12. EDG PERFORMANCE MONITORING AND MAINTENANCE

Learning Objectives

In the early stages of nuclear power in the US, more regulatory attention was paid to the design and engineering of the plants than to the requirements for long-term maintenance of plant systems. Once a plant was placed in service the licensees then put varying degrees of attention on system maintenance.

Due to the complexity of EDG's and the critical nature of their safety function as the onsite emergency power supply, they have attracted much attention. As a result, they were one of the first major NPP systems to have regulated maintenance, primarily requirements in Technical Specifications to follow the manufacturer's recommended intervals for maintenance. That caused a number of problems because the guidance from most EDG manufacturers was based on set intervals designed for units in year-around commercial service (e.g., stationary power, tugboats, and locomotives). Unfortunately, those maintenance instructions simply were not appropriate for nuclear applications, which typically involved intermittent standby service with frequent starts but very short run durations

In response, the maintenance philosophy at many nuclear plants today has evolved toward a hybrid condition-based program relying on extensive engine parameter monitoring. In recognition of the need for that approach, IEEE 387-1995 requires that licensee's monitor and track a number of important EDG parameters, those listed in Table 11-2 of the previous Chapter. Other data are needed for a complete, effective monitoring and trending program, including analyses of fuel oil, lubricating oil, etc.

Upon completion of this lesson you will be familiar with the wide range of EDG monitoring and maintenance techniques that help assure reliable operation and you will have a working knowledge of:

1. The difference between Prescriptive (periodic) and Predictive (condition-based) EDG maintenance, and how licensees have benefited from the trend to a Predictive approach.

2. An overview of the key regulatory requirements for maintenance, including the "NRC Maintenance Rule."

3. Monitoring, trending, and analysis of key EDG parameters, including specific engine and support system values during runs, as well as the fuel oil, lubricating oil, cooling water, etc.

4. The importance of baseline data, parameter trending, competent analysis, and follow-up to assure effectiveness.

5. The necessity for observations before, during and after EDG runs, and also in conjunction with any maintenance on (or even in the vicinity of) the EDG.

6. Some applications of EDG monitoring systems…including the human senses.

7. Information on the contribution of each EDG subsystem to the failure rate, and some observations regarding that.

12.1 EDG Maintenance and the Critical Need for Condition Monitoring

The two basic approaches to maintenance of EDG systems will be briefly discussed and compared.

Prescriptive (Calendar-Based) Method

One reason diesel engines were selected to power on-site emergency power systems is their very long history of reliable service in diverse, demanding applications such as locomotives, trawlers, tugboats and oilfield equipment, mostly continuous-duty uses, where equipment may provide power for more than 8000 hours/year.

Manufacturers had published maintenance schedules with daily, weekly, monthly, semi-annual, and annual frequencies. These schedules were acceptable for "continuous service" but inappropriate for nuclear service, where engines are shut down most of the time and typically ran for infrequent, short intervals. Prescriptive maintenance schedules resulted in many unnecessary, intrusive inspections, disassembly for parts replacement, etc. Those operations were not only unnecessary (and costly) but each one gave an opportunity to make errors detrimental to engine reliability. Actual examples include leaving cleaning rags and other foreign objects inside engines, use of improper gaskets, over/under-torque of engine components upon reassembly, etc. An uneducated (yet wise) mechanic might have dryly observed regarding this situation "If it ain't broke, don't fix it."

An additional factor in this equation is that many licensees were also testing EDG's by fast starting, with immediate application of design loads. (Some still are.) It has been estimated that one such start causes wear equal to 35-50 hours run time! A number of failures resulted from this practice.

Predictive (Condition-Based) Method

An increasing number of licensees have adopted much more effective maintenance practices based on equipment condition, as determined by comprehensive monitoring, trending, and competent analysis of EDG system parameters. This method can head off failure by detecting early warning signs such as abnormal temperature, pressure, vibration, wear products, etc.

The condition monitoring program typically includes a wide range of techniques, from simple observation and logging of data by the operator, to chemical analyses of the fuel oil, lube oil, and cooling water, to the use of infra-red (IR) thermal scanning and various types of engine analyzers. All of these techniques require a commitment to more than mere collection of data. It has to be trended and analyzed by competent individuals who can assess the results, make decisions, and get things done. Data that sits in a file or a computer…no matter how accurate and comprehensive…is of no value without human action to make effective use of it.

A well-executed program of predictive, condition-based maintenance will increase EDG reliability, reduce unscheduled down-time, and can reduce maintenance cost as well. It may also prevent a very costly plant outage at some point.

12.2 Overview of Regulatory Criteria Pertaining to System Maintenance

10 CFR 50.65: "Requirements for Monitoring Effectiveness of Maintenance at Nuclear Power Plants." Known unofficially as the **"NRC Maintenance Rule,"** this requires the licensee to monitor the performance of their structures, systems, and components against preset performance goals or criteria they establish, commensurate with safety significance. For EDG's, this document compliments the licensee's FSAR, Tech Specs, and other commitments to maintenance.

Regulatory Guide 1.160, "Monitoring the Effectiveness of Maintenance at Nuclear Power Plants" provides NRC guidance for implementation of the "Maintenance Rule" (discussed above).

NRC Inspection Manual, Chapter 0609, Appendix K is the "Maintenance Risk Assessment and Risk Management Significance Determination Process." It incorporates a method to evaluate licensee maintenance program effectiveness using the Significance Determination Process (SDP) plus Inspection Procedure 7111.13, "Maintenance Risk Assessment and Emergent Work Control."

NUMARC 93-01, Rev 1 (now NEI 1996a) Originally the Nuclear Management and Resource Council, now the Nuclear Energy Institute "Industry Guideline for Monitoring Effectiveness of Maintenance at Nuclear Power Plants" was prepared to give more guidance on 10 CFR 50.65 "Maintenance Rule" implementation.

12.3 EDG Parameter Monitoring and Trending Fundamentals

An effective predictive monitoring program requires an understanding of present diesel generator conditions for each parameter, including the optimum range or value and what represents unacceptable conditions. It further requires systematic trending of each parameter during successive EDG operating cycles or time periods. When a parameter trend begins to deviate significantly toward the unacceptable level during successive monitoring periods, it must trigger an alert for investigation of the underlying cause, to determine what action is required to head off the adverse trend.

This methodology allows for planned, need-based maintenance rather than reactionary corrective maintenance, or the previously discussed prescriptive, "one size fits all" scheduled maintenance. The data from such parameter monitoring can be used to extend the frequency of what scheduled maintenance is still felt to be necessary.

Parameter monitoring will not guarantee elimination of unplanned maintenance on EDG's but the effective application of this approach can minimize the frequency of such events. That fact alone will improve equipment readiness time and resource allocation, which will ultimately reduce the cost of plant operations.

The preferred predictive monitoring applications are those that can be implemented with the engine in service. The various monitoring methods and types of equipment available provide different indications which may be used for determining diesel engine performance and predicting problem trends. For instance, one engine analysis technique may look at phased cylinder pressure characteristics, another at oil condition and contaminants (including wear products), and yet another at vibration signatures or other operating parameters.

The information from monitoring techniques may overlap, providing different indications of the same condition(s). In these cases, integrated analysis of the information can help to confirm adverse trends and isolate problem areas. With diesels or any type of engine, generally no one symptom or test can tell the whole story. Furthermore, all parameter monitoring technology is useless without the resulting data being analyzed competently and used effectively. The effective application of this technology is somewhat engine-specific and with some newer, complex engine analyzers the ability to draw specific conclusions about engine condition from the output is still a work in progress. Even so, the data will still serve to raise a flag indicating some change has occurred in the engine.

The main focus of this Chapter is to review application of the more proven monitoring technologies/techniques, and to introduce some others that may not be as mature or widely accepted. An approach for the integration and systematic analysis of data obtained using these applications will be provided in the summary. Although only partially implemented by the nuclear power industry, integration and analysis of data from monitoring parameters has already improved the success rate for predicting needed maintenance or design changes.

12.4 Monitoring Prerequisites

Equipment Calibration

Data measurements obtained from gauges, meters, or monitoring systems is useless unless its accuracy is verified, meaning a system of equipment calibration is in place. All measurements need to be "traceable" to reference standards maintained by NIST, the National Institute of Standards and Technology (formerly NBS, the National Bureau of Standards), a part of the US Department of Commerce. The licensee should have an equipment calibration system that is certified for compliance to an acceptable standard such as ISO 170125 or MIL-STD-45662A (1985), "Calibration Systems Requirements," the successor document to MIL-C-45662, itself still widely used and referenced by industry.

Ambient Conditions Data

The temperature of engine intake air and cooling air or water (as applicable) can have a substantial engine performance impact. Atmospheric pressure, especially as determined by altitude, is also a major factor. Even humidity can be significant to engine operation. Therefore, the ambient conditions are an important part of engine performance data.

Fuel Oil (Diesel Fuel) Characteristics

Although not a direct engine parameter, diesel fuel qualities can have a profound impact on engine performance and even service lifetime. Accordingly, principal diesel fuel qualities will be covered before discussing EDG parameter monitoring:

12.5 Fuel Oil Quality Monitoring

The EDG manufacturer's qualified output ratings are based upon use of a specific fuel oil having the characteristics needed for proper operation. To ensure that fuel qualities and properties are maintained, the licensee is required to implement a fuel oil monitoring program. The primary standard governing fuel oil monitoring at nuclear power plants is ASTM D-975, "Limiting Requirements for Diesel Fuel Oils." Criteria for diesel fuel oil quality and property limits from ASTM D-975 are incorporated into the plant-specific fuel oil monitoring program.

Licensee failure to maintain appropriate fuel quality and required characteristics can result in the inability of the EDG to perform its design safety function when called upon. Important fuel oil characteristics monitored by the program, and their significance, are discussed below:

Flash point (°F): This is the lowest fuel oil temperature at which continuous vapor generation will sustain flame at a free surface exposed to an oxygen source in the presence of an ignition source. This property is of interest more from a fire protection standpoint than it is for engine performance, although fuels with lower flash points will also typically have lower ignition points. Fire protection codes often encourage fuels with flash points of 65°C (150°F) or above.

Specific Gravity or API Gravity @ 60°F: Relates the weight of fuel to water. Diesel fuels are lighter than water, with specific gravity's under 1.0. However, the API gravity index uses an inverse scale starting at 10.0 for water where the lighter diesel fuels have a higher API gravity number.

Pour point (°F): This is the temperature of the fuel at which it ceases to flow.

Cloud point (°F): This test determines the fuel temperature at which wax present in the fuel will start to form crystals. The name is derived from the fact that the fuel begins to have a cloudy appearance as the effect begins. This characteristic can have a large impact on the performance of filters and injection equipment because the wax crystals will cause clogging/plugging in these components.

NOTE: The manufacturer's qualification rating fuel oil specification may not fit site-specific conditions, particularly those for the temperature sensitive requirements of pour point and cloud point. If the specific licensee's fuel storage temperatures can drop below the temperature specified by the manufacturer for these properties, it puts the EDG in an unanalyzed condition for operation. Temperatures below that specified for pour point cause the fuel oil to become viscous (gel). There may be problems in transporting fuel oil from the storage tanks to the engine cylinders. Temperatures below that specified for cloud point will cause wax crystals to precipitate within the fuel and cloud it. These wax crystals plate out within the fuel oil system including on the critical components such as the fuel injector nozzle tips/orifices. There is considerable increased resistance to flow of the fuel from the increased viscosity and wax crystals particularly through the fuel filters. (Refer to Chapter 13 case studies and IN 94-19.)

Water and Sediment, by centrifuge (% volume): This indicates fuel cleanliness. Water and sediment can result in serious operational impact that may involve fuel injection components. Sediment can foul fuel filters but water also promotes the growth of microbes in diesel fuel storage tanks. In addition to bio-fouling, they can cause microbiologically-induced corrosion, especially of steel pipe and tanks.

Color: Ranges from dark-amber to light-golden. A fuel's natural color (darker or lighter) is not as much concern as changes in color during shipping and storage. Changes in color, usually in the form of darkening, can indicate fuels with unstable properties subject to separation.

Carbon residue, % by weight: This indicates the carbon depositing characteristic of a fuel which can foul injector tips , cylinder head exhaust valves, and piston rings.

Ash (% by weight): Fuel ashes are non-combustible trace minerals and metals in fuels, such as silicon and vanadium. Most are undesirable, as they tend to have an abrasive or corrosive effect on engine components or result in formation of engine deposits. Vanadium in fuels is especially troublesome because it forms Vanadium pentoxide, which can be highly corrosive under certain diesel operating conditions.

Distillation temperatures, (°F) at 90% and end points, at STP: This relates to the volatility or the vaporization tendency of fuel during distillation. In lighter diesel fuels, such as those used in diesels at nuclear facilities, the 90% distillation point is often used. Lighter, more volatile fuels tend to have lower ignition points, which can affect engine starting and running.

Viscosity @ 100°F (Saybolt Universal Sec, SUS): This relates to flow characteristics of the oil. Oils with lower API gravity numbers tend to be more viscous (thicker).

Sulfur *(%* by weight): Trace sulfur contaminates in the fuel can result in acid formation under engine post combustion conditions (i.e. in the presence of water vapor at the required temperature). Lower sulfur fuels are typically preferred for this reason and are especially encouraged under more recent emissions regulations. Because sulfur serves as a lubricant, very low sulfur fuel have additives to provide lubricity. See Chapter 13 discussion of potential issues with **ultra-low sulfur fuel oil,** including lube oil incompatibility.

Copper strip corrosion test (comparative test): This test predicts the copper corrosion characteristics of a fuel, which can be important for engines using copper gaskets and components in fuel system applications.

Cetane number ignition quality test (comparative-qualitative rating). One of the more critical properties of fuels relating to smooth engine operation. The comparison is between cetane with a high ignition quality and heptamethylonane with a low ignition quality. Ignition quality can effect diesel starting times and load acceptance response time among other things. Fuels with higher cetane numbers provide more responsive start times and load acceptance.

Heating value (BTU per lb.). One of the more critical property of fuel. Diesels are heat engines (i.e. they convert stored chemical energy into heat in the engine cylinder to produce work). Fuels with higher heating values per pound tend to be the lighter fuels, but the lighter fuels have lower specific / API gravities. Although the lighter fuels have a higher BTU content per pound, the net effect is that they have a lower BTU content per gallon. Since diesel fuel storage and consumption are monitored in gallons, BTUs per gallon is the critical parameter. As an example, diesels used in nuclear applications frequently had fuel consumption tests performed based on a fuel oil with an API gravity of 28. If those are operated on a lighter fuel (i.e. API gravity of 29 or above) than their initial fuel consumption tests were based on, they will have to burn more fuel to generate the equivalent heat required to produce the same power output. This would place into question the sufficiency of on-site fuel oil storage tanks for the EDG systems.

The time to determine the acceptability of fuel oil shipments is before they are off-loaded into on-site storage tanks. Pro-active licensees will subject samples of delivered fuel to appropriate quality tests before accepting or permitting the fuel to be off-loaded. A program should also be in place to periodically assess the quality of diesel fuel in tanks, as it can be impacted by moisture (condensation / infiltration), tank deterioration (leaks / rusting), aging, and microbial growth.

NOTE: Biodiesel is a particular concern that will be discussed in Chapter 13. It has potential to cause a number of problems.

12.6 Lube Oil Analysis and Trending

Lubrication oil analysis can provide a good general indication of the engine's internal condition. To be representative, the oil samples should be taken downstream of the supply pump and prior to the filter, with the system at normal operating temperature and pressure. Oil analysis will provide information relating to the following:

Lubrication oil condition: Oil properties which indicate condition and age include viscosity, oxidation, total base number / total acid number (TBN / TAN), and the applicable additive concentrations. Typical values for new oil of the type being used should be readily available from the oil supplier or producer. Alert and action values should be established which warn of pending end-of-useful-life for the oil.

Contamination: Contamination of lube oil is usually due to the operating environment. Contaminants monitored may include water, glycol, TBN / TAN changes, SO_x or NO_x level changes, fuel dilution, viscosity changes, and dirt (i.e. silicon, aluminum). Allowable concentrations of contaminants may be given by the engine manufacturer or determined through use of accepted industry standards (e.g. ASTM, etc.). In the absence of these, engineering judgment should be used to establish allowable contamination concentrations relative to a baseline sample of new oil. However, in the latter, the effect of each contaminant on engine life and performance should also be considered independent of the baseline oil contaminant concentration. This is to acknowledge that even baseline new oil samples may contain higher levels of some contaminants than desired, depending on the supplier's formulation and process control. Alert and action values should be established which will allow recognition of contaminated oil early enough to avoid engine damage.

Engine internal component condition: Indications of engine internal mechanical condition and wear are based on metal "wear" particle concentrations in the oil. Typical engine wear metals of interest may include iron, copper, lead, tin, chromium, aluminum, and silver to name a few. The owner/operator should specify expected wear metals of concern to the laboratory performing lubrication oil sample tests to ensure they are included for analysis. Engine component contributors to these wear metals should be identified, and may vary between engine models. Initial guidelines for wear metal alert and action concentrations should be obtained from the engine manufacturer, if available. In the absence of recommendations from the manufacturer, alert/action values should be based on operating experience and engineering judgment, using know values of metal concentrations in oil from the same engine or model when in good mechanical condition.

The licensee is ultimately responsible for the evaluation and interpretation of oil analysis results and needs to stay very engaged in the process, to maximize the value of this application. The success of oil analysis is frequently disappointing whenever this responsibility is turned over to a laboratory or other organization without experience in diesel engine operations. Laboratory personnel are familiar with sampling procedure, technique, and accuracy but frequently lack the knowledge of engine detail and history, which are essential for comprehensive evaluation of the results. Major engine problems have developed and been overlooked due to inappropriate alert limits or the fact that no alert limits had been set at all. Similarly, oversights have occurred when the results were not reviewed in a timely manner by experienced, qualified personnel.

CASE EXAMPLE: Crankcase Explosions

Engine failures occurred in which there were wear metal trend precursors that should have alerted the operators and enabled them to head off the problem. The crankcase explosion events involved the Cooper-Bessemer KSV engines that power EDG units at several nuclear power plants. Figures 12-1 and 12-2 are photographs of two pistons from an engine following an explosion. Fig. 12-1 illustrates a piston with a substantial amount of its tin coating wiped off onto the cylinder liner. Figure 12 2 illustrates a piston with virtually all of its tin coating wiped off, as well as piston and ring damage. The piston was near a seizure condition due to metal scuffing and there is evidence of combustion blow-by.

Even after the first crankcase explosion there was a lack of understanding about the failure mechanism(s) involved, as the situation was complex. Most agreed the failures were due to insufficient lubrication of the surfaces between the piston and the cylinder liner. However, there were other contributing factors, including fast starts, cold intake combustion air, and the engine design including an oil scraper ring (intended to reduce engine oil consumption in typical "continuous-run" commercial service but not appropriate for intermittent duty applications such as EDG's). Before effective corrective action was identified and taken, a total of 13 crankcase explosions occurred at nuclear plants! Changes were made to minimize fast starts, to preheat intake combustion air, and to provide better lubrication to the piston-to-cylinder liner interface. Following these design and procedural modifications, no additional failures of this type occurred in the KSV engine. (For more information, see IN 92-78.)

NOTE: When analyzing oil parameters and characteristics, the rate of change is often a very important consideration for evaluating the significance of findings and determining what action may be needed. Each engine and oil variation in use is unique and must be monitored with that fact in mind. Baseline concentrations of contaminants must be used for reference and trended as part of the process. If engine oil is changed, the prior values and trend data must continue to be part of the analysis. Otherwise all of the accumulated information from past testing and trend analyses of that engine's lube oil is lost.

A good lube oil monitoring program also samples for fuel oil dilution, as this is helpful in determining engine degradation of the type that can make it susceptible to an engine crankcase explosion. Some sources of fuel in the engine crankcase are injectors with leaky or defective needles and seats, leaking fuel injector fittings, or a serious mechanical problem such as a cylinder that is badly worn or misfiring.

12.7 EDG/Support Systems Monitoring

By monitoring, trending, and analyzing EDG operational data an engineer can identify gradual changes in temperatures, pressures, and flows that may indicate a deteriorating condition or impending failure. This can head off problems likely to impact the availability, operational reliability, or performance of the EDG in an emergency.

Engine and support system parameter monitoring provides general indication of mechanical condition and combustion performance. For valid results, the EDG should be operated at repeatable baseline conditions with the monitored parameters stabilized prior to the collection of data. Progressive or step changes in engine or support system parameter values should be analyzed to determine cause. Some of the more important engine and support system parameters and conditions to monitor are as follows:

NOTE: This list includes parameters from IEEE 387-1995 Table 4 that are shown as mandatory "during test" items. (Table 4 is reproduced in Chapter 11 of this Manual and discussed in 11.7). Of course, those NPP's licensed under older revisions of IEEE 387 and RG 1.9 have no obligation to monitor all of these parameters. However, they are required to have an effective system of monitoring the performance of their systems. The relevant items taken from Table 4 are followed by other EDG parameters that can help assess engine and generator condition, as part of the licensee's maintenance program. They are identified with a unique bullet point (➢).

Pressures
- Lube Oil: Engine Inlet
- Lube Oil: Turbo Inlet
- Lube Oil: Engine, Filter Differential
- Lube Oil: Turbo, Filter Differential
- Lube Oil: Engine Header
- Crankcase (Positive/Negative)
- Fuel Oil (Pressure and Flow)
- Cylinder Combustion Air Inlet Manifold
- Cylinder Inlet Manifold Boost Pressure

Temperatures
- Lube Oil: Engine Inlet and Outlet
- Jacket Water: Engine Inlet, Outlet
- Exhaust: Each Power Cylinder
- Exhaust: Turbo Outlet
- Exhaust: Manifold (if applicable)
- Cylinder Combustion Air Inlet Manifold
- Engine Bearings
- Generator Stator

Electrical
- Frequency
- Power (KW)
- Reactive (KVAR)
- Current: Generator, All Phases
- Voltage: Generator, All Phases
- Current: Generator Field
- Voltage: -- Generator Field

Level
- Jacket Water: Standpipe/Expansion Tank Level
- Engine Lube Oil Sump Level
- Generator Bearing Oil Reservoir Level

Other Parameters
- Engine speed
- Fuel rack settings.
- All Alarmed Indications
- Engine bearing temperatures.
- Ambient conditions (temperature, etc)
- Engine hours (calendar time plot)

As discussed in 'Monitoring Prerequisites' (12.4), instrument and gauge calibration is essential for the results of monitoring to be valid and useful. Modifications, repairs, and replacement of equipment or devices should always be accompanied by a fresh calibration to assure continued accuracy. The following case study illustrates this: A generator outboard bearing oil level sight gage was relocated such that the oil level indication showed higher than the actual level. Subsequently, during an endurance run (24-hour), the bearing overheated and caught fire from insufficient lube oil. Root cause was failure to calibrate the oil level gage following a modification that could affect its accuracy. For more info see NRC violation “Catastrophic Failure of Generator Outboard Bearing on Emergency Diesel Generator 14,” dated 30 June 2001.

Engine parameter data may be collected manually from hand written logs, hand held "data-loggers" or with monitoring systems having digital storage-retrieval capabilities. Smart or expert system monitoring and controls have been developed in conjunction with programmable logic controllers (PLC's). Collected data may be stored, manipulated, and evaluated in tables and graphs using a variety of available databases. Even in tabular form, step changes are usually obvious. However, trend graphs help to quickly identify slower progressive changes. They also provide visualization of the magnitude and rate of changes.

Standard troubleshooting and response techniques should be developed for operators to systematically identify and correct the cause of commonly experienced parameter deviations in excess of pre-established limits.

12.8 Jacket and Cooling Water Analysis

Cooling water analysis can provide useful information on cooling system condition and potential problems. Closed loop cooling water testing commonly includes Ph, conductivity, chloride titration, microbiological growth (bacteria count), and additive concentrations. Open loop cooling water sampling usually looks at Ph, total dissolved solids, salt hardness, and microbiological growth as a minimum. For both the main concerns are cooling system fouling, scaling and component corrosion and wastage. Severe fouling, scaling or corrosion can degrade system integrity or heat transfer performance. Poor cooling system performance can ultimately result in degraded engine performance or failure.

12.9 Exhaust Emissions Analysis

Exhaust emissions analysis has developed in more recent years, largely due to government influence through the Environmental Protection Agency (EPA). Therefore, whether or not emissions testing is performed and what is sampled for is often viewed from a regulatory compliance standpoint. However, in a broader sense emissions testing can reveal useful information on engine combustion performance and condition. This can be useful to identify an engine in need of closer monitoring or adjustments. As with other applications, data collected for emissions analysis should be under repeatable and comparable conditions. Exhaust emissions analysis typically includes the following parameters:

Primary Combustion Byproducts:

Carbon Monoxide (CO) - Possible rich fuel/air equivalence or high temperature dissociation. This is a measure of combustion efficiency.

Unburned hydrocarbons (HC) - Possible crevice volume effect, flame quench, lubricating oil. Associated with engine condition and efficiency.

Particulate (soot) - Possible rich unburned fuel spray/fuel-core zone or lubricating oil.

Secondary Byproducts Linked to the Combustion Process:

Nitrogen Oxides (NOx) - Usually nitrogen reaction with high temperature burned gases. Largely related to combustion temperature (i.e. thermal NOx), it can be associated with possible injection timing, spray pattern or air temperature issues.

Sulfur Oxides (SOx) - Usually associated with fuel sulfur content. They have very little value for monitoring engine performance, especially with Ultra-Low Sulfur fuels.

Increases in emission levels from baseline values can be caused by things such as timing changes, degraded fuel system performance or general engine/cylinder condition.

If exhaust emissions testing technology, and equipment costs continue to improve, this may become an increasingly valuable quick check to evaluate general engine combustion performance and condition.

12.10 The Use of "Engine Analyzers" to Monitor EDG Performance

Engine analyzers are available that monitor cylinder pressures, temperatures, and vibration, integrating the resulting data with crankshaft angle and fuel rack position. Supplementary equipment can monitor lube oil parameters "on-line" (as the EDG runs), providing additional real-time data. The systems trend the data and compared it to baseline. Such comprehensive, whole-engine monitoring is costly but it gives EDG operators a potentially powerful tool to monitor engine performance and health. As with any other monitoring scheme, the key is to have competent analysis and follow-up of the resulting data. The US Navy has done work in this area using their Integrated Condition Assessment System (ICAS). The lube oil analysis can either be done on-line as indicated, or by the more common off-line method, where samples are regularly sent to a laboratory for test. This type of integrated monitoring can often predict (and, thereby, prevent) many potential engine failures. A discussion of some specific engine analyzers and engine monitoring equipment follows:

12.10.1 Phased Cylinder Pressure Type

Phased cylinder pressure data can provide important information on individual cylinder pressure characteristics through engine cycles. (See Figures 12-3 through 12-6.) Relative comparison of cylinders can provide an indication of overall engine performance and balance. This type of equipment provides the following data:

- Peak firing pressure spreads, deviation
- Peak firing pressure angle (phased cylinder pressure)
- Rate of cylinder pressure change (first derivative, psi/degree)
- Mean effective pressure
- Indicated horsepower
- Reference compression pressure
- Reference exhaust terminal pressure
- Reference intake terminal pressure

When this information is reviewed considering load, fuel rack position, air intake temperature, manifold pressure, and cylinder exhaust temperature, a picture of engine performance by cylinder is obtained. Pressure data is typically reviewed in tabular form and/or on pressure-time (PT, often related to crankshaft angle) and pressure-volume (PV) curves.

The engine average cylinder peak pressure and peak pressure spread are reliable indicators to monitor for engine deviation from baseline conditions. The magnitude of individual cylinder peak pressure can provide an indication of stress within that cylinder. Therefore, cylinders with excessive peak pressures should be considered for the possible effects on component integrity.

NOTE: Matching peak firing pressures between cylinders within a predetermined band is the most accurate method of engine balancing (peak firing pressure balancing). However, high cylinder peak pressure can occur for a variety of reasons and in some cases the cylinder with the highest peak pressure is not the cylinder actually carrying the highest load (although the anomaly still warrants correction).

There are more accurate (and much more complex) means to balance engine cylinder load but they are generally not considered worth the effort, as they exceed industry expectations for overall engine balancing. Therefore, peak pressure balancing is often accepted as the best available method for balancing. It enables adjustments to be made that improve engine balance, timing, and cycle efficiency (i.e. performance). Later in this Chapter a more simple method of cylinder balancing will be covered, one that is frequently practiced in the field.

12.10.2 Phased Engine Vibration (VT) and Ultrasonic (UT) Type

Phased vibration and ultrasonic traces can provide valuable insight to engine component mechanical condition and combustion events. Data is typically collected at the same time as cylinder pressures. Probes used to collect cylinder vibration and ultrasonic traces should be placed in the same location each time, for consistent and comparable data. When relocating probes to improve data collection, potential differences in traces should be considered when compared with earlier traces.

The phased VT and UT traces obtained from this equipment can provide an indication of engine mechanical performance and condition, including the following attributes:

- Valve train condition
- Main bearing condition
- Piston to cylinder interaction
- Injector nozzle characteristics
- High pressure injection pump status
- Cylinder combustion characteristics
- Piston blow-by and cylinder-ring interaction
- Magnitude and duration of the exhaust blow-down event
- Piston pin, articulated pin, or connecting rod bearing condition
- Base/frame looseness or alignment.
- Turbocharger and/or supercharger status, including bearing condition

These phased analyzers provide a means to monitor for vibration and ultrasonic frequency anomalies and changing conditions for the EDG components noted above. These signatures can be graphed over a cylinder/engine cycle. Each graph has a VT5 trace which represents ultrasonic noise and a VT4 trace that represents vibration monitored at selected points for each cylinder. The cylinder's pressure trace can also be superimposed on the same graph. Intake and exhaust valve opening and closure event anomalies can often be identified. Of these anomalies, the most common is a collapsed valve hydraulic lifter. However, other valve anomalies detected have included valve stem galling or separation of chrome plating (resulting in sticking valves) and defective valve roller tappets.

This monitoring of injection pumps and nozzles has detected leaking injector needle valves and fuel pump delivery valves. Less frequently, degrading fuel injection pump tappets may be detected.

12.11 Practical Cylinder Balancing by an Approximation Method

Smooth and reliable engine operation depends on an even power balance between the cylinders. This balance is determined from the temperatures and pressures occurring in each cylinder. Cylinder exhaust temperature is measured by pyrometers located in the exhaust gas outlet elbows adjacent to the cylinder exhaust ports. Cylinder pressures are frequently measured using special gauges connected to cylinder test ports with passages connecting to the combustion space.

Although cylinder pressures are the *preferred method* of balancing an engine, the pyrometers remain connected to the engine during operation whereas the cylinder test gauges are connected only long enough to take the required readings and then removed (as they will not provide reliable service for long periods in that harsh environment). Therefore, cylinder temperatures are often used and are the most convenient indicator of cylinder balance during routine operation. As a "rule of thumb," balanced engines will normally have:

- Cylinders with exhaust temperature deviations **<** 150 ºF on the average.
- Cylinders with cylinder firing pressure deviations **<** 150 PSI on the average.

NOTE: In the past cylinder balance has often been done in the field by adjusting fuel control racks to increase or decrease fuel to individual cylinders until balanced temperature conditions are reached with the EDG at or close to full load. However, this practice can result in fuel delivery and cylinder temperature biasing at other than full load. Cylinder temperatures can then vary widely (in excess of the recommended 150°F average) at less than full load conditions. The preferred method for engine balancing is by cylinder firing pressures, accomplished by timing adjustments and/or injection equipment performance improvements.

12.12 Crankcase Oil Mist Detection of Engine Mechanical Distress

Several companies offer crankcase oil mist detection systems that warn of engine mechanical issues such as cylinder wall or piston scuffing, incipient bearing failure, etc. All depend on the fact these problems are accompanied by localized hot spots that cause lube oil to boil, producing oil mist in air samples aspirated from the engine. Although all engines have some oil mist in their crankcase area, the concentration in a normal engine is typically below 2 mg/liter, while the lower explosive limit (LEL) for lube oil mist is ≈ 50 mg/liter. The better instruments provide calibrated oil mist concentrations, likely using forward-scatter of an LED light beam into a photodiode receiver, much as a modern photoelectric smoke detector. As the problem gets worse, rising mist concentrations are logged (with alarms at set levels). See Figure 12-7.

12.13 Infrared (IR) Scanning -- An Effective, Under-Utilized Tool

Many operational anomalies and incipient failures in engines, generators, electrical systems, and support equipment result in pronounced temperature variations from the norm. Overheating is often the first sign of impending failure in a generator winding or bearing, an electrical circuit, transformer, or switchgear, a pump motor, etc. Large variations in cylinder loading may be seen as temperature differences between those cylinders, where the exhaust manifold connects. These and other anomalies may be detected by an IR scan that is compared to a baseline scan. In some situations the temperature gradient is so pronounced as to not even require baseline data. Portable equipment to take IR images of equipment is very easy to use, readily available, and can be very cost-effective. Once again, the item being observed should be stabilized at a steady-state load.

12.14 Visual & Other Human Senses Have a Vital Role in Reliability

12.14.1 The "Walk Around" Inspection

The emphasis thus far in this Chapter has been on the use of technology, some of it high-tech and high-cost, for EDG condition monitoring. However, visual observations and other human senses can be extremely effective in identifying equipment anomalies.

Think of the aviation example, where a crewmember of a highly instrumented aircraft costing perhaps 50 million dollars or more takes the time for a simple walk-around before flight, checking for tire problems, leaking fluids, damaged (or gust locked) control surfaces…anything that could represent a potential problem to safe flight (often based on industry experience).

Likewise, an EDG operator is required to visually check the system before run, to verify it's configured properly and that no anomalies are apparent. Following each run a repeat inspection is required, to check the equipment over for problems and to verify it has been configured for possible automatic (emergency) use.

The need for such systematic checks before and after each EDG run was demonstrated by a number of failures that occurred simply because a switch or valve or some other control was inadvertently placed in or left in the wrong position. In many cases that occurred following some very routine EDG check or maintenance procedure.

A simple walk-around inspection with a check list provides a first-hand assessment of engine and support systems status. While such inspection is primarily visual, other senses can provide valuable input. An overheating transformer or motor will often manifest itself through unusual odor. An experienced hand on a generator bearing housing may detect unusual heating as a signal of distress and eventual failure. The protesting sound of a fuel oil pump or engine room cooling fan, or unusual noise from a relay, etc. should trigger action.

NOTE: Knowledge of critical components especially what is normal, versus marginal or abnormal, is vital to success.

Engine visual inspections often provide the most information regarding the condition of specific components. They can discover new conditions previously unidentified by monitoring, or confirm indications from engine monitoring systems. Regardless, suspect indications obtained from engine monitoring systems will generally require some degree of inspection to determine the scope of corrective actions necessary. This is the pay line. An oversight at this stage can negate the information gained from sophisticated engine monitoring equipment.

12.14.2 Assembled Inspections

Assembled visual inspections are the least intrusive and frequently involve use of boroscopic/videoscopic equipment with tape or disk storage capabilities. Minimal disassembly and/or removal of engine access covers is usually all that is required. Since this is the least intrusive it is the most desirable form of visual inspection and may be scheduled periodically or as a condition-based task. High resolution imaging equipment can then be used to evaluate potential component degradation. When using various imaging equipment such as boroscopes, fiberscopes, or videoscopes, the inspection plan should consider the limitations of the inspection equipment and engine access limitations. For example, upper or mid piston skirt scuffing may go undetected due to access limitations from an engine lower end inspection.

12.14.3 Disassembled Inspections

Disassembled inspections are the most intrusive form of visual inspection and may require extensive engine or component tear-down. Disassembled inspections are the last resort in visual inspections. They are only recommended if justified by cross checking analysis results from other monitoring applications or by assembled inspections.

For either type of engine or component visual inspection, a clear roadmap for the effort is essential. The following should be planned and discussed with inspection personnel prior to commencing:

- Areas to be inspected
- Expected normal condition
- Any areas of special concern
- Suspected abnormal condition(s).
- Information on the availability of parts
- Preliminary action plan if an abnormal condition is confirmed by the inspection

Monitoring Summary

Engine and technology improvements have affected data collection and analysis for EDG systems. None of the described monitoring schemes or systems will provide complete, conclusive information on engine health and maintenance needs. However, the integration and competent analysis of data from all the means employed will greatly enhance system reliability and availability. A successful EDG predictive monitoring program will have:

- Access to monitored data collected under consistent and reproducible conditions, and compared to baseline data.
- Review by experienced personnel who are knowledgeable with engine design details and operations.

Whenever an alert limit is reached, two things should immediately happen:

- Confirm the alert by additional analysis or inspections.
- Review other available data that may either confirm or refute the indication.

Analysis and corrective action are expected for all confirmed EDG anomalies.

12.15 Selected Maintenance Concerns and Observations for EDGs

Lubrication and Oil Changes

Engine oil change interval is typically based on manufacturer recommendations. Due to the large volume of engine oil used (1-2 gallons per hour), oil change frequently involves monitoring engine oil analysis results for degrading conditions which would warrant oil change.

Generator pedestal bearing oil changes are frequently conducted on some set periodicity, such as 18 to 24 months, due to the smaller quantities involved.

Governor oil changes are also frequently conducted on some set periodicity, such as 18 to 24 months, due to the smaller quantities involved.

Exposed linkages and mechanisms such as the fuel control linkages, racks, and overspeed trip devices require occasional lubrication and frequent inspections to maintain them in an operational condition.

Improper lubrication or lubricants can lead to component damage or EDG inoperability. Consider the following case study examples.

Example 1: Improper Generator Bearing Oil

On March 3, 2000, while conducting 18-month preventive maintenance, personnel added the incorrect oil (too low viscosity) to the inboard and outboard bearings of the generator for EDG 11. Low oil viscosity might cause bearing degeneration and failure during EDG operation. From March 3 until April 1, the plant was operated at various levels of power up to 97 percent. The plant was shut down from April 2 to April 12 during which the bearing oil was replaced with the correct oil. Based upon the Significant Determination of Risk Process, the EDG was considered inoperable between the periods of March 3 to April 12. The risk significance was considered low because the other three EDG units were operable during this time. (Refer to NRC NCV, May 19, 2000.)

Example 2: Formulation Changes of Engine Lube Oil

Recommended engine lube oils used in EMD engines contained a chlorinated additive that made the waste oil unacceptable for disposal. An oil was authorized which did not contain the chlorinated compound. This oil had been successfully used by the railroads in their EMD engines for several years. However, the operating conditions and demands on the lube oil are different. Railroad engines start slowly and infrequently and run almost all the time. Nuclear plant engine start fast and often and run infrequently.

Three nuclear plants reported wrist pin bearing failures after the change in oil. Consultant evaluations were made to determine root causes. They reported:

1. The chlorinated additive in the previous oil was there specifically to increase the oil's ability to cling to bearing surfaces during

long periods of shutdown and to provide extreme pressure lubrication capabilities.

2. The new oil did not provide the equivalent extreme pressure capabilities or the adherence qualities of the former oil.

3. The lubrication problem is aggravated by frequent starts and long shutdown procedures.

4. There is concern for the other bearings in the engine.

5. Lube oil analysis wear metals alert level may be too high.

For a detailed description of this problem, refer to NRC IN 2002-22, "Degraded Bearing Surfaces in GM/EMD Emergency Diesel Generators," including consultant reports.

EDG Support Systems are Major Contributors to Inoperability Incidents

Most long-term studies have attributed EDG systems failures to engine-mechanical in only 5% to 10% of cases. This record is testimony to the durability and reliability of diesels. The logical question then is why put so much emphasis on monitoring the engine if it causes so few failures? The answer, of course, is that such failures are usually catastrophic and very costly, while problems with support systems can be addressed in much less time, at lower cost.

This statistic points out the need for a comprehensive approach to EDG system reliability, one that puts adequate resources on support system operability. For data on the approximate failure rate of each EDG sub-system, based on many years of licensee event reports (LERs), refer to Figure 12-8 at the end of this Chapter.

Post-Maintenance Inspections Critical

Many EDG failures have been attributed to the lack of an effective post-maintenance inspection after any work is done on the EDG, any of its support systems, or just in the vicinity of the EDG. Some examples will be discussed in Chapter 13. These failures are completely preventable, which is what makes them so unnecessary, yet some of them have occurred again and again. The most common involve maintenance work in the vicinity of the EDG (but not on it), such as painting the engine room, cleaning the floor, or plumbing problems a level above.

Engine "Air Roll" or "Bar" Check

Following engine maintenance the post-maintenance run begins with an air roll to verify freedom of movement. The air roll is performed with the cylinder test cocks open and the fuel control racks in the no fuel position. A start signal is generated to rotate the engine several times to clear out any moisture trapped in the cylinders. Maintenance personnel observe the test cocks during the air roll for signs of water or other liquids present in the cylinder. A small mist of water, sometimes mixed with oil emitted from the test cocks is acceptable. Test cocks are then closed and the engine is placed in an operational mode.

NOTE: Failure to close the test cocks will not prevent engine start but flames will shoot out of each one, with much noise!

Engine Owner Groups

To pool the knowledge and experience gained by various nuclear facilities, owners groups have been formed. The common denominator in these groups is the model or brand of engine used. For example, in 1982 or 1983, those plants having installed Enterprise model R&RV diesel engines formed the TDI (Transamerica-DeLaval) Owner's Group. Their effort lead to the development of the Design Review Quality Revalidation (DRQR) program. Each TDI engine was disassembled, extensively inspected, modified, and reassembled to assure it could reliably perform its vital safety function when called upon.

Currently, there are numerous active nuclear EDG owners groups in operation. Licensees should be encouraged to network with other owners on common, relevant EDG operational and performance issues.

Long Term Aging Concerns, and NPP Operating License Extensions

These comments pertain to PNL-10717, "A Review of Information Useful for Managing Aging in Nuclear Power Plants" (Compiled by W. C. Morgan and J. V. Livingston, Nov 1997). In Section 9 "Emergency Diesel Generator" it specifically addresses EDG aging issues, which have been heightened by the extension of many NPP licenses.

The report states, "Most of the EDG components were designed for continuous use, not for standby and intermittent service. However, except for the periodic testing requirements imposed under Regulatory Guide 1.108 (U.S. Nuclear Regulatory Agency 1977) (now withdrawn), stressors affecting the aging of EDG units at nuclear power plants are quite similar to those imposed on EDG systems supplying hospitals, military facilities, and other critical installations."

PNL-10717 further observes that "An important finding of these studies was that the EDG fast-starting and fast-loading testing program, undertaken in response to the old Regulatory Guide 1.108 (U.S. Nuclear Regulatory Agency 1977), was itself a major contributor to premature aging of the EDG units. The current applicable Regulatory Guide 1.9, Revision 3 has greatly reduced this source of aging stressors." *(Ed note: Rev 4 now applies.) However, not all licensees have embraced the new test procedures designed to lower unnecessary engine stressing and wear.*

Comprehensive Report on Diesel Engine Analyzers, Their Use, and Limitations

The subject of diesel engine analyzers is far too broad and complex for full treatment in this Manual. Those who wish to learn more about the application of these system are encouraged to obtain and study the EPRI 'Diesel Engine Analysis Guide' (TR-107135), prepared in 1997 and made available to the public in December, 2006. This illustrated, 143-page Guide is available for download at no cost from EPRI and other web sites. It includes a summary of the engine analysis equipment offered by four manufacturers.
http://my.epri.com/portal/server.pt?space=CommunityPage&cached=true&parentname=ObjMgr&parentid=2&control=SetCommunity&CommunityID=404&RaiseDocID=TR-107135&RaiseDocType=Abstract_id

Tin removed from side of piston, exposing the base metal (dark area).
Some scoring of piston base metal, plus indication of sticking rings.
The direct result of inadequate lubrication (multiple underlying causes).
Figure, 12-2 shows this effect on another piston with more severe damage.

Figure 12-1 Piston with Advanced Tin Smear

Essentially all tin removed from sides, exposing the base metal (dark area).
Scoring of piston base metal, entrapped rings, and evidence of blowby.
The direct result of inadequate lubrication (multiple underlying causes).

Figure 12-2 Failed Piston -- Tin Wiped Off

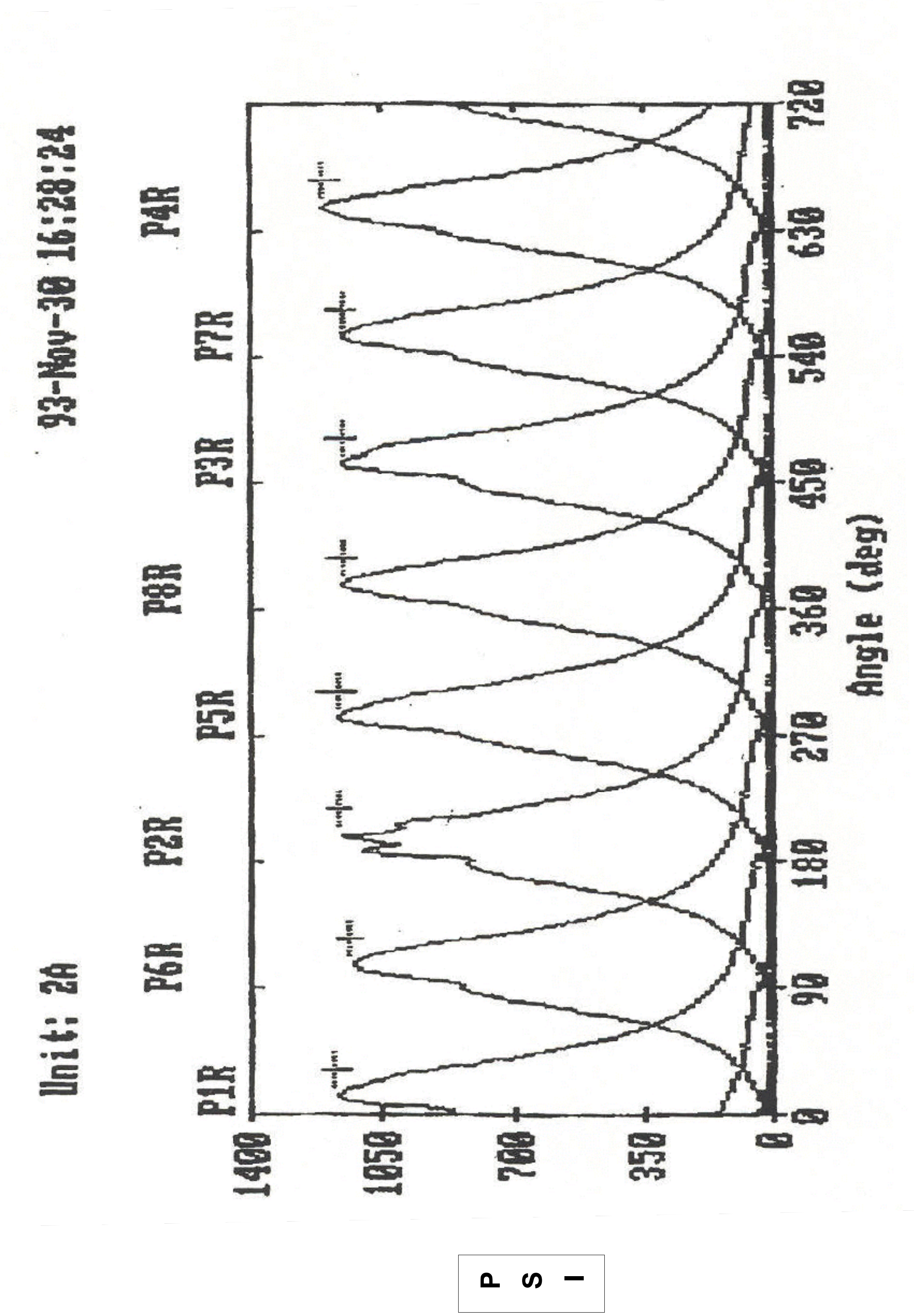


Figure 12-3 EDG Diagnostic Report – PFP vs. Crank Angle (Right Bank)

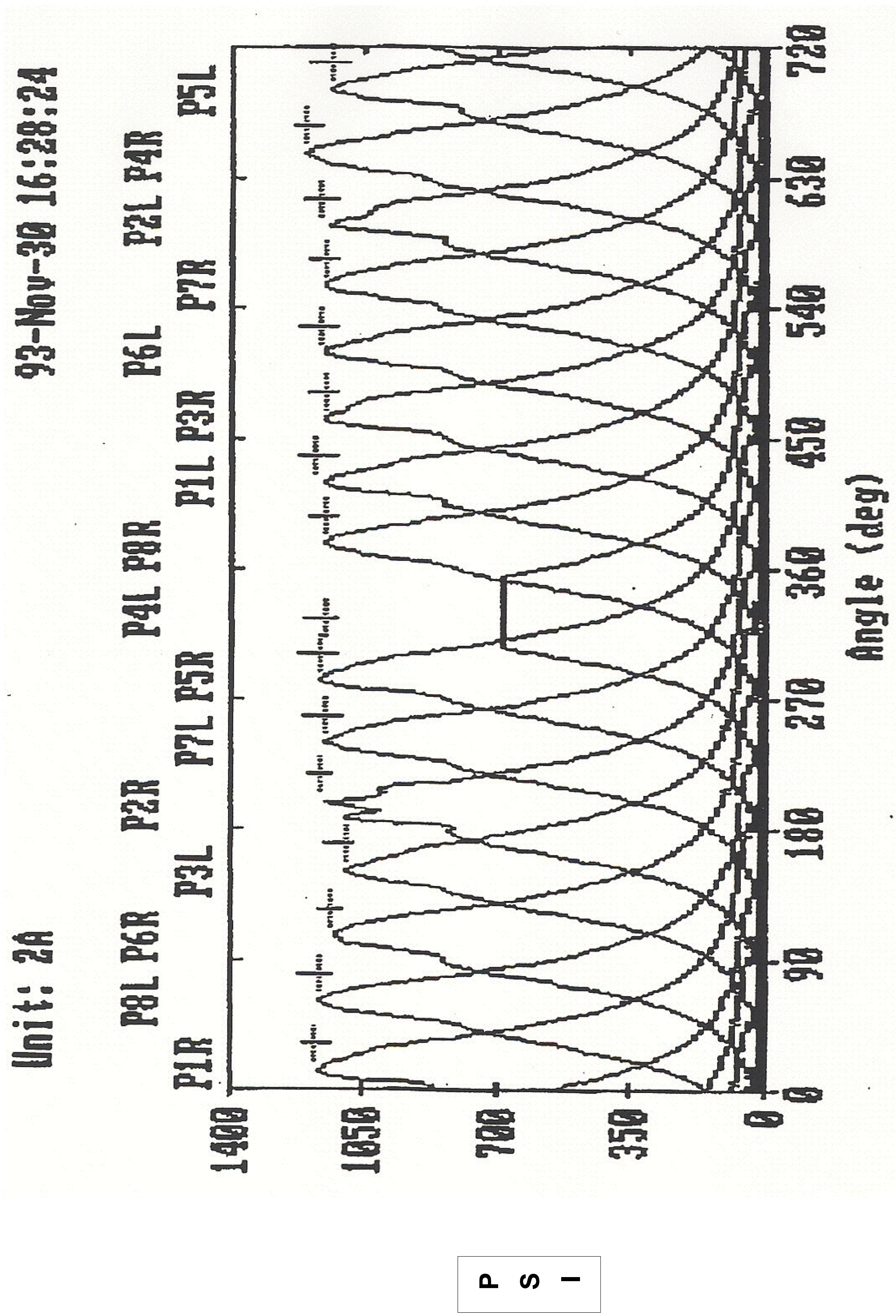


Figure 12-4 EDG Diagnostic Report – PFP vs. Crank Angle (16 Cylinders)

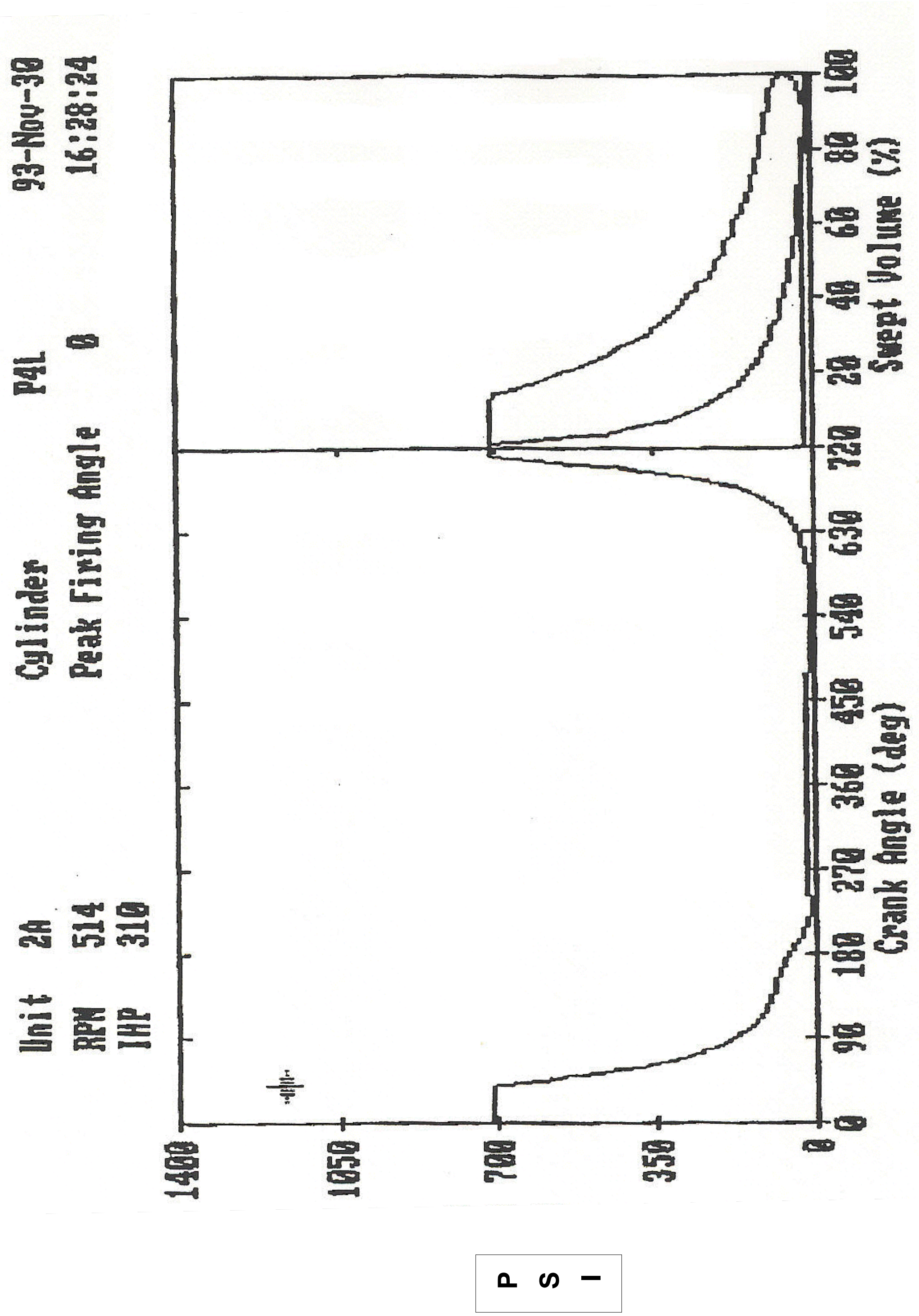


Figure 12-5 EDG Diagnostic Report – PFP vs. Crank Angle (& Swept Volume (4L)

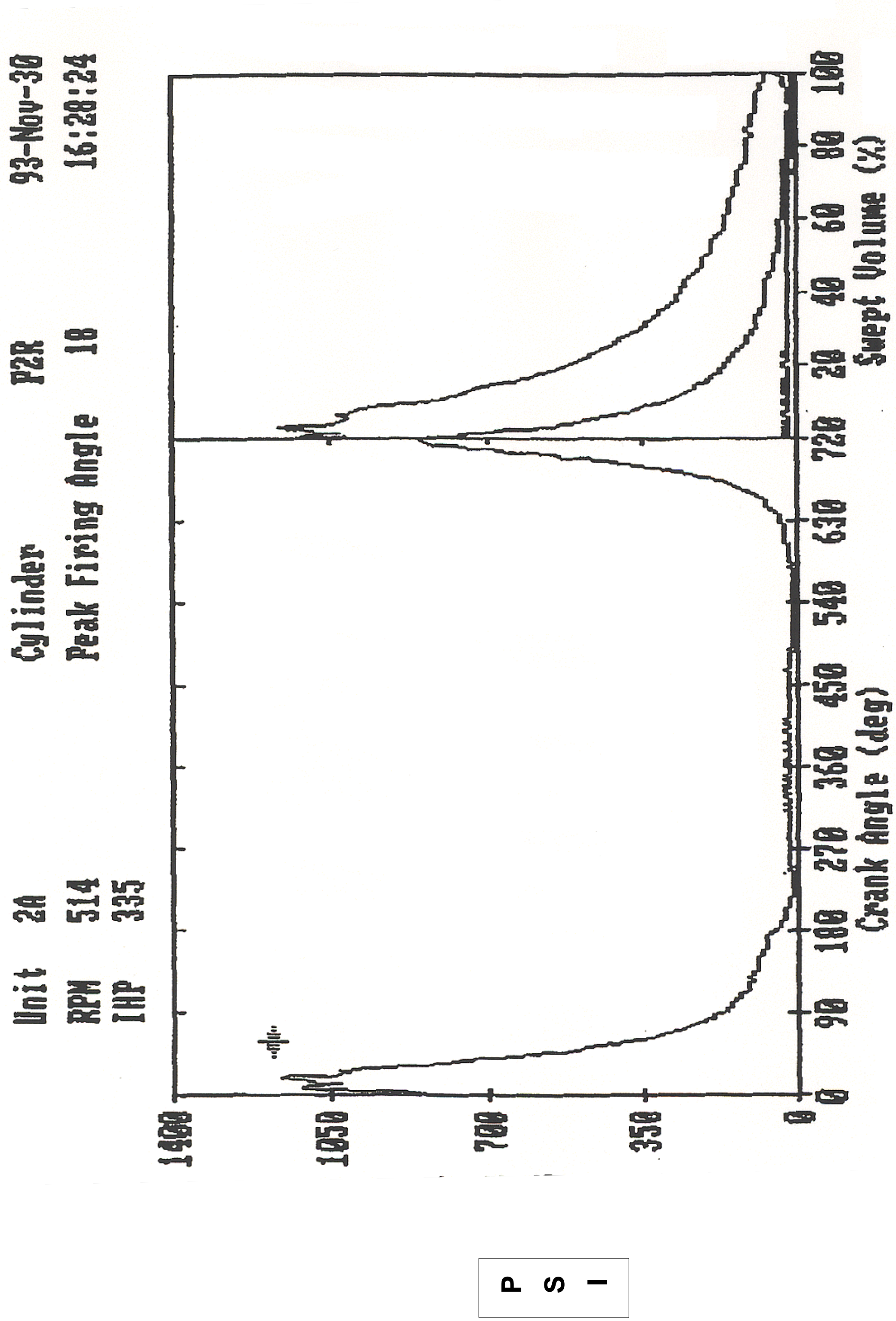
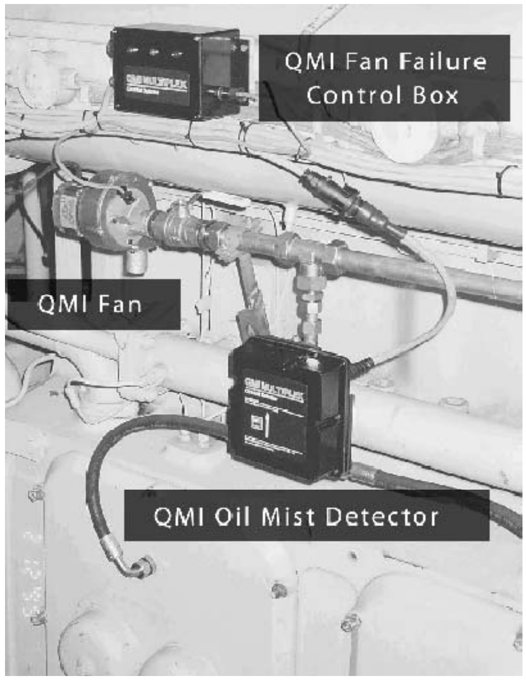


Figure 12-6 EDG Diagnostic Report – PFP vs. Crank Angle (& Swept Volume (2R)



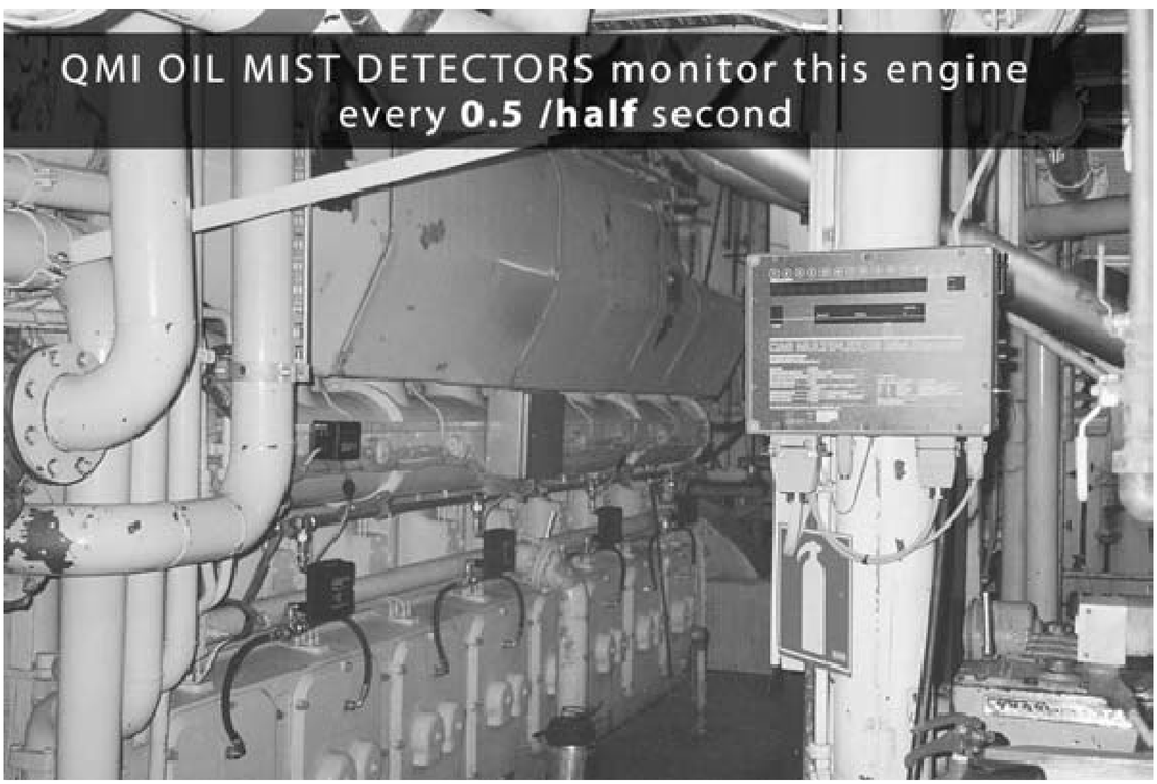


Figure 12-7 Crankcase Oil Mist Monitoring System

System	Source			
	INEL	SwRI	U.S. Navy	NPRDS
I&C	30.1%	14.4%	0%	17.3%
Fuel Oil	24.9%	23.9%	24.6%	10.1%
Electrical	22.7%	20.8%	5.3%	0%
Cooling Water	7.6%	8.9%	19.3%	9.4%
Engine Mechanical	4.9%	10.3%	36.8%	4.6%
Lube Oil	4.5%	8%	7%	11.9%
Air Start	4.5%	13.8%	7%	46.9%
Ventilation	0.7%	0%	0%	0%

NOTES:

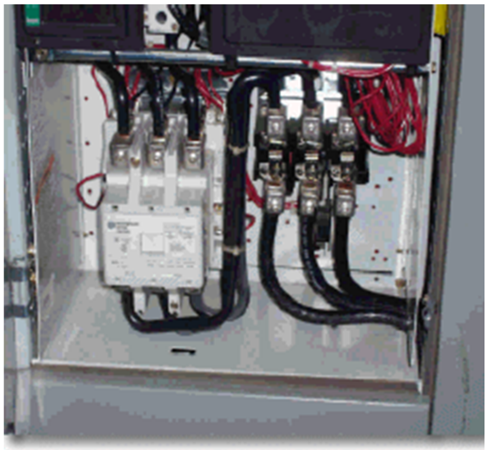
Idaho National Engineering Laboratory (INEL) data is for 353 LERs, 1987-1993.

Southwest Research Institute (SwRI) data is based on 689 LERs, 1968-1982.

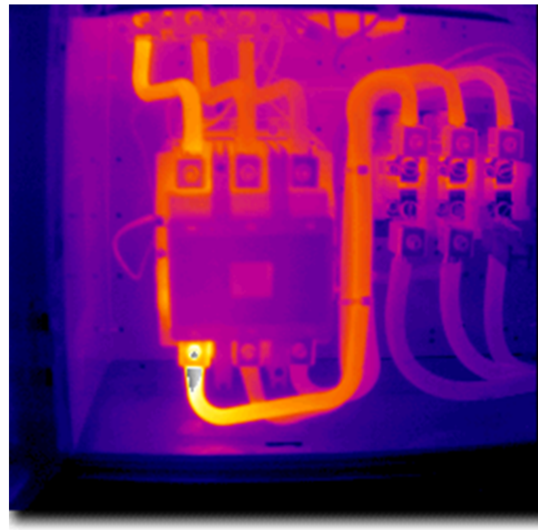
US Navy data is skewed by piston-cylinder failures with one engine family, plus a high rate of cooling water problems. Their Instrumentation and Control data also does not correlate with the other sources.

Nuclear Plant Reliability Data System (by Institute of Nuclear Power Operations) includes many EDG event reports that are not in NRC's LER system due to being a non-demand situation and, therefore, not required to be reported.

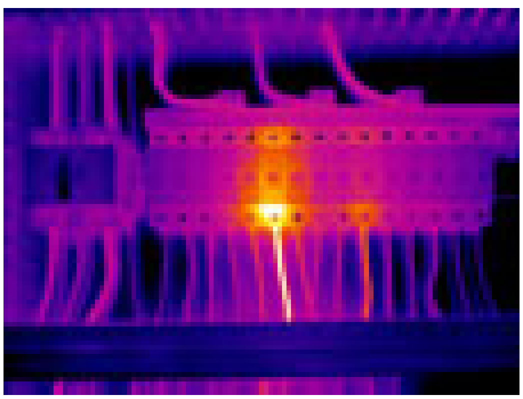
DG Failures by Responsible System



ORDINARY VISUAL INSPECTION

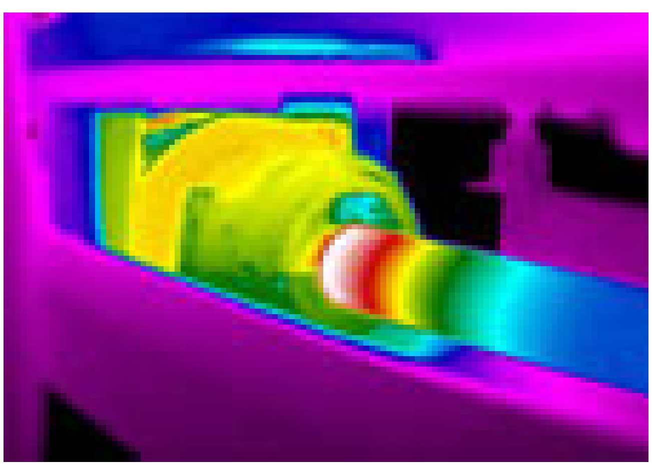


IR THERMOGRAPH OF SAME EQUIPMENT



FAILING ELECTRICAL TERMINATION

FAILING LEG OF 3-PHASE FUSE BLOCK



⇦ FAILING SHAFT BEARING

Figure 12-9 IR Thermographs of Impending Failures