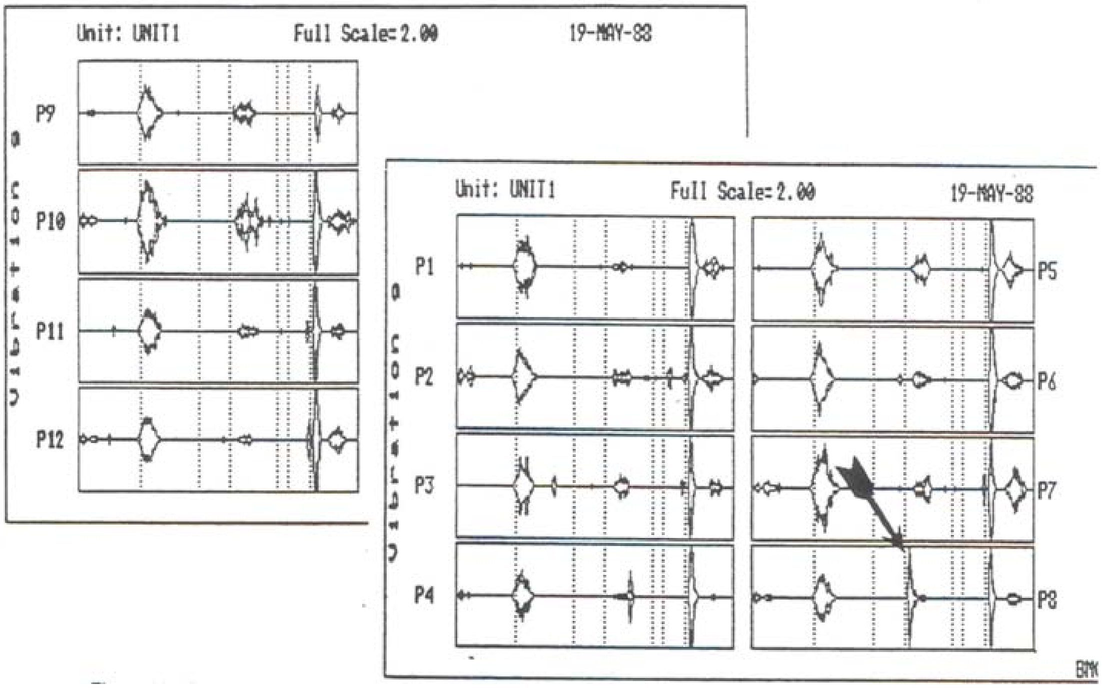


Figure 11 – Power Cylinder Vibration Patterns are displayed in groups of 8 for easy comparison

The vertical dotted lines mark the bounds of the exhaust, intake and fuel injection events, as detailed in Figure 13.

Recalling that the POWERHEALTH Report determined that P8 was anomalous in the window 360 – 450 degrees, we note that the pattern for P8 has an anomalous event just after exhaust valve closure.

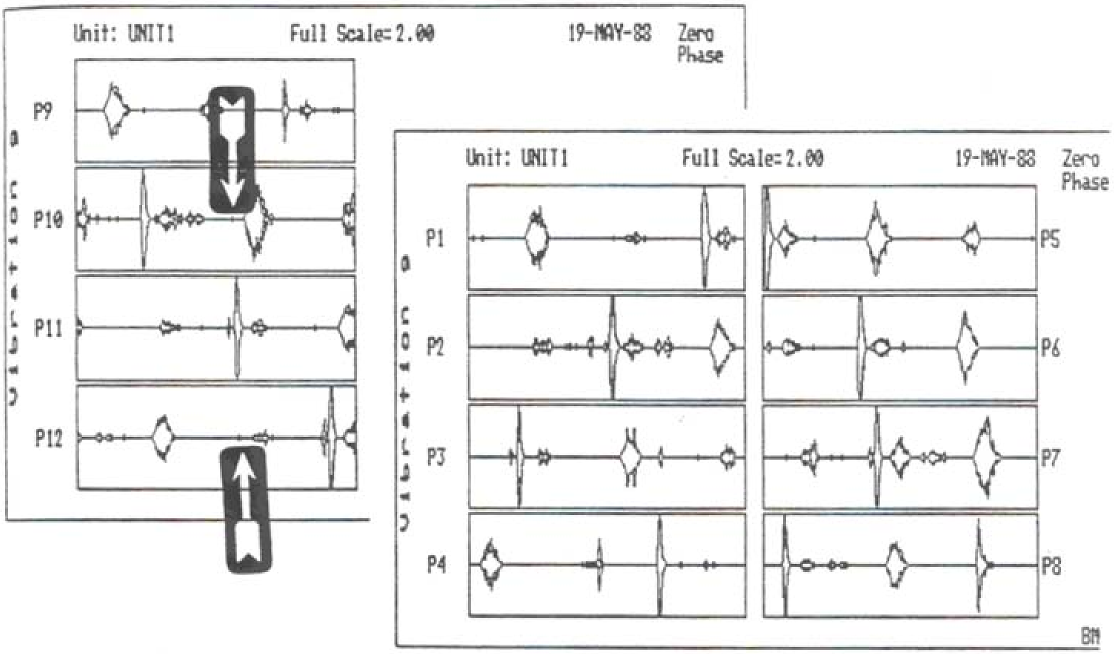


Figure 12 – Cylinder vibration data can be plotted with respect a common reference rather than to TDC of each cylinder

Figure 12 presents the same data as shown in Figure 11, illustrating the power and flexibility of digital data processing. This display is used to show crosstalk to adjacent cylinders. It is often used to shed light on the origin of smaller, otherwise unidentifiable signals. Crosstalk may be seen in the traces for P10 and P12 from the closure of the fuel valve in P11.

5.1.6 The Power Cylinder Signature

Another analytical display, the power cylinder signature, combines the timing diagram with the vibration-time and pressure-time curves. The analyst typically turns to this plot to determine the relationship between the major events in the cylinder and the vibration and pressure data.

Recall that P8 was flagged as anomalous in the POWERHEALTH Report; Figure 13 confirms that the exhaust valve is closing hard.

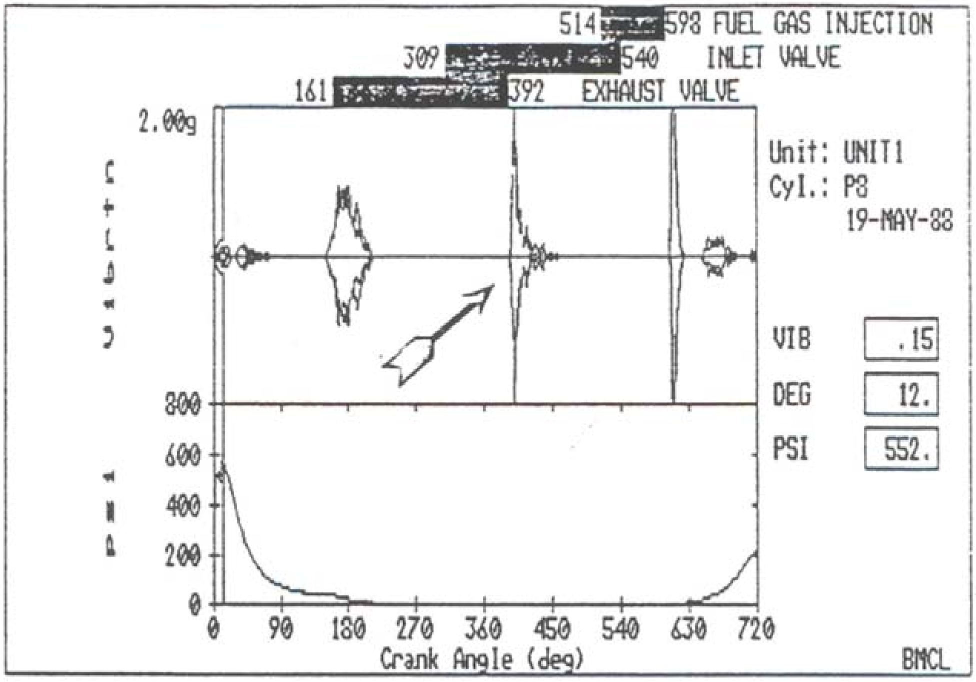


Figure 13 – The power cylinder signature relates the timing of exhaust, inlet, and fuel injection events to the vibration-time and pressure-time traces

5.1.7 Data Archives

After the data is processed, it is placed into the data archives where comparisons may be done.

Figure 14 contains the CODA display, where new, previous and baseline data are plotted on the same graph. The analyst can place a cursor anywhere on the display, and can then see actual levels at each degree along the plot.

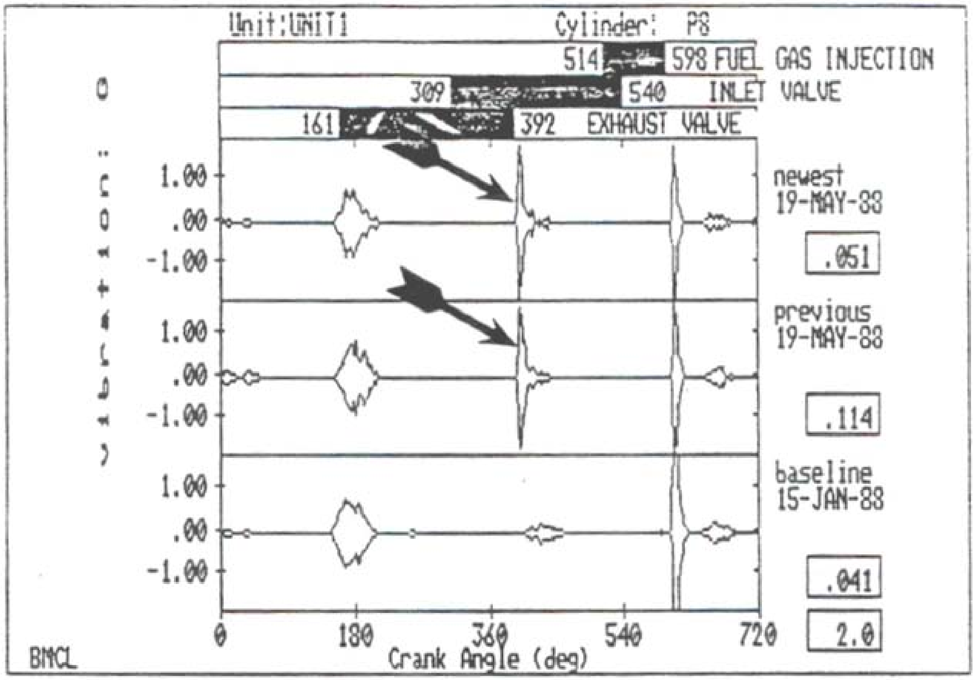


Figure 14 – The CODA Display lets you compare today's vibration data with historical data

Two sets of readings were collected on 19 May, 1988 and both of them show that the exhaust valve is behaving differently from 15 January, 1988. If we assume that the baseline data represents the healthy state of the unit, we must conclude that the health of P8 has deteriorated.

The new and baseline data can be overlaid to detect more subtle changes, as shown in Figure 15. In this display, the regions where the new data exceeds the baseline data are emphasized.

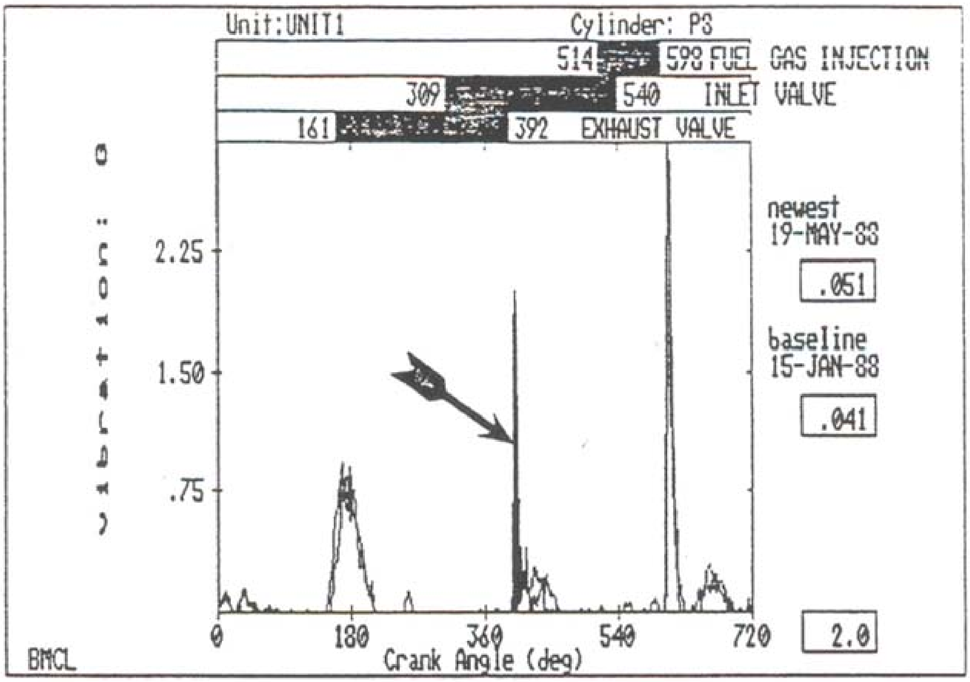
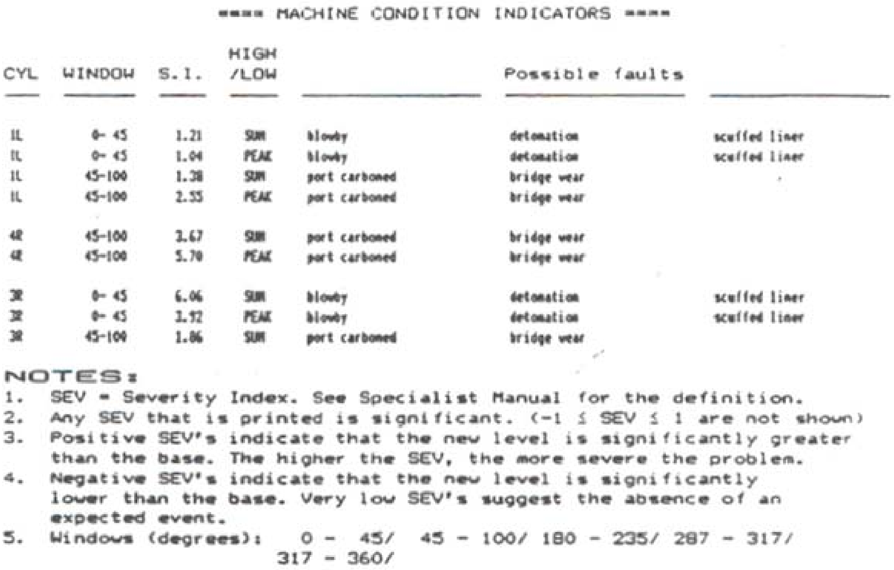


Figure 15 – The new over baseline display emphasizes differences

5.2 Liner and Ring Anomalies

This section presents selected results from the analysis of a large two-cycle engine. Part 2 of the relevant POWERHEALTH Report (Figure 16) indicates several problems.



```
                ==== MACHINE CONDITION INDICATORS ====

                 HIGH
CYL  WINDOW  S.I. /LOW                       Possible faults
---  ------  ---- ----  -----------------  -----------------  -----------------

1L     0- 45  1.21  SUM   blowby             detonation         scuffed liner
1L     0- 45  1.04  PEAK  blowby             detonation         scuffed liner
1L    45-100  1.38  SUM   port carboned      bridge wear
1L    45-100  2.55  PEAK  port carboned      bridge wear

4R    45-100  3.67  SUM   port carboned      bridge wear
4R    45-100  5.70  PEAK  port carboned      bridge wear

3R     0- 45  6.06  SUM   blowby             detonation         scuffed liner
3R     0- 45  3.92  PEAK  blowby             detonation         scuffed liner
3R    45-100  1.86  SUM   port carboned      bridge wear

NOTES:
1.   SEV = Severity Index. See Specialist Manual for the definition.
2.   Any SEV that is printed is significant. (-1 ≤ SEV ≤ 1 are not shown)
3.   Positive SEV's indicate that the new level is significantly greater
     than the base. The higher the SEV, the more severe the problem.
4.   Negative SEV's indicate that the new level is significantly
     lower than the base. Very low SEV's suggest the absence of an
     expected event.
5.   Windows (degrees):   0 -  45/  45 - 100/ 180 - 235/ 287 - 317/
                    317 - 360/
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Figure 16 – The POWERHEALTH Report, Part 2, identifies cylinders whose mechanical condition has changed significantly since the baseline was recorded

The analyst then review the vibration envelope display in Figure 17, to confirm the problems.

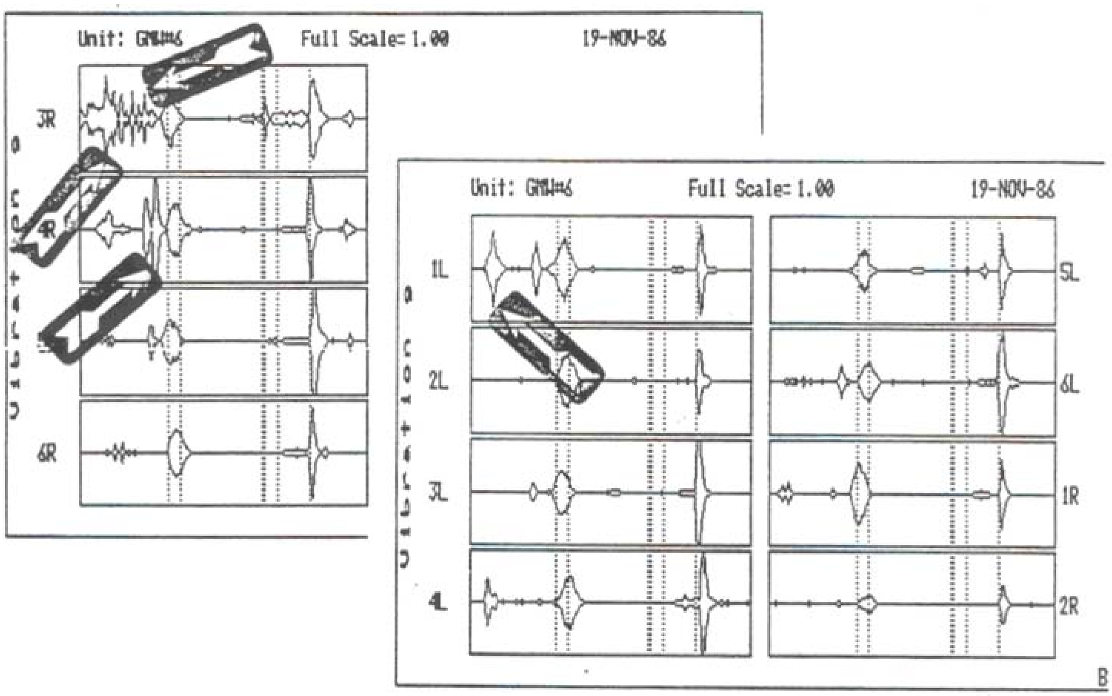


Figure 17 – Power cylinder vibration patterns indicating problems in liners and rings

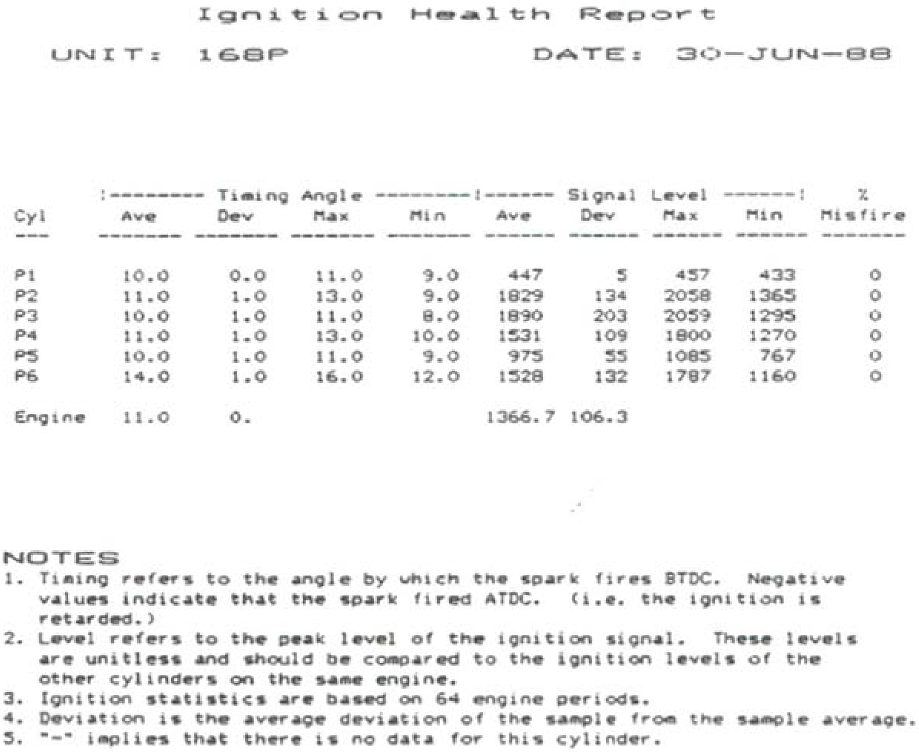
The pattern for Cylinder 1L illustrates a ring blowby case. We can be confident that ring blowby is the problem in the region of 0 – 45 degrees because the pressure in the cylinder rises to a maximum and there are no major mechanical events in this region.

Cylinder 3R exhibits both ring blowby and cylinder liner scuffing during the power stroke. The rounded pattern is indicative of the passage of gas and the sharp, narrow patterns tend to indicate mechanical impacts.

Cylinder 4R exhibits ring clip as two rings pass the exhaust port at approximately 85 – 90 degrees.

5.3 Ignition Analysis

The IGNITION HEALTH Report in Figure 18 presents a statistical analysis of an ignition secondary. The RECIP-TRAP records 64 timing angles, and determines the average, average deviation, maximum and minimum of these. Statistics for the signal level and percentage of misfires are also calculated.



```
                    Ignition  Health  Report

        UNIT:  168P                   DATE:  30-JUN-88



         !--------- Timing Angle ---------!------ Signal Level ------!      %
Cyl        Ave      Dev      Max      Min     Ave    Dev    Max    Min   Misfire
---      -------  -------  -------  -------  ------ ------ ------ ------ -------

P1         10.0     0.0     11.0      9.0     447      5    457    433      0
P2         11.0     1.0     13.0      9.0    1829    134   2058   1365      0
P3         10.0     1.0     11.0      8.0    1890    203   2059   1295      0
P4         11.0     1.0     13.0     10.0    1531    109   1800   1270      0
P5         10.0     1.0     11.0      9.0     975     55   1085    767      0
P6         14.0     1.0     16.0     12.0    1528    132   1787   1160      0

Engine     11.0     0.                     1366.7  106.3



NOTES
1. Timing refers to the angle by which the spark fires BTDC.  Negative
   values indicate that the spark fired ATDC.  (i.e. the ignition is
   retarded.)
2. Level refers to the peak level of the ignition signal.  These levels
   are unitless and should be compared to the ignition levels of the
   other cylinders on the same engine.
3. Ignition statistics are based on 64 engine periods.
4. Deviation is the average deviation of the sample from the sample average.
5. "-" implies that there is no data for this cylinder.
```

Figure 18 – The IGNITION HEALTH Report summarizes the condition of the ignition system

For this unit, note that the timing for P6 is earlier than for the other five cylinders, indicating that the distributor board assembly switch for P6 is probably out of place.

Figure 19 shows ignition primary traces generated by the RECIP-TRAP system.

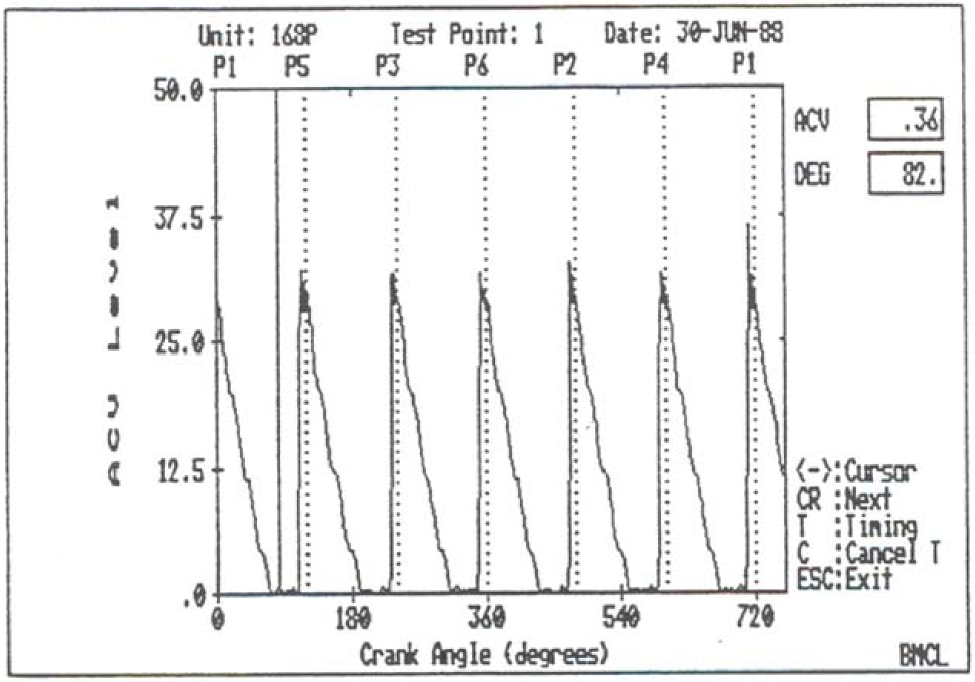


Figure 19 – Ignition primary patterns can be used to evaluate the ignition system

6. Conclusion

Detection and diagnosis of faults in reciprocating machinery is viable. The benefits that can be obtained justify the effort that is required.

Current methods require significant expertise, which is difficult to obtain and maintain. They also require a significant amount of time. The RECIP-TRAP overcomes these limitations, primarily by using computer based analysis.